

Modifications of Coherent Structures in Fan Blade Wakes for Broadband Noise Reduction

Aurelien Borgoltz

Dissertation submitted to the Faculty of the Virginia Polytechnic Institute
and State University in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

In

Aerospace Engineering

William J. Devenport, Chair

Ricardo Burdisso

Wing F. Ng

Joseph A. Schetz

Roger L. Simpson

October 29, 2007
Blacksburg, Virginia

Keywords: Turbulence, Coherent Structures, Aircraft Engine, Fan,
Broadband, Noise, Rotor-stator interaction, Serrated Trailing Edge, Trailing
Edge Blowing.

Copyright © 2007 by Aurelien Borgoltz

Modifications of Coherent Structures in Fan Blade Wakes for Broadband Noise Reduction

Aurelien Borgoltz

(Abstract)

The effects of trailing edge flow control on the wakes of a linear cascade of idealized fan blades was investigated experiments with a view to the likely effects on broadband aircraft engine interaction noise. Single and three-component hotwire velocity measurements were made downstream of the cascade for a chord Reynolds number of 390,000 and a Mach number of 0.07. Measurements of the two-point velocity correlation were used extensively to evaluate the impact of various flow control strategies on the organization of the coherent structures of the wakes and their potential to generate noise.

A baseline flow was established by measuring the wake downstream of unmodified GE-Rotor-B blades. Four sets of serrated trailing edge blades (with two different serration sizes and with two trailing edge cambers) and three sets of blades with trailing edge blowing (a simple rectangular slot, rectangular slot with Kuethe-vane vortex generators, and rectangular slot with serrated lips) were tested.

The serrated trailing edges introduce corrugations into the wake, increase the wake decay and width as well as turbulence levels (possibly because of the blunt trailing edge created at the serration valley). The serrated trailing edges also increase the turbulence scales in the direction perpendicular to the plane of the wake because of the injection of streamwise vorticity. In almost all cases the serrations reduce the spanwise and streamwise turbulence scales. Serrations do not, however, affect the apparent time scale of quasi-periodic structures in the wake, and this appears to limit the potential of this trailing edge treatment to reduce broadband noise. The analysis of the characteristic eddies (obtained from proper orthogonal decomposition combined with linear estimation) revealed that the serrations do not change the qualitative form of the eddies.

Trailing edge blowing was found to significantly decrease the wake deficit and width as well as the turbulence levels at all blowing rates. Blowing through the simple

rectangular slot, at mass flow rates between 1.4 and 2.0% of the total passage through flow, was shown to significantly affect the size, the organization and the strength of the coherent structures. For small blowing rates the strong spanwise eddies near the trailing edge actually appear to be enhanced. For larger blowing rates, however, the turbulent scales are reduced in all directions. The addition of Kuethe vanes on the suction side of the blowing blade results in a low momentum region just downstream of the vanes that may result from flow separation there. This further enhances the shedding and increases the blowing rate needed to overcome it. The serrated blowing blades show the greatest potential to reduce broadband noise as they reduce the turbulence levels and scales without creating potentially detrimental structures.

While no acoustic measurements were made, analysis of hypothetical perpendicular and parallel interactions of blades with these wakes has made possible to characterize for the first time the impact of the changes in the eddy structure of these wakes on their potential to generate broadband noise. The serrated trailing edges (especially the larger serrations) actually increase the potential of the wake to generate broadband noise (a direct consequence in the overall increase in turbulence scale and intensity). In contrast, every trailing edge blowing configuration was found to produce large reductions in the potential noise (a maximum of 6dB reduction was obtained at 2.0% blowing). The addition of Kuethe vanes on the suction side of the blowing blades significantly reduced the efficiency of the simple blowing configuration (a result of the increased coherency associated with the shedding of streamwise vorticity by the vanes). The serrated blowing configuration was found to yield reductions similar to the simple blowing configuration.

Acknowledgements

I would like to begin by thanking my family. First of all my parents, none of this could have been possible without the unconditional support and love from my parents, Brigitte and Frédéric Borgoltz. You have provided the best environment anybody could hope to grow up in and always encouraged me to pursue my dreams, even when it meant moving half-way across the world. For this I will always be deeply indebted to you. I would also like to thank my brother, Alexandre Borgoltz. You have been an inspiration all my life and a role model in more ways than you know. This dissertation is dedicated to all of you.

Next, I would like to acknowledge my advisor and mentor, Dr. William Devenport. You have taught me much more than technical knowledge. Your kindness and selflessness might be only equaled by your remarkable ability to always ask for more data. You are the teacher and researcher that I hope someday I can become.

As for my doctoral work described in this dissertation, I would like to thank Dr Edmane Envira and Dr. Brian Fite at NASA Glenn for their support through the grant NCC3-1026. Very special thanks go to my advisory committee consisting of Dr. Ricardo Burdisso, Dr. Wing Ng, Dr. Joseph Schetz, and Dr. Roger Simpson for their time, advice, and constructive comments throughout this project. I would also like to acknowledge Dr. Chittiapa Muthanna for teaching me the fundamentals of hot-wire anemometry. In this regard great appreciation goes to Dr. Ruolong Ma who spent several hours teaching me the importance of proper equipment set-up along with the dark art of repairing hot-wire probes. I would also like to express my gratitude to Dr. Patrick Mish who introduced me to the subject of aero-acoustics and *guided* me during my undergraduate research.

Bruce Stanger and James Lambert in the AOE Machine Shop also deserve all my gratitude for helping putting the trailing edge blowing system together. Their craftsmanship has been a blessing on numerous occasions.

I must thank all of my friends here at Virginia Tech who, over the past 7 years, have made Blacksburg my home away from home. I would like to thank Beatriz Diaz

Acosta and JV Larssen, Nicolas Spitz, Derek Geiger, Dustin Grissom, and Liz Craig for making research and life in Blacksburg so much more enjoyable. I would also like to thank the current members of the Advanced Turbulent Flows Research Group: Erin Crede, Bill, and especially Ben U.W. Smith and Josh TheK. Staubs.

Finally, I would like to thank my friend Dr. Nanyaporn Intaratep who spent countless hours helping me setting up measurements. Most importantly, you have helped me (so much more than you know) and pushed me to move forward when things appeared insurmountable. You made me better.

Aurelien Borgoltz

November 2007

Blacksburg, VA

Table of Contents

<i>Nomenclature</i>	x
<i>List of Tables</i>	xiii
<i>List of Figures</i>	xv

<i>Chapter 1 - Introduction</i>	1
1.1. Background on Aircraft Noise Restrictions.....	1
1.2. Fan Noise Reduction.....	3
1.3. Current Research Motivations: Wake Management Solutions for Broadband Noise Reduction.....	5
1.4. Objectives and Approach to Wake Management Solutions for Broadband Noise Reduction	5
1.5. Dissertation Layout.....	7

<i>Chapter 2 - Literature Review</i>	10
2.1. Research Interest: Wake Management.....	10
2.1.1. Review of Previous Passive Wake Management Research	10
2.1.2. Review of Previous Active Wake Management Research	13
2.1.2.1. Fundamental Research on Active Wake Management: Momentumless Wakes	13
2.1.2.2. Active Wake Management Research Conducted on Cascades and Model Engines	15
2.2. Previous Studies Conducted in the Virginia Tech Low Speed Cascade Wind Tunnel	22
2.3. Synthesis of Previous Work on Wake Management.....	26
2.4. Statistical Methods for Turbulent Wakes	26
2.4.1. Proper Orthogonal Decomposition	27
2.4.2. Compact Eddy Structures	27
2.4.3. Broadband Excitation.....	28

<i>Chapter 3 - Instrumentation and Measurement Techniques</i>	31
3.1. Virginia Tech Low Speed Linear Cascade Wind Tunnel	31
3.1.1. Upstream Section	31
3.1.2. Test Section.....	32
3.1.2.1. Inlet Section	32
3.1.2.2. Blade Row.....	33
3.1.2.3. Downstream Section	36
3.2. Measurement Equipment	37
3.2.1. Pressure Sensing	37

3.2.1.1.	Pitot-Static Measurements	37
3.2.1.2.	Surface Pressure Measurements	38
3.2.2.	Hot-wire Anemometry	38
3.2.2.1.	Hot-Wire Probes	38
3.2.2.2.	Constant Temperature Anemometers	39
3.2.2.3.	Calibration process.....	39
3.3.	Probe Mounting and Positioning	40
3.3.1.	Probe Holders.....	40
3.3.2.	Three-Axis Traverse	41
3.4.	Coordinate Systems	41
3.5.	Facility Calibration	42
3.6.	Sampling Schemes and Measurement Uncertainties	44
Chapter 4 - Modified Blade Designs.....		52
4.1.	Serrated Trailing Edge Blades	52
4.1.1.	1.27cm Serration	53
4.1.2.	1.27cm Serration with Droop.....	55
4.1.3.	2.54cm Serration	57
4.1.4.	2.54cm Serration with Droop.....	59
4.2.	Trailing Edge Blowing System.....	61
4.2.1.	Blowing Blade Geometries	61
4.2.1.1.	Simple Blowing Blades.....	63
4.2.1.2.	Kuethe Blowing Blades	63
4.2.1.3.	Serrated Blowing Blades.....	65
4.2.2.	Air Delivery System	65
4.2.3.	Stabilizing Pins	66
4.2.4.	Blowing System Calibration	67
Chapter 5 - Select Single Point Results.....		77
5.1.	Blade Loading	77
5.1.1.	Baseline Blades	77
5.1.2.	Serrated Trailing Edge Blades	79
5.1.3.	Trailing Edge Blowing Blades.....	80
5.2.	General Downstream Flow Characteristics	84
5.2.1.	Baseline Blades.....	84
5.2.2.	Serrated Trailing Edge Blades	86
5.2.3.	Trailing Edge Blowing Blades.....	88
5.3.	Basic Wake Analysis	89
5.3.1.	Definition of Wake Parameters.....	89
5.3.2.	Baseline Wake Characteristics.....	90
5.3.3.	Serrated Trailing Edge Blade Wake Characteristics.....	92
5.3.3.1.	Mean Velocity Results.....	92
5.3.3.2.	Turbulence Stress Results	92
5.3.4.	Trailing Edge Blowing Wake Characteristics.....	93
5.3.4.1.	Mean Velocity Results.....	93
5.3.4.2.	Turbulence Stress Results	95

Chapter 6 - Two-Point Measurements.....	113
6.1. Theoretical background	113
6.1.1. Two-Point Velocity Correlation	113
6.1.2. Statistical Methods for Turbulent Wakes	114
6.1.2.1. Proper Orthogonal Decomposition	115
6.1.2.2. Compact Eddy Structures	116
6.2. Measurements Strategies	117
6.2.1. Measurement Schemes.....	117
6.2.1.1. Pitchwise Measurements.....	117
6.2.1.2. Spanwise Measurements.....	118
6.2.1.3. Sampling Scheme.....	119
6.2.2. Measurement Locations.....	119
6.2.2.1. Baseline Blades.....	119
6.2.2.2. Serrated Trailing Edge Blades	120
6.2.2.3. Trailing Edge Blowing Blades.....	122
6.3. Data Reduction.....	124
6.3.1. Pitch and Yaw Rotations.....	124
6.3.2. Single-Point Data Adjustment	124
6.3.3. Formatting the Two-Point Space-Time Correlation Data.....	125
6.4. Results and Discussion	127
6.4.1. Two-Point Time Delay Correlation in the Z-direction	127
6.4.1.1. Baseline blades.....	127
6.4.1.2. Serrated Trailing Edge Blades	133
6.4.1.2.1. 1.27cm Serrations	133
6.4.1.2.2. 1.27cm Drooped Serrations	135
6.4.1.2.3. 2.54cm Serrations	137
6.4.1.2.4. 2.54cm Drooped Serrations	139
6.4.1.3. Trailing Edge Blowing Blades.....	142
6.4.1.3.1. Simple Blowing Blades.....	143
6.4.1.3.2. Kuethe Blowing Blades	149
6.4.1.3.3. Serrated Blowing Blades.....	151
6.4.2. Two-Point Time Delay Correlation in Y-direction.....	155
6.4.2.1. Summary	158
6.4.3. Characteristic Eddy Decomposition	163
6.4.3.1. Characteristic Eddies associated with the Baseline Blades	164
6.4.3.2. Impact of Trailing Edge Serrations on the Characteristic Eddies...	167
6.4.3.3. Impact of Trailing Edge Blowing on the Characteristic Eddies	171
6.4.3.4. Summary	174

Chapter 7 - Acoustic Estimations.....	224
7.1. Theoretical Background.....	225
7.1.1. Perpendicular Blade-Wake Interaction	225
7.1.2. Parallel Blade-Wake Interaction	227
7.2. Broadband Excitation.....	228
7.2.1. Perpendicular Blade-Wake Interaction	228
7.2.1.1. Impact of Trailing Edge Serrations on the Broadband Excitation..	230

7.2.1.2.	Impact of Trailing Edge Blowing on the Broadband Excitation	234
7.2.2.	Parallel Blade-Wake Interaction	237
7.2.3.	Summary	240
Chapter 8 - Conclusions.....		272
8.1.	Impact of Flow Control Strategies on the Turbulence Structure	273
8.2.	Impact of Flow Control Strategies on the Broadband Excitation	275
8.3.	Future Work	277
Bibliography		279
Vita.....		283

Nomenclature

Abbreviations

<i>BET</i>	B roadband E xcitation T erm
<i>BPF</i>	B lade P assing F requency
<i>CES</i>	C ompact E ddy S tructure
<i>FFT</i>	F ast F ourier T ransform
<i>IFFT</i>	I nverse F ast F ourier T ransform
<i>POD</i>	P roper O rthogonal D ecomposition
<i>TKE</i>	T urbulence K inetic E nergy

Roman

b	Cutting blade half-chord
c	Blade total chord
c_a	Blade axial chord
C_p	Static pressure coefficient
C_{p0}	Total pressure coefficient
C_{ps}	Surface pressure coefficient
E	Average energy in a fluctuating velocity field
E_N	Turbulence kinetic energy contained in the first N POD modes
f_N	Nyquist frequency
F	Sampling rate
g	Blade response function
G_{ij}	Velocity spectrum tensor
h_{trip}	Boundary layer trip strip height
i, j	Indices running from 1 to 3 (associated with the three velocity components)
J''	Broadband excitation term for a parallel blade-wake interaction

$J^\perp$	Broadband excitation term for a perpendicular blade-wake interaction
k	Turbulence kinetic energy
K	Constant used for trip strip height calculation
L_u'	Half-wake width (based on the streamwise Reynolds stress profile)
L_w	Half-wake width (based on mean streamwise velocity profile)
M	Mach number
N_s	Number of sample divided by 2
N_z	Number of distinct points across the wake (for two-point measurements)
p	Radiated acoustic pressure
P	Local static pressure in the tunnel
P_∞	Inlet freestream static pressure
P_0	Local total pressure in the tunnel
P_s	Blade surface static pressure
$P_{0\infty}$	Inlet freestream total pressure
$\mathbf{r}$	Position vector relative to the origin
Re	Reynolds number
Re_{ft}	Reynolds number per foot
R_{ij}	Time delay velocity correlation
R_{ww}	Upwash cross-spectrum
S_{pp}	Acoustic pressure spectrum
u', v', w'	Fluctuating velocity components (wake aligned system)
$\overline{u'^2}, \overline{v'^2}, \overline{w'^2}$	Time averaged normal Reynolds stress components
$\overline{u'v'}, \overline{u'w'}, \overline{v'w'}$	Time averaged shear stress components
u^{LSE}	Estimated velocity field (from linear stochastic estimation)
U, V, W	Mean velocity components in wake aligned coordinate system
U_∞	Freestream inlet velocity
U_e	Wake edge velocity
U_u'	Wake deficit (based on the peak streamwise Reynolds stress)

U_w	Maximum wake deficit (based on the mean streamwise velocity)
x, y, z	Cascade aligned coordinate system (referenced to lower end wall)
x_b, y_b, z_b	Cascade aligned coordinate system (referenced at the blade tip)
X, Y, Z	Wake aligned coordinate system
z_{fixed}	Fixed hot-wire probe pitchwise location
z_{moving}	Moving hot-wire probe pitchwise location

Greek

Γ	Blade circulation
ζ	Normal-to-wake range of integration
η	Distance along the blade thickness
θ	Momentum thickness
$\kappa_i^{(n)}$	i^{th} component of the n^{th} Compact Eddy Structure
$\lambda^{(n)}$	POD Eigenvalue for the n^{th} mode
ξ	Distance along the blade chord
ρ	Density
τ	Time delay
$\phi_i^{(n)}$	i^{th} component of the POD modal profile for the n^{th} mode
ω	Frequency

List of Tables

Table 3.1 Coordinates of the GE Rotor B airfoil.....	33
Table 3.2 Two-point four-sensor hotwire measurement absolute uncertainties.....	44
Table 4.1 Coordinates of the pressure ports on the 1.27cm serration blades. Cascade aligned coordinates are referenced from the leading edge and normalized on the axial chord.....	54
Table 4.2 Coordinates of the pressure ports on the 1.27cm drooped serration blades. Cascade aligned coordinates are referenced from the leading edge and normalized on the axial chord.....	56
Table 4.3 Coordinates of the pressure ports on the 2.54cm serration blades. Cascade aligned coordinates are referenced from the leading edge and normalized on the axial chord.....	58
Table 4.4 Coordinates of the pressure ports on the 2.54cm drooped serration blades. Cascade aligned coordinates are referenced from the leading edge and normalized on the axial chord.....	60
Table 4.5 Coordinates of the pressure ports on trailing edge blowing blades. Cascade aligned coordinates are referenced from the leading edge and normalized on the axial chord.....	62
Table 4.6 Blowing jet velocity variation with blowing rate for the simple blowing blades. Velocity is normalized on the inflow velocity U_∞	63
Table 4.7 Blowing jet velocity variation with blowing rate for the Kuethe blowing blades. Velocity is normalized on the inflow velocity U_∞	64
Table 4.8 Blowing jet velocity variation with blowing rate for the Kuethe blowing blades. Velocity is normalized on the inflow velocity U_∞	65
Table 5.1 Blade circulation $\Gamma/U_\infty c_a$ for the various blowing configuration.....	82
Table 5.2 Wake parameters for the baseline configuration at axial locations of $x/ca=0.61$, 1.18, 1.82, and 2.38. (Geiger, 2005).....	90
Table 6.1 Two-point measurement locations for the serrated trailing edge blades (see figure 5.11 to visualize positions).....	121
Table 6.2 Half-wake width $L_{u'}$ and wake deficit $U_{u'}$ downstream of the serrated trailing edge blades.....	121
Table 6.3 Two-point measurement locations for the trailing edge blowing blades (see Figure 5.12 through 5.14 to visualize positions).....	123
Table 6.4 Half-wake width $L_{u'}$ and wake deficit $U_{u'}$ downstream of the trailing edge blowing blades.	123
Table 6.5 Turbulence lengthscales (normalized on half-wake width $L_{u'}$) generated by the serrated trailing edge blades.....	159

Table 6.6 Absolute turbulence lengthscales (normalized on the axial chord c_a) generated by the serrated trailing edge blades.....	160
Table 6.7 Turbulence lengthscales (normalized on the half-wake width $L_{u'}$) generated by the trailing edge blowing blades.	162
Table 6.8 Absolute turbulence lengthscales (normalized on the axial chord c_a) generated by the trailing edge blowing blades.	163

List of Figures

Figure 1.1 Relative Importance of Various Noise Sources in Aircraft with High Bypass Ratio Engine (Adpated from Envia, 2001).	9
Figure 2.1 Fourier Decomposition of the mean velocity profiles of Geiger (2005) measured 1.8 axial chord downstream of the trailing edge.	30
Figure 2.2 Fourier Decomposition of the mean velocity profiles of Craig (2006) measured 1.8 axial chord downstream of trailing edge blowing blades with (a) simple blowing (b) Kuethe blowing.	30
Figure 3.1 Virginia Tech Low Speed Linear Cascade Wind Tunnel overall layout. (<i>Dimensions in meters</i>) From Muthanna, 2002.	46
Figure 3.2 Views of the upstream section of the linear cascade wind tunnel. Modified from Geiger (2005).	46
Figure 3.3 Top view of the Virginia Tech Linear Cascade Wind Tunnel Test Section. (<i>Dimensions in meters</i>). Adapted from Muthanna (2002).	47
Figure 3.4 Cross-section of the Boundary Layer Scoops and Blade Row.	47
Figure 3.5 GE Rotor B profile.	48
Figure 3.6 Side Scoop of Blade 8.	48
Figure 3.7 Schematic of a four-sensor Kovaznay-type, subminiature hotwire probe. From Intaratep, 2006.	49
Figure 3.8 Four-sensor hot-wire probe holders. (a) Top View (b) Side View.	49
Figure 3.9 Two-point four-sensor hot-wire probe set-up inside the test-section.	50
Figure 3.10 Three-axis traverse system (adapted from Intaratep, 2006).	50
Figure 3.11 Coordinate systems definitions.	51
Figure 3.12 Downstream calibration plot for the baseline GE Rotor B blades.	51
Figure 4.1 Geometric views of the 1.27cm serration blade: (a) Isometric view (model) (b) plan view (actual), (c) tip view (model), (d) close-up of serrations (model) (all dimensions in cm). <i>From Geiger (2005)</i>	68
Figure 4.2 Geometric views of the 1.27cm drooped serration blade: (a) Isometric view (model) (b) plan view (actual), (c) tip view (model), (d) close-up of serrations (model) (all dimensions in cm). <i>From Geiger (2005)</i>	69
Figure 4.3 Geometric views of the 2.54cm serration blade: (a) Isometric view (model) (b) plan view (actual), (c) tip view (model), (d) close-up of serrations (model) (all dimensions in cm). <i>From Geiger (2005)</i>	70
Figure 4.4 Geometric views of the 2.54cm drooped serration blade: (a) Isometric view (model) (b) plan view (actual), (c) tip view (model), (d) close-up of serrations (model) (all dimensions in cm). <i>From Geiger (2005)</i>	71
Figure 4.5 Simple blowing blade.	72
Figure 4.6 Kuethe blowing blade.	73

Figure 4.7 Serrated blowing blade.	74
Figure 4.8 Trailing edge blowing blades internal passage and convergent nozzle designs. NASA Glenn.	75
Figure 4.9 Trailing edge blowing blade stabilizing pins: (a) conceptual diagram and photographs of (b) trailing edge pin (c) leading edge pin.	76
Figure 5.1 GE Rotor B blade loading.	98
Figure 5.2 Blade loading variation with incidence angle – Panel method results.	98
Figure 5.3 Re-measurement of the 2.54cm serration blade loading.	99
Figure 5.4 Simple blowing blade loading for various blowing rates (expressed as fraction of the mass flux through the passage).	99
Figure 5.5 Kuethe vane blowing blade loading for various blowing rates (expressed as fraction of the mass flux through the passage).	100
Figure 5.6 Variation of the blade circulation with blowing rate for the simple, Kuethe, and serrated blowing blades.	100
Figure 5.7 Serrated blowing blade loading for various blowing rates (expressed as fraction of the mass flux through the passage).	101
Figure 5.8 Pitot-Static cross-section of the mean streamwise velocity at $x/ca=0.84$ downstream of the baseline blades. <i>Note the horizontal axis direction is reversed.</i>	101
Figure 5.9 Pitot-Static cross-section of the mean streamwise velocity at $x/ca=1.88$ downstream of the baseline blades. <i>Note the horizontal axis direction is reversed.</i>	102
Figure 5.10 Pitot-Static cross-section of the mean streamwise velocity at $x/ca=0.84$ downstream of the serrated trailing edge blades (From Geiger, 2005). <i>Note the horizontal axis direction is reversed.</i>	102
Figure 5.11 Pitot-Static cross-section of the mean streamwise velocity at $x/ca=1.88$ downstream of the serrated trailing edge blades (From Geiger, 2005). <i>Note the horizontal axis direction is reversed.</i>	103
Figure 5.12 Pitot-Static cross-section of the mean streamwise velocity at $x/ca=1.88$ downstream of the simple blowing blades (From Craig, 2006).	103
Figure 5.13 Pitot-Static cross-section of the mean streamwise velocity at $x/ca=1.88$ downstream of the Kuethe blowing blades (From Craig, 2006).	104
Figure 5.14 Pitot-Static cross-section of the mean streamwise velocity at $x/ca=1.88$ downstream of the serrated blowing blades.	104
Figure 5.15 Wake parameters definition.	105
Figure 5.16 Half-wake streamwise variations downstream of the baseline blades.	105
Figure 5.17 Wake deficit streamwise variations downstream of the baseline blades.	106
Figure 5.18 Normalized streamwise mean velocity profiles for the baseline blades.	106
Figure 5.19 Pitchwise and spanwise averaged TKE for the serrated trailing edge blades at $x/ca=1.88$	107
Figure 5.20 Normalized streamwise velocity profiles for the trailing edge blowing blades at $x/ca=1.88$ plotted for various blowing rates (expressed as % of the mass flux through the passage). Simple and Kuethe blowing data reproduced from Craig (2006).	107

Figure 5.21 Half-wake width variations with blowing rate for the trailing edge blowing blades obtained at different axial locations between $x/ca=0.6$ and 2.4. Baseline values are indicated at a blowing rate of 0%. Simple and Kuethe blowing data from Craig (2006).	108
Figure 5.22 Momentum thickness variations with blowing rate for the trailing edge blowing blades obtained at different axial locations between $x/ca=0.6$ and 2.4. Baseline values are indicated at a blowing rate of 0%. Simple and Kuethe blowing data from Craig (2006).	108
Figure 5.23 Pitchwise averaged TKE for the trailing edge blowing blades at $x/ca=1.88$ as a function of blowing rate (expressed as % of the mass flux through the passage).	109
Figure 5.24 Streamwise Reynolds stress $\overline{u'^2}$ profile downstream of the serrated trailing edge blowing blades at $x/ca=1.88$ for various blowing rates.	110
Figure 5.25 Spanwise Reynolds stress $\overline{v'^2}$ profile downstream of the serrated trailing edge blowing blades at $x/ca=1.88$ for various blowing rates.	110
Figure 5.26 Normal-to-wake Reynolds stress $\overline{w'^2}$ profile downstream of the serrated trailing edge blowing blades at $x/ca=1.88$ for various blowing rates.	110
Figure 5.27 Reynolds shear stress $\overline{u'w'}$ profile downstream of the serrated trailing edge blowing blades at $x/ca=1.88$ for various blowing rates.	111
Figure 5.28 Reynolds shear stress $\overline{u'v'}$ profile downstream of the serrated trailing edge blowing blades at $x/ca=1.88$ for various blowing rates.	111
Figure 5.29 Reynolds shear stress $\overline{v'w'}$ profile downstream of the serrated trailing edge blowing blades at $x/ca=1.88$ for various blowing rates.	111
Figure 5.30 Turbulence kinetic energy profile downstream of the serrated trailing edge blowing blades at $x/ca=1.88$ for various blowing rates.	112
Figure 6.1 Measurement grid for the two-point pitchwise profiles. Fully populated grid is indicated by x and actual measurement grid shown with o.	175
Figure 6.2 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the baseline blades, plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$	176
Figure 6.3 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the baseline blades. <i>The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.</i>	177
Figure 6.4 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 1.27cm serration blades (serration valley), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$	178
Figure 6.5 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 1.27cm serration blades (serration valley). <i>The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation</i>	

maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	179
Figure 6.6 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 1.27cm serration blades (serration peak), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$	180
Figure 6.7 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 1.27cm serration blades (serration peak). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau Ue/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	181
Figure 6.8 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 1.27cm drooped serration blades (serration valley), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$	182
Figure 6.9 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 1.27cm drooped serration blades (serration valley). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau Ue/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	183
Figure 6.10 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 1.27cm drooped serration blades (serration peak), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$	184
Figure 6.11 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 1.27cm drooped serration blades (serration peak). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau Ue/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	185
Figure 6.12 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 2.54cm serration blades (serration valley), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$	186
Figure 6.13 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 2.54cm serration blades (serration valley). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau Ue/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	187
Figure 6.14 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 2.54cm serration blades (serration peak), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$	188
Figure 6.15 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 2.54cm serration blades (serration peak). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau Ue/L_{u'}$ on the horizontal. For each component, the time-delay	

correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	189
Figure 6.16 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 2.54cm drooped serration blades (serration valley), plotted against normalized normal to wake directions Z/L_u and Z'/L_u	190
Figure 6.17 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 2.54cm drooped serration blades (serration valley). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance Z/L_u on the vertical axis and normalized time delay $\tau Ue/L_u$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	191
Figure 6.18 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 2.54cm drooped serration blades (serration peak), plotted against normalized normal to wake directions Z/L_u and Z'/L_u	192
Figure 6.19 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 2.54cm drooped serration blades (serration peak). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance Z/L_u on the vertical axis and normalized time delay $\tau Ue/L_u$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	193
Figure 6.20 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the simple blowing blades at a blowing rate of 1.4%, plotted against normalized normal to wake directions Z/L_u and Z'/L_u	194
Figure 6.21 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the simple blowing blades at a blowing rate of 1.4%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance Z/L_u on the vertical axis and normalized time delay $\tau Ue/L_u$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	195
Figure 6.22 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the simple blowing blades at a blowing rate of 2.0%, plotted against normalized normal to wake directions Z/L_u and Z'/L_u	196
Figure 6.23 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the simple blowing blades at a blowing rate of 2.0%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance Z/L_u on the vertical axis and normalized time delay $\tau Ue/L_u$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	197
Figure 6.24 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the simple blowing blades at a blowing rate of 2.6%, plotted against normalized normal to wake directions Z/L_u and Z'/L_u	198
Figure 6.25 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the simple blowing blades at a blowing rate of 2.6%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance Z/L_u on the vertical axis and normalized time delay $\tau Ue/L_u$ on the horizontal. For each component, the time-delay	

correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	199
Figure 6.26 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the Kuethe blowing blades at a blowing rate of 2.0%, plotted against normalized normal to wake directions Z/L_u and Z'/L_u	200
Figure 6.27 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the Kuethe blowing blades at a blowing rate of 2.0%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance Z/L_u on the vertical axis and normalized time delay $\tau U_e/L_u$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	201
Figure 6.28 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the serrated blowing blades at a blowing rate of 1.4%, plotted against normalized normal to wake directions Z/L_u and Z'/L_u	202
Figure 6.29 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the serrated blowing blades at a blowing rate of 1.4%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance Z/L_u on the vertical axis and normalized time delay $\tau U_e/L_u$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	203
Figure 6.30 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the serrated blowing blades at a blowing rate of 2.0%, plotted against normalized normal to wake directions Z/L_u and Z'/L_u	204
Figure 6.31 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the serrated blowing blades at a blowing rate of 2.0%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance Z/L_u on the vertical axis and normalized time delay $\tau U_e/L_u$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.	205
Figure 6.32 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the R_{11} component for the baseline and serrated trailing edge blades. Correlations are normalized on (a) the peak TKE and (b) the edge velocity.	206
Figure 6.33 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the R_{11} component for the baseline and trailing edge blowing blades. Correlations are normalized on (a) the peak TKE and (b) the edge velocity.	207
Figure 6.34 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the R_{22} component for the baseline and serrated trailing edge blades. Correlations are normalized on (a) the peak TKE and (b) the edge velocity.	208
Figure 6.35 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the R_{22} component for the baseline and trailing edge blowing blades. Correlations are normalized on (a) the peak TKE and (b) the edge velocity.	209

Figure 6.36 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the <i>R33</i> component for the baseline and serrated trailing edge blades. <i>Correlations are normalized on (a) the peak TKE and (b) the edge velocity.</i>	210
Figure 6.37 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the <i>R33</i> component for the baseline and trailing edge blowing blades. <i>Correlations are normalized on (a) the peak TKE and (b) the edge velocity.</i>	211
Figure 6.38 Effects of the serration size on the normal-to-wake scales.	212
Figure 6.39 Effects of the serration size on the streamwise scales.	212
Figure 6.40 Effects of the blowing rate on the normal-to-wake scales.	213
Figure 6.41 Effects of the blowing rate on the streamwise scales.	213
Figure 6.42 POD eigenvalue spectrum of the baseline blades in the Z-direction (left) and cumulative energy spectrum (right).	214
Figure 6.43 Modal profiles of the first three modes obtained from the POD of the baseline blades.	214
Figure 6.44 Compact Eddy Structures associated with the first 3 modes - Baseline Blades. Contours indicate spanwise velocity component.	214
Figure 6.45 POD eigenvalue spectra and modal profiles of the first 3 modes of the baseline blades for different computational grids.	215
Figure 6.46 POD eigenvalue spectra of the serrated trailing edge blades in the Z-direction (left) and cumulative energy spectrum (right). Baseline values are indicated by black circles.	215
Figure 6.47 Modal profiles of the first three modes obtained from the POD of the 1.27cm serration blades – serration valley.	216
Figure 6.48 Compact Eddy Structures associated with the first 3 modes – 1.27cm serration blades – serration valley. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	216
Figure 6.49 Modal profiles of the first three modes obtained from the POD of the 1.27cm serration blades – serration peak.	216
Figure 6.50 Compact Eddy Structures associated with the first 3 modes – 1.27cm serration blades – serration peak. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	216
Figure 6.51 Modal profiles of the first three modes obtained from the POD of the 1.27cm drooped serration blades – serration valley.	217
Figure 6.52 Compact Eddy Structures associated with the first 3 modes – 1.27cm drooped serration blades – serration valley. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	217
Figure 6.53 Modal profiles of the first three modes obtained from the POD of the 1.27cm drooped serration blades – serration peak.	217
Figure 6.54 Compact Eddy Structures associated with the first 3 modes – 1.27cm drooped serration blades – serration peak. Contours indicate spanwise velocity component.	

Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	217
Figure 6.55 Modal profiles of the first three modes obtained from the POD of the 2.54cm serration blades – serration valley.....	218
Figure 6.56 Compact Eddy Structures associated with the first 3 modes – 2.54cm serration blades – serration valley. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	218
Figure 6.57 Modal profiles of the first three modes obtained from the POD of the 2.54cm serration blades – serration peak.....	218
Figure 6.58 Compact Eddy Structures associated with the first 3 modes – 2.54cm serration blades – serration peak. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	218
Figure 6.59 Modal profiles of the first three modes obtained from the POD of the 2.54cm drooped serration blades – serration valley.	219
Figure 6.60 Compact Eddy Structures associated with the first 3 modes – 2.54cm drooped serration blades – serration valley. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	219
Figure 6.61 Modal profiles of the first three modes obtained from the POD of the 2.54cm drooped serration blades – serration peak.....	219
Figure 6.62 Compact Eddy Structures associated with the first 3 modes – 2.54cm drooped serration blades – serration peak. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	219
Figure 6.63 POD eigenvalue spectra of the serrated trailing edge blades in the Z-direction (left) and cumulative energy spectrum (right). Baseline values are indicated by black circles.	220
Figure 6.64 Modal profiles of the first three modes obtained from the POD of the simple blowing blades at a blowing rate of 1.4%.....	221
Figure 6.65 Compact Eddy Structures associated with the first 3 modes – simple blowing blades at a blowing rate of 1.4% Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	221
Figure 6.66 Modal profiles of the first three modes obtained from the POD of the simple blowing blades at a blowing rate of 2.0%.....	221
Figure 6.67 Compact Eddy Structures associated with the first 3 modes – simple blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	221
Figure 6.68 Modal profiles of the first three modes obtained from the POD of the simple blowing blades at a blowing rate of 2.6%.....	222
Figure 6.69 Compact Eddy Structures associated with the first 3 modes – simple blowing blades at a blowing rate of 2.6% Contours indicate spanwise velocity component.	

Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	222
Figure 6.70 Modal profiles of the first three modes obtained from the POD of the Kuethe blowing blades at a blowing rate of 2.0%.	222
Figure 6.71 Compact Eddy Structures associated with the first 3 modes – Kuethe blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	222
Figure 6.72 Modal profiles of the first three modes obtained from the POD of the serrated blowing blades at a blowing rate of 1.4%.	223
Figure 6.73 Compact Eddy Structures associated with the first 3 modes – serrated blowing blades at a blowing rate of 1.4% Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	223
Figure 6.74 Modal profiles of the first three modes obtained from the POD of the serrated blowing blades at a blowing rate of 2.0%.	223
Figure 6.75 Compact Eddy Structures associated with the first 3 modes – serrated blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).	223
Figure 7.1 Schematic description of (a) perpendicular blade-wake interaction and (b) parallel blade-wake interaction.	243
Figure 7.2 Broadband Excitation Term (BET) Spectra for the 5 driving modes – Baseline Blades.	244
Figure 7.3 Relative contributions of the 5 driving modes to the total broadband excitation - Baseline Blades.	244
Figure 7.4 Compact Eddy Structures associated with the 5 driving modes - Baseline Blades. Contours indicate spanwise velocity component.	245
Figure 7.5 Impact of the trailing edge serrations on the broadband excitation for a perpendicular blade-wake interaction. Changes (in dB) are expressed relative to the baseline excitation.	246
Figure 7.6 Relative contributions of the 5 driving modes to the total broadband excitation – 1.27cm serration blades - serration valley.	246
Figure 7.7 Relative contributions of the 5 driving modes to the total broadband excitation – 1.27cm serration blades - serration peak.	247
Figure 7.8 Compact Eddy Structures associated with the 5 driving modes – 1.27cm serration blades – serration valley. Contours indicate spanwise velocity component.	248
Figure 7.9 Compact Eddy Structures associated with the 5 driving modes – 1.27cm serration blades – serration peak. Contours indicate spanwise velocity component.	249
Figure 7.10 Relative contributions of the 5 driving modes to the total broadband excitation – 1.27cm drooped serration blades - serration valley.	250
Figure 7.11 Relative contributions of the 5 driving modes to the total broadband excitation – 1.27cm drooped serration blades - serration peak.	250

Figure 7.12 Compact Eddy Structures associated with the 5 driving modes – 1.27cm drooped serration blades – serration valley. Contours indicate spanwise velocity component.....	251
Figure 7.13 Compact Eddy Structures associated with the 5 driving modes – 1.27cm drooped serration blades – serration peak. Contours indicate spanwise velocity component.....	252
Figure 7.14 Relative contributions of the 5 driving modes to the total broadband excitation – 2.54cm serration blades - serration valley.....	253
Figure 7.15 Relative contributions of the 5 driving modes to the total broadband excitation – 2.54cm serration blades - serration peak.....	253
Figure 7.16 Compact Eddy Structures associated with the 5 driving modes – 2.54cm serration blades – serration valley. Contours indicate spanwise velocity component.	254
Figure 7.17 Compact Eddy Structures associated with the 5 driving modes – 2.54cm serration blades – serration peak. Contours indicate spanwise velocity component.	255
Figure 7.18 Relative contributions of the 5 driving modes to the total broadband excitation – 2.54cm drooped serration blades - serration valley.	256
Figure 7.19 Relative contributions of the 5 driving modes to the total broadband excitation – 2.54cm drooped serration blades - serration peak.....	256
Figure 7.20 Compact Eddy Structures associated with the 5 driving modes – 2.54cm drooped serration blades – serration valley. Contours indicate spanwise velocity component.....	257
Figure 7.21 Compact Eddy Structures associated with the 5 driving modes – 2.54cm drooped serration blades – serration peak. Contours indicate spanwise velocity component.....	258
Figure 7.22 Impact of the trailing edge blowing on the broadband excitation for a perpendicular blade-wake interaction. Changes (in dB) are expressed relative to the baseline excitation.....	259
Figure 7.23 Relative contributions of the 5 driving modes to the total broadband excitation – Simple blowing blades at a blowing rate of 1.4%.....	259
Figure 7.24 Compact Eddy Structures associated with the 5 driving modes – Simple blowing blades at a blowing rate of 1.4%. Contours indicate spanwise velocity component.....	260
Figure 7.25 Relative contributions of the 5 driving modes to the total broadband excitation – Simple blowing blades at a blowing rate of 2.0%.....	261
Figure 7.26 Compact Eddy Structures associated with the 5 driving modes – Simple blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component.....	262
Figure 7.27 Relative contributions of the 5 driving modes to the total broadband excitation – Simple blowing blades at a blowing rate of 2.6%.....	263
Figure 7.28 Compact Eddy Structures associated with the 5 driving modes – Simple blowing blades at a blowing rate of 2.6%. Contours indicate spanwise velocity component.....	264
Figure 7.29 Relative contributions of the 5 driving modes to the total broadband excitation – Kuethe blowing blades at a blowing rate of 2.0%.	265

Figure 7.30 Compact Eddy Structures associated with the 5 driving modes – Kuethe blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component.....	266
Figure 7.31 Relative contributions of the 5 driving modes to the total broadband excitation – Serrated blowing blades at a blowing rate of 1.4%.....	267
Figure 7.32 Compact Eddy Structures associated with the 5 driving modes – Serrated blowing blades at a blowing rate of 1.4%. Contours indicate spanwise velocity component.....	268
Figure 7.33 Relative contributions of the 5 driving modes to the total broadband excitation – Serrated blowing blades at a blowing rate of 2.0%.....	269
Figure 7.34 Compact Eddy Structures associated with the 5 driving modes – Serrated blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component.....	270
Figure 7.35 Impact of the flow control strategies on the broadband excitation for a parallel blade-wake interaction. Changes (in dB) are expressed relative to the baseline excitation.....	271
Figure 7.36 Impact of the flow control strategies on the broadband excitation for a perpendicular blade-wake interaction. Changes (in dB) are expressed relative to the baseline excitation.....	271

Chapter 1 - Introduction

1.1. Background on Aircraft Noise Restrictions

The aviation industry contributes in excess of \$36 billion and provides nearly 1 million jobs to the U.S. economy (NASA, 1997). This contribution is likely to increase with the globalization of the market. With the explosion of aircraft travel over the past 20 years, air traffic has more than doubled and is estimated to keep steadily increasing by about 5% a year. There are however many problems that could prevent this growth if not carefully addressed. The three major issues are security, fuel consumption, and noise emissions.

The recent events of 2001 highlighted the need for increased security and lead to the creation in the U.S. of the Transportation Security Administration (TSA) the same year. The task of making flying safer has since then been shared by both the airlines and TSA. The rising price of oil (as of November 2007, the barrel of crude oil is set to reach a record high \$100) is pushing the scientific community along with its industrial partners to improve fuel efficiency. Today's world fleet is about 70% more efficient per passenger kilometer than in the 1960s (IATA, 2007). During the 1990's alone, fuel efficiency was improved by 17%. Specifically, in 1998, 160 billion liters were consumed by airlines around the world, corresponding to 4.8 liters per passenger carried over 100 kilometers (or 4.8 liters per 100 passenger-kilometers). With technological improvements, it is not uncommon nowadays to meet consumptions as low as 3 liters per 100 passenger-kilometers. The International Air Transport Association (IATA, a global trade organization representing 260 cargo and passenger airlines around the world, combining for 94% of international scheduled air traffic) and its members actually plan to achieve an additional 10% fuel efficiency improvement by the 2000-2010 period.

The last major obstacle to the aviation industry economic growth is noise emissions. While the previous two issues were directly related to airlines and governmental agencies, noise emissions have to be handled by the aircraft and engine manufacturers alone, along with the scientific community. The noise emission problem

arises from a simple fact: as air traffic intensifies, aircraft are forced to fly over populated areas (either because of increased number of flight paths or because of population growth in the vicinity of airports). These fly-overs lead to noise nuisance for these populations and complaints from the local governments put pressure on the aviation industry to find new ways to reduce these emissions. Accordingly, authorities in both Europe and the United States have set noise emission goals. The Advisory Council for Aeronautics Research in Europe (ACARE) has projected a 15dB cumulative reduction from today's standards by 2010, while NASA's Aerospace Technology Enterprise (ATE) is aiming for a 25dB reduction by the same year. ACARE and ATE are then hoping for 40dB and 75dB cumulative reductions respectively by 2025 (Krammer *et al.*, 2003). One of the difficulties of reducing noise emissions resides in the numerous sources of noise throughout an aircraft. These sources can be divided in two main categories: airframe noise and engine noise. As higher bypass ratio engines have become more common and aircraft have become larger, interest in airframe-related noise has grown, but engine noise still accounts for most of the aircraft external noise (Envia, 2001).

Figure 1.1 shows the relative importance of various aircraft noise sources. Consequently, most of the recent efforts have been focused on reducing propulsion noise. Here again, as shown in Figure 1.1, several components contribute to the overall acoustic signature of the engine. Among the most significant are the fan (inlet and exhaust), compressor, turbine, exhaust nozzle and jet. Identifying the cause and propagation mechanisms involved with each of these components is a very complex process namely because noise sources usually arise from complex aerodynamic phenomena, while their propagation is predominantly of acoustic order. It is therefore of primary importance to understand the fundamental aerodynamic mechanisms that create these noise sources to be able to reach the noise reduction goals mentioned above.

Several programs in both the United States and Europe have started to develop promising noise reducing technology. In the United States, under the Advanced Subsonic Technology Program (AST), the Advanced Ducted Propulsor (ADP), a scale model fan technology demonstrator designed and built by Pratt & Whitney in conjunction with NASA, proved the feasibility of obtaining the AST noise reduction goal of 6 EPNdB (Effective Perceived Noise dB), (Envia (2001)). The AST program was then followed by

the Quiet Aircraft Technology Program (QAT) that calls for reduction of perceived noise levels by 50% by 2010 and 75% by 2025.

1.2. Fan Noise Reduction

Engine noise studies indicate that fan noise dominates the total engine flyover acoustic signature during both takeoff and approach operations. This dominance is greatly due to the advance of high bypass ratio (BPR, the ratio of mass of air going through the fan nozzle to the mass of air going through the core of the engine) turbofan engines. Currently, the latest engines have BPR's around 10:1 (9:1 for the General Electric GE90 that powers the Boeing 777), but BPR's are projected to rapidly increase. The Pratt & Whitney PW8000 is expected to have an 11:1 BPR and should enter the market to power the next generation of Boeing 737 and Airbus A320). Engines tend to go towards higher BPR because the "bypassed" air provides additional thrust without burning any more fuel, thus increasing fuel efficiency. Unfortunately, higher BPR means larger diameter fans, but also means increased fan noise. This trend therefore highlights the need to understand how fan noise is produced and how it can be reduced. Extensive research has been, and currently is, done to control fan noise through the use of acoustic liners, swept and leaned outlet guide vanes (OGV's), active noise control, geared fan, and wake management.

As a matter of fact, the ADP used sweeping and leaning of the OGV's to produce effective perceived noise reductions of 3 EPNdB over the entire range of tested fan tip speeds (Envia, 2001). The EPNdB is a weighted scale that measures the "annoyance" of a given sound (usually aircraft flyover) by considering the frequencies audible to humans and emphasizes any tones present. EPNdB is the unit used for FAA (Federal Aviation Administration) certifications. The ADP also demonstrated, using actuators embedded in the casing or in the stator vanes, that active noise control (creation of an acoustic field of equal magnitude and opposite phase of the acoustic field desired to be cancelled) could produce reduction of 18dB on average, over the range of fan speeds tested.

The PW8000 on the other hand will make use of a geared fan to reduce fan noise. The Pratt & Whitney prototype will indeed use a gearbox to decouple the fan from the

compressor core, thus allowing lower fan tip speeds. Fans operate best at slower speeds while compressors and turbines run more efficiently at high speeds. Decoupling the fan from the compressor core enables the fan and the compressor and turbine to achieve their most efficient operating speeds simultaneously, resulting in quieter and more fuel efficient engine.

More recently, studies started to focus on the wake shed by the fan blades and how these wakes interact with the downstream stators to produce noise. As the fluid flows over the fan rotor blades, viscous losses in the boundary layer create a wake beyond the trailing edge of the fan blades. Since the size and weight of the engine is limited for efficiency reasons, the axial distance between the rotor blades row and the stator vanes is on the order of a few axial chords (usually around 2). The direct consequence of that spatial organization is that the viscous wake created by the rotor blades then interacts with the stator vanes. The resulting noise, usually called rotor-stator interaction noise, is the product of the unsteady pressure fluctuations caused by the wake disturbance on the surface of the stator vane that in turn couple to the duct acoustic modes.

Wake management consists of removing or attenuating the wake disturbance by either filling in the momentum deficit arising from the viscous losses on the blades, removing the low momentum fluid, or diffusing the wake more rapidly. Since the strength of the deficit directly correlates with the acoustic levels, removing the harmonic content of the wake will lead to substantial reductions of the fan tone noise. However, removing the harmonic content of the wake would tackle only one component of the noise problem. Performing a spectral analysis of the flow exiting the fan of a high bypass ratio engine will show that the noise generated is made of two major components. The first component is a non-random, rotor-correlated content resulting from the interaction of the rotor wake disturbance periodically impinging on the stator vanes, as discussed above. This first component occurring at harmonics of the blade passing frequency (BPF) is the tone noise element of fan noise. The second component is a random component, uncorrelated with the rotor BPF. While the tone noise is correlated with the wake deficit, the random content of fan noise is the product of the interaction between the flow

turbulence inside the wake and the stator vanes cutting through it. The byproduct of this interaction is called broadband noise.

1.3. Current Research Motivations: Wake Management Solutions for Broadband Noise Reduction

The literature review presented in the following chapter highlights a significant number of studies of wake management solutions, whether active (like trailing edge blowing) or passive (serrated trailing edges) targeting rotor-stator interaction noise. The vast majority of these focused on identifying, quantifying and addressing tone noise attenuation. Some of them have quantified certain effects of wake management on broadband levels (e.g. Langford, 2005b), or hypothesized on possible consequences. Understanding these effects could lead the scientific community and the aviation industry to reassess the current wake management strategies to combine tone and broadband noise reduction into a more efficient solution to the fan noise problem. The actual effects of wake management on the flow mechanisms responsible for broadband noise generation can only be identified by studying the turbulence of the rotor wakes. While several studies, like that of Cimbala and Park (1990), have examined the Reynolds stress field, characterizing the influence of wake management solutions on broadband generating structures requires the knowledge of both the scale and the magnitude of the turbulence involved, something that to this day has not been yet documented.

1.4. Objectives and Approach to Wake Management Solutions for Broadband Noise Reduction

The goal of the current research is to provide a fundamental understanding some of the turbulent wake structures responsible for broadband noise generation in aircraft engines and devise wake management solutions that will most efficiently tackle this problem. Various active (trailing edge blowing) and passive (trailing edge serrations) wake management solutions are tested in an idealized fan blade row to identify, quantify and understand their effects on both the scale and the magnitude of the turbulence inside

the wake, quantities that can only be obtained by measuring the two-point velocity correlation. The potential of the modified wakes to produce broadband noise can be then predicted. The fundamental understanding gained can then be used for recommendations on future rotor-stator design. The present study also provides benchmark data on active and passive wake management solutions that can be used to develop and validate computational fluid dynamics (CFD) models.

Consequently, the objectives of the current research are

1. To reproduce the relevant features of the wake of an aircraft engine fan in an idealized low-speed laboratory wind tunnel.
2. To document in detail the form and structure of the idealized fan blade wakes in terms of mean flow, turbulent structures and two-point space time correlations.
3. To reveal and quantify the influence of trailing edge serrations and blowing on the coherent structures of the wakes.
4. To quantify and compare the potential of the wakes shed by the serrated and blowing blades to produce broadband noise when interacting with a hypothetical stator downstream, using measured two-point statistics.
5. Formulate recommendations on future rotor blade design.
6. Provide benchmark data for development and validation of turbulence models.

These objectives were attained using the Virginia Tech Low Speed Linear Compressor Cascade wind tunnel. This cascade tunnel was designed to produce blade loading and passage flow features similar to subsonic aircraft high bypass ratio fan blades during take-off and landing maneuvers.

The linear cascade configuration enabled the measurement of some fundamental characteristics of the fan-blade type wakes. The tunnel configuration allows for a variety of blades (with active and passive wake management geometries) to be tested. Measurements were made on these blades and their wakes, and used to estimate effects on a (hypothetical) set of stator blades downstream.

The above goals were achieved by using three-component hot-wire anemometry to measure the two-point space-time correlation within a dense grid across the wake shed by

the idealized fan blades with different serrations geometries and blowing configurations. A combination of Proper Orthogonal Decomposition (POD) and Linear Stochastic Estimates (LSE) was used to reveal the typical eddy structures present in the wakes. The methods of Glegg and Devenport (2001) and Amiet (1975) were then used to infer the potential of these wakes to produce broadband noise.

1.5. Dissertation Layout

This dissertation presents a detailed description of the different wake management solutions and their effects on the coherent structures responsible for broadband noise generation, and possible prediction methods. To do so, the dissertation is organized as follows:

Chapter 2 reviews some pertinent work previously carried out on relevant subject such as momentumless wakes, or passive and active wake management.

Chapter 3 presents a detailed description of the facility used for this study (the Virginia Tech Low Speed Cascade wind tunnel), as well as other apparatus used for the experiment. This includes the data acquisition system, the pressure sensing equipment, the hotwire anemometry.

Chapter 4 describes the different wake management geometries, and the trailing edge blowing supply system.

Chapter 5 reviews the single-point measurements of serrated trailing edge and trailing edge blowing, which have already been presented respectively by Geiger (2005) and Craig (2005) in addition to an extra blowing configuration yet to be documented. This includes discussion on wake deficit, wake spreading, Reynolds stress field analysis, and comparison with plane wake data.

Chapter 6 presents the two-point correlation measurements on both active and passive solutions and discusses the implication on the organization of the coherent structures. This includes description and analysis of zero-time delay correlation and zero-separation time-delayed correlation maps. Chapter 6 also describes the numerical methods used to extract information on the type of the coherent structures present in the wakes. This includes a review and discussion of proper orthogonal decomposition and compact eddy structures.

Chapter 7 is dedicated to the evaluation of the potential of the measured wakes to generate broadband noise when interacting with a hypothetical downstream stator blade.

Chapter 8 summarizes the findings of each chapter and draws general conclusions and recommendations.

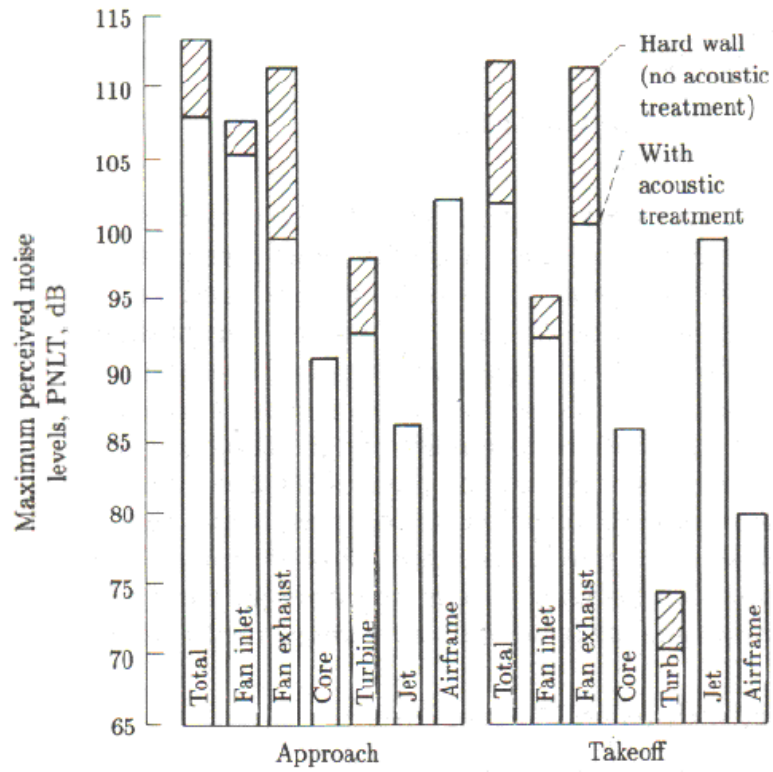


Figure 1.1. Relative Importance of Various Noise Sources in Aircraft with High Bypass Ratio Engine (Adpated from Envia, 2001).

Chapter 2 - Literature Review

2.1. Research Interest: Wake Management

The present study focuses on the fundamental aerodynamic understanding needed for fan noise reduction through wake management. As mentioned earlier, the ideal wake management solution would create a uniform steady inflow to the stator vanes by removing the momentum deficit (resulting from viscous losses on the rotor blades) and reducing the wake turbulence.

There are several ways to apply wake management to the rotor-stator interaction problem that can be classified in two main categories: passive and active. In both cases, the goal is to fill in or diffuse the momentum deficit of the wake and reduce the wake turbulence. Passive strategies usually consist in modifying the trailing edge geometry of the rotor blade to enhance the mixing inside the wake. Possible trailing edge geometries include serration or corrugation. Active strategies on the other hand use slots or holes near the trailing edge of the rotor blades to inject high momentum fluid into the wake, thus reducing the wake deficit and turbulence. Active solutions are usually referred to as simply Trailing Edge Blowing (TEB). Wake management solutions have been tested on flat plate airfoils, wind turbines, model aircraft engines, and linear cascades. The following sections will present a collection of previous research performed on wake management, both passive and active, with an emphasis on some of those research who focused on the aero-acoustic consequences of wake management.

2.1.1. Review of Previous Passive Wake Management Research

The passive wake management studied in the present research is serration of the trailing edge. While there is almost no prior literature of such geometry being applied for wake management purposes, serrations have been used in the past as a mean of flow control to increase aerodynamic performance or manage trailing edge noise (the noise created as the viscous layer passes over the trailing edge).

Early studies of serrations, like that of Vijgen *et al.* (1989), investigated the possible improvement in aerodynamic performance they could produce. Vijgen *et al.* considered the effects of planar serrations (serrations in the plane of the trailing edge) and non-planar serrations (serrations at the trailing edge of a two-dimensional flap mounted at the airfoil trailing edge perpendicular to the airfoil pressure side, also known as “Gurney” flaps). Two sets of measurements were taken. The first involved an untwisted 0.33m span wing, with a 12.56 aspect ratio, and NASA NLF(1)-0414F airfoil section. This model was tested in the 14ft by 22ft (4.3m by 6.7m) Subsonic Wind Tunnel at NASA Langley at a Reynolds number based on the chord of 1.1×10^6 . To fully comprehend the effects of serrated trailing edge, the wing described above was tested bare, with trailing edge solid extensions, and with trailing edge triangular serrations (saw tooth) and scallops (each serration is shape as a quadrant). All three trailing edge modifications were 3.8% chord long. The maximum lift coefficient for the baseline (bare) wing was reached at 14° and therefore the authors decided to take measurements on the modified geometries only up to 14° (thus limiting the conclusion on how serrations could be used to delay boundary layer separation).

At 14° , the lift coefficient with the serrated and solid extensions was increased by 4 and 8 % respectively. The scalloped and serrated trailing edge configurations produced drags lower than the baseline for $C_L > 0.3$ and $C_L < 0.5$. At lower lift coefficient, the drag was actually 5 to 10 counts less than the baseline. At the very least this indicates that serrations have the potential to reduce wake momentum thickness, presumably through cleaning up the trailing edge flow. This would likely be beneficial in the fan application. Triangular serrations also increased the maximum lift-to-drag ratio by 5%. Pitching moment did not seem to be affected by the serrations.

Vijgen *et al.* then investigated the effects of higher Reynolds number on the planar and non-planar serrations by testing a 1.88m chord and 3.96 aspect ratio wing with a NASA HSNLF(1)-0213 airfoil section in the 30ft by 60ft (9.2m by 18.3m) Tunnel at NASA Langley with a Reynolds number based on the chord of 3.67×10^6 . Results did not show any significant reduction in drag with the planar triangular serration and only a slight increase in maximum lift-to-drag ratio. However, planar serrations did delay separation, supporting the theory that the serrations did re-energize the boundary layer,

thus delaying separation. The solid Gurney flaps at high Reynolds number produced more drag at low angles of attack while adding serrations resulted in drag count similar to that of the bare wing, reinforcing that the serrations did re-energize of the viscous layer. Finally, water tunnel tests at a Reynolds number of about 10,000 were performed and showed evidence that the serration produced near-streamwise vortices which are stretched and entrained by the spanwise von Kàrmàn vortical structures (Vijgen *et al.*, 1989). The water tests also showed that adding serrated Gurney flaps pushed the separation point on the suction side downstream, thus proving that the serration did influence the boundary layer by inducing higher-momentum fluid near the surface of the airfoil, thus delaying separation and controlling the wake.

Serrations are not the only trailing edge geometries to have been considered. Weygandt and Mehta (1995) investigated the effects of corrugated trailing edge on the aerodynamic performance of the turbulent plane wakes shed by a flat plate, and found that the strong array of streamwise vorticity injected by the corrugation had mixed effects on the structure of the wake depending on the distance from the trailing edge. Close to the edge (less than 500 the momentum thickness), the wake spreading and decay are faster than for the bare flat plate. As the distance from the trailing edge increases, the spreading and decay are actually slowed down compared to the simple flat plate. Weygandt and Mehta believe that the injection of relatively strong streamwise vorticity at the trailing edge leads to reduced growth and defect decay in the far-field by breaking-up the spanwise structures, making them more three dimensional and, hence, reducing their entrainment efficiency, while in the near-field this effect is compensated for by increased entrainment from the streamwise structures (Weygandt and Mehta, 1995).

One of the earliest aero-acoustic studies of serrated trailing edges was done by Howe (1991). Howe developed a model to predict trailing edge noise produced by the flow over a flat plate airfoil with serrated trailing edge of different geometries. Assuming that the merging of turbulent streams from opposite sides of the airfoil does not substantially modify the turbulence characteristics within one boundary layer thickness of the trailing edge, the solution can be approximated as that of a diffraction problem where the near-field pressure fluctuations of the turbulence are scattered by the impedance discontinuity at the trailing edge (Howe, 1991). According to Howe, since the intensity of

trailing edge noise is proportional to the product of the spanwise correlation length of the turbulence near the edge and the length of edge wetted by the flow, using serrations should effectively reduce the correlation length and therefore the intensity of the radiation. Howe's model predicts reductions in the radiated sound as long as the serration angle does not exceed 45° with the mean flow and the serration size is on the order of the boundary layer thickness. The model also predicts that sharp, or "saw tooth", serrations will produce larger reduction than sinusoidal serrations.

Following this theoretical study, serrations were then applied to several configurations, including wind turbines. Compiling a review of work performed in Europe with serrated trailing edges, Guidati (2000) lists total trailing edge noise reduction of up to 4 to 6dB for a serration aspect ratio of 5, with low frequency showing decreased noise levels, while high frequency levels are increased.

Most of the aero-acoustic research performed on passive solutions has been focused on investigation the effects of trailing edge geometry on trailing edge noise. It is the possible benefits of such techniques to reduce interaction noise that are analyzed in this dissertation.

2.1.2. Review of Previous Active Wake Management Research

2.1.2.1. Fundamental Research on Active Wake Management:

Momentumless Wakes

Early investigations of trailing edge blowing were related to the study of momentumless wakes. The fundamental studies by Cimbala and Park (1990) and Park and Cimbala (1991) investigated the effects of trailing edge flow injection on the turbulence structure in momentumless wakes. Cimbala and Park (1990) studied the influence of the injection regime on the wakes. Four regimes were investigated: pure wake (no injection), weak wake (some injection), momentumless wake (injection required to cancel drag), and weak jet wake (more injection than necessary to cancel drag). Cimbala and Park used an airfoil shape model with a rounded leading edge, blunt trailing edge, a 89mm chord, and a 965mm span. The air was blown through a 3.2mm slot (corresponding to 17% of the blunt trailing edge thickness) covering 80% of the

airfoil span. The airfoil spanned the 0.3m by 0.97m test-section and was immersed in a 4.2m/s stream with a background turbulence intensity on the order of 0.1%, resulting in a Reynolds number based on the thickness of 5400. Both single and dual-sensor hotwire anemometry, as well as smoke wire flow visualization was performed for all four injection regimes. Smoke flow visualization revealed well defined pure and weak wakes, with evidence of von Kàrmàn vortical structures (confirmed by spectral analysis). In contrast, the momentumless and weak-jet wakes exhibited disorganized formations near the center-line, with more wake-like aspects near the edges. Hotwire measurements revealed that the momentumless wake had a faster wake centerline defect decay but slower spreading rate than the pure wake case. It was noted that the mean velocity profiles were extremely sensitive to small mismatches of momentum injection and to misalignment of the model with the freestream direction. The authors also found that the rate of decay of the axial and transverse intensities were identical, and much higher than that of a plane wake. Spectral analysis confirmed the presence of quasi-periodic bursts of turbulent energy, convecting into the freestream, and observed as fluctuations in the transverse velocity. As the bulge of turbulent energy is ejected of the wake, it loses its energy by dissipation in the freestream. In other words, the momentumless wake loses energy periodically as these turbulence bulges are ejected. Additionally, since the injected wake is a combination of a wake and a jet, vortical structures of the wake component are cancelled by opposite vortical structures of the jet component, resulting in added turbulence decay. The authors therefore believe that the reasons for the fast turbulence decay of the injected wake is not simply due to gradient diffusion, but also to interaction between the wake and jet components, as well as periodic ejection of turbulence energy.

Following the findings of Cimbalà and Park (1990), Park and Cimbalà (1991) then focused on studying the effects of the injection method on momentumless wakes. To do so, they used the same flow conditions and facility described in Cimbalà and Park (1990). The model used had the same physical dimensions except the airfoil had two 1.6mm wide slots instead of one 3.2mm as previously. Using this dual jet configuration, Park and Cimbalà were able to compare the central single-jet injection case reported by Cimbalà and Park (1990) with single asymmetric jet injection as well as dual jet

injection. Smoke flow visualization revealed that asymmetric and dual jet injection produced wavy-flow like patterns in the wake, as opposed to the disorganized structure seen in the central jet case. Additionally, the von Kàrmàn vortical structures observed by Cimbala and Park (1990) were believed to interact with the two jets of the dual jet configuration to enhance flapping effects. The dual jet configuration was found to produce momentumless wakes that both decayed and spread faster than the asymmetric and the central jet. The mean velocity profile of the dual jet was very similar to that of the central jet, whereas the asymmetric jet produced profiles exhibiting local jet and wake components. However, the asymmetric jet wake still produced momentumless mean velocity profiles, indicating that the mean velocity is highly dependent on the initial conditions. In contrast, the rate of decay of the axial turbulence intensity was found to be identical in all three cases, although the actual magnitude of the intensity depends on the injection mode (twice as large for the dual jet as for the central jet, while the asymmetric jet falls in between). The authors concluded that while the rate of decay of the turbulence intensity was independent of the injection configuration (i.e. the initial conditions), the wake defect, spreading rate, mean velocity profile, and magnitude of the turbulence intensity were highly dependent on these initial conditions.

2.1.2.2.Active Wake Management Research Conducted on Cascades and Model Engines

The proven capabilities of trailing edge blowing to produce momentumless wakes was the initial step towards direct application of such technology to model aircraft engines and the quieting of interaction noise.

Sell (1997) studied the effects of trailing edge injection on two-dimensional wakes shed by a linear cascade of three fan blades. Each blade was 210mm spanwise and 251mm chordwise and were designed to scale the conditions found in the Pratt & Whitney ADP. Sell tested both addition and removal of mass. Mass was injected through an array of 1.3mm diameter tubes 3.8mm apart, located at 80% chord through an array of ports at 80% chord. Suction was achieved through the use of an array of slots, 12.7mm long (spanwise) by 1.6mm wide (chordwise), 3.2mm apart, located on both suction and

pressure sides, at 50 and 80% chord. Measurements were performed at a Reynolds number based on the chord of about 250000. Trailing edge suction of 1.25% of the fan throughflow at 80% chord on the suction side resulted in reductions of 50% of the momentum thickness, 43% of the wake deficit, and 10% of half wake width (the distance from the wake centerline where the velocity defect is half that of the wake centerline). Sell found that an injection rate of 1.08% of the fan throughflow produced an almost momentumless wake with a wake deficit reduced by 67%, the wake width by 6.85%, and the maximum turbulence levels by 44.5%. Based on these results, Sell estimated that tone noise reductions of 8.0dB to 24.4dB and broadband noise reduction of 7.0dB were possible.

Based on the study by Sell (1997), Brookfield (1998) and then Brookfield and Waitz (2000) went on to study the application of trailing edge blowing to the more realistic environment of a fan stage, including three-dimensional effects and acoustic modes. The investigation featured a 16 bladed fan stage, 40 stator blades, with a hub-to-tip ratio of 0.5, a 1.7 chord length separation between the blade rows, a pressure ratio of 1.2, a tip Mach number of 0.8 and an inlet Mach number of 0.45. Kulite pressure transducers, flush mounted, were used to take flow field measurements, while duct microphone pairs were placed on the casing, $1/16^{\text{th}}$ of the circumference apart, one axial chord upstream and downstream of both blade rows. Unsteady loading of the stator vanes was monitored with one stator blade instrumented with 13 Kulite pressure transducers distributed between the suction and pressure surfaces. The rotor blades were designed to match the external blade shape of a typical high bypass ratio fan, except for the 5 discrete orifices near the trailing edge used for the mass injection. The blowing mass flow rate was less than 2% of the fan throughflow. Tip weighted and midspan weighted injection were investigated and showed similar filling of the wake and reduction of the turbulence intensities. All of the flow properties varied with the blade span. The wake relative Mach number, BPF (blade passing frequency), and 2xBPF harmonic amplitudes at 0.1 chords downstream of the blade row with trailing edge blowing were near or below those at 1.5 chords downstream for the baseline, suggesting that active wake management could be used to considerably reduce the spacing between the rotor and stator blade rows without

significant increase in radiated tone noise. The stator unsteady loading was also improved, resulting in a 10dB tone reduction at BPF with tip weighted injection.

In an attempt to reduce the noise produced by the rotor blades cutting through the wakes from upstream stators (also known as stator-rotor interaction noise), Leitch *et al.* (2000) used a turbofan simulator fitted with a special inlet. The inlet was equipped with four stators or inlet guide vanes (IGV's) located 0.75 chord lengths upstream of the turbofan simulator fan face and produced a zero turning angle. Each IGV had a series of six equally spaced blowing holes with varying diameter to account for the non-uniform pressure inside the supply air plenum of the blade. The turbo fan simulator was composed of 18 fan blades and 26 outlet guide vanes (OGV's). Acoustic measurements were performed in the Virginia Tech Anechoic Chamber ($4 \times 2.7 \times 2$ m with a cut-off frequency of 200 Hz) at fan speeds of 30,000 rpm, 50,000 rpm and 70,000 rpm. Static and total pressure measurements across the fan face showed that the wakes of the stators could be filled with less than 1.0% of the total fan mass through-flow. The wake filling reduced the tonal sound pressure level as well as its first harmonic, but had little effect on the broadband noise. Acoustic measurements were made with Bruel and Kjaer microphones at 12 points from 0° to 110° on a circular arc 1.2m from upstream the fan face. For the fan speed of 30,000 rpm, the maximum tone noise reduction was found to be 8.9dB tone noise at 80° , while the average reduction was close to 6.2dB between 30° and 90° . The maximum reductions were 5.5dB and 2.6dB at 50,000 and 70,000rpm respectively. The smaller reductions at higher fan speeds was thought to be due to the possible limitations of the blowing system to provide enough air to re-energize the wakes at such speeds or possibly because at such speeds a combination tone ("buzz-saw" noise) dominates the acoustic signature. It is possible that trailing edge blowing may not be an effective mean to reduce such noise (Leitch *et al.*, 2000).

Following the findings of Leitch *et al.* (2000), Rao *et al.* (2001) used the same experimental set-up but added an active wake control system designed to adjust the amount of blowing air as a function of the fan speed so that the optimum amount of mass flow required to fill in the wake could be reached. Flow injection through each trailing edge blowing hole was controlled using MEMS (Micro-Electro-Mechanical System) micro-valves. Noise reductions occurred over the entire range of speeds. At 30,000 rpm

there was an 8.2 dB BPF tone noise reduction at 20° and 6 to 3 dB reduction over the first four harmonics. At 40,000 rpm, the BPF tone noise reduction was 7.3 dB at 20°, and the sound pressure level (SPL) remained the same between 60° to 110°. Sound power level at 1BPF showed a 4.4 dB reduction at 30,000 rpm and a 2.9 dB reduction at 40,000 rpm. Rao found no significant change in the broadband levels.

One of the first acoustic measurements made on a realistic fan was done by Sutliff *et al.* (2002) on the 1.2m Active Noise Control Fan (ANCF) at NASA Glenn Research Center. This ducted fan produces a 130m/s tip speed with a blade passing frequency of 500 Hz. The tests were performed with a 16-bladed rotor and 14-bladed stator rows. The rotor blades had internal passages optimized to provide injection through the trailing edge slot with minimal losses. Sutliff *et al.* tested three injection regimes: no blowing (where the trailing-edges were fixed with inserts to eliminate vortex shedding or flow separation due to bluntness), self-blowing of 0.6% mass through-flow (where blowing was induced by centrifugal acceleration), and blowing rates between 0.5% and 2.0% fan mass through-flow at fan speeds of 25Hz to 31.6Hz. Two-component hot wire measurements were taken one axial chord downstream of the rotor blades at 15 to 25 radial locations. Three stator blades equipped with 30 microphones each provided surface pressure measurements. A rotating downstream rake was used to map the ducted modes while 28 microphones measured the acoustic far-field of the baseline and optimum blowing cases. Hotwire measurements showed reduction of the wake deficit from the hub to 50% span for all three regimes. Over the outer half of the blade (50% to the tip) self-blowing increased the wake velocity deficit while the optimum blowing case over-filled the wake which most likely a consequence of centrifugal acceleration. At 20% chord line of the stator blades, surface pressure fluctuation measured at 20% chord of the stator vane decreased with the optimum blowing rate of 1.8%, especially near the tip on both the suction and pressure sides. Duct measurements showed noise reductions for the majority of the tones at the inlet and exhaust. For 1BPF, measurements showed a tone noise reduction of 11.5 dB and tonal noise increase of 0.1 dB at the inlet and exhaust respectively, at 2BPF showed noise reductions of 7.2 dB (inlet) and 11.4 dB (exhaust) were observed while at 3BPF the measurements showed noise reductions of 11.8 dB (inlet) and 19.4 dB (exhaust). These reductions were validated with far-field

measurements where noise level reductions of 5.4 dB at 1BPF 10.6 dB at 2BPF and 12.4 dB at 3BPF were measured. Sutliff *et al.* conjectured that blowing may have broadband noise benefits, but that further study of this issue was needed. Most importantly, although the prediction codes (both aerodynamic and acoustic) used to design this test were validated as reliable tools for predicting the behavior of low speed fan equipped with trailing edge blowing, the amount of air required to fill in the wake deficit was too large to be practical for an operational engine.

The study of Sutliff (2002) was then followed by an extensive study of new designs. The fruits of this joint effort between NASA Glenn and Virginia Tech are reported in Halasz *et al.* (2005) and Langford *et al.* (2005 a,b). This effort was aimed at developing and testing new trailing edge blowing configuration that would require a more realistic amount of air to be injected. The first part of this study, reported by Halasz *et al.* (2005), focused on advanced trailing edge blowing (ATEB) techniques, where fluid injection is varied circumferentially (for example injection can be applied to every other rotor blade, cutting the amount of air being blown by two). Such method basically reduces the tones at the BPF and its harmonics, but adds new tones in between, bringing them closer to the broadband levels. This technique increases the efficiency of the acoustic liners and reduces the amount of air bled from the compressor while still providing significant noise reduction. Halasz *et al.* made acoustic measurements in the ANCF set-up described by Sutliff *et al.* (2002), and numerical studies using the V072 Rotor Wake / Stator Interaction Code from NASA and the Eversman Finite Element Radiation Code. Two ATEB configurations were tested: ATEB 1x1 (where every other rotor blade is used for injection), and ATEB 2x2 (where two consecutive rotor blades are used, while the following two blades are left bare). Halasz *et al.* predicted that a traditional TEB (with all rotor blades involved) would produce a 17.4dB total reduction (8.9dB from wake filling and 8.5dB from acoustic liners), while using 1.5% of the fan throughflow. The ATEB 1x1 produced a 14.1dB reduction but with only 0.9% of the mass flow rate through the fan. Of these 14.1dB, 4.3dB were contributed by the wake filling, while 9.8dB came from the acoustic liners, thus proving the increased efficiency of the technique.

Based on these results, Langford *et al.* (2005a) went on to test different injection geometries in a blow-down linear transonic cascade wind tunnel to identify the most effective way of filling the two-dimensional wakes. A total of 8 different blowing configurations were tested including slots, jets arranged in crossing patterns, vortex generating jets, jets located at the trailing edge, and jets upstream of the trailing edge on both surfaces of the blades. Langford *et al.* took pressure and DPIV (Digital Particle Image Velocimetry) wake measurements and found that a series of 12 jets on both suction and pressure side, at 80% chord, led to great mixing between the injected flow and the viscous wake, while requiring the least amount of air (about 0.75% of the fan throughflow) and momentum.

The final step in this investigation consisted in combining the findings of Halasz *et al.* (2005) and Langford *et al.* (2005a) into a new TEB design to determine the optimal distribution for three-dimensional fan rotors. This work was reported by Langford *et al.* (2005b). The blowing arrangement was selected from the results of Langford (2005a) and CFD analysis was performed to find the optimum blowing jets distribution (in other words, the number of jets and the circumferential injection angle). The numerical analysis predicted that a tip-weighted distribution of 13 jets with a total mass flow of 1.57% could effectively fill in the rotor wake. Therefore, rotor blades with 13 jets on each side located at 80% chord (following Langford *et al.*, 2005a) were built and structurally tested before they were installed in the ANCF. Far-field acoustic measurements were taken using 28 microphones, 5° apart, on a 12.2m radius away from the ANCF. Measurements were conducted for no blowing (baseline case, with the blowing holes covered), and a series of 11 blowing rates (from 0.32 to 0.86% of the throughflow), with 0.5 axial chord spacing between rotor and stator. The greatest tonal attenuation was obtained at 0.68% blowing rate, with a supply gauge pressure of 34.5kPa. This corresponded to a total attenuation of 6.8dB (5.6dB in the inlet section, and 7.5dB in the aft section), with most of the attenuation occurring in the 2nd and 3rd BPF. As a comparison, Halasz *et al.* (2005) obtained a 7.5dB total attenuation with the slotted injection for a blowing rate of 1.5%.

With the rotor-stator spacing increased to 1 axial chord, the attenuation at 0.68% blowing rate increased to 9.9dB. Hot-wire anemometry measurements 0.5 and 1 axial chords downstream the rotor indicated that the increased attenuation with the larger

spacing was a consequence of a better mixing between the injection jets and the viscous wake, as radial discontinuities (regions of overfilling followed by regions of wake deficit) in the wake profiles diffused with the 1 axial chord spacing. The authors believed that the large attenuation might have been the result of a phase cancellation between the regions of overfilling and wake deficit. ATEB designs (namely the ATEB 1x1 from Langford *et al.*, 2005a) were also tested with the surface-blowing rotors but turned out to be less effective than it had been for the slot-blown configuration. Finally, it was also noted that although significant tonal attenuation was obtained with the surface-blown design, broadband levels were actually increased at higher frequencies (above 6kHz) due to the turbulent mixing of the TEB jets. However, such increase in high frequency should not contribute to the overall broadband power level since the high frequency noise is more easily attenuated by the fan's acoustic liners than the lower frequency tonal noise (Langford *et al.*, 2005b).

To further validate the benefits of trailing edge blowing in a realistic engine environment, Fite (2006) tested a new fan model, called Rotor 9, set up in the NASA Glenn Ultra High Bypass (UHB) rig mounted in the Glenn 9 by 15ft (2.8 by 4.6m) Low Speed Wind Tunnel. The fan tested had a tip speed of 256m/s and was designed to produce similar performance as a Pratt & Whitney – NASA Low Noise Fan, called Fan 1. The main goal of the study was to quantify noise reductions, measure impacts on fan aerodynamic performance, and document the flow field created by the trailing edge blowing. The model fan was 0.56m diameter, with 18 rotor blades (with full span TEB), 45 stator vanes, and a bypass ratio of 13.3. Aerodynamic measurements of total pressure and temperature showed that the fan with trailing edge blowing Rotor 9 was behaving closely to the baseline case. Far-field acoustic results showed that the optimal blowing rate was about 2% of the fan throughflow, producing rotor-stator interaction noise tone and broadband levels reductions from the baseline. An overall reduction of 2dB was reported throughout the range of tested speeds. Tone reductions of up to 6dB or more were observed, while broadband levels went down by up to 2dB (especially below 6kHz). The author suggested that, combined with advanced stators designed for minimal interaction tone generation, TEB could be used to target broadband noise. Hotfilm cross-wire data was taken at two different axial locations downstream the rotor and three rotor

speeds (corresponding to approach, cutback, and takeoff). However, dual-over-heat-ratio analysis of the data showed that the high speed cases (cutback and takeoff) required correction due to the change in total temperature. For the approach condition, the data indicated that the TEB success in reducing the mean blade wake velocity deficit relative to the baseline varied with spanwise location. The TEB configuration was not effective at reducing the mean blade wake velocity deficit at the tip, while near the hub the TEB resulted in overblowing of the mean wakes, suggesting non-uniform blowing. Turbulence measurements confirmed that higher turbulence levels were found near the tip but lower levels inner of 75% span. Near the hub, the turbulence levels were actually significantly lower (50% less) than with the baseline configuration. This reduction in turbulence is thought to explain the reduction in broadband seen in the acoustic results.

2.2. Previous Studies Conducted in the Virginia Tech Low Speed Cascade Wind Tunnel

The flow inside the Virginia Tech Low Speed Cascade Wind Tunnel has been the subject of numerous studies. Built in 1996, the cascade tunnel was originally designed to simulate the blade loading and flow features seen in a high bypass ratio aircraft engine during take-off conditions. It has been the focus of downstream flow survey (Muthanna, 1998), two-point measurements of the tip leakage vortex (Wenger (1998) and Wenger et al (2004)), investigation of the flow inside the passage (Muthanna (2002) and Muthanna et al (2004), and Intaratep (2006)), single-point measurements of wakes shed by blades with serrated trailing edges (Geiger, 2005) and blades with trailing edge blowing (Craig, 2006).

One of the first studies conducted in the cascade tunnel was that of Muthanna (1998). Muthanna took three-component hotwire measurements of the mean and turbulent velocity fields, as well as velocity spectra at 5 streamwise stations (1.4, 2.1, 2.8, 3.8, and 4.6 axial chords from the leading edge) for tip gap settings of 0.8%, 1.7%, and 3.3% chord. The results revealed that the endwall region is dominated by an oval area of large streamwise velocity deficit and a circular region of enhanced streamwise vorticity identified as the tip leakage vortex. Downstream measurements of the wake showed

characteristic features of two-dimensional plane wakes, and spectral analysis revealed some vortex shedding from the trailing edge.

Wenger (1999) and Wenger et al (2004) took two-point measurements in the same cross-sections as Muthanna (1998) for a tip gap of 1.7% chord of the velocity spectra and space-time correlation in the tip leakage vortex. The spectral analysis showed no evidence of low frequencies typically associated with vortex wandering. The turbulent motions between adjacent blade wakes or tip leakage vortices were found to be uncorrelated. Large-scale anisotropic structures were found inside the tip leakage vortex. Wenger used linear stochastic estimates in conjunction with Taylors hypothesis to obtain a three-dimensional instantaneous velocity field and vorticity iso-surfaces. The results suggested the presence of intense elongated eddies skewed at 30 degrees with respect to the leakage vortex axis.

Passage flow studies were performed by Muthanna (2002), Muthanna et al (2004), and Intaratep (2005). Muthanna (2002) and Muthanna et al (2004) measured the effects of grid generated freestream turbulence on the flow field through the passage. Three-component hotwire anemometry measurements with a 1.7% chord tip gap were taken at 8 streamwise stations (2 upstream and 6 downstream of the leading edge line). Oil flow visualization revealed that the tip-leakage vortex appears at approximately 0.27 axial chords downstream of the leading edge, and its structure and behavior significantly change between axial locations of 0.77 and 0.98. The freestream turbulence proved to increase blade loading by 4%, reduce the vorticity levels by 20% in the tip leakage vortex, and increase the size of the tip leakage vortex by 30%. Intaratep (2005) studied the effects of unsteady inflow and moving endwall at tip gaps of 1.7, 3.3 and 5.7 % chord. The results indicated that the vortex starts forming near the blade tip at the 12% chord location for a tip gap of 3.3% chord but does not shed across the passage until the quarter chord (as seen in the oil flow by Muthanna (2002)). The shedding location also moves downstream as the tip gap increases while the unsteadiness in the vortex is significantly amplified after the shedding location.

More recently, an effort to identify possible wake management methods to attenuate tone noise resulting from rotor-stator interaction was undertaken in the facility. Geiger (2005) studied the effects of passive trailing-edge serrations on the wakes shed by

representative fan blades. Four sets of serrated trailing-edge designs were studied at four downstream locations with a 1.7% chord tip gap: 1.27cm serrations, 1.27cm serrations with added trailing-edge camber (droop), 2.54cm serrations, and 2.54cm serrations with droop. Larger serration size was found to increase the blade loading, while increased camber lowered it. Pitot measurements downstream of the trailing edge revealed the corrugated pattern of the wakes that directly correlates with the serration geometry. These cross-sections also showed that the structure of the tip-leakage vortex and the upper end-wall boundary layer were not altered by the presence of serrations. Three-component hotwire anemometry showed that the streamwise velocity, turbulent kinetic energy, and turbulent kinetic energy production in the tip-leakage region were the same as those of the baseline (bare) blades. Larger serration size was found to increase the wake spreading rate and the velocity deficit decay rate, with no significant improvement from adding camber. In an aircraft engine, the improved spreading and decay rates would result in smaller pressure fluctuation on the stator vanes, resulting in tone noise attenuation. Fourier decomposition of the mean velocity profiles measured at 1.8 axial chord downstream of the blade row (presented in Figure 2.1) showed that the large serrations could lead to 8 to 13dB reductions at 4 and 5BPF. Note that the BPF mentioned here is notional since the facility used by Geiger has a fixed blade row. Such BPF is obtained from the ratio of the tangential velocity (parallel to the blade row) and the blade spacing. The value of this BPF corresponding to Geiger's conditions is about 100Hz. At the first and second BPF, all serrations resulted in a 1dB increase.

The mean velocity and turbulence quantities were also compared to those of plane wakes, and the smallest serrations (with no added camber) were found to create wake with the same self-similar features seen in plane wakes and with no serrations (i.e. the baseline blade configuration). A noticeable increase in the average turbulence kinetic energy was seen for the larger serrations (with and without camber) while smaller serrations produced equivalent or lower average turbulence than the baseline. This suggests that only the smaller serration could be beneficial in terms of broadband attenuation.

Craig (2006) studied the effects of active trailing edge blowing on the same configuration described by Geiger (2005). For this study, the four center baseline blades

were replaced by rapid prototyped blades fitted with internal passages and a trailing edge blowing slot covering the entire span. The internal passages were designed by CFD to produce uniform blowing through the entire slot. Air was supplied to the blades by an external fan. Two blowing configurations were tested: simple blowing (same geometry as the baseline blade, with a blowing slot) and Kuethe vane blowing (similar to the simple blowing geometry with Kuethe vortex generators located near the trailing edge). Three-component hotwire anemometry downstream of the cascade revealed that surprisingly the wake of the simple blowing case at 1.4% of the throughflow was noticeably deeper than for the passive suction case (where the blowing slot was left open without any blowing applied). The deficit decreased until the optimum blowing rate of 2.5% (that produced a momentumless wake) is reached, after which overfilling occurred. For the Kuethe vane case, the 1.4% data showed agreement with the baseline case, but no optimum blowing rate was found within the range tested (up to 2.7% of the through flow). In fact, for 2.7%, only the extreme pressure side of the wake showed signs of cancellation for the Kuethe vanes.

For both blowing configurations, mean velocity profiles also exhibited an asymmetry that was possibly due to a misalignment of the blowing jet. Single-component hotwire cross-sections normal to the span were further analyzed by Borgoltz et al (2006). The measurements were made at zero blowing rate with a taped slot and an open slot. The taped slot results reveal a large region of low momentum fluid originating 0.15 chords upstream of the trailing edge on the suction side and extending to 0.1 chords downstream. This low momentum region generates a deep and wide wake seen in the downstream profile with non-blowing blades. With the slot open, however, a mild suction is produced that greatly cleans up the trailing edge flow and results in a shallower and thinner wake. Applying trailing edge blowing through the slot does surprisingly little to improve the trailing edge aerodynamics of the blade, as the jet simply superimposes itself onto the thick trailing edge flow. Momentum and displacement thicknesses for both simple and Kuethe blowing cases were lower than the baseline, at all stations. Fourier decomposition of the mean velocity profiles revealed possible tone noise reductions of up to 32dB and 23dB for the simple and Kuethe vane blowing configurations respectively at the 1BPF. At 5BPF, both configurations yield tone increase of 10 and 6dB for the simple

and Kuethe blowing respectively. The Reynolds stress field was lower than the baseline at all streamwise locations, for both blowing configurations, suggesting possible broadband noise benefits.

2.3. Synthesis of Previous Work on Wake Management

There has been extensive work on the effects of wake management strategies on the mean wake. Trailing edge serrations were shown to alter the mean velocity profile by increasing the wake decay and spreading rate. Serrations were also found to introduce corrugation in the mean wake and tend to increase mean turbulence levels.

Trailing edge blowing was found to produce large reductions in the wake deficit resulting in significant tone noise reductions. The turbulence intensity downstream of trailing edge blowing blades was also significantly reduced.

Most of the work done on wake management strategies has been focused on quantifying tone noise reductions. The few studies that report the effects of such strategies on broadband noise sources have been limited to observations of Reynolds stress in wakes and acoustic measurements in model fan. Reynolds stress provides information only about the intensity of the turbulence, while acoustic measurements are limited to the ultimate pressure radiation. So far, there have been no studies seeking to quantify the impact of wake management strategies on the turbulence structure of fan blades. In this dissertation, for the first time, the impact of various wake management strategies on the turbulence structure is established by measuring both the scale and the intensity of the turbulence. Such information is required to evaluate the effects of the wake management strategies on the potential of the wakes to generate broadband noise.

2.4. Statistical Methods for Turbulent Wakes

This section summarizes some of the numerical methods available that are used in the current research to extract information on the potential of the treated wakes to produce broadband noise.

2.4.1. Proper Orthogonal Decomposition

Proper Orthogonal Decomposition (POD) is a linear procedure based on spectral theory that makes no assumptions about the linearity of the problem to which it is applied (Berkooz et al, 1993). This method was first applied to the problem of turbulence in fluids by Lumley (1967) and later by Berkooz et al (1993).

This technique identifies the motions that contain the most energy on average (Pope, 2000). The unsteady velocity field is described by a set of optimum modes that represent a superposition of regularly appearing eddy types and thus the main eddies in the flow. As implied by its name, the POD modes are orthogonal and uncorrelated (Lumley, 1968). Lumley actually showed that the modes were eigenfunctions of the two-point correlation tensor and the corresponding eigenvalues their spectrum. The magnitudes of the eigenvalues correspond to the proportion of kinetic energy produced by the corresponding eigenfunction or mode. Each mode represents the best fit, on average, to the instantaneous velocity field. POD is very attractive due to its linear nature and because it can provide a description of the main eddies with the minimum number of modes.

2.4.2. Compact Eddy Structures

While POD can provide one-dimensional information on the structure and intensity of the turbulence motions, it can only do so in inhomogeneous directions. In homogeneous directions (such as in time and spanwise across the rotor wake) POD reduces to a simple Fourier decomposition that does not provide much useful information about the types of eddies present in the wake and results in a large number of modes. To generate compact representations of the typical eddy structures responsible for the turbulent motions, Glegg and Devenport (2001) suggested obtaining the velocity field in the streamwise direction associated with each proper orthogonal mode by making a linear stochastic estimate (LSE) of the field based on the modal profile. LSE seeks to minimize the error between the turbulent fluctuations and the terms in a modal expansion (Glegg and Devenport, 2001). The use of LSE in turbulent flows was first suggested by Adrian (1975). Adrian used a conditional eddy (that he measured at discrete locations in the

flow) in isotropic turbulence along with velocity correlation measurements to estimate the conditions at the remaining spatial locations. Adrian used second order estimation but later showed that higher order terms in the stochastic estimates had insignificant contributions so that only first order terms (linear) could be used to provide accurate estimation (Tung and Adrian, 1980). It follows that the velocity at a given position can be obtained from the measured velocity at another point and the correlation function between these two locations.

Therefore, it is possible to obtain a two-dimensional velocity field by combining POD in the inhomogeneous direction and LSE in the streamwise direction. The resulting velocity field produced from the modal decomposition of the correlation tensor (and therefore representative of the eddies associated with it) is termed ‘Compact Eddy Structures’ (CES). CES turn out to be given by the inner product of the two-point correlation function and the proper orthogonal modes.

As noted by Glegg and Devenport (2001), the CES do not necessarily occur in the flow as specific features, but they do represent average structures. In other words, the CES are related to the ensemble average of the flow. In an aircraft engine, these eddies shed by the rotor blades would then couple with the stator vane response function to give the spectral response of the rotor-stator interaction, i.e. the broadband signature of the system.

2.4.3. Broadband Excitation

While CES can be used to provide a two or three-dimensional picture of the turbulent eddies implied by a correlation function, our main interest in them here is also as a tool to evaluate the potential of the turbulent wake to produce broadband noise when interacting with a solid surface (rotor-stator interaction).

Glegg and Devenport (2001) showed that the power spectral density of sound generated by an isolated interaction between an inhomogeneous turbulent flow and a lifting surface could be obtained as a function of the POD and CES of this turbulent flow, namely the summation Fourier transforms of the spanwise component of the CES field (in other words the upwash seen by the cutting blade) and the POD mode. As noted by Glegg and Devenport (2001), the CES do not necessarily occur in the flow as specific

features, but they do represent average structures (since they are based on the most probable velocity profiles obtained from the POD). While the CES are not basis functions of the instantaneous velocity field like the POD modes are, they are basis functions of the space-time correlation function. Therefore, phenomena that depend upon the correlation function (like the broadband radiation resulting from the rotor-stator interaction) can be decomposed using CES.

Since the formulation of the power spectral density of the radiated pressure field depends only on the POD and CES, i.e. the changes in the turbulence at a specific frequency, the relative contributions to the sound from all the modes at a specific frequency can be characterized entirely in terms of its CES and POD components. These Broadband Excitation Terms (BET) provide an objective relative measure of the potential of the wake turbulence to generate broadband noise at each frequency.

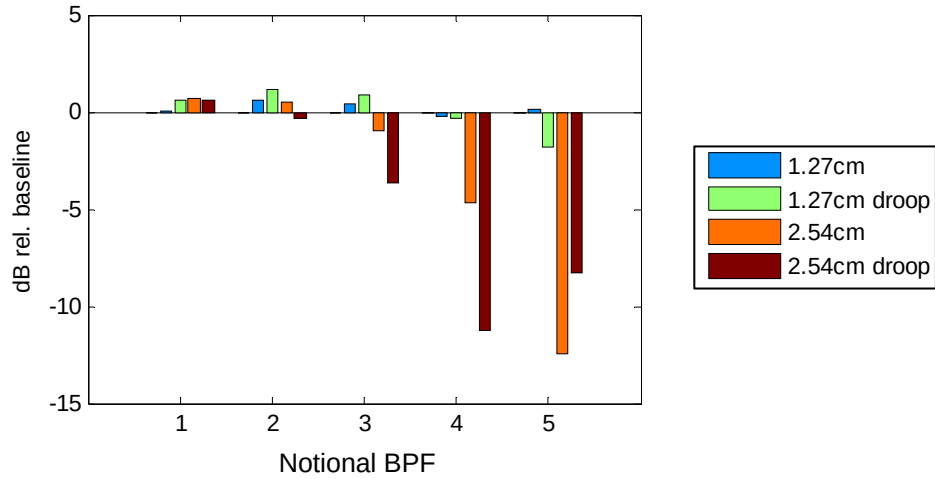


Figure 2.1 Fourier Decomposition of the mean velocity profiles of Geiger (2005) measured 1.8 axial chord downstream of the trailing edge.

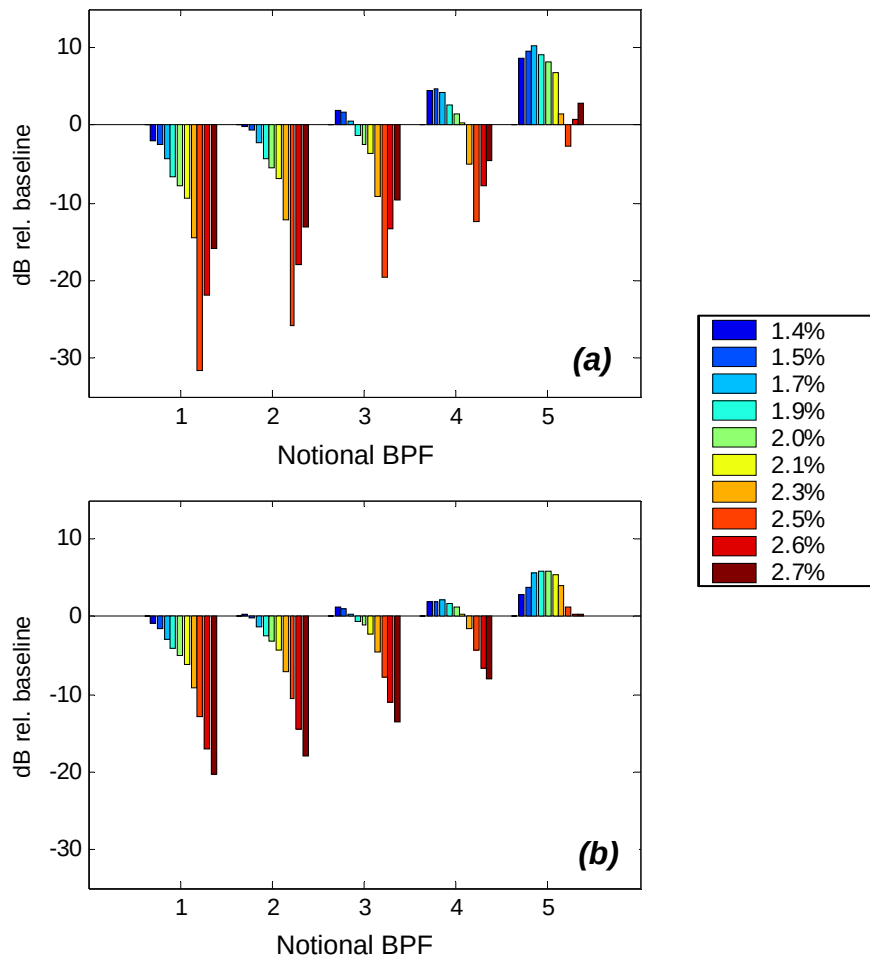


Figure 2.2 Fourier Decomposition of the mean velocity profiles of Craig (2006) measured 1.8 axial chord downstream of trailing edge blowing blades with (a) simple blowing (b) Kuethe blowing.

Chapter 3 - Instrumentation and Measurement Techniques

All the experimental work presented in this dissertation was performed in the Virginia Tech Low Speed Linear Cascade Wind Tunnel. This section describes in details this facility along with the measurement system and techniques used.

3.1. Virginia Tech Low Speed Linear Cascade Wind Tunnel

There are two particular aspects of the cascade wind tunnel facility that make it particularly attractive for the study of aircraft fan blade flows. The first is the linear cascade configuration that simulates the rotor wakes in a stationary frame of reference, greatly simplifying the measurement. The second is the blade geometry which produces blade loading and passage flow features that are similar to an aircraft engine fan at take-off conditions (Muthanna and Devenport, 2004). The overall layout of the tunnel is presented in Figure 3.1. Detailed descriptions are also given by Muthanna (2002), Geiger (2005), and Intaratep (2006).

3.1.1. Upstream Section

Shown in Figure 3.2, the upstream section comprises the fan, the diffuser, the settling chamber and the contraction. The flow is supplied to the tunnel through a 15-hp AC motor centrifugal fan with a 0.521m^2 exit area. The flow is slowed down through the 1:2.86 expansion ratio diffuser before entering a series of flow conditioning screens in the 1.85m long diffuser to reduce turbulence levels and swirling. The flow is then accelerated into the rectangular test section (described in the next section) through a two-dimensional contraction with a 6.43:1 ratio.

3.1.2. Test Section

The test section shown in Figure 3.3 is made of three main parts: the inlet section (where various boundary layer treatments ensure a uniform inflow to the blade row), the blade row itself, and the downstream section.

3.1.2.1. Inlet Section

The flow exiting the contraction enters the inlet section through a 0.762m wide by 0.305m high rectangular cross-section. The flow in the potential core travels normal to the rectangular cross-section. While the inlet width and height are constant until the flow enters the blade row, it should be noted that due to the angling induced by the staggering of the blades one sidewall is 0.85m in length (short-wall) where the other is 2.35m long (long-wall). This creates a 1.81m wide exit plane oriented 24.9° with respect to the potential core direction.

At the exit of the inlet section 25.4mm high boundary layer scoops parallel to the blade leading edge plane and shown in Figure 3.4, are used on both the section floor and ceiling to deliver a thin (about 15mm at the leading edge line) and pitchwise uniform boundary layer to the blade row. As the boundary layer is removed, the potential core effectively sees a sudden increase in cross-sectional area that would result in an artificial deceleration of the flow and the creation of a pressure gradient. The reduction of the test section height from 0.305m in the inlet to 0.254m downstream of the boundary layer scoops prevents such mechanism from occurring, insuring uniform inflow to the blade row free of any streamwise pressure gradient. The scoops use the pressure difference between the inside and the outside of the tunnel to remove the proper amount of air. This pressure difference can be adjusted by using a set of screens (described in section 3.1.2.3) at the exit of the downstream section. Additionally, a set of flanges located on the exit of the scoops can be adjusted to refine this pressure difference.

The height of the boundary layer scoops was designed by estimating the boundary layer thickness using a $1/7$ velocity distribution (Muthanna, 2002). To ensure that the scoops would adequately remove the boundary layer, metal plates located at the scoops exhaust can be adjusted to control the amount of air that is bled. Additionally, a

boundary layer bleed, consisting in a 762mm wide by 63.5mm long sheet of perforated steel on the lower end wall, is located 483mm downstream of the contraction exit. This additional bleed insures that no boundary layer spillage over the lower end wall scoop. The new boundary layer originating from the leading edge of the boundary layer scoop is then tripped on the lower end wall to ensure pitchwise uniformity. The trip consists of a square cross-section wire (2.5mm wide) and is located 7mm downstream of the scoop leading edge and can be seen in Figure 3.4.

Typical freestream velocities U_∞ in the inlet section are on the order of 25m/s with turbulence levels of 0.12%, with a streamwise lengthscale of $0.06c_a$ (8mm) (Muthanna, 2002).

3.1.2.2. Blade Row

The wind tunnel is equipped with a baseline blade row, each blade has a core compressor section with a 25.4cm total chord (c), a 13.89cm axial chord (c_a), and an aspect ratio of one. The blade spacing is 236mm (along the leading edge line). The blade profiles are GE Core Compressor Rotor B blades (a 4% thick modified circular arc section with rounded leading and trailing). This profile results in a 15° trailing edge metal angle (the angle between the tangent to the camber line at the trailing edge and the chordline). The coordinates of the GE Rotor B profile (along the chord ξ/c and thickness η/c) are given in Table 3.1 and plotted in Figure 3.5. The number of blade/passages was determined after the computational study by Moore *et al.* (1996) showed that 5 or more passages were sufficient to simulate an infinite cascade.

Table 3.1 Coordinates of the GE Rotor B airfoil.

Pressure Side		Suction Side	
ξ/c	η/c	ξ/c	η/c
0.00000	0.00000	0.00000	0.00000
0.00044	0.00060	0.00006	-0.00149
0.00141	0.00105	0.00092	-0.00317
0.00293	0.00132	0.00260	-0.00501
0.00497	0.00139	0.00509	-0.00697
0.00752	0.00121	0.00841	-0.00902

0.01060	0.00078	0.01258	-0.01110
0.01420	0.00014	0.01760	-0.01318
0.01905	-0.00075	0.02347	-0.01524
0.02912	-0.00255	0.03019	-0.01729
0.03918	-0.00430	0.03775	-0.01940
0.04923	-0.00600	0.04586	-0.02159
0.09696	-0.01342	0.09315	-0.03348
0.14456	-0.01978	0.14059	-0.04394
0.19206	-0.02516	0.18816	-0.05303
0.23947	-0.02960	0.23582	-0.06079
0.28681	-0.03317	0.28357	-0.06728
0.33410	-0.03593	0.33139	-0.07255
0.38136	-0.03793	0.37925	-0.07664
0.42859	-0.03922	0.42716	-0.07961
0.47579	-0.03983	0.47510	-0.08149
0.52298	-0.03975	0.52307	-0.08226
0.57017	-0.03899	0.57106	-0.08194
0.61735	-0.03757	0.61906	-0.08049
0.66452	-0.03560	0.66710	-0.07767
0.71168	-0.03300	0.71515	-0.07328
0.75889	-0.02960	0.76318	-0.06716
0.80619	-0.02524	0.81113	-0.05916
0.85365	-0.01977	0.85895	-0.04914
0.90134	-0.01301	0.90656	-0.03696
0.94933	-0.00478	0.95391	-0.02246
0.95946	-0.00284	0.96383	-0.01911
0.96962	-0.00083	0.97373	-0.01565
0.97979	0.00125	0.98361	-0.01207
0.98998	0.00342	0.99348	-0.00839
0.99305	0.00409	0.99644	-0.00726
0.99704	0.00356	0.99947	-0.00467
1.00000	0.00000	1.00000	0.00000

The blade row is cantilevered from an aluminum superstructure positioned outside the test section. The superstructure allows individual setting the pitch and tip gap of each blade through a combination of bolts and screws. Therefore the blade span inside

the tunnel is always 254mm minus the tip gap. The tip gap used for this study was set to 4mm or 1.65%*c* for the baseline blades.

Blades are inserted in the test section through close-fitting slots in the 6.35mm thick Plexiglas roof. A 1mm gap is maintained around the periphery of each blade root where it intersects with the upper endwall (based on CFD simulations Tweedt (2006)). The gap is maintained using blade root covers made of galvanized steel sheets 0.5mm thick with an enlarged GE Rotor B profile cut-out. The resulting mass flow out of the facility through this gap was found to greatly reduce the tendency for the flow to develop a corner stall at the root.

The blades are 23.6cm apart in the blade row, at a stagger angle of 56.9 degrees and an inlet angle of 65.1 degrees. Even though the blade row is fixed, it is possible to determine a notional blade passing frequency for this facility corresponding to the ratio of the tangential velocity (parallel to the leading edge line at the entrance of the blade row) and the blade spacing. For an inlet freestream velocity of 24.5m/s, the tangential velocity is $24.5 \sin(65.1) = 22.2\text{m/s}$, corresponding to a notional blade passing frequency of 94Hz.

Each blade is fitted on each side with 6.35mm-wide boundary layer trip strips (created from 0.5mm diameter glass beads) located 2.54cm from the leading edge. The boundary layers were tripped to ensure the boundary layers on each side would undergo transition to turbulent flow, preventing the flow from detaching from the blade surface. The location of the trip strip was selected to ensure it would result in flow transition without perturbing the pressure distribution. The height of the strip was obtained by using the method of Barlow (1999), where:

$$h_{trip} = \frac{12K}{\text{Re}_f} \quad (3.1)$$

where h_{trip} is the height of the trip strip (in inches), K a constant, and Re_f is the Reynolds number (per foot) based on the freestream speed.

The constant K , that depends on the trip roughness, varies is 600 for Reynolds number greater than 100,000 (based on the freestream speed and the distance from the leading edge to the trip strip). For very low Reynolds numbers, the value of K increases to 1000. In the cascade tunnel, the freestream Reynolds number per foot in the test-section is 480,000, while the Reynolds number based on the distance from the leading

edge to the trip strip is 40,000. While this value is smaller than 100,000 it is not considered a very low Reynolds number (as per Barlow). Consequently, a value of 800 was assumed for K , leading to a trip strip height of $h_{trip}=0.02\text{in}$ or 0.5mm (the size of the glass beads).

Side scoops, formed by the gap between the blade surface and the long- and short-walls are located at each end of the blade row to remove the side wall boundary layers. These side scoops, seen in Figure 3.6, are used in conjunction with the boundary layer scoops and bleeds described above to insure the flow uniformity along the blade row. The flange seen in Figure 3.6 could be adjusted to control the amount of air removed from the test section.

The blades were chosen based on the work by Wisler (1981) who designed this blade section as the third stage in the core compressor of aircraft engines. While these are compressor blades, the loading they produce in this configuration is quantitatively similar to that seen in a subsonic aircraft engine fan at take-off conditions, see Muthanna and Devenport (2004).

3.1.2.3. Downstream Section

The downstream section is a 1.81m wide by 0.254m high section extending downstream, parallel to the potential core direction, as seen in Figure 3.3.

The upper end wall of the downstream section is made of two main parts. The upstream part is made of a 6.35mm-thick foam board to use with the 3-dimensional traverse system described later. A 6.35mm Plexiglas with slots cut parallel to the blade row and reinforced with aluminum angle can also be used. However, the foam boards provide more flexibility for slot cutting to match any 3-dimensional probe traversing scheme.

Adjustable tailboards, hinged to the surfaces of blades 1 and 8, are used to insure that the baseline blades produce the design turning angle of 11.8° with negligible net pressure gradient along the blade row. The tailboards can be adjusted separately as seen in Figure 3.3.

At the downstream section exit, a set of two screens is used to control the back pressure in the facility. The steel mesh (with a 69.5% open ratio) is used along with one horizontal and three vertical strips of tape to obtain the desired blockage. Back pressure is monitored using three aluminum pressure ports, 0.762mm in diameter, located on the lower end wall, 127mm upstream of the exit plane. The three ports were connected together using Tygon tubes of 1.6 mm diameter to acquire an average reading of the back pressure. The average pressure of the three ports is recorded during the facility calibration and monitored during each measurement. The back pressure is set so that the pressure coefficient between the exit plane and the inlet is 0.44.

3.2. Measurement Equipment

3.2.1. Pressure Sensing

Pitot-static and surface pressure measurements were used to obtain velocities in the inlet and downstream of the blade row in addition to blade loadings. The present section describes the Pitot-static probes, pressure transducers, and multi-channel pressure sensing equipment utilized to make these measurements.

3.2.1.1. Pitot-Static Measurements

Pitot-static measurements were used to determine the freestream velocity in the inlet section as well as the calibration profiles (see section 3.5) and spanwise cross-sections (discussed in Chapter 5).

Inlet freestream velocity was measured with a Dwyer Instruments standard model 160 Pitot-static probe (model 167-12) located 0.95m downstream of the contraction exit, at mid-height of the inlet section, and 0.15m away from the long-sidewall (as shown in Figure 3.3).

Downstream calibration profiles and cross-sections were measured using a second Dwyer 167-12 Pitot-static probe at various locations.

For all measurements, two Setra pressure transducers (model 239) were used. These transducers have a 0-5V output range with 0-5 and 0-15in. of water input pressure ranges respectively and primary uncertainties of 0.005inH₂O.

Voltages from the pressure transducers are passed to an Agilent E1432A, 16-bit, 16 channel digitizer controlled by a laptop PC. Data was acquired at a rate of 3200Hz. 10 records of 1024 samples each were used.

3.2.1.2. Surface Pressure Measurements

Blade loadings were determined from surface pressure measurements using an array of pressure ports imbedded in the blades surface as described in Chapter 4. These ports were connected to a multi-channel Scanivalve system using a series of metallic and Tygon tubing. The Scanivalve Corp. CTRLR2P/S2-S6 system can automatically read pressure from 48 ports using one transducer. The transducer (Setra Model 239 described above) is connected to the different ports by a computer controlled mechanical switch. The system was controlled by an IBM/AT286 computer running QBASIC with a data translation DT2801-A A/D converter. 1000 samples were recorded at 6400Hz over 10 records.

3.2.2. Hot-wire Anemometry

Three-component measurements of the mean and turbulent velocities downstream of the blade row were accomplished using four-sensor hot-wire anemometers. The probes, the constant temperature anemometers and the calibration process are described below.

3.2.2.1. Hot-Wire Probes

Three-component turbulence measurements were made using miniature four-sensor Kovaznay type hot-wire probes (see Figure 3.7). These probes are custom made by Auspex and based on the AVOP-4-100 model. Each probe consists of two orthogonal X-wire arrays with each sensor inclined at a nominal 45° from the probe axis. The four 3.8mm etched tungsten wires are about 1.2mm in length yielding a measurement volume of approximately 0.75mm³. More information on the development of such probe along with further description can be found in Wittmer (1998).

3.2.2.2. Constant Temperature Anemometers

Four-sensor hot-wire probes were operated using a Dantec Dynamics 90C10 StreamLine Constant Temperature Anemometry (CTA) System running Dantec Dynamics Streamware software with a overheat ratio of 1.7. The system, optimized to yield a flat frequency response up to 18kHz, contains a built-in signal conditioner (high and low pass filters, DC-offset) and amplifier. The DC-offset and the amplifier gain were set to produce the best input voltage resolution for the data acquisition described below. For this particular study, the built-in frequency filters were disabled. The CTA units signal were passed on to an Agilent E1432A 16 bit, 16 channel digitizer controlled by a laptop PC. The E1432A module is capable of taking 51,200 simultaneous samples per second on each of its 16 data acquisition channels. The module has digital signal processing capabilities, transducer signal conditioning, and anti-aliasing filters.

3.2.2.3. Calibration process

There are two main steps required to calibrate a four-sensor hot-wire probe. The first consists in a velocity calibration where the probe is inserted in a jet of known velocity. The probe longitudinal axis is aligned with the jet axis and the jet velocity is varied. The voltage output from each sensor is recorded to extract the sensor voltage response to velocity change using King's Law. To do so, the probes were positioned in a uniform jet. The velocity components are determined by means of a direct angle calibration during which the probe is pitched and yawed over a range of angles (between -45° and 45° for both pitch and yaw). The true relation between the flow angle and the velocities are determined by comparing the probe outputs at known pitch and yaw angles through a look-up table (Wittmer *et al.* 1998). This calibration is known as the angle calibration.

The anemometer was also dynamically balanced to produce a flat frequency spectrum up to 18kHz by measuring its impulse response. The method of Bearman (1971) was used to correct for small temperature variations during measurement and calibration.

Velocity calibrations are taken before and after each measurement run. Angle calibrations of the four-sensor probes are run every 3 to 6 months. Angles are adjusted using an automated turn-table with a primary uncertainty of 0.05° .

3.3. Probe Mounting and Positioning

3.3.1. Probe Holders

The four-sensor hot-wire probes were positioned in the tunnel using the probe holders shown in Figure 3.8. This design allowed for the probe to be yawed and pitched, setting its orientation relative to the flow before each measurement. This is of particular importance for the two-point measurements. To obtain the desired minimum probe separation of 5mm (refer to Chapter 6 for full description of these measurements), the two probes had to be yawed towards each other (as shown in Figure 3.9). The angular separation between the probes was computed from the known probe holder length of each probe (defined as the distance from the probe holder vertical shaft to the probe tip) and the distance between the two probe holder shafts. The angular separation between the probes was adjusted so that each probe would be yawed at less than 15° from the potential core flow direction. This would ensure minimum angular uncertainties and flow interference in the measurements. In fact, the interference between the two probes (i.e. the influence that one probe has on the flow field sensed by the other) was found to be within the uncertainties of the measurement (presented in section 3.6). The yaw angles for the fixed and moving probe were -8.8° and 11.6° respectively (in the wake aligned coordinate system defined in Section 3.4).

The probes were positioned using a Mylar[®] template attached to the lower end wall. This template was referenced to the blade row location and indicated the projection on the lower end wall of the baseline wake propagation direction, the 1.8 axial chord location (where two-point measurements were taken). The template also featured the desired orientation for both probe along with the location for the probe holder shafts and probe tips.

Once the probes were correctly aligned, the probe locations were set using a gage block ($\pm 0.0003\text{mm}$ resolution) placed on the lower end wall. One of the lower corner of the block was positioned at a known location on the Mylar[®] template. Since the dimensions of the gage block were known, the upper corner of the block (associated with the lower corner placed on the template) was used as a known reference point in the three-dimensional space. Two cathetometers were then set to this reference corner. Once the gage block is removed, the measurement volumes of the probes were moved to match that point (as seen through the cathetometers).

Such method yields uncertainties of $\pm 0.5\text{mm}$ in the axial (perpendicular to the blade row) and pitchwise (parallel to the blade row) locations. Spanwise location uncertainties are equivalent to the gage block resolution. The use of the transparent template resulted in a maximum uncertainty of 1mm in the minimum probe separation.

3.3.2. Three-Axis Traverse

Hot-wire and Pitot-static probes were traversed using a computer controlled 3-axis traverse system shown in Figure 3.10. The system is made of a 2-axis traverse (that allows motion in the spanwise and pitchwise directions) mounted on a secondary traverse (that enables axial motion). The 2-axis traverse is mounted on the secondary traverse using an aluminum I-beam. Motion is achieved through four Compumotor stepper motors, model S-57-83-MO controlled by Parker PDX13 single-axis package mini-step drives. The resolution of the programmable traverse is 0.025mm.

3.4. Coordinate Systems

There are three coordinate systems used throughout the present study. These coordinate systems can be divided in two categories: cascade aligned (aligned with the frame of reference of the blade row) and flow aligned (aligned with the flow direction downstream of the cascade) coordinate systems. Figure 3.11 provides a visual description of all 3 systems. The blades in the cascade are numbered from 1 to 8 as seen in Figure 3.3.

The main cascade aligned system, or axial-pitchwise system, has the x -axis aligned with the axial direction (perpendicular to the line connecting the blade leading edges) referenced at the trailing edge of the baseline blade 5 (the center blade), the z -axis follows the pitchwise direction (parallel to the blade row leading edge line), while the y -axis completes the right hand rule (and is therefore parallel to the blade span) with its origin on the lower end wall. The origin of this referential is located at the trailing edge of blade 5 on the lower end wall. In such coordinate system, the leading edge of the blade row is located at $x/c_a=-1$.

A second blade aligned coordinate system is also used, primarily to present blade loading information. This system is equivalent to the axial-pitchwise coordinate system except the x_b -axis is now referenced at the tip of the leading edge of baseline blade 5. The other two axes (y_b and z_b) are aligned with the spanwise and pitchwise directions respectively. This coordinate system is primarily used to present blade surface pressure distribution.

The flow aligned coordinate system is used to present the velocity correlation results. In this system, the X -axis is aligned with the spanwise averaged wake propagation direction (inclined 36.7° from the z -direction) and is referenced at the trailing edge of blade 5 on the lower end wall. The Y - and Z -axes are respectively along the span and normal to the wake (the Z -axis being referenced at the wake centerline). In this coordinate system, the X , Y , and Z components of the mean velocity are defined as U , V , and W . The associated fluctuating velocity components are referred as u' , v' , and w' .

3.5. Facility Calibration

The main purpose of a cascade tunnel calibration was to generate the optimal flow characteristic inside the tunnel for operation of the linear cascade. These are:

1. No acceleration or deceleration of the inflow entering the blade row
2. No velocity gradients in the potential core of the inflow
3. No net pitchwise pressure gradients upstream or downstream of the blade row

4. Constant back pressure, matching the average pressure downstream of the blade row in condition 3.

These requirements are verified from local pressure measurements across the test section for both upstream and downstream locations at the midspan height ($y/c_a=0.92$). The measurements were performed using a Dwyer Instruments Standard Model 160 Pitot-static probe traversed pitchwise at 0.87 axial chord upstream of the cascade leading edge plane and 1.8 axial chord downstream of the trailing edge plane. Results are presented in terms of total pressure and static pressure coefficients calculated from the following equations.

$$C_{p0} = \frac{P_0 - P_\infty}{P_{0\infty} - P_\infty} \quad (3.21)$$

$$C_p = \frac{P - P_\infty}{P_{0\infty} - P_\infty} \quad (3.3)$$

where P_0 and P are the local total and static pressures, respectively, and the ∞ index represent the freestream inlet conditions.

Figure 3.12 shows a typical calibration plot obtained for a calibrated facility fitted with the GE Rotor B blades. The horizontal represent the normalized pitchwise distance z/c_a and the vertical axis the coefficients of pressures C_p and C_{p0} and the normalized velocity U/U_∞ . The normalized velocity is obtained from

$$\frac{U}{U_\infty} = \sqrt{C_{p0} - C_p} \quad (3.4)$$

Figure 3.12 shows the wakes of blades 3 to 6, seen as the defects in the C_{p0} and U/U_∞ curves, are periodic both in deficit and spacing (the black boxes are scaled to match the 236mm or $0.93c$ blade spacing). The total pressure coefficient curve shows that the potential core stagnation pressure is 1. The static pressure coefficient curve shows that the net pressure gradient in the pitchwise direction (the slope of the linear fit) is negligible and that the average static pressure coefficient level is 0.43 which matches the values of the back pressure recorded during the experiments (varying from 0.42 to 0.44).

The calibration was performed after the installation of each new blade set and was also checked periodically.

3.6. Sampling Schemes and Measurement Uncertainties

The two-point velocity measurements were sampled at a frequency of 51.2kHz in 50 records of 2048 samples each, corresponding to about 3 records per second. High-pass anti-aliasing filters with cut-off frequency of 25kHz were used to acquire the data.

The uncertainties associated with the two-point four-sensor hotwire measurements were computed using the method outlined by Ma (2003) based on the technique of Kline and McIntok (1953). The uncertainty in hotwire measurements can be separated in two components: random and bias errors. The bias errors occurring during the A/D voltage conversion are absorbed during the velocity calibration, leaving a random uncertainty in the A/D converter that is twice the RMS random error. The RMS random voltage for the Agilent 1432 system is listed as $45\mu V$ resulting in a random A/D converter error of $90\mu V$. Other major sources of uncertainty arise from uncertainties in the velocity and angle calibrations. Uncertainties were computed at two locations inside the wake (including the wake center) and in the freestream. Uncertainties were found to be consistent at all locations. The typical measurement uncertainties for the three wake-aligned mean velocities U , V , and W , the six independent Reynolds stresses and the turbulence kinetic energy k (defined as $\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)/2$) are listed in Table 3.2.

Table 3.2 Two-point four-sensor hotwire measurement absolute uncertainties

Quantity	Uncertainty (20:1 odds)
$\delta U / U_\infty$	7.405×10^{-3}
$\delta V / U_\infty, \delta W / U_\infty$	9.802×10^{-3}
$\overline{\delta u'^2} / U_\infty^2$	2.962×10^{-7}
$\overline{\delta v'^2} / U_\infty^2$	3.135×10^{-7}
$\overline{\delta w'^2} / U_\infty^2$	4.346×10^{-7}
$\overline{\delta u'v'} / U_\infty^2, \overline{\delta u'w'} / U_\infty^2, \overline{\delta v'w'} / U_\infty^2$	2.887×10^{-7}
$\overline{\delta k} / U_\infty^2$	6.123×10^{-7}

The uncertainty in the velocity correlation (presented in Chapter 6) between two points is function of the position of these two points. Therefore the uncertainties in the correlation coefficient can be expressed as

$$\delta\left(\overline{u'_i|_1 u'_j|_2} / \overline{u'_i|_1} \overline{u'_j|_2}\right) = \frac{\delta\overline{u_i u_j}}{\overline{u_i} \overline{u_j}} \bigg|_{ref} \sqrt{\overline{u'_i|_1} \overline{u'_j|_2}} \quad (3.5)$$

where i and j are indices running from 1 to 3 and corresponding to the three components of the fluctuating velocity (u , v , and w), where $|_1$, $|_2$ and $|_{ref}$ represent the conditions at point 1, point 2, and a reference points respectively. For a reference point at the wake center, the uncertainty in the correlation coefficient then varies from 0.02 to 0.06.

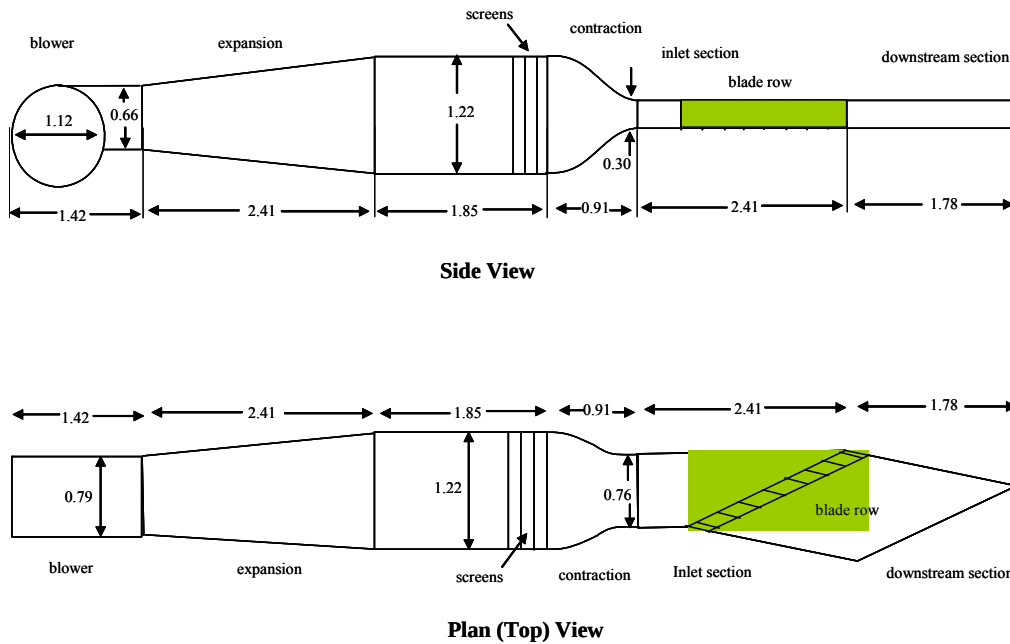


Figure 3.1 Virginia Tech Low Speed Linear Cascade Wind Tunnel overall layout.

(Dimensions in meters) From Muthanna, 2002.

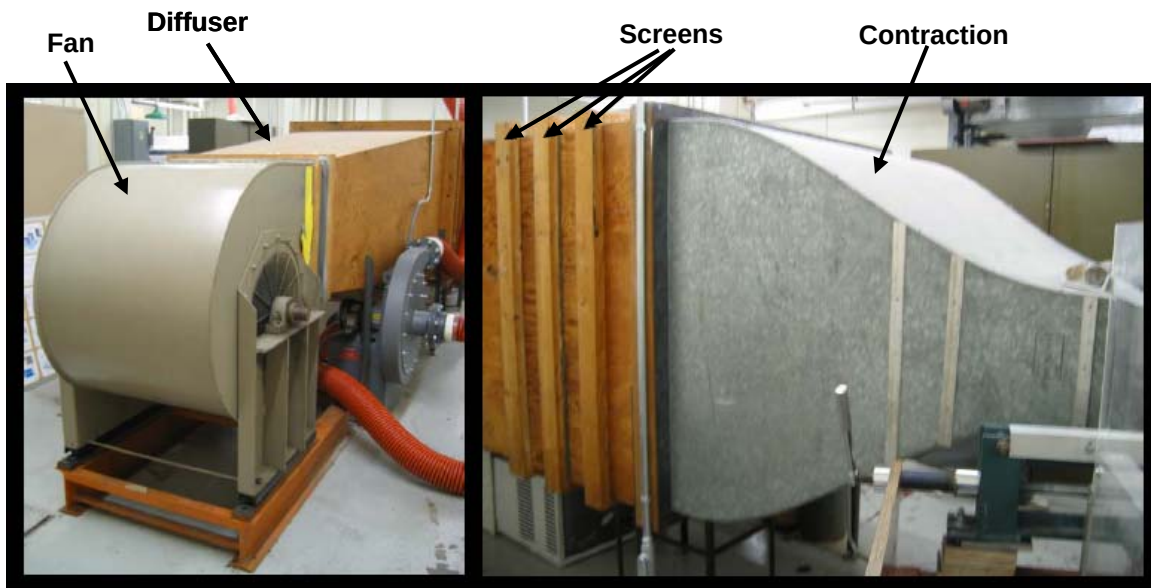


Figure 3.2 Views of the upstream section of the linear cascade wind tunnel. Modified from Geiger (2005).

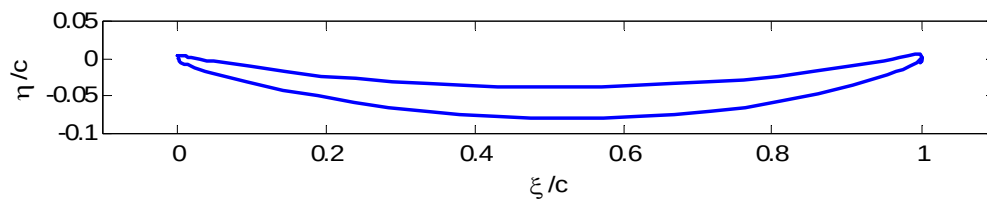


Figure 3.5 GE Rotor B profile.

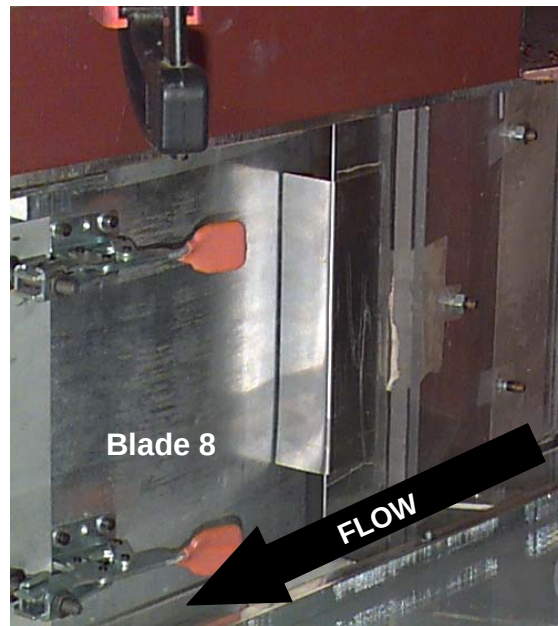


Figure 3.6 Side Scoop of Blade 8.

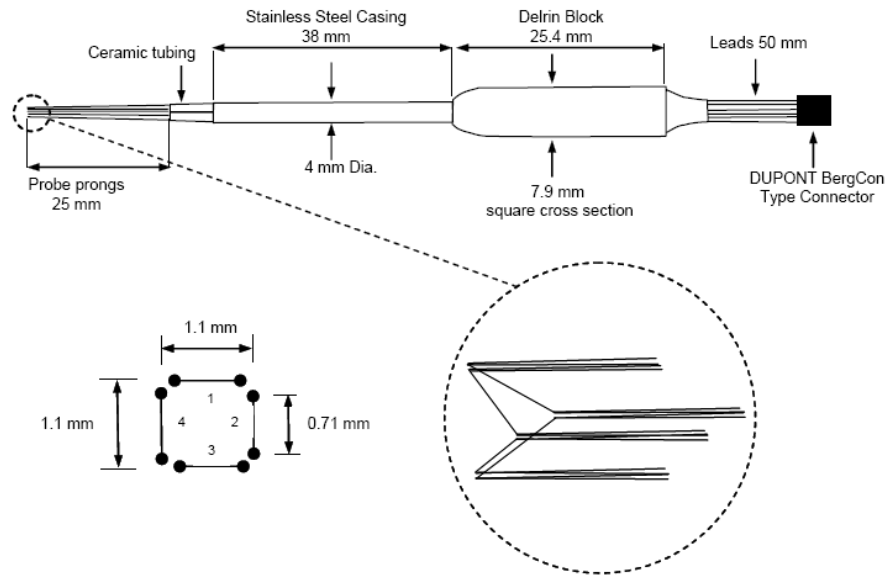
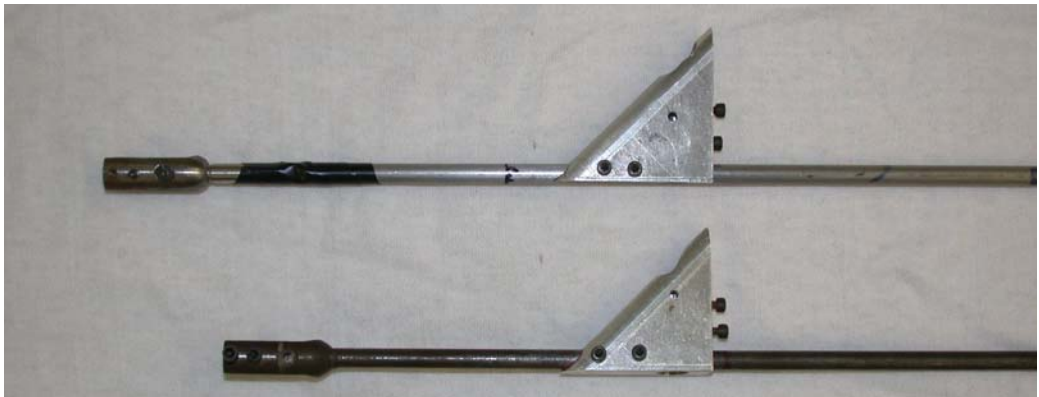


Figure 3.7 Schematic of a four-sensor Kovaznay-type, subminiature hotwire probe. From Intaratep, 2006.



(a)



(b)

Figure 3.8 Four-sensor hot-wire probe holders. (a) Top View (b) Side View.

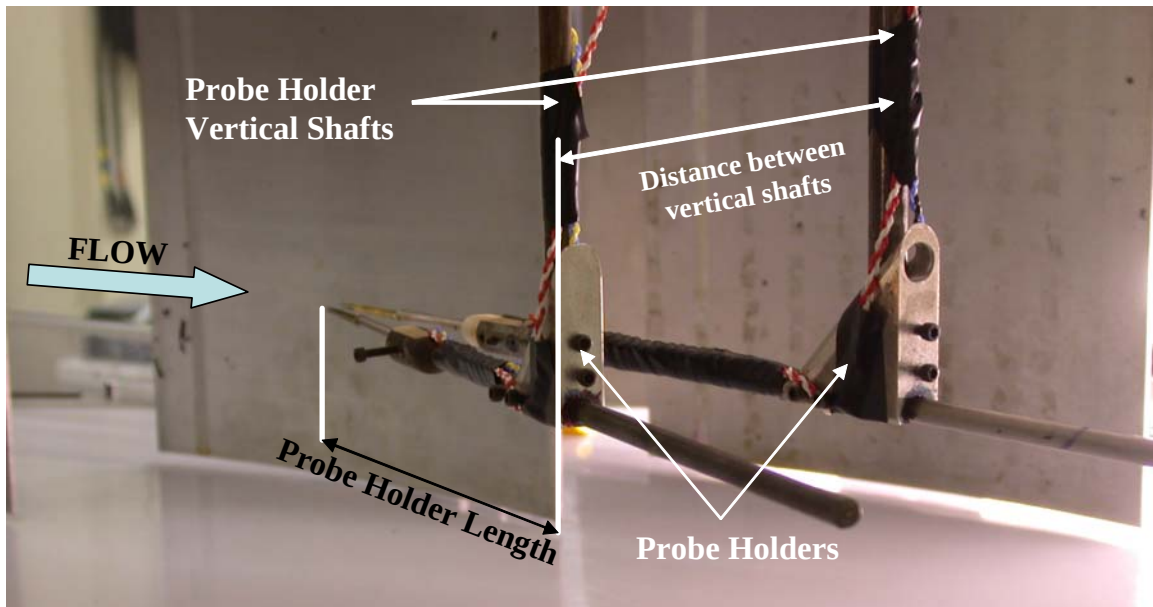


Figure 3.9 Two-point four-sensor hot-wire probe set-up inside the test-section.

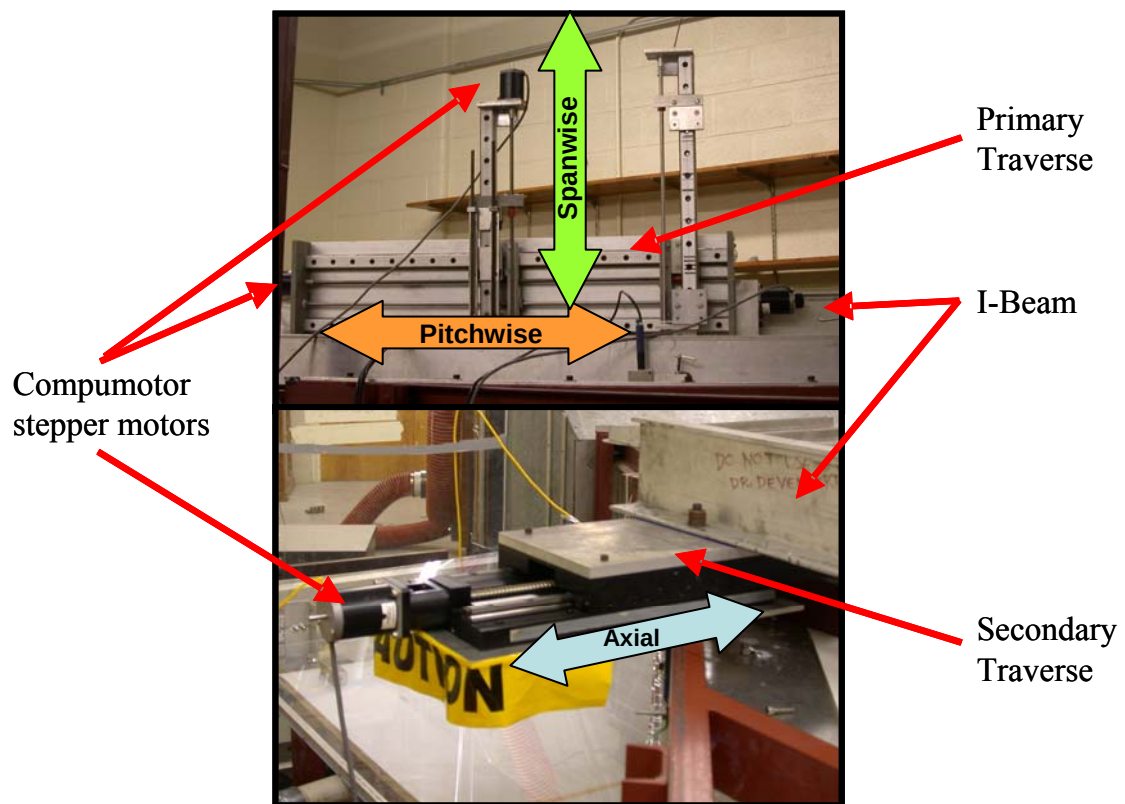


Figure 3.10 Three-axis traverse system (adapted from Intaratep, 2006).

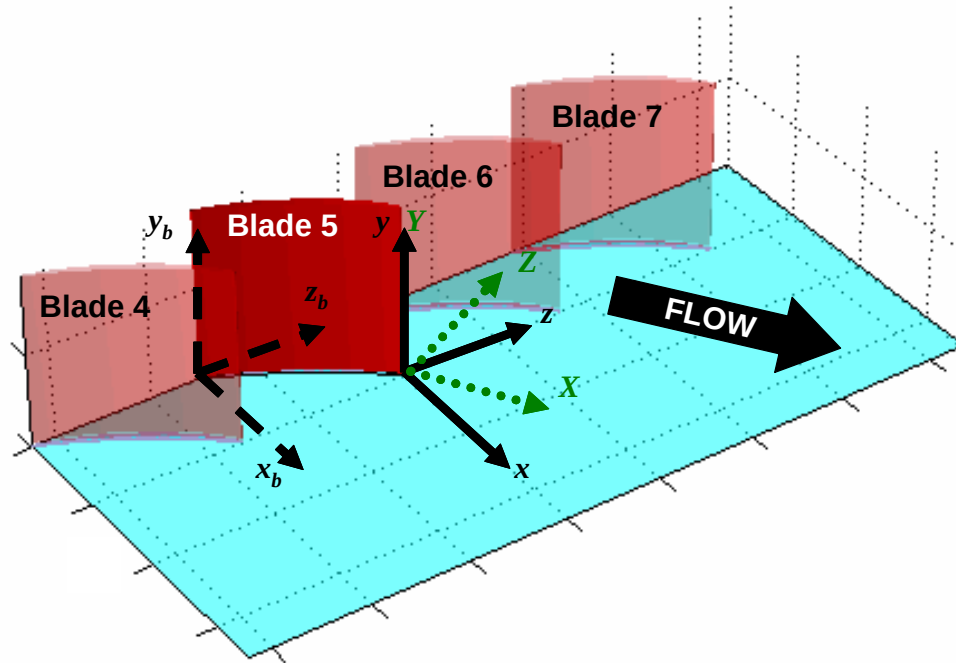


Figure 3.11 Coordinate systems definitions.

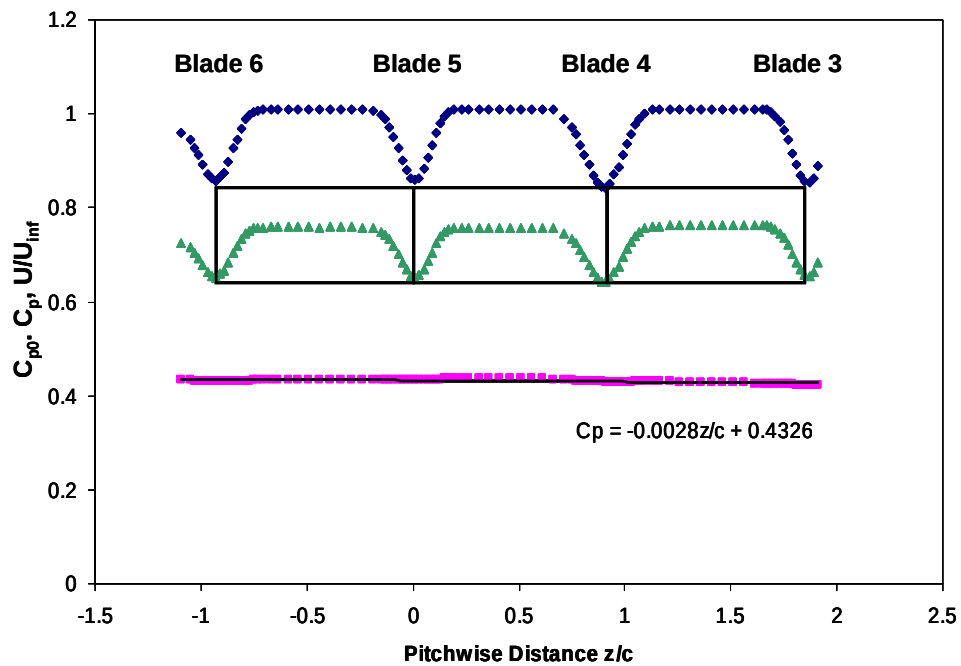


Figure 3.12 Downstream calibration plot for the baseline GE Rotor B blades.

Chapter 4 - Modified Blade Designs

4.1. Serrated Trailing Edge Blades

The four serrated trailing edge blades are shown in Figures 4.1 through 4.4. The blade design variations are based on three design parameters: the serration size, serration period, and the serration camber (droop). The serration consists of planar triangular shaped serrations. The serration size is defined as the distance along the camber line between the serration valley and tip. The serration period is the distance between two consecutive serration peaks (or valleys). The droop (added camber) consists in increasing the penetration of the serrations by increasing the trailing edge metal angle compared to the baseline. Four configurations were tested where two different serration sizes (1.27 and 2.54cm) and two different droops (0 and 5° increase in trailing edge metal angle) were used. The modified blades were design to share many similarities with the GE Rotor B blades including the blade profile over the majority of the chord, the span and the blunt trailing edge tip. The serrated trailing edge blades were manufactured to have the same mounting base as the baseline blade to ensure identical blade location and incidence. The mounting configuration is described in detail by Geiger (2005).

To ensure a meaningful comparison between the results from the serrated trailing edge and baseline blades, the modified blades have to produce the same blade loading and turning angle. They were therefore designed to match the GE Rotor B profile over the first 85% to 95% of the chord (for the large and small serrations respectively). The change in profile is limited to the last 15%chord where the addition of serration and/or droop occurs (figure 4.1c through 4.4c). Unknown to Geiger when he tested these blades, the modified blades were also built with an adjusted incidence metal angle to account for the addition of the serration and/or the droop. This variation in the blade geometry is believed to have been introduced to produce a blade loading similar to the baseline for each combination of serration size and droop. This change in incidence is described below for each configuration.

The spans of all the modified blades are identical at 28.9cm. This is 0.95cm longer than the baseline blade. However, as described in Geiger (2005), this difference is accounted for when the blades are mounted in the superstructure so that the effective span of the blades inside the test-section is always the height of the test-section (25.4cm) minus the tip gap. For all the serrated trailing edge blade configurations, a tip gap of 1.65%chord was used.

For each configuration, four blades were used to replace the 4 center blades of the cascade. This ensured flow periodicity over the 2 center passages (downstream of which all the measurements were done). The two center blades were instrumented with pressure ports in a chordwise row located 12.7cm from the blade tip (corresponding to the midspan when mounted inside the test-section). Blade 4 was instrumented with 24 ports on its suction side and blade 5 with 24 ports on its pressure side so that when combined they would represent the blade loading associated with the center passage flow. The coordinates of the pressure ports varies between configurations and are therefore listed in the following sections.

4.1.1. 1.27cm Serration

The 1.27cm serrated trailing edge blades are shown in Figure 4.1 and are named after the serration size (shown in figure 4.1) that is 1.27cm (5%chord) along the mean camber line. The serration spanwise period is 2.12cm (8.4%chord) leading to a serration aspect ratio of 1.67. Consequently, the 1.27cm span is made of 15 serration periods, 11 of which are inside the test-section when mounted. The serration aspect ratio leads to an angle of 39.8° between the serration face and a plane perpendicular to the span.

The nature of the saw-tooth like serration produces a spanwise variation of the chordlength from a minimum of 24.9cm at the serration valley to 26cm at the tip. The resulting 25.5cm mean chord is thus kept close to the baseline dimensions (25.4cm). The trailing edge thickness at the tip (1.1% c) is comparable to the baseline trailing edge thickness (1.3% c). The nature of the serration geometry (which is, in effect, formed by cutting out or extending the GE rotor B section) creates a blunt trailing edge near the valley where serrations valleys have a thickness of 2.0% c .

As discussed in the next chapter, following Geiger's study, the serrated trailing edge blades were found to have been manufactured with a different blade incidence (resulting from a difference in the metal angle). For the 1.27cm serration blades, this difference was found to be negligible.

The coordinates of the 48 pressure ports used to measure these blade loadings are given in Table 4.1. The spanwise location of the pressure ports is half-way between the 6th serration valley and the 7th serration peak from the blade tip.

Table 4.1 Coordinates of the pressure ports on the 1.27cm serration blades. Cascade aligned coordinates are referenced from the leading edge and normalized on the axial chord

<i>Port Number</i>	<i>Pressure Side</i>			<i>Suction Side</i>		
	x_b/c_a	y_b/c_a	z_b/c_a	x_b/c_a	y_b/c_a	z_b/c_a
1	0.021	0.943	-0.014	-0.001	0.943	-0.020
2	0.035	0.943	-0.048	0.009	0.943	-0.057
3	0.050	0.943	-0.081	0.021	0.943	-0.092
4	0.065	0.943	-0.115	0.032	0.943	-0.128
5	0.080	0.943	-0.149	0.045	0.943	-0.164
6	0.120	0.943	-0.233	0.078	0.943	-0.251
7	0.161	0.943	-0.315	0.113	0.943	-0.338
8	0.204	0.943	-0.397	0.151	0.943	-0.424
9	0.248	0.943	-0.478	0.191	0.943	-0.508
10	0.294	0.943	-0.559	0.233	0.943	-0.593
11	0.341	0.943	-0.638	0.278	0.943	-0.675
12	0.389	0.943	-0.717	0.324	0.943	-0.756
13	0.439	0.943	-0.795	0.373	0.943	-0.837
14	0.490	0.943	-0.872	0.423	0.943	-0.916
15	0.542	0.943	-0.949	0.475	0.943	-0.995
16	0.594	0.943	-1.025	0.529	0.943	-1.072
17	0.648	0.943	-1.100	0.586	0.943	-1.146
18	0.702	0.943	-1.173	0.645	0.943	-1.220
19	0.759	0.943	-1.247	0.708	0.943	-1.291
20	0.817	0.943	-1.318	0.773	0.943	-1.359
21	0.877	0.943	-1.389	0.841	0.943	-1.425
22	0.901	0.943	-1.417	0.869	0.943	-1.450
23	0.926	0.943	-1.444	0.898	0.943	-1.475

24		0.951	0.943	-1.472		0.927	0.943	-1.499	

4.1.2. 1.27cm Serration with Droop

The 1.27cm drooped serration blades are presented in Figure 4.2. In this configuration, the serration size and depth are identical to the 1.27cm serration blades. The serration camber is larger by 5° compared the baseline mean camber at the trailing edge resulting in more penetration on the pressure side. The droop is applied at one discrete location (95%chord). The variation between the 1.27cm drooped and baseline profiles can be seen in figure 4.2. The metal incidence of the 1.27cm drooped blades is 0.3° lower than the baseline.

The addition of droop effectively changes the chordlength so that the maximum chord (at the serration tip) is now 25.8cm while the minimum is 24.7cm, producing an average chord comparable to the baseline blade. The trailing edge at the serration peak matches the $1.3\%c$ of the baseline. The blunt trailing edge created at the serration valley is $2.1\%c$ thick.

The coordinates of the 48 pressure ports (also located half-way between the 6th serration valley and the 7th serration peak from the blade tip) are given in Table 4.2.

Table 4.2 Coordinates of the pressure ports on the 1.27cm drooped serration blades. Cascade aligned coordinates are referenced from the leading edge and normalized on the axial chord

<i>Port Number</i>	<i>Pressure Side</i>			<i>Suction Side</i>		
	x_b/c_a	y_b/c_a	z_b/c_a	x_b/c_a	y_b/c_a	z_b/c_a
1	0.021	0.943	-0.014	-0.001	0.943	-0.020
2	0.035	0.943	-0.048	0.009	0.943	-0.057
3	0.050	0.943	-0.081	0.021	0.943	-0.092
4	0.065	0.943	-0.115	0.032	0.943	-0.128
5	0.080	0.943	-0.149	0.045	0.943	-0.164
6	0.120	0.943	-0.233	0.078	0.943	-0.251
7	0.161	0.943	-0.315	0.113	0.943	-0.338
8	0.204	0.943	-0.397	0.151	0.943	-0.424
9	0.248	0.943	-0.478	0.191	0.943	-0.508
10	0.294	0.943	-0.559	0.233	0.943	-0.593
11	0.341	0.943	-0.638	0.278	0.943	-0.675
12	0.389	0.943	-0.717	0.324	0.943	-0.756
13	0.439	0.943	-0.795	0.373	0.943	-0.837
14	0.490	0.943	-0.872	0.423	0.943	-0.916
15	0.542	0.943	-0.949	0.475	0.943	-0.995
16	0.594	0.943	-1.025	0.529	0.943	-1.072
17	0.648	0.943	-1.100	0.586	0.943	-1.146
18	0.702	0.943	-1.173	0.645	0.943	-1.220
19	0.759	0.943	-1.247	0.708	0.943	-1.291
20	0.817	0.943	-1.318	0.773	0.943	-1.359
21	0.876	0.943	-1.389	0.841	0.943	-1.425
22	0.901	0.943	-1.417	0.869	0.943	-1.450
23	0.927	0.943	-1.443	0.897	0.943	-1.475
24	0.954	0.943	-1.469	0.927	0.943	-1.499

4.1.3. 2.54cm Serration

The 2.54cm serrated trailing edge blades can be seen in Figure 4.3. Similar to the 1.27cm serration blades, the 2.54cm blades are based on the GE Rotor B blade with 2.54cm long serrations. The serration spanwise period is also increased to 4.29cm. The serration aspect ratio of 1.67 is kept identical to the 1.27cm blades (with and without droop).

The increased serration size results in a minimum chord of 24.4cm at the serration valley and 26.7cm at the tip. The trailing edge thickness at the tip matches the baseline trailing edge thickness, while serrations valleys are twice as thick ($2.6\%c$). The metal incidence of the 2.54cm serration blades is 0.7° lower than the baseline. This change of incidence will be shown in Chapter 5 to explain some of the discrepancies reported by Geiger (2005) in the blade loading between the serrated trailing edge and baseline blades.

The blade loading was measured using 48 pressure ports (24 on each side) whose coordinates are presented in Table 4.3. The pressure ports are aligned half-way between the 3rd serration valley and 4th serration peak (starting from the blade tip) as seen in Figure 4.3.

Table 4.3 Coordinates of the pressure ports on the 2.54cm serration blades. Cascade aligned coordinates are referenced from the leading edge and normalized on the axial chord

<i>Port Number</i>	<i>Pressure Side</i>			<i>Suction Side</i>		
	x_b/c_a	y_b/c_a	z_b/c_a	x_b/c_a	y_b/c_a	z_b/c_a
1	0.025	0.943	-0.013	0.001	0.943	-0.019
2	0.039	0.943	-0.046	0.012	0.943	-0.056
3	0.053	0.943	-0.080	0.023	0.943	-0.092
4	0.069	0.943	-0.114	0.035	0.943	-0.127
5	0.084	0.943	-0.147	0.048	0.943	-0.162
6	0.123	0.943	-0.231	0.080	0.943	-0.250
7	0.164	0.943	-0.314	0.115	0.943	-0.337
8	0.208	0.943	-0.396	0.154	0.943	-0.423
9	0.252	0.943	-0.477	0.193	0.943	-0.508
10	0.297	0.943	-0.557	0.235	0.943	-0.591
11	0.344	0.943	-0.636	0.280	0.943	-0.674
12	0.392	0.943	-0.715	0.326	0.943	-0.756
13	0.442	0.943	-0.793	0.374	0.943	-0.836
14	0.492	0.943	-0.870	0.424	0.943	-0.916
15	0.544	0.943	-0.947	0.476	0.943	-0.994
16	0.596	0.943	-1.022	0.529	0.943	-1.072
17	0.650	0.943	-1.098	0.586	0.943	-1.147
18	0.704	0.943	-1.172	0.645	0.943	-1.221
19	0.760	0.943	-1.245	0.706	0.943	-1.293
20	0.817	0.943	-1.318	0.770	0.943	-1.362
21	0.877	0.943	-1.389	0.838	0.943	-1.428
22	0.901	0.943	-1.417	0.865	0.943	-1.454
23	0.925	0.943	-1.445	0.893	0.943	-1.479
24	0.950	0.943	-1.472	0.922	0.943	-1.504

4.1.4. 2.54cm Serration with Droop

The last serrated trailing edge blade set was based on the 2.54cm serration blades with the addition of droop. These blades are shown in Figure 4.4. The serration camber is 5° greater than the baseline. The droop is discretely applied at 85%chord. The variation between the 2.54cm drooped and baseline profiles can be seen in figure 4.4. The metal incidence of the 2.54cm drooped blades is 0.9° lower than the baseline.

The addition of droop effectively changes the chordlength so that the maximum chord (at the serration tip) is now 26.3cm while the minimum is 24.2cm, producing an average chord comparable to the baseline blade. The trailing edge thickness at the serration tip matches the baseline thickness. The combination of the droop and the large serrations produce a blunt trailing edge at the serration valley that is $3.1\%c$ thick.

The coordinates of the 48 pressure ports used to measure the blade loading are given in Table 4.4.

Table 4.4 Coordinates of the pressure ports on the 2.54cm drooped serration blades. Cascade aligned coordinates are referenced from the leading edge and normalized on the axial chord

<i>Port Number</i>	<i>Pressure Side</i>			<i>Suction Side</i>		
	x_b/c_a	y_b/c_a	z_b/c_a	x_b/c_a	y_b/c_a	z_b/c_a
1	0.025	0.943	-0.013	0.001	0.943	-0.019
2	0.039	0.943	-0.046	0.012	0.943	-0.056
3	0.053	0.943	-0.080	0.023	0.943	-0.092
4	0.069	0.943	-0.114	0.035	0.943	-0.127
5	0.084	0.943	-0.147	0.048	0.943	-0.162
6	0.123	0.943	-0.231	0.080	0.943	-0.250
7	0.164	0.943	-0.314	0.115	0.943	-0.337
8	0.208	0.943	-0.396	0.154	0.943	-0.423
9	0.252	0.943	-0.477	0.193	0.943	-0.508
10	0.297	0.943	-0.557	0.235	0.943	-0.591
11	0.344	0.943	-0.636	0.280	0.943	-0.674
12	0.392	0.943	-0.715	0.326	0.943	-0.756
13	0.442	0.943	-0.793	0.374	0.943	-0.836
14	0.492	0.943	-0.870	0.424	0.943	-0.916
15	0.544	0.943	-0.947	0.476	0.943	-0.994
16	0.596	0.943	-1.022	0.529	0.943	-1.072
17	0.650	0.943	-1.098	0.586	0.943	-1.147
18	0.704	0.943	-1.172	0.645	0.943	-1.221
19	0.760	0.943	-1.245	0.706	0.943	-1.293
20	0.817	0.943	-1.318	0.770	0.943	-1.362
21	0.878	0.943	-1.388	0.838	0.943	-1.428
22	0.904	0.943	-1.413	0.866	0.943	-1.454
23	0.932	0.943	-1.438	0.896	0.943	-1.477
24	0.958	0.943	-1.464	0.927	0.943	-1.498

4.2. *Trailing Edge Blowing System*

4.2.1. Blowing Blade Geometries

The three blades are presented in Figure 4.5 through 4.7. The blowing blades are all based on the baseline blades. Three blowing configurations were tested. The first one consists in a replica of the baseline blade with the addition of a blowing slot just upstream of the trailing edge on the suction side. This configuration is referred to as the “simple blowing” configuration. The second set of blades is identical to the simple blowing blades with the addition of vortex generators (based on the design detailed by Kuethe, 1972) upstream of the blowing slot on the suction side. This configuration is referred to as the “Kuethe blowing” configuration. The final set of blowing blades has its blowing slot located at the actual trailing edge of the blade (as opposed to the first two sets). Additionally, the blowing slot edges are serrated making this configuration the “serrated blowing” configuration.

Four blades for each configuration were used to replace the four center blades in the cascade thus ensuring flow periodicity around the center passage. Similar to the serrated trailing edge blades, the two center blades were instrumented with pressure ports to form the blade loading around the center passage. Blade 4 was instrumented with 21 pressure ports on its suction side. Blade 5 had 24 ports on its pressure side. The coordinates of the pressure ports (located 126mm from the blade tip, i.e. at the blade midspan) are identical for all three blowing blades sets and can be found in Table 4.5 below.

Table 4.5 Coordinates of the pressure ports on trailing edge blowing blades. Cascade aligned coordinates are referenced from the leading edge and normalized on the axial chord

<i>Port Number</i>	<i>Pressure Side</i>			<i>Suction Side</i>		
	x_b/c_a	y_b/c_a	z_b/c_a	x_b/c_a	y_b/c_a	z_b/c_a
1	0.016	0.909	0.022	-0.006	0.909	0.029
2	0.030	0.909	0.056	0.004	0.909	0.065
3	0.045	0.909	0.090	0.016	0.909	0.101
4	0.060	0.909	0.124	0.028	0.909	0.136
5	0.075	0.909	0.157	0.041	0.909	0.172
6	0.115	0.909	0.241	0.074	0.909	0.259
7	0.157	0.909	0.323	0.109	0.909	0.346
8	0.200	0.909	0.405	0.148	0.909	0.431
9	0.245	0.909	0.486	0.188	0.909	0.516
10	0.291	0.909	0.566	0.231	0.909	0.599
11	0.339	0.909	0.645	0.276	0.909	0.682
12	0.387	0.909	0.723	0.323	0.909	0.763
13	0.437	0.909	0.801	0.372	0.909	0.843
14	0.488	0.909	0.878	0.423	0.909	0.922
15	0.541	0.909	0.954	0.476	0.909	0.999
16	0.594	0.909	1.029	0.531	0.909	1.075
17	0.648	0.909	1.104	0.589	0.909	1.150
18	0.704	0.909	1.177	0.650	0.909	1.222
19	0.761	0.909	1.250	0.713	0.909	1.291
20	0.819	0.909	1.321	0.779	0.909	1.358
21	0.880	0.909	1.390	0.848	0.909	1.422
22	0.905	0.909	1.417			
23	0.930	0.909	1.444			
24	0.955	0.909	1.471			

4.2.1.1. Simple Blowing Blades

The simple blowing blades, shown in Figure 4.5, are externally identical to the baseline GE Rotor B blades with the exception of the presence of the blowing slot on the suction side near the trailing edge. The simple blowing blades have a 25.4cm chord and a 28.8cm span. As mentioned earlier for the serrated trailing edge blades, this longer span does not affect the effective span inside the test-section once the blades are mounted.

The blowing slot is nominally 1.4mm wide and extends 241mm along the blade span (starting 6.3mm from the blade tip). The slot is located 9.5mm (3.7%chord) upstream of the trailing edge on the suction side. While the simple blowing blades were designed to closely match the baseline profile, the blade thickness at the blowing slot exit was found to be 2%chord thick (compared to 1.8% for the baseline). The trailing edge thickness of the simple blowing blades is 1.2%c (0.1%c less thick than the baseline). For detailed dimensions refer to Craig (2006). The blowing jet velocity measured at the blowing slot exit is listed in Table 4.6 for various blowing rates. Blowing rates are expressed as fractions of the total mass flux through one passage of the cascade.

Table 4.6 Blowing jet velocity variation with blowing rate for the simple blowing blades. Velocity is normalized on the inflow velocity U_∞

<i>Blowing Rate (% through flow)</i>	<i>Blowing Jet Velocity (U/U_∞)</i>
1.40	1.22
1.50	1.28
1.70	1.45
2.00	1.66
2.30	1.89
2.50	2.01
2.60	2.15

4.2.1.2. Kuethe Blowing Blades

The Kuethe blowing blades (Figure 4.6) are based on the simple blowing blade design with the addition of Kuethe vortex generators. The purpose of these surface mounted vane-type vortex generators is to extract high momentum core flow to mix the

lower momentum boundary layer fluid thus reducing or eliminating boundary layer separation. This type of generators has been tested on a Clark Y airfoil at a Reynolds number of 700,000. The generators were 3%*c* wide, 24%*c* long and inclined at 15° from the local flow direction. They were found to decrease the wake deficit and turbulence levels but also increase the spanwise correlation due to the periodic streamwise velocity injection (Kuethe, 1972).

The Kuethe blowing blades have a 25.4cm chord and a 28.8cm span. The 1.4mm wide blowing slot is located 3.7%*c* upstream of the trailing edge and extends over 241mm (starting 6.7mm from the blade tip).

The vortex generators are similar to those tested by Kuethe (1972) and consist of semi-circular cross-section elements (4.7mm in diameter or 2%*c*) manufactured on the suction side of the blade. The generators are evenly spaced across the span (every 25.4mm starting 32mm from the blade tip) and inclined at an angle of 15° from the local flow direction. This spacing leads to a total number of 9 vortex generators per blade. Each element is 46mm long (18%*c*) and 4.7mm wide. The spanwise row of Kuethe vanes is located 24.8mm upstream of the trailing edge or 15.2mm from the blowing slot exit. The chordwise row of pressure ports on the suction side is located at the mid-height of the fifth element from the blade tip. See Craig (2006) for more details about this configuration. The blowing jet velocity measured at the blowing slot exit is listed in Table 4.7 for various blowing rates.

Table 4.7 Blowing jet velocity variation with blowing rate for the Kuethe blowing blades. Velocity is normalized on the inflow velocity U_∞

<i>Blowing Rate (% through flow)</i>	<i>Blowing Jet Velocity (U/U_∞)</i>
1.40	1.01
1.50	1.09
1.70	1.25
2.00	1.44
2.30	1.72
2.50	1.79
2.60	1.89

4.2.1.3. Serrated Blowing Blades

The serrated blowing blades (Figure 4.7) share few similarities with the other two blowing blade configuration. They are designed to match the baseline profile over more than 99% of the chord. The major difference with the simple and Kuethe blowing resides in the blowing slot configuration. The blowing slot is now located at the trailing edge of the blade (instead of upstream of it on the suction side) so that the blade chord is reduced to 253.4mm. The span is the same as the other two blowing configuration at 28.8cm.

The blowing slot has a nominal width of 1.4mm and a span of 241mm (starting at 6.7mm from the blade tip). The slot is serrated on both sides with a total of 36 serrations. On the suction side of the slot edge, the serration consists of planar triangular serrations (similar to those used for the serrated trailing edge blades). Each serration is 5.5mm long chordwise ($2\%c$) with a spanwise period of 6.9mm producing a serration aspect ratio of 1.25. On the pressure side, the serration dimensions are identical. However, half of the serrations are not planar. Every other serration has a reduced angle (resulting in increased penetration in the blowing jet). The difference in the serration droop results in a pitchwise amplitude of 3mm from the peak of a planar serration to the peak of the following drooped one. The blowing jet velocity measured at the blowing slot exit is listed in Table 4.8 for various blowing rates.

Table 4.8 Blowing jet velocity variation with blowing rate for the Kuethe blowing blades. Velocity is normalized on the inflow velocity U_∞

<i>Blowing Rate</i> <i>(% through flow)</i>	<i>Blowing Jet Velocity</i> <i>(U/U_∞)</i>
1.40	1.18
1.70	1.34
2.30	1.56
2.60	1.88

4.2.2. Air Delivery System

The air injected at the trailing edge of these blades was provided by a supply system made of a blower (separate from the wind tunnel fan), a plenum, and a set of

nozzles. The air supplied by the blower passes through a plenum to ensure equal amount of air is directed to each blowing blade. The air is directed to the blades through a delivery pipe connecting the plenum on one hand and the nozzle on the other. An air conditioning unit was connected at the inlet of the blower to balance the increase in temperature due to internal frictions occurring inside the supply system (mainly in the blower, the nozzles and blades). This was of particular importance as hotwire measurement would be biased if there was a temperature gradient between the air injected at the trailing edge and the flow passing through the cascade. Detailed description of the blowing system can be found in Craig (2006).

The blades were rapid prototyped with an internal passage (seen in figure 4.8) designed using CFD predictions to create a spanwise uniform injection. The convergent nozzles were designed to provide uniform inflow to the internal passage. The air enters the internal passage from an opening at the root of the blade, passes through 5 channels before exiting the blade at the trailing edge. This can be seen in figure 4.8. The connection between the nozzles and the blades were covered with silicon sealant to prevent any flow leaks. The nozzles were instrumented with 8 pressure ports (4 mounted equally spaced around the circular inlet and 4 around the outlet). These pressure ports were used to calibrate the nozzle by measuring the pressure difference across the nozzle for a series of mass flow rates (obtained by measuring the variation of the velocity across the nozzle outlet). The calibration, performed at 17 different blowing rates for each of the four nozzles, produced a curve fit of the relation between blowing rate and pressure difference across the nozzle. A set of pipes connecting the plenum to each delivery nozzles was then configured so that each nozzle would deliver the same amount of air. Such calibration ensures blade to blade periodicity of the blowing. Details on the nozzle and their calibrations can be found in Craig (2006).

4.2.3. Stabilizing Pins

It should be noted that when the simple blowing blades were first mounted in the test-section they were found to twist significantly when subjected to the aerodynamic loading. To prevent this, stabilizing pins (one near the leading edge and one near the trailing edge) were inserted at the tip of the blades (for all 3 blowing configurations).

Matching holes were drilled in the lower end-wall of the test-section to ensure proper positioning of the pins, and therefore of the blades. A diagram of this set-up can be seen in Figure 4.9a. The leading edge pin was located 18mm from the leading edge while the trailing edge pin was inserted 27mm from the trailing edge (Figure 4.9b and c). To ensure that the pin would induce as little strain as possible on the blades, the tip gap was reduced from $1.65\%c$ (used for the baseline and serrated trailing edge blades) to $0.4\%c$. The effects of these pins on the flow downstream of the blades were investigated by taking Pitot-static cross-sections. The main concern was that the small tip gap would lead to corner separation at the lower end wall. However, the Pitot-static cross-sections revealed no evidence of such phenomenon. Details about the locations and validation of these pins can be found in Craig (2006).

4.2.4. Blowing System Calibration

Once the system was put together and the blowing blades were mounted in the tunnel, two main measurements were made to ensure proper functioning of the system for each blade configuration. As mentioned earlier, since the core of the measurements made downstream of the blowing blades was realized using constant temperature hotwire anemometry, a temperature gradient between the air injected at the blowing slot and the flow through the cascade would create a bias. To ensure that the air conditioning unit balances the heat generated inside the supply system by internal friction, a thermocouple was used to measure the temperature directly downstream of the blowing slot. The maximum temperature difference between the blowing jet and the cascade flow were found to be less than 0.5°C . The second measurement consisted in single hotwire measurements of the mean streamwise velocity directly downstream ($0.02x/c_a$) of the blowing slot to verify the uniformity of the blowing across the slot. All three blowing configurations were found to produce closely uniform blowing at the slot exit. These blowing slot uniformity measurements are reported in greater details in Craig (2006).

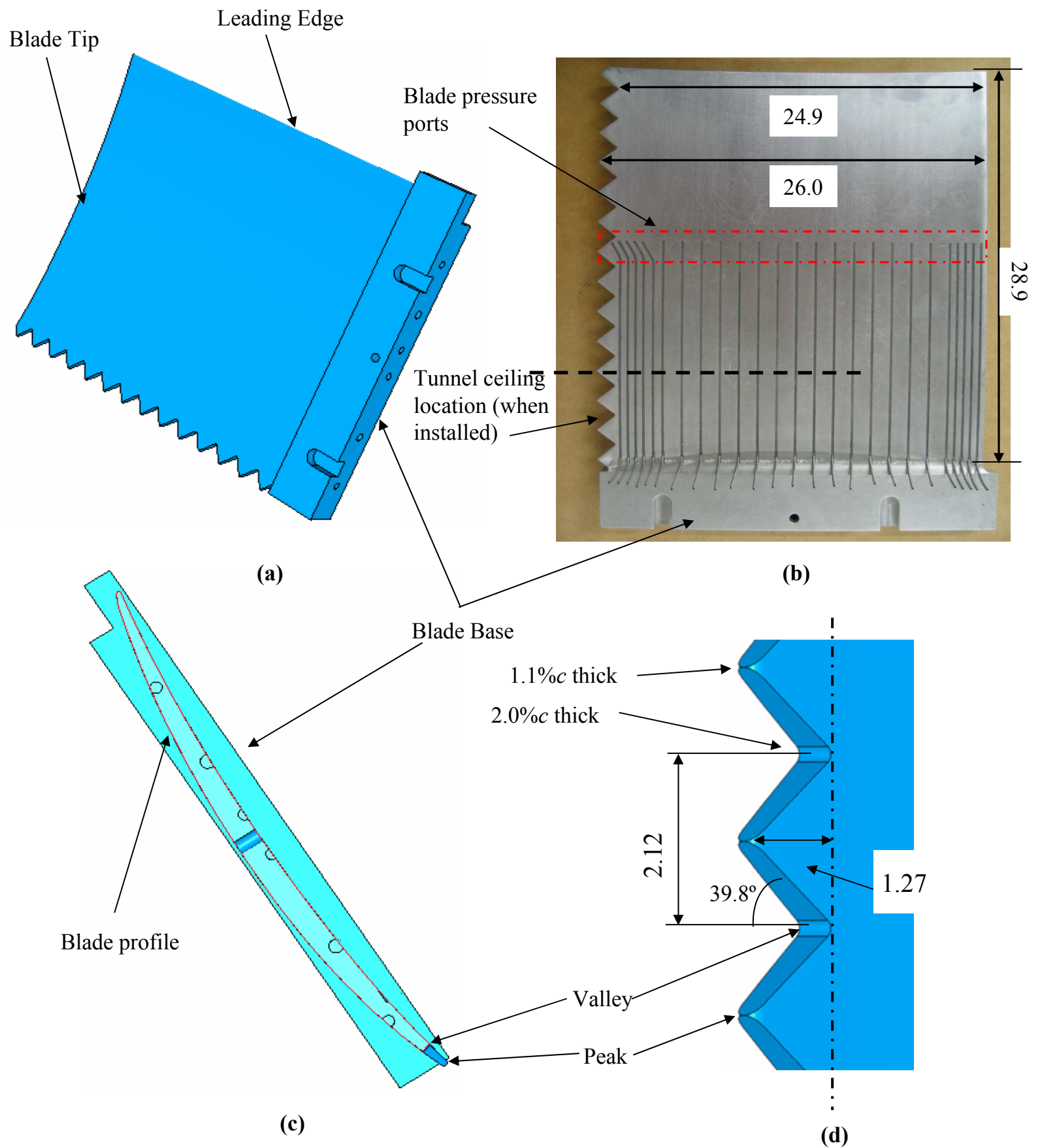


Figure 4.1 Geometric views of the 1.27cm serration blade: **(a)** Isometric view (model) **(b)** plan view (actual), **(c)** tip view (model), **(d)** close-up of serrations (model) (all dimensions in cm). From Geiger (2005).

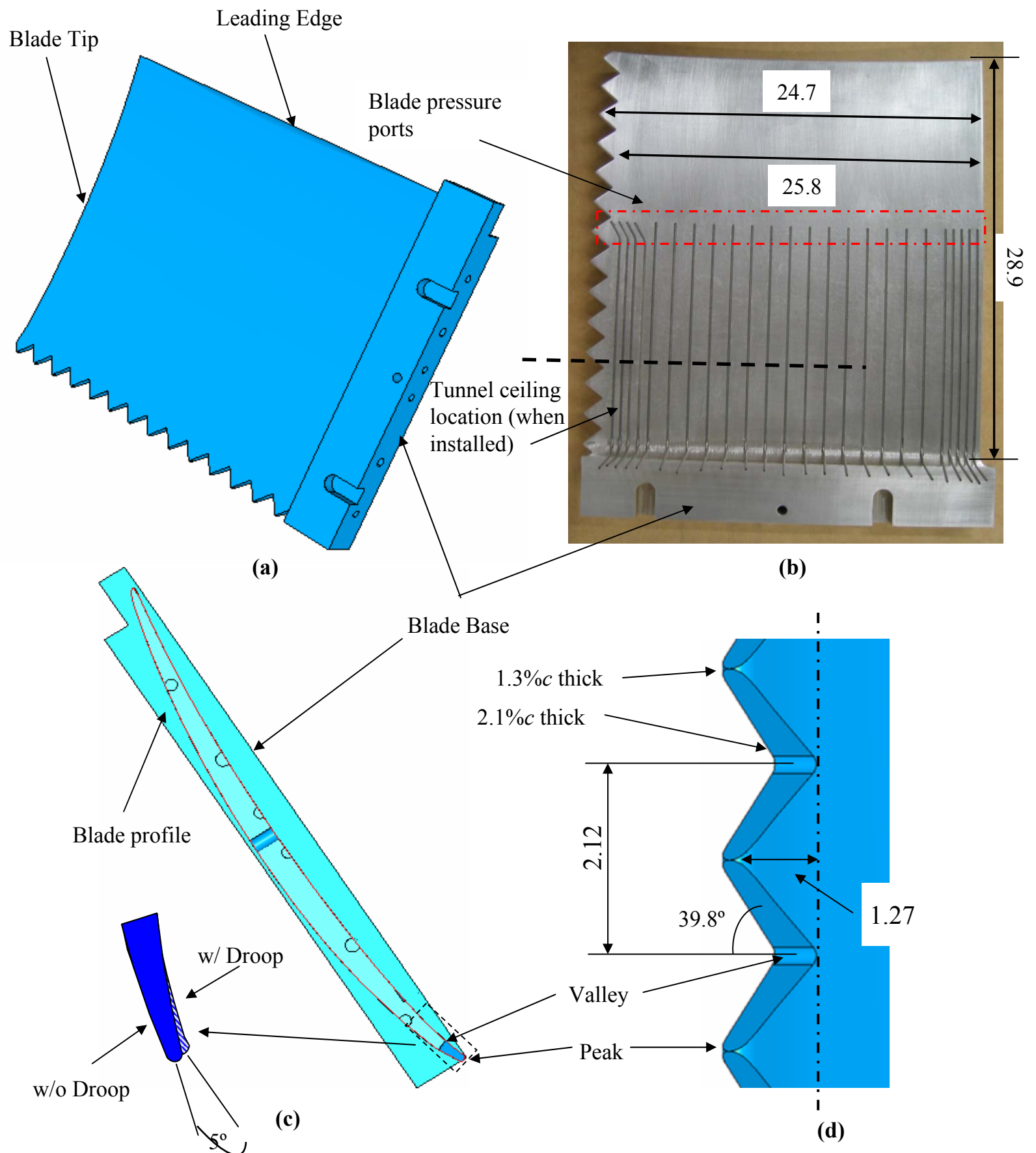


Figure 4.2 Geometric views of the 1.27cm drooped serration blade: (a) Isometric view (model) (b) plan view (actual), (c) tip view (model), (d) close-up of serrations (model) (all dimensions in cm). From Geiger (2005).

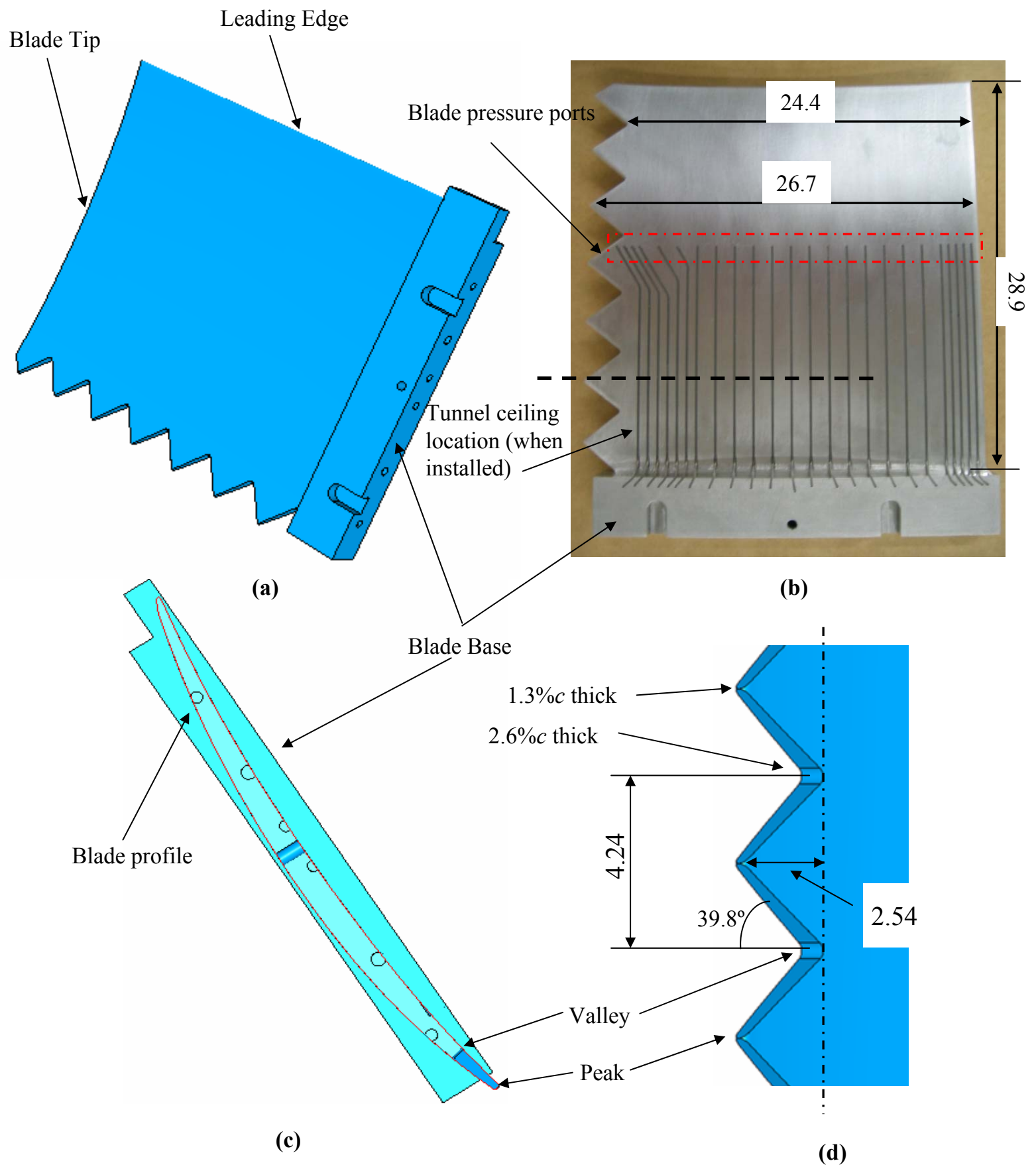


Figure 4.3 Geometric views of the 2.54cm serration blade: **(a)** Isometric view (model) **(b)** plan view (actual), **(c)** tip view (model), **(d)** close-up of serrations (model) (all dimensions in cm). From Geiger (2005).

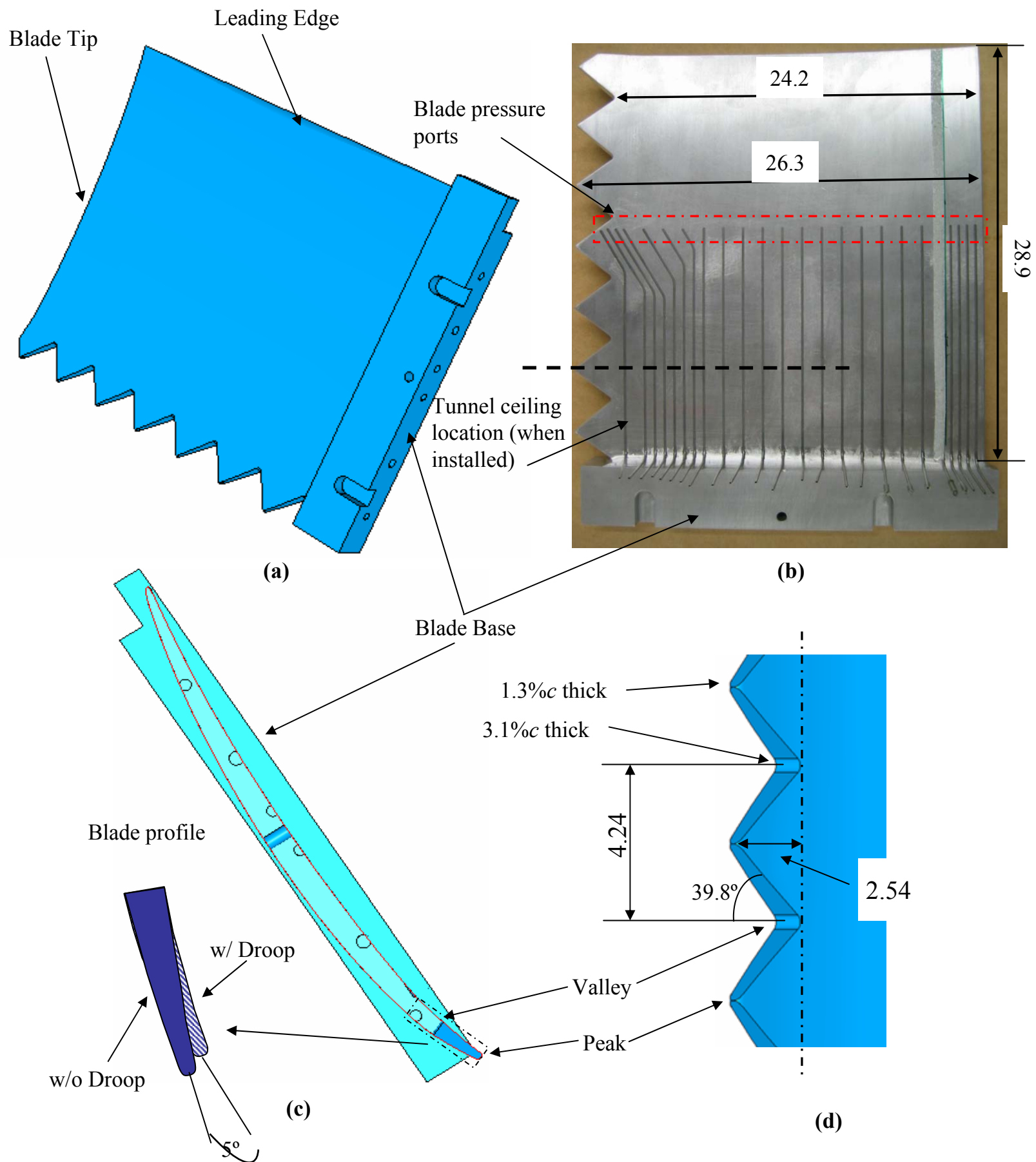


Figure 4.4 Geometric views of the 2.54cm drooped serration blade: **(a)** Isometric view (model) **(b)** plan view (actual), **(c)** tip view (model), **(d)** close-up of serrations (model) (all dimensions in cm). From Geiger (2005).

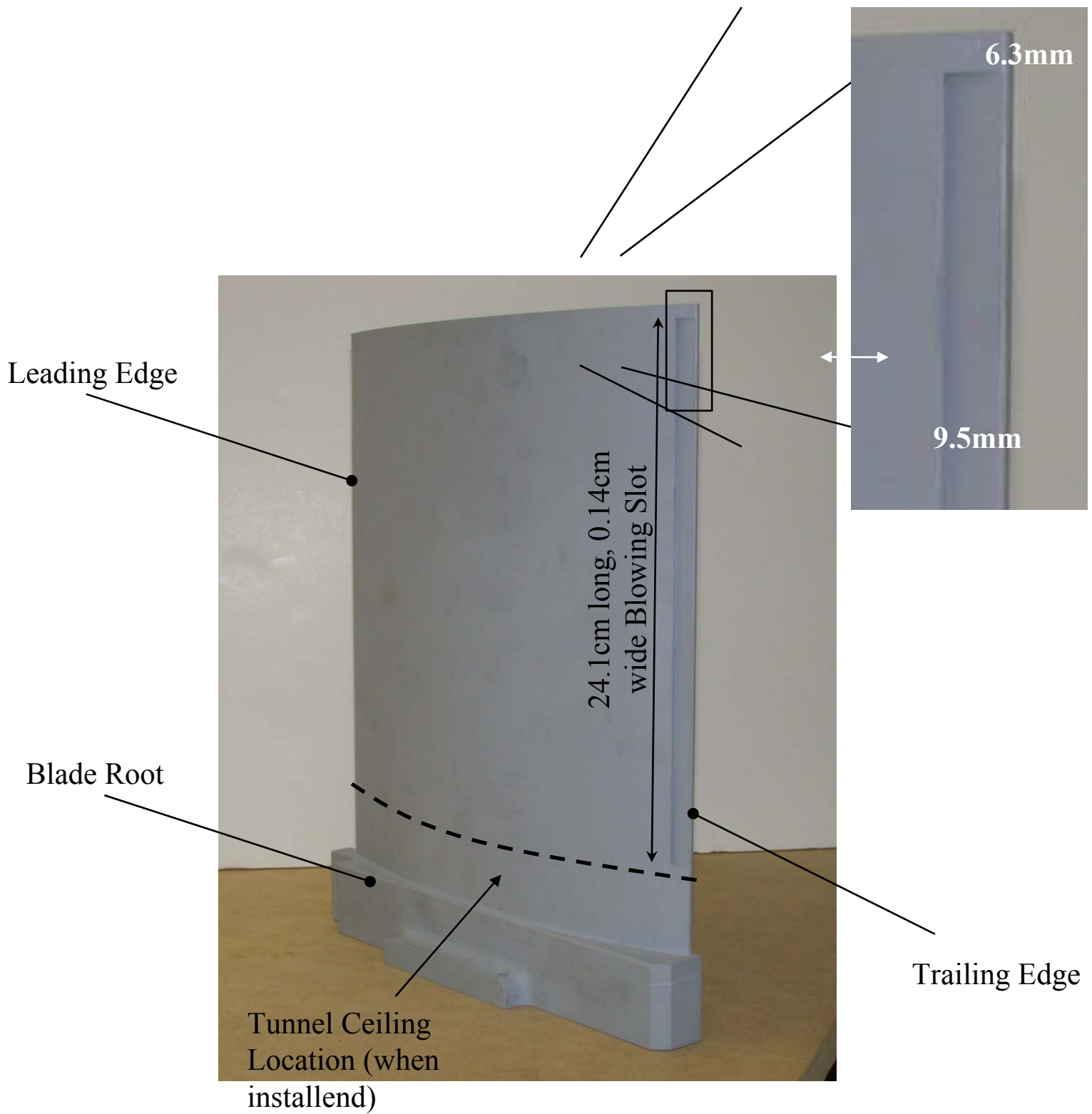


Figure 4.5 Simple blowing blade.

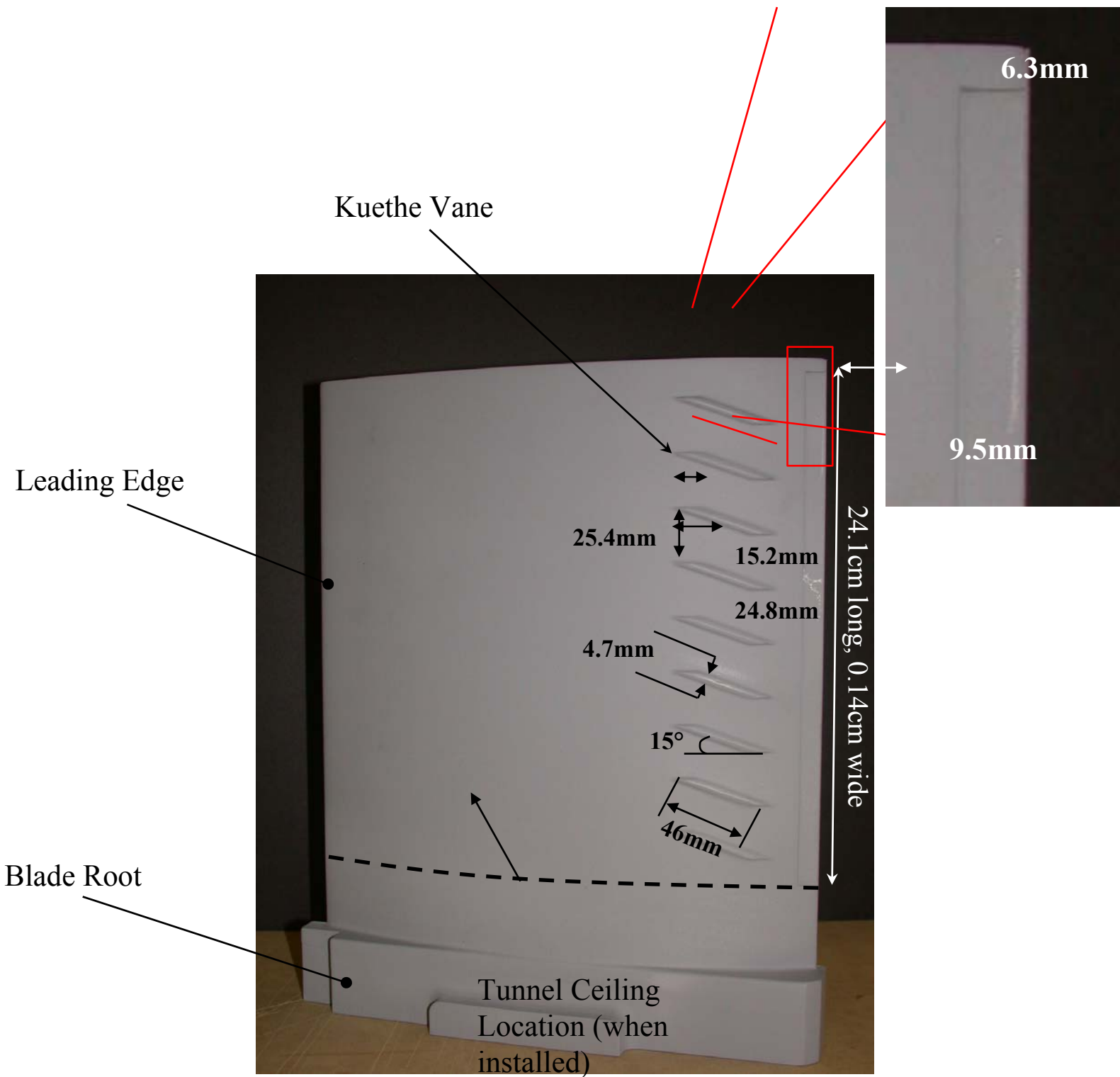


Figure 4.6 Kuethe blowing blade.

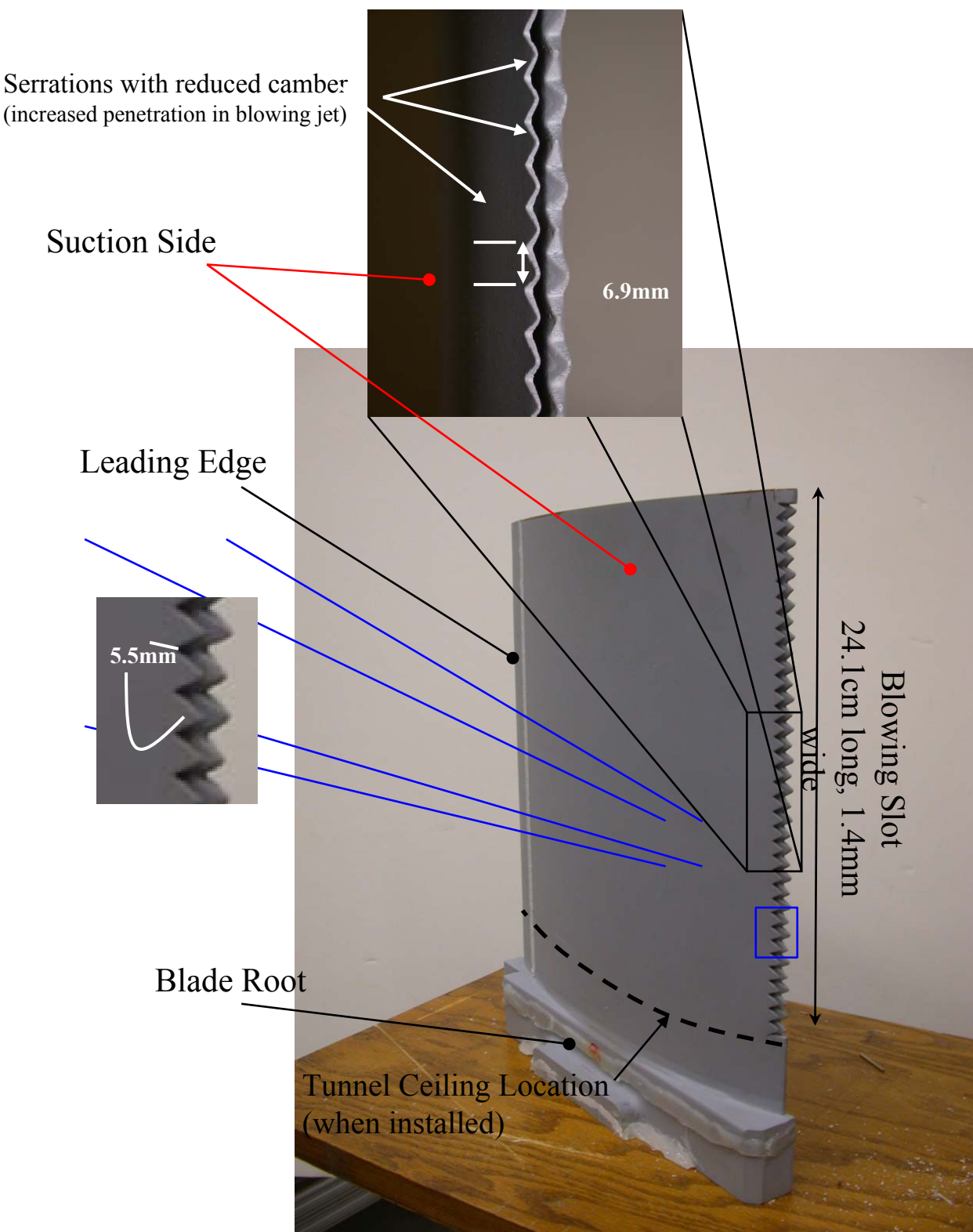


Figure 4.7 Serrated blowing blade.

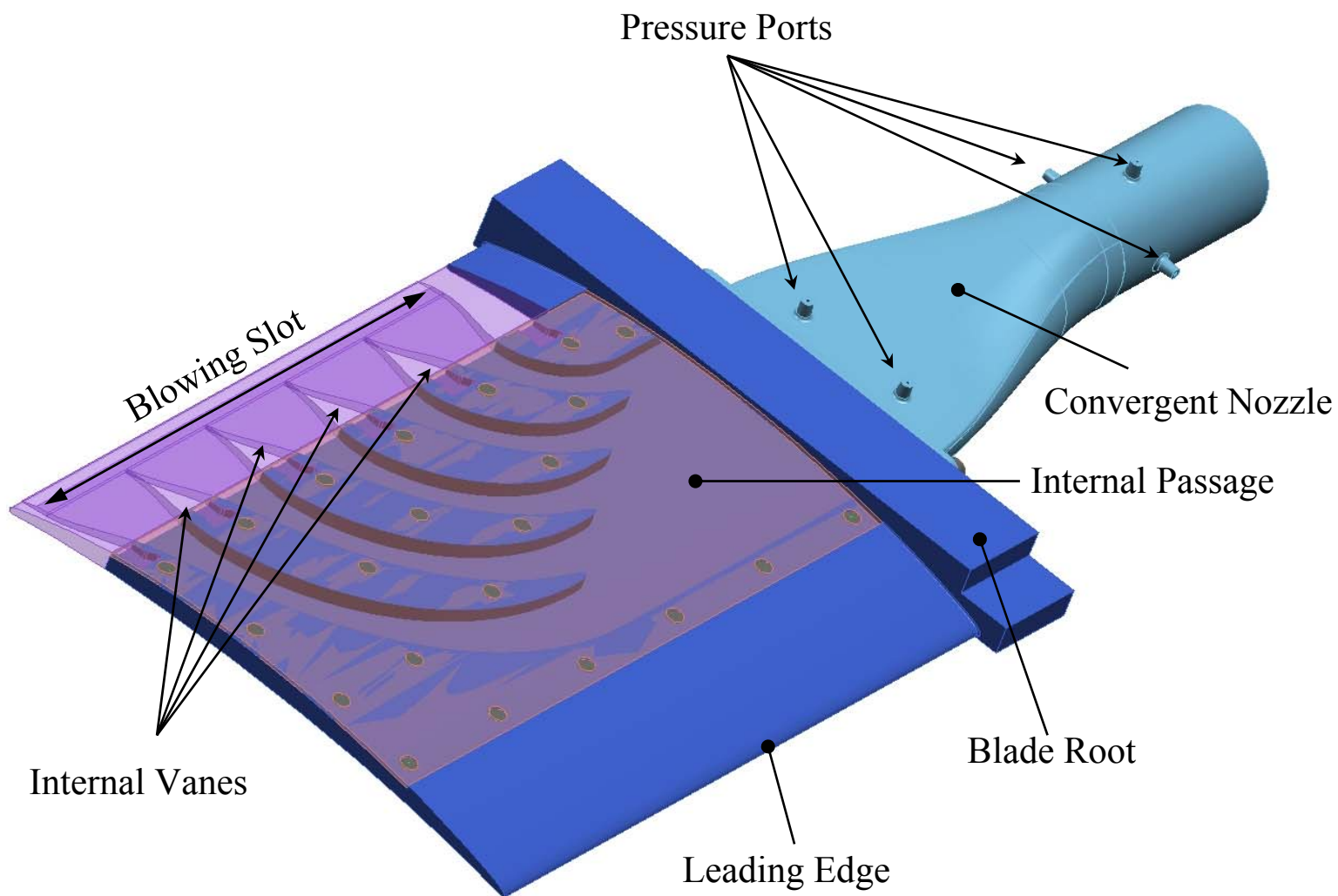


Figure 4.8 Trailing edge blowing blades internal passage and convergent nozzle designs.
NASA Glenn.

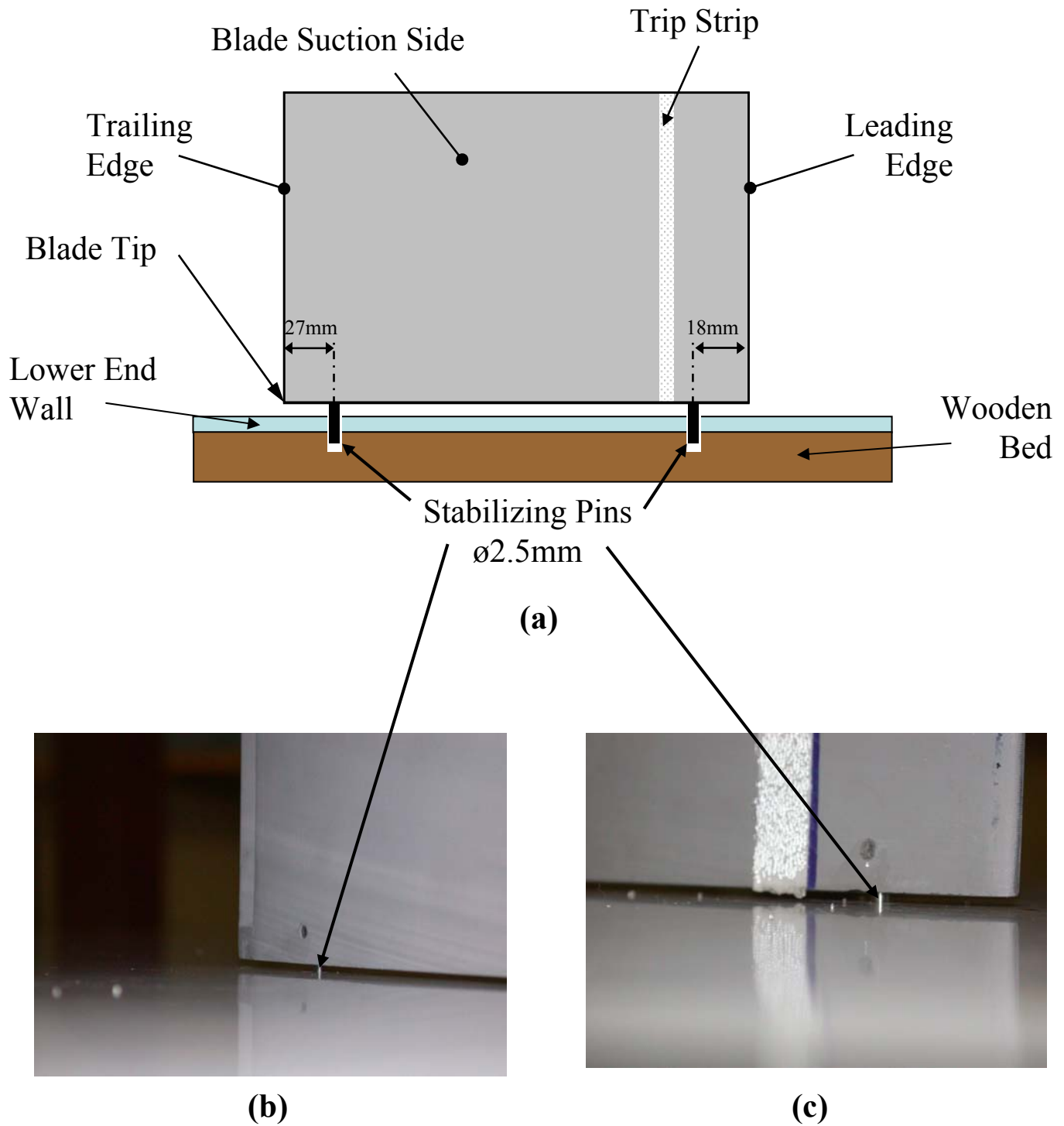


Figure 4.9 Trailing edge blowing blade stabilizing pins: (a) conceptual diagram and photographs of (b) trailing edge pin (c) leading edge pin.

Chapter 5 - Select Single Point Results

In this chapter, the main features of the flow downstream of the different blade configurations are described using single point measurements. While most of these single point measurements have been reported by Geiger (2005) and Craig (2006), this chapter also introduces new analysis of those data and new measurements (made namely downstream of the 2.54cm serrated trailing edge and serrated blowing blades). Once the blade surface pressure distributions are presented, the flow downstream of the cascade is described in terms Pitot-static cross-sections (measured parallel to the trailing edge plane) to define the spatial organization of the wakes and pitchwise mean velocity and turbulent stresses profiles to quantify the impact of the strategies on these wakes. These measurements were performed for inlet velocities of $24.8 \pm 0.4 \text{ m/s}$, corresponding to a Reynolds number of 395,000 and a Mach number of 0.07.

5.1. Blade Loading

5.1.1. Baseline Blades

The blade loading, or surface pressure distribution, was measured using the arrays of surface pressure ports described in Chapter 4. The information extracted from the blade loading is valuable as it not only provides insight on the flow around the blade but also because it enables the calculation of the blade circulation which can be used through the Kutta-Joukowski theorem to deduce the lift on the blade.

The blade loading presented here is a re-measurement of that presented by Geiger (2005), and differs from Geiger's result. The difference is believed to be due to a difference between the blade turning angle and the adjustable side walls. The new loading is presented as the variation of the surface coefficient of pressure C_{ps} , defined in Eq.(5.1), against the normalized axial distance from the leading edge x_b/c_a :

$$C_{ps} = \frac{P_s - P_\infty}{P_{0\infty} - P_\infty} \quad (5.1)$$

where P_s is the surface static pressure.

The oscillations in the surface pressure that are seen on both the suction and pressure side near the leading edge (between $x_b/c_a = 0$ and 0.05) of the baseline blade (Figure 5.1) are manifestations of the boundary layer trip strips, located at $x_b/c_a = 0.078$. Over the first 20% of the axial chord, the flow experiences a favorable pressure gradient on the suction until the minimum pressure of $C_{ps} = -0.24$ is obtained at $x_b/c_a = 0.2$. The remainder of the suction is dominated by an adverse pressure gradient that leads to a maximum pressure on the suction side of $C_{ps} = 0.30$ near the trailing edge. The pressure side experiences a very strong adverse pressure gradient on the first 15% of the axial chord. The flow then progressively slows down on the next 60% c_a to reach a maximum pressure of $C_{ps} = 0.49$ at $x_b/c_a = 0.75$. At that point, a small favorable pressure gradient occurs all the way to the trailing edge as the flow accelerates to satisfy the Kutta condition.

Assuming that the flow direction is parallel to the blade profile, the blade circulation can be computed from the surface pressure distribution as follows:

$$\Gamma = \oint_S U ds \quad (5.2)$$

where $U = U_\infty \sqrt{1 - C_{ps}}$ is the edge velocity just outside the boundary layer as estimated from the pressure distribution using Bernoulli's equation, and ds is an elemental distance along the closed curve of the blade section. The line integral in Eq.(5.2) has a direction starting from the leading edge on the suction side to the trailing edge, and reversing back to the leading edge on the pressure side. The so-defined change in the s -direction yields a negative integrand on the pressure side and a positive on the suction. The integration is performed using a trapezoidal rule where points evidently deviating from the ideal distribution are ignored. Based on Eq.(5.2), the baseline blade circulation is $0.52 U_\infty c_a$.

5.1.2. Serrated Trailing Edge Blades

Geiger (2005) measured the surface pressure distributions of four sets of modified trailing edge GE-Rotor B blades (described in Chapter 4). The loadings were measured using the embedded pressure ports located at $Y_b/c_a=0.94$ on the suction side of blade 4 and pressure side of blade 5. Please refer to Geiger (2005) for detailed description of these results.

The serrated trailing edge blades were designed to match the baseline profile in both camber and thickness, with the only difference being the serration of the trailing edge. Following the results of Geiger (2005), careful inspection of the blades however proved that there was incidence difference between these blades and the baseline (due to a metal angle difference). A two-dimensional inviscid vortex panel analysis of one cascade blade was conducted to evaluate the impact of variations in angle of attack on blade loading. The results are presented in Figure 5.2. This figure presents three different loadings obtained for the GE Rotor B section at the nominal 65.1° , as well as at a larger and smaller incidence (65.8° and 64.4° respectively). Figure 5.2 shows that differences as little as 0.7° can create significant differences in the surface pressure coefficient as much as $0.04C_{ps}$.

While it was not practical to separately measure the loading on all 4 sets of blades as part of the present study, the blade loading measurements conducted on the 2.54cm serration blades were re-measured and are presented in Figure 5.3. The blade loading is plotted against the normalized axial distance from the leading edge x_b/c_a . The baseline loading (presented in section 5.1.1) is added in Figure 5.3 for comparison. Examination of the suction side pressure distribution (the lower part of Figure 5.3) reveals that the 2.54cm serrations produce a blade loading which is higher than the baseline over the first $60\%c_a$ before blending with the baseline distribution over the last 40%. The minimum pressure for the 2.54cm serrated blades is $0.06C_{ps}$ above the baseline. On the pressure side, the 2.54cm serrations produce a pressure distribution that is consistently $0.03C_{ps}$ lower than the baseline blade (increasing to $0.06C_{ps}$ towards the trailing edge). This loss of lift is consistent with the $0.04C_{ps}$ variations produced by the vortex panel method with a 0.7° incidence difference. Upon inspection, the 2.54cm serrated blades were found to have a metal angle difference of 1° with respect to the baseline blades. The blade

circulation associated with the blade loading presented in Figure 5.3 is $0.4U_\infty c_a$ (a 20% decrease in lift largely associated with the decreased incidence).

5.1.3. Trailing Edge Blowing Blades

Measurements of the simple and Kuethe trailing edge blowing blades were conducted by Craig (2006). These measurements are re-plotted in Figure 5.4 and 5.5. Note that while these plots show Craig's data, they do correct a plotting error in that original publication, in which the baseline data was plotted in axial coordinates while the blowing cases were presented in blade-aligned coordinates. Blade loadings were measured using the pressure ports arrays described in Chapter 4 for a variety of blowing rates (expressed as percentage of the mass flow through a single cascade passage and ranging from 0 to 3%).

As seen on Figure 5.4, the surface pressure distribution produced by the simple blowing blade displays some sizeable differences from the baseline. On the pressure side, there is a region extending from 7.5% to 40% c_a with pressure levels significantly lower than the baseline (up to 0.11 C_{ps}). This deviation, which is also seen to varying extent with the other blowing blade configurations, in some way resembles the pressure distribution one might expect to see under a separation bubble. However, the flow visualizations of Craig showed no evidence of this. Another possibility is that this represents a manufacturing defect in the blowing blades or their pressure taps all of which (unlike the serrated and baseline blades) were manufactured using rapid prototyping technology. While we are unable to find any clear explanation for this difference, the affects do appear local to the leading edge region and were thus likely not a major factor in controlling the form and behavior of the flow in the trailing edge region, which is of most interest here. However, beyond the 40% c_a location, the loading closely matches the baseline. Near the trailing edge (after 90% c_a), the passive suction case seems to sustain lift longer than any of the blowing rates. Such behavior could be to the result of flow from the pressure side being re-energized as it is entrained by the trailing edge jet (when the blowing is turned on).

Once the trailing edge blowing is switched on, increasing the blowing rate produces little to no variation of the pressure side loading. On the suction side, the differences

between the simple blowing and the baseline blades are more apparent. The simple blowing pressure follows the same type of behavior than the baseline. However, the pressure distribution on the suction side varies significantly with blowing rate. The greater lift is obtained with the passive suction case. By passive suction case, we mean when the blowing slot is left open but no blowing is applied. The flow is driven by the back pressure of the wind tunnel that creates a pressure difference equal to 44% of the inlet freestream dynamic pressure. At this pressure we would expect a maximum negative mass flow into the blowing slot of 0.93% of the passage mass flux. Any losses in the ducting and internal blade passages would subtract from this. The mild suction generated near the trailing edge results in a pressure distribution that is consistently $0.04C_{ps}$ lower than the baseline (over the entire chord). Turning the blowing on at a rate of 1.4% of the passage through flow produces a loading that closely matches the baseline. Further increase of the blowing rate to 2.0 and 2.6% progressively lowers the pressure on the suction side back towards the levels seen in the passive suction configuration. At 2.0%, the pressure on the suction side is $0.014C_{ps}$ lower than the baseline. The difference increases to $0.02C_{ps}$ for a blowing rate of 2.6%.

The blade circulation was computed for each blowing rate using the method described in section 5.1.1. The variation of the blade circulation with blowing rate for the simple blowing configuration (as well as the two other configurations) is presented in Figure 5.6. Figure 5.6 shows that the blade lift is little affected by the blowing rate. The circulation is within 3% of the baseline circulation over the range of blowing rates tested (1.4 to 2.7%). It does appear that the section lift increases almost linearly with blowing rate. The values of the circulation for the various blowing configurations can be found in Table 5.1.

Table 5.1 Blade circulation $\Gamma/U_\infty c_a$ for the various blowing configuration

Blowing Rate	Simple Blowing	Kuethe Blowing	Serrated Blowing
0.0%	0.54	0.48	0.51
1.4%	0.50	0.45	0.47
1.5%	0.51	<i>n/a</i>	0.47
1.7%	0.51	<i>n/a</i>	0.47
1.9%	0.51	<i>n/a</i>	0.48
2.0%	0.51	0.46	0.48
2.1%	0.52	<i>n/a</i>	0.48
2.3%	0.52	<i>n/a</i>	0.48
2.5%	0.52	<i>n/a</i>	0.49
2.6%	0.52	0.46	0.49

The Kuethe blowing blades yield different results. As seen in figure 5.5, the pressure side distribution for the Kuethe blades is significantly lower than for the baseline. The passive suction case results in the largest difference ($0.09C_{ps}$ lower than the baseline). The influence of the blowing rate on the pressure side flow seems to be very much non-linear. Switching the blowing on to 1.4% of the throughflow brings the pressure $0.04C_{ps}$ closer to the baseline levels. Increasing the blowing rate to 2.0% raises the difference from the baseline to $0.07C_{ps}$. At 2.6% of the passage flow, the pressure is back to the levels displayed at 1.4% blowing. Independently of the blowing rate, the pressure distribution near the leading edge (from 7.5 to $40\%c_a$) on the pressure side of the Kuethe vane blades displays the same behavior as the simple blowing blades (possibly due to a manufacturing defect). In the mean time, the variations on the suction side appear much closer to the baseline than those seen on the pressure side. On the first $20\%c_a$, the Kuethe vanes results in a pressure distribution identical to the baseline, independently of the blowing rate. From 20 to $40\%c_a$, the flow on the Kuethe blowing blade seems to decelerate compared to the baseline as the pressure there is 0.03 to $0.05C_{ps}$ greater. Over the last $60\%c_a$ of the suction side, the variations are greatly dependent on the blowing rate. The passive suction results in the lowest pressure (on average $0.05C_{ps}$ lower than the baseline over the last $60\%c_a$). At 1.4% blowing rate, the pressure is closely following the baseline levels. Raising the blowing rate to 2.0 and 2.6% progressively

reduces the pressure, increasing the difference from the baseline to 0.02 and $0.03C_{ps}$ respectively. Interestingly, this behavior of the suction side flow is the exact same behavior seen in the simple blowing results where:

- the passive suction results in the lowest pressure.
- switching the blowing on to a low blowing rate brings the pressure back to the baseline levels.
- if the blowing rate is further increased, the pressure progressively decreases away from the baseline levels.

The circulation for the Kuethe blades (given in Table 5.1) can be seen to be 10% smaller than the baseline. This is believed to stem from the significant difference in the pressure loading, possibly suggesting some late separation over the vortex generators on the suction side of the blade. The variation of the circulation with blowing rate seems to also be linear for non-zero blowing rates as seen in Figure 5.6, although the changes are much smaller.

The serrated blowing blade results are presented in Figure 5.7 plotted against the normalized axial distance from the leading edge x_b/c_a . These results contrast starkly with the two other blowing configurations. On the pressure side, the loading closely follows the baseline distribution, independently of the blowing rate. There is some small deviation occurring over the last $15\%c_a$ possibly due to the combined effects of the serrations and shorter blade chord. It should be noted that the passive suction case (with the blowing slot fully opened) closely matches the baseline over the entire chord. The difference between the serrated blowing blade and the two other blowing configurations is most apparent on the suction side. There, the loading matches the baseline distribution over the last 40% of the axial chord. From $x_b/c_a=0.1$ to 0.6 , the serrated blowing blades produce a loading slightly higher than the baseline (about $0.05C_{ps}$ on average). The minimum pressure generated by the serrated blowing is on the order of $0.18C_{ps}$ (compared to $0.24C_{ps}$ for the baseline).

Interestingly, the blowing rate has very little influence on the pressure distribution of the suction side. The change is consistent over the chord at about $0.02C_{ps}$ over the entire range of blowing rates tested (1.4% to 2.6%). In contrast, the passive suction case is the one that deviates the most from the baseline. Near the quarter chord, the passive

suction is only $0.03C_{ps}$ higher than the baseline (compared to $0.05C_{ps}$ for the other blowing rates). However, beyond $45\%c_a$, the loading starts to deviate so that by the $85\%c_a$ location the passive suction results in a pressure that is $0.08C_{ps}$ lower than the baseline. Such slow deviation could be the manifestation of the mild suction combining with the serrated nature of the trailing edge to reenergize the boundary layer (by removing the low momentum fluid close to the blade surface). This behavior is mirrored in the lower blowing rates (1.4 and 1.5%) that generate pressure distributions progressively closer to the baseline (compared to the passive suction).

The blade circulation for the serrated blowing configuration is computed for the different blowing rates and tabulated in Table 5.1. The same linear behavior detailed in the simple and Kuethe blowing configurations is found here. The rate of change of circulation with blowing rate is comparable to the rate of change for the simple blowing. The lower levels of circulation reported here (6 to 9% lower than the baseline) could be due to the higher minimum pressure on the suction side along with the shorter chord resulting from the blowing slot design.

5.2. General Downstream Flow Characteristics

5.2.1. Baseline Blades

Pitot-static cross-sections parallel to the trailing edge plane of the blade row were taken at two axial distances of $x/c_a = 0.84$ and 1.88 downstream of the trailing edge of blade 5 to reveal the spatial organization of the baseline wake. These cross-sections are also used to assess whether the wake can be considered two-dimensional near the midspan ($y=127\text{mm}$) and the extent and structure of the end wall flows. These cross-sections were measured by Geiger (2005), and greater detail as well as additional data can be found in his master thesis (Geiger, 2005). Both total and static coefficients of pressure were measured, here we present only the mean streamwise velocity results inferred from these measurements.

Cross-sections of the mean streamwise velocity U/U_∞ (normalized on the inlet freestream velocity) are plotted in Figures 5.8 and 5.9 as functions of the pitchwise distance z on the horizontal axis and spanwise distance y on the vertical, both normalized on the axial chord. In these figures, the suction side of the wake is located on the right

hand-side of the figure (negative z direction), while the pressure side is on the left. Also, the blade root is located at the top of the figure, while the tip of the blade is at the bottom. There are 4 main characteristics to such figures: the potential core (region outside the wake), the wake itself, the upper end wall boundary layer and the tip leakage vortex. The potential core can be seen on both Figures 5.8 and 5.9 as the region of dark red color, where the streamwise velocity is uniform and equal to $0.78U/U_\infty$.

The horizontal structure seen at the very top of Figures 5.8 and 5.9 is the ceiling boundary layer. It should be noted that both at $x/c_a=0.84$ and 1.88 , the ceiling boundary layer is much thicker on the suction side of the wake (right side of the picture) than on the pressure side. At $x/c_a=0.84$, the boundary layer on the upper end wall is about $0.16c_a$ on the suction side, and $0.2c_a$ at $x/c_a=1.88$. The oval structure of low velocity that appears in the bottom left corner corresponds to the tip leakage vortex. This vortex, created by the rollup of fluid from the pressure side of the blade traveling through the tip gap, actually originates from blade 4. Figure 5.8 shows that at $x/c_a=0.84$ the vortex center, where the streamwise velocity defect is the largest, is located at $z/c_a=0.55$ and $y/c_a=0.18$ where the streamwise velocity is $0.4U_\infty$. At $x/c_a=1.88$, the defect has decreased (U/U_∞ is now 0.52 at the vortex center) and the vortex has significantly increased in size and moved toward the suction side to the point where it clearly interacts with the wake. The wake itself can be seen as the linear vertical structure with lower velocity levels near the center of the figures. While Figure 5.8 shows the wake to be closely two-dimensional near the midspan ($y/c_a=0.92$), it also shows some noticeable curvature near the top and the bottom of the picture (namely below $y/c_a=0.7$ and above $y/c_a=1.2$), probably caused by the velocity induced by the vorticity near the end walls. At $x/c_a=1.88$, the arcing becomes more pronounced as both the ceiling boundary layer and the tip leakage vortex develops. It should be noted that the velocity near the center of the two-dimensional portion of the wake is on the order of $0.58U_\infty$ and $0.65U_\infty$ at $x/c_a=0.84$ and 1.88 respectively. As a comparison, these values are 1.25 and 1.45 times larger than the velocity in the vicinity of the tip leakage vortex at the same axial locations.

The apparent overall pitchwise width of the wake increased from about $0.36c_a$ at $x/c_a=0.84$ to $0.55c_a$ at $x/c_a=1.88$. It is also important to note that the wake displays some asymmetry in the sense that it seems to be larger on the suction side than on the pressure

side. While this is difficult to observe this near the midspan on Figure 5.8, it is more apparent towards the upper end wall. It becomes even more evident on Figure 5.9. Confirming these observations requires the analysis of the two-dimensional wake from which actual parameters (like wake deficit, half-wake width or momentum thickness) can be computed.

5.2.2. Serrated Trailing Edge Blades

Pitot-static cross-sections were taken parallel to the trailing edge plane at the same two axial locations downstream of the serrated trailing edge blades. Figures 5.10 and 5.11 present the mean streamwise velocity cross-sections plotted against the normalized pitchwise distance z/c_a on the horizontal axis and the normalized spanwise distance y/c_a on the vertical. These were measured at $x/c_a=0.84$ and 1.88 respectively. For descriptive purposes, the wake centerline (defined as the line connecting the point of lowest velocity at every spanwise location) is plotted in the black dash-dotted line. Since the focus of the present study is the wake comparison of two serration configurations, this section concentrates on describing the features of the wake itself (rather than the ceiling boundary layer or the tip leakage vortex).

At $x/c_a=0.84$, the influence of the larger serrations on the wake shape is evident. The 2.54cm serrations (both with and without droop) produce significant distortion of the wake in the form of spanwise sinusoidal variation of the wake-centerline location. This deformation can be quantified by measuring the pitchwise “peak-to-peak” amplitude of the wake centerline. The pitchwise peak-to-peak amplitudes of the large serrations wakes are 0.13 and $0.15c_a$ for the 2.54cm and 2.54cm droop blades respectively. These distortions are additionally almost periodic along the spanwise direction. The spanwise wavelength of these wake structures is equal to the serration period of $0.31c_a$. In contrast, the small serrations show very little spanwise variation of the wake center location. The pitchwise peak-to-peak amplitude defined earlier (barely discernable in figure 5.10) is only 0.03 and $0.04c_a$ for the 1.27cm and 1.27cm droop respectively. These amplitudes are about 4 times smaller than the larger serrations (which are 2 times larger). The 1.27cm droop configuration does show some sinusoidal variations on the wake edges (especially on the pressure side). These variations have a spanwise wavelength that is equal to the

serration period ($0.15c_a$ for the 1.27cm droop blades). This is a direct consequence of the droop that results in increased serration penetration on the pressure side of the blade. Similar variations, although much less evident, can be seen downstream of the 1.27cm blades.

Looking at the results for the serrated blades in Figure 5.10 we see that, while the wake can be sinuous, the wake deficit is comparable to the levels of the baseline configuration. The velocity near the wake center is about $0.59U_\infty$ and rather uniform spanwise for the baseline and small serrations (with variations of 3 to 4% from the spanwise-averaged centerline velocity). Both 2.54cm serration configurations have larger variations of the mean velocity near the wake center (5 to 6% of the spanwise-averaged centerline velocity). The bigger velocity deficit occur downstream of the serration peak (where the chord is the longest). This behavior may be a consequence of the shorter development length the wake experiences downstream of the serration peak. It should also be noted that while the 1.27cm (with and without droop) and the 2.54cm serrations resulted in spanwise averaged centerline velocities (averaged over one serration period) of $0.58U_\infty$ (compared to $0.59U_\infty$ for the baseline deficit), the 2.54cm droop blades generated centerline velocities of $0.62U_\infty$ (5% greater).

From the above analysis, it seems that the additional camber that results from the drooping of the serration has a different impact based on the serration size. As the 1.27cm and 1.27cm cross-sections showed, the addition of droop to the smaller serrations results in a simple pitchwise redistribution of the flow (manifested by the sinuous wake shape) with very little variation in the wake centerline velocity. For the larger serrations, this pitchwise redistribution is also accompanied by larger variations in the wake centerline velocity (along with an increase in the spanwise-averaged mean centerline velocity).

It is possible to examine the development of these wakes further downstream, namely at $x/c_a=1.88$ in Figure 5.11. Looking first at the smaller serration size, it is clear that the distortions visible in the wake at $x/c_a=0.84$ have now disappeared as the wake has diffused. The centerline line velocity spanwise variations closely match the baseline with spanwise averaged velocities of $0.64U_\infty$ (same value as the baseline). The larger serrations still exhibit spanwise variations in both the wake shape and centerline velocity. The variations are however more subtle (pitchwise peak-to-peak amplitude has decreased

to $0.1c_a$). Additionally, the wake has become more uniform spanwise in terms of centerline velocity. For larger serrations, the spanwise variations in centerline velocity dropped to about 2% of the spanwise-averaged mean velocity deficit (half that at $x/c_a=0.84$). Incidentally, at $0.67U_\infty$, the spanwise-averaged centerline velocity of the 2.54cm droop blades is still larger (about 3%) than for the smaller serrations or the baseline ($0.64U_\infty$).

5.2.3. Trailing Edge Blowing Blades

The effects of the trailing edge blowing on the spatial organization of the wakes are presented in Figure 5.12 to 5.14 for the simple, Kuethe, and serrated blowing blades respectively. These figures present the mean velocity U/U_∞ obtained from the Pitot-static measurement made at various blowing rates at $x/c_a=1.88$. Figure 5.12 shows that the effects of the blowing rate on the wake downstream of the simple blowing blades are much as one might expect. At 1.4%, the wake can be clearly seen as the vertical structure. The wake seems to be nominally two-dimensional near the midspan. The ceiling boundary layer and the tip leakage vortex do not seem to be affected by the trailing edge blowing. Increasing the blowing rate to 2.0% reduces the deficit consistently along the span. The reduction is more apparent near the blade tip. This could be due to the combined mixing resulting from the interaction of the blowing jet and the tip leakage vortex. At 2.6%, the wake is clearly overblown all along the span.

Figure 5.13 presents similar results for the Kuethe blowing blades. Interestingly, the presence of the Kuethe vanes on the suction of the blades can be seen on the pressure side of the wake at 2.0%. It should also be noted that the wake appears to be wider at 1.4% blowing, suggesting some possible separation off the vortex generators. At 2.6%, the wake appears to be asymmetric where it is overblown (on the pressure side) but not on the suction side.

The cross-section of the mean velocity 1.88 axial chord downstream of the serrated blowing blades can be seen in Figure 5.14. The wake at 1.4% appears to be nominally two-dimensional around the midspan. No evidence of the blowing slot serrations can be seen. At 2.0%, the wake not only appears to be shallower near the tip (due to the combined effects of the blowing jet and the tip leakage vortex) but it also appears thinner

than near the midspan. At 2.6%, the wake appears to be slightly overblown on the pressure side.

5.3. Basic Wake Analysis

In order to quantify the evolution of the wake once it sheds from the blade, this section compares two-dimensional wake data from Geiger (2005) and Craig (2006) to previous plane wake studies by looking at key parameters namely the edge velocity U_e , wake deficit U_w , the half-wake width L_w , and the momentum thickness θ .

5.3.1. Definition of Wake Parameters

The four main parameters that are described in this section not only offer information on the wake development, but they can also be used to normalize various quantities (such as the mean velocity profile or the Reynolds stresses for example) to provide even more insight on the wake characteristics.

The first three parameters of interest are the edge velocity, wake deficit and half-wake width. It should be noted that these parameters are traditionally expressed for velocity profiles in the direction perpendicular to the wake (the Z -direction in Figure 3.6). As mentioned in Chapter 3, the profiles are measured in the pitchwise direction (z , parallel to the blade row). Consequently, the parameters are first computed from the pitchwise profiles and then transformed to normal-to-wake coordinate by multiplying by the cosine of the angle between the normal-to-wake and pitchwise directions (53.3°). Note that this method neglects the effects of streamwise development on the shape of the profile over short distances.

The edge velocity U_e is defined (Figure 5.15) as the velocity in the local potential core (outside the wake). In the Virginia Tech Low Speed Linear Cascade Wind Tunnel, the edge velocity is on the order of $0.78U_\infty$. The maximum wake deficit U_w is then defined as the difference between the edge velocity U_e and the minimum velocity in the wake (i.e. at the wake center). The half-wake width L_w is defined as the distance between the locations where the difference between the edge velocity and the velocity profile is one half of the maximum wake deficit U_w .

This method for defining the wake deficit and half-wake width becomes problematic for the trailing edge blowing cases. Indeed, as we will see later, large blowing rates results in over-blowing of the wake so that the profile becomes inverted. To account for this inversion, the new maximum deficit U_u became the square root of the maximum value of the streamwise Reynolds normal stress. Since the shape of this Reynolds stress profile is consistent for all blowing rates, the wake half-width was calculated as the distance between the locations where the stress is half of its maximum value. It was renamed L_u for clarity. Note that this nomenclature will apply only to the blowing results presented in this chapter.

The final parameter of interest is the momentum thickness θ defined as the integral of the momentum flux through the wake:

$$\theta = \int_{-\infty}^{\infty} \frac{U}{U_e} \left(1 - \frac{U}{U_e} \right) dZ \quad (3.3)$$

This parameter is particularly important as it can be proven that in the far wake the total drag is directly proportional to the momentum thickness. It will therefore provide additional information on the impact of the trailing edge serration configurations on the blade performance.

5.3.2. Baseline Wake Characteristics

The baseline wake characteristics are determined from the four-sensor hotwire data measured by Geiger (2005) at axial locations of $x/c_a = 0.61, 1.18, 1.82$, and 2.38 and presented in Table 1.2.

Table 5.2 Wake parameters for the baseline configuration at axial locations of $x/c_a=0.61, 1.18, 1.82$, and 2.38 . (Geiger, 2005)

<i>Location x/c_a</i>	U_e/U_∞	U_w/U_∞	L_w/c_a	θ/c_a
0.61	0.750	0.204	0.056	0.025
1.18	0.729	0.136	0.073	0.025
1.82	0.727	0.108	0.090	0.025
2.38	0.747	0.099	0.106	0.027

Previous studies notably that of Cimbala et al. (1990) showed that the far-field wake spreading rate of fully developed small-deficit plane wakes should be proportional $(X/\theta)^{0.5}$. Likewise, the wake deficit should decrease as $(X/\theta)^{-0.5}$. To determine if the baseline wake meet these conditions, the half-wake width L_w is normalized by the momentum thickness θ and plotted against the normalized streamwise distance (X/θ) in figure 5.16. Similarly, the maximum wake deficit U_w is normalized by the edge velocity U_e and also plotted against the normalized streamwise distance (X/θ) as shown in figure 5.17. From figures 5.16 and 5.17 it appears that the baseline wake spreading rate is proportional to $(X/\theta)^{0.45}$ while the decay rate varies as $(X/\theta)^{-0.55}$ (note that these rates differ from those presented by Geiger (2005) as the data measured by Geiger at $x/c_a=0.002$ has been ignored here). In other words, the baseline wake spreads slower but decays faster than a fully developed small deficit wake.

To determine the extent to which the wake behaves as though it is fully developed, the wake deficit $U-U_e$ is normalized by the maximum defect U_w and plotted for all four axial locations against the normal-to-wake distance Z normalized by the half-wake width L_w as shown in Figure 5.18 (for further details on the curve fits seen in Figure 5.18 please refer to Geiger (2005)). Such normalization seems to produce identical velocity profiles, independently of the axial location (especially beyond 0.61 axial chords downstream). In other words, beyond $x/c_a=0.61$, the wake is close to reaching self-similarity. However, as discussed by Geiger (2005), while self-similarity has been reached in the mean streamwise velocity profile, turbulence profiles seem to be still developing.

The turbulence measurements reported by Geiger (2005) downstream of the baseline blades showed that the Reynolds stresses followed the typical profiles seen downstream of asymmetric airfoils. The turbulence is dominated by the streamwise and normal-to-wake fluctuations. The presence of small $\overline{u'v'}$ and $\overline{v'w'}$ stresses (that never exceed 20% of the $\overline{u'w'}$ stress) suggest that the baseline wakes are not exactly plane wake possibly due to weak vorticity introduced by three-dimensional effects. Additionally, Geiger reports that by $x/c_a=2.38$ the wake turbulence has not yet reached self-similarity and is therefore still developing.

5.3.3. Serrated Trailing Edge Blade Wake Characteristics

5.3.3.1. Mean Velocity Results

Geiger measured mean velocity profiles downstream of the serrated trailing edge blades at various spanwise locations across the serration period closest to the midspan. These measurements showed that the wake spreads faster downstream of the serration peaks for the 1.27 cm and the 2.54 cm cases. There, the spreading rates are respectively varying as $(X/\theta)^{0.47}$ and $(X/\theta)^{0.54}$ which is larger than the baseline rate of $(X/\theta)^{0.45}$. Increasing the serration size increases the spreading rate, but adding droop did not show any apparent improvement. In most cases, as the spreading rates downstream of the serration tips were accelerated, the spreading rate downstream of the serration valley decreased as was seen in the 2.54 cm cases. The decay of the centerline velocity deficit also showed the same trends. Increasing the spreading and decay rates will reduce the periodic fluctuations of the mean streamwise velocity seen at the stator leading edge thus reducing tonal noise. For further details on the mean velocity measurements and wake parameter analysis, please refer to Geiger (2005).

5.3.3.2. Turbulence Stress Results

The turbulence measurements downstream of the serrated trailing edge blades showed that the 1.27cm configuration had little effect on the streamwise and spanwise fluctuations (that display values identical to the baseline) but increased the $\overline{v'w'}$ shear stress. The addition of droop reduced the normal stresses but did not affect the shear stresses. The stronger streamwise vorticity resulting from the added serration penetration increases the turbulence in the near wake (upstream of $x/c_a=0.6$) but decreases it further downstream. Increasing the serration size resulted in a normal stress increase over the baseline for all three velocity components but did not seem to affect the shear stress field. Adding droop to the large serrations resulted in increased $\overline{u'v'}$ shear stress across the serration period. The spanwise and normal-to-wake stresses ($\overline{v'^2}$ and $\overline{w'^2}$) were also found to be consistently increased. Downstream of the serration peak, the $\overline{u'w'}$ shear stress was found to be significantly increased.

For all the serrated blades, the turbulence levels were found to be the largest downstream of the serration peaks. The average TKE (obtained by integrating the TKE profile across the wake and across one serration period) presented in Figure 5.19 shows that the small serrations tend to decrease the wake turbulence while larger serrations increase it. For both serration sizes, the addition of droops magnifies the changes. Figure 5.19 shows that at $x/c_d=1.819$, the 1.27cm serrations have decreased the average TKE by 3%. Adding droop to the small serrations increases the reduction to 7%. In contrast, the 2.54m serrations increase the turbulence levels by 2%. This increase is amplified by the addition of droop, resulting in an average TKE 13% greater than the baseline. These changes in the turbulence levels suggest that small trailing edge serrations have the potential to reduce the broadband noise if the wake were to interact with a downstream blade, while larger serrations tend to increase the broadband component.

5.3.4. Trailing Edge Blowing Wake Characteristics

5.3.4.1. Mean Velocity Results

Craig (2006) analyzed the impact of trailing edge blowing on the wake characteristics by examining the variation in the normalized streamwise velocity profiles at $x/c_d=1.819$ with blowing rate. These mean velocity profiles are reproduced in Figure 5.20 for the simple and Kuethe blowing blades. Similar results for the serrated blowing blades (previously unpublished) are also presented in Figure 5.20. The simple blowing mean velocity profiles seen in Figure 5.20 show that the deficit at 1.4% blowing is increased from the baseline. Increasing the blowing rate decreases the deficit until a region of over-blowing appears on the pressure side of the wake at 2.5% blowing. The same asymmetry was found in the wake downstream of the Kuethe blades. This suggests that the blowing jet is not correctly aligned with the wake propagation direction. This misalignment is also confirmed at lower blowing rates where the pressure side of the wake is most affected by the blowing. The variations of the streamwise velocity profile suggest that the blown wake is a complex flow that has a “jet-like” component on the pressure side and a “wake-like” component on the suction side. The addition of the serration to the blowing slot in a more uniform wake at lower blowing rates (up to 1.7%) in that sense that the asymmetry seen in the first two blowing configurations is less

pronounced. This is most likely a consequence of the blowing slot configuration that it now located at the trailing edge (instead of upstream of the trailing edge on the suction side as it is located in the simple and Kuethe blowing). Figure 5.20 also shows that the serrated blowing configuration is much more efficient at low blowing rate at reducing the deficit. At 1.4%, the maximum mean velocity deficit for the serrated blowing configuration is 17% smaller than the baseline. This is a significant improvement over the simple and Kuethe blades that produce deficits equivalent or larger than the baseline at 1.4%. This suggests that the serrated blowing blades would be the most efficient geometry to reduce tone noise. As the blowing rate is increased, the asymmetry in the mean velocity profile of the serrated blowing blades becomes more pronounced confirming the possibility of a blowing jet misalignment.

Craig found that the blown wakes are consistently thinner than the baseline for all the blowing rates (between 1.4 and 2.7% of the mass through flow) and blowing geometries tested. Craig also reported that for the simple blowing blades great reductions in the half-wake width (based on the streamwise Reynolds stress) were obtained at low blowing rates (between 1.4 and 2%). Further increasing the blowing rate tends to widen the wake. The half-wake width data also showed that the Kuethe vane generates a wider wake than the simple blowing blades, possibly because of late separation downstream of the Kuethe vanes. Craig's data has been reproduced in Figure 5.21 along with the half-wake width obtained from the serrated blowing blade. Interestingly, this configuration can be seen to consistently decrease the wake width between 1.4 and 2%. Beyond 2%, the wake width stays relatively constant around $0.145c_a$ (about 50% of the baseline wake width). Since the wake width is based on the streamwise Reynolds stress profile, this suggests that at higher blowing rates, the turbulence (at least in the streamwise fluctuations) becomes almost independent of the blowing rate.

Momentum thickness results (Figure 5.22) show that a momentumless wake is obtained for a blowing rate of 2.5% for the simple blowing case. The Kuethe blown wake does not reach a momentumless state over the range of blowing rate tested. For both configurations, the momentum thickness is smaller than the baseline at all blowing rates suggesting drag reduction even at low blowing rates. The serrated blowing results confirm that this configuration is more efficient at low blowing rates (1.4 to 1.7%) where

the momentum thickness is smaller than the simple blowing case. However, at larger blowing rates, the drag reduction is larger for the simple blowing blades.

These results show that the trailing edge blowing has great potential to reduce tone noise since the wake deficit is consistently decreased. However, the amount of air required to produce the results (with the current geometries) would prevent such technology from being applied to a full scale engine. Lower blowing rates can be obtained by distributing the injection along the blade span using an array of discrete jets or slots (Langford *et.al.*, 2005). This is beyond the scope of the current study (that is focused on the impact of trailing edge blowing on two-dimensional wakes).

5.3.4.2. Turbulence Stress Results

The turbulence profiles of the blown wakes revealed that the simple blowing consistently decreased the normal stresses up to 2.3% blowing. Beyond this blowing rate, the asymmetry of the blowing jet results in an increase of these stresses on the pressure side of the wake. The shear stresses were found to be at least one order of magnitude smaller than the normal stresses. The pitchwise-averaged TKE (obtained by integrating the TKE profile and normalizing it on the blade spacing of 236mm and reproduced in Figure 5.23) shows that the turbulence is continuously decreased with increased blowing rate until it reaches a minimum of $0.7 \times 10^{-5} U_{\infty}^2$ at 2.3% of the through flow. This is 90% reduction from the baseline turbulence level. Further increasing the blowing rate increases the turbulence suggesting that an optimal blowing rate of 2.3% is required to minimize the TKE. However, even at 1.4% of the mass flux through the passage, the turbulence levels are 45% lower than the baseline. These reductions in the TKE are one order of magnitude greater than those seen for the small trailing edge serrations and suggest that the simple blowing configuration has great potential to reduce the broadband component of rotor-stator interaction noise.

The Kuethe vane blowing blades show similar results with some notable differences. The normal stresses are comparable to the simple blowing configuration (and therefore lower than the baseline), however the maximum spanwise normal stress $\overline{v'^2}$ is significantly increased on the suction side of the wake. For a blowing rate of 1.4%, the maximum spanwise normal stress is actually comparable to the baseline. This significant

increase in the spanwise fluctuations is believed to be due to some separation caused by the Kuethe vanes (located on the suction side of the blades). This separation reduces the efficiency of the simple blowing configuration (since the Kuethe blades are essentially simple blowing blades with vortex generators on the suction side). Consequently the pitchwise-averaged TKE (reproduced in Figure 5.23) shows that the optimal blowing rate (required to minimize the TKE) has not been reached by 2.7%. While the Kuethe blowing configuration was found to be less efficient than the simple blowing configuration, the TKE reductions are nevertheless significant. At 1.4% of the passage mass flux, the turbulence levels are 33% lower than the baseline (compared to 45% for the simple blowing) and decrease to 10% of the baseline at 2.7%.

The Reynolds stresses (normalized on the inlet velocity U_∞) measured downstream of the serrated blowing blades are plotted in Figures 5.24 to 5.29. In these figures, the baseline values are presented as solid black lines. Additionally, the simple blowing results of Craig are reproduced for comparison. The normal stresses (Figures 5.24 to 5.26) can be seen to be significantly reduced by the blowing. They are also all slightly smaller than the simple blowing configuration at low blowing rates suggesting that the addition increased the efficiency of the trailing edge blowing to reduce the fluctuations. This reduction could be the result of the re-energizing of the boundary layer on both sides of the blade through the blowing slot serration, thus reducing the wake turbulence at its source. Interestingly, at high blowing rates (2.4% and higher) the normal stresses seems to become independent of the blowing rate (as seen in Figure 5.24 to 5.26 where the curves for 2.4, 2.5, and 2.6% are indistinguishable). Figure 5.27 and 5.29 shows that the $\overline{u'w'}$ and $\overline{v'w'}$ shear stresses are continuously reduced with increased blowing rate. The $\overline{u'v'}$ stress on the other hand can be seen to be increased from 1.4 to 1.7% blowing. At blowing rates larger than 1.7%, the shear stress decreases continuously. Interestingly, all three shear stresses also display some self-similarity with blowing rates larger than 2.4%. The TKE profiles at various blowing rates can be seen in Figure 5.30. This figure shows that for blowing rates between 1.4 and 1.7%, the serrated blowing configuration is more efficient at reducing the velocity fluctuations than the simple blowing configuration. However, the simple blowing configuration becomes more efficient at larger blowing rates. This is also seen in the pitchwise-averaged TKE in

Figure 5.23. At 1.4%, the average TKE for the serrated and simple blowing blades are 2.9×10^{-4} and $3.9 \times 10^{-4} U_{\infty}^2$ respectively. These values represent 40 and 55% of the baseline TKE. Conversely, at 2.0%, the serrated blowing blade value has decreased to $1.8 \times 10^{-4} U_{\infty}^2$ (84% lower than the baseline value) while the simple blowing averaged TKE has dropped to $1.0 \times 10^{-4} U_{\infty}^2$. These results show that all the blowing configurations tested produce significant turbulence reductions from the baseline. These reductions range between 33 and 60% at 1.4% of the passage through flow, and can be as high as 90% (for the simple blowing configuration at 2.3% of the passage mass flux). Considering that the blowing rates involved are already too large to be realistic, the serrated blowing results suggest that this geometry would be the most efficient at reducing both tonal and broadband noise and could therefore be regarded as the best candidate for full scale application.

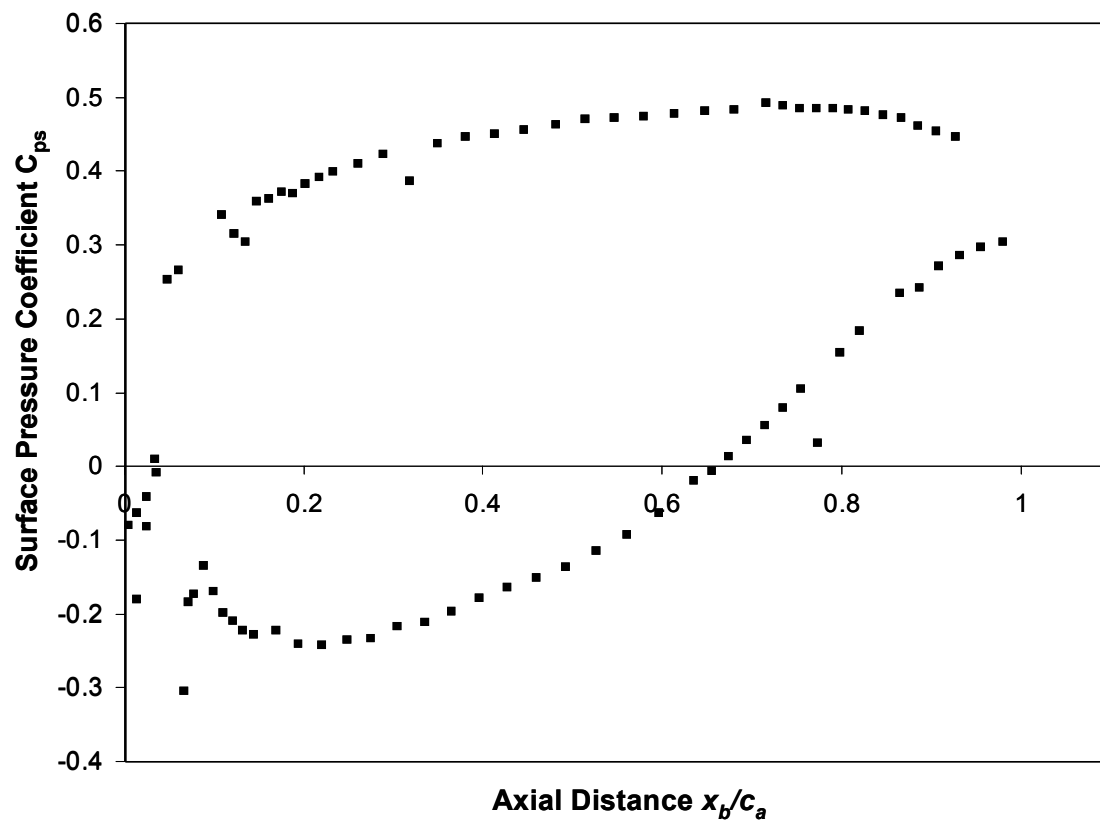


Figure 5.1 GE Rotor B blade loading.

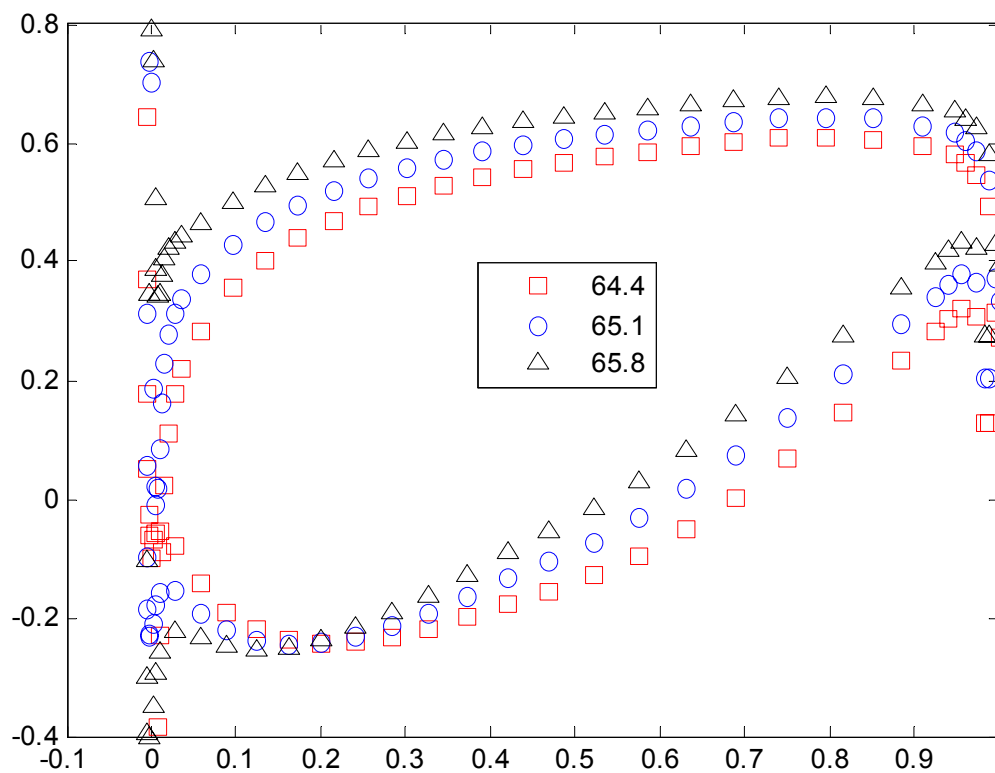


Figure 5.2 Blade loading variation with incidence angle – Panel method results.

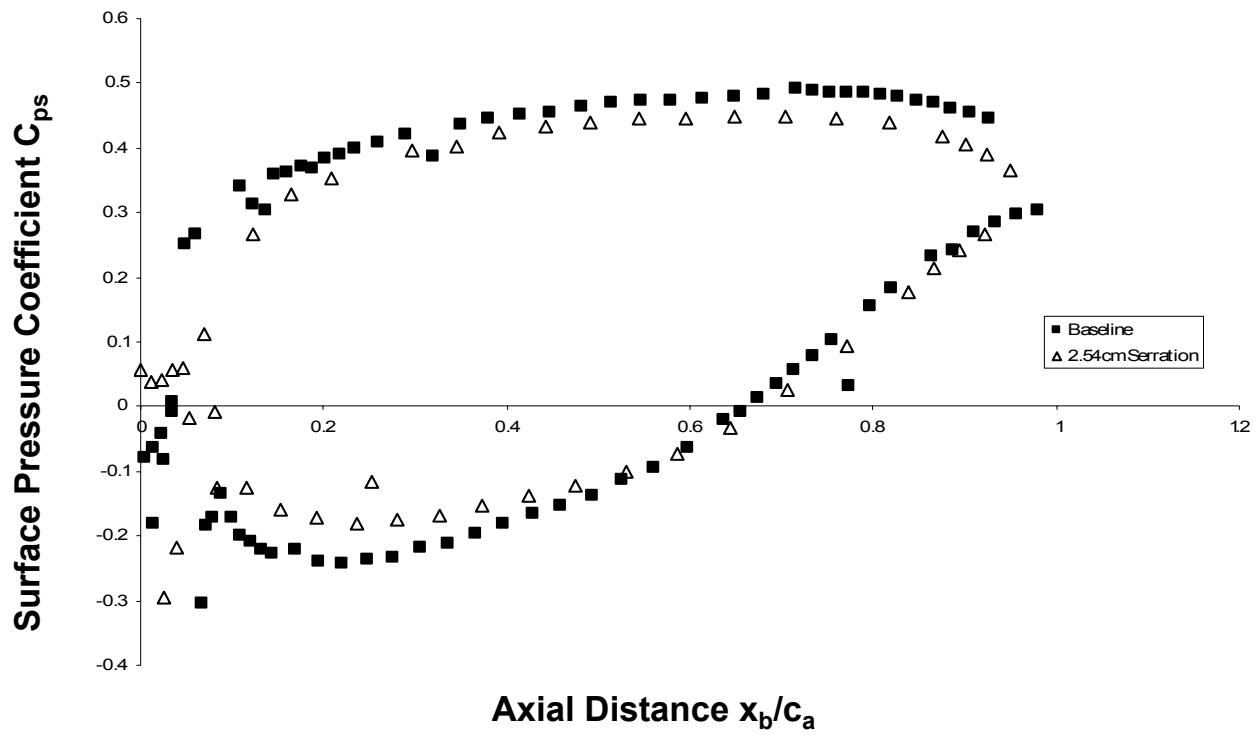


Figure 5.3 Re-measurement of the 2.54cm serration blade loading.

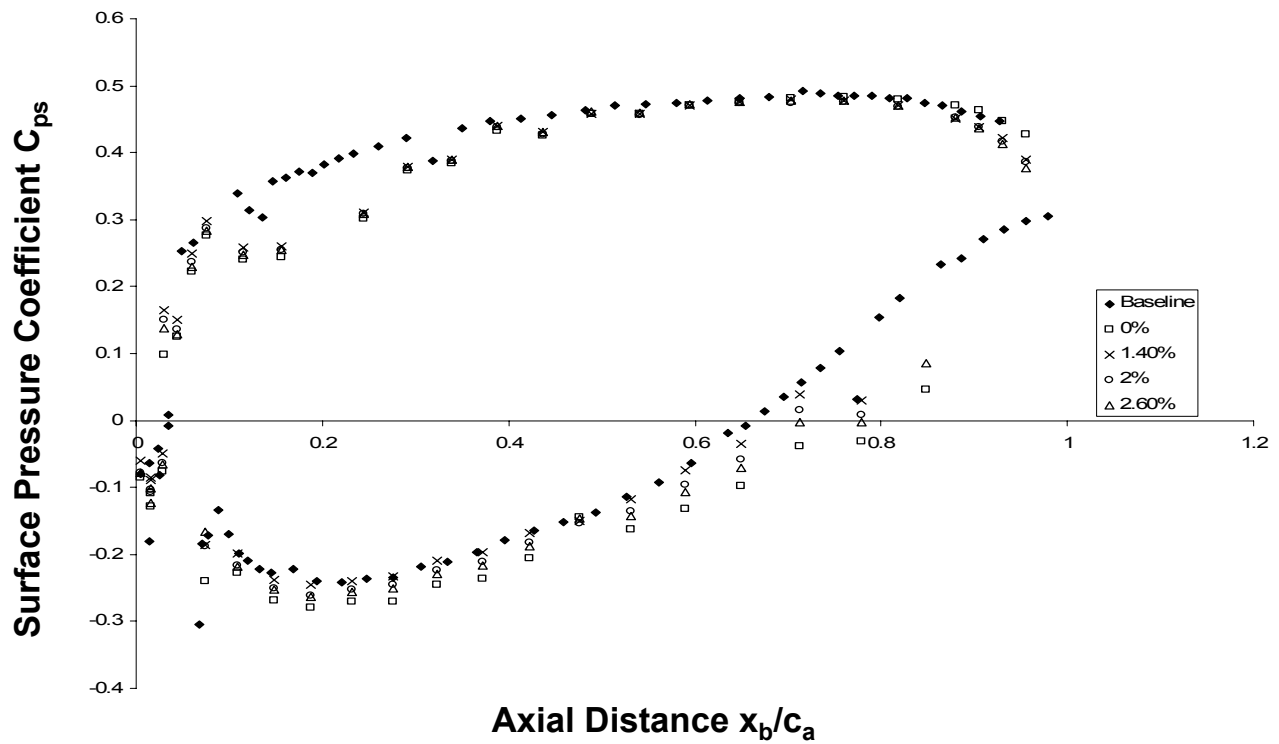


Figure 5.4 Simple blowing blade loading for various blowing rates (expressed as fraction of the mass flux through the passage).

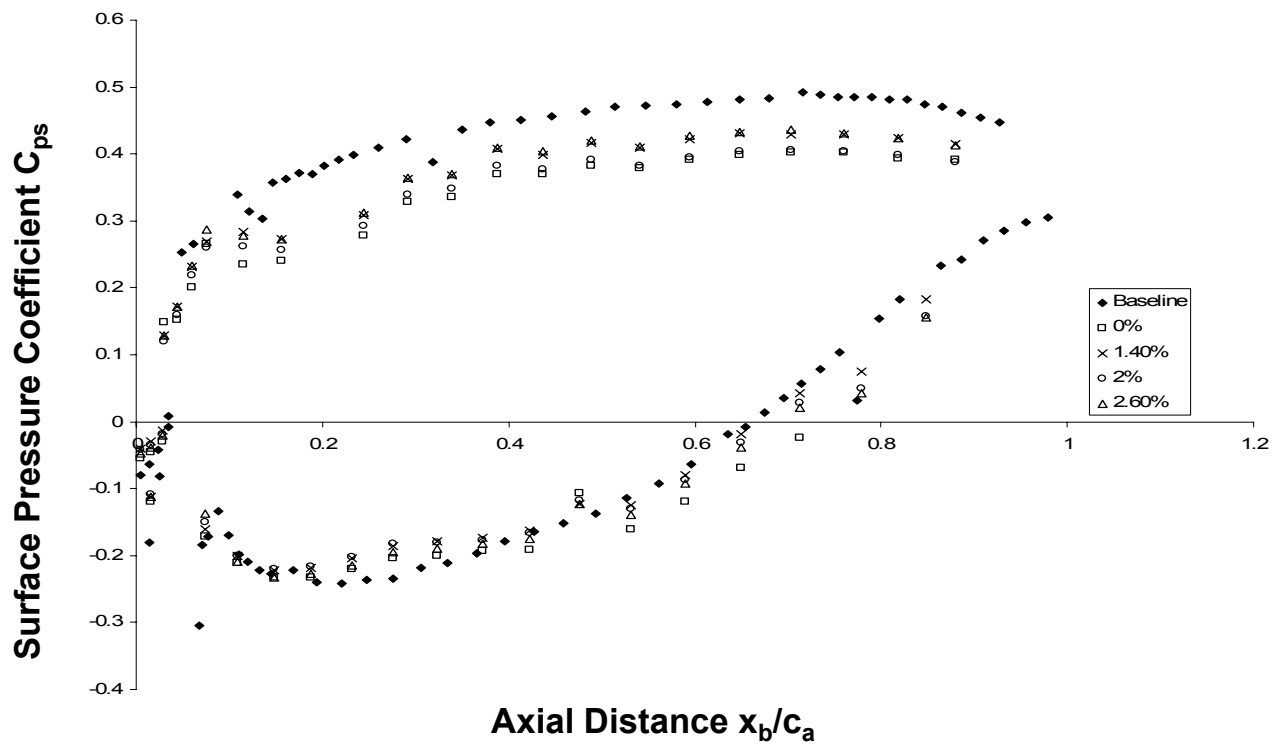


Figure 5.5 Kuethe vane blowing blade loading for various blowing rates (expressed as fraction of the mass flux through the passage).

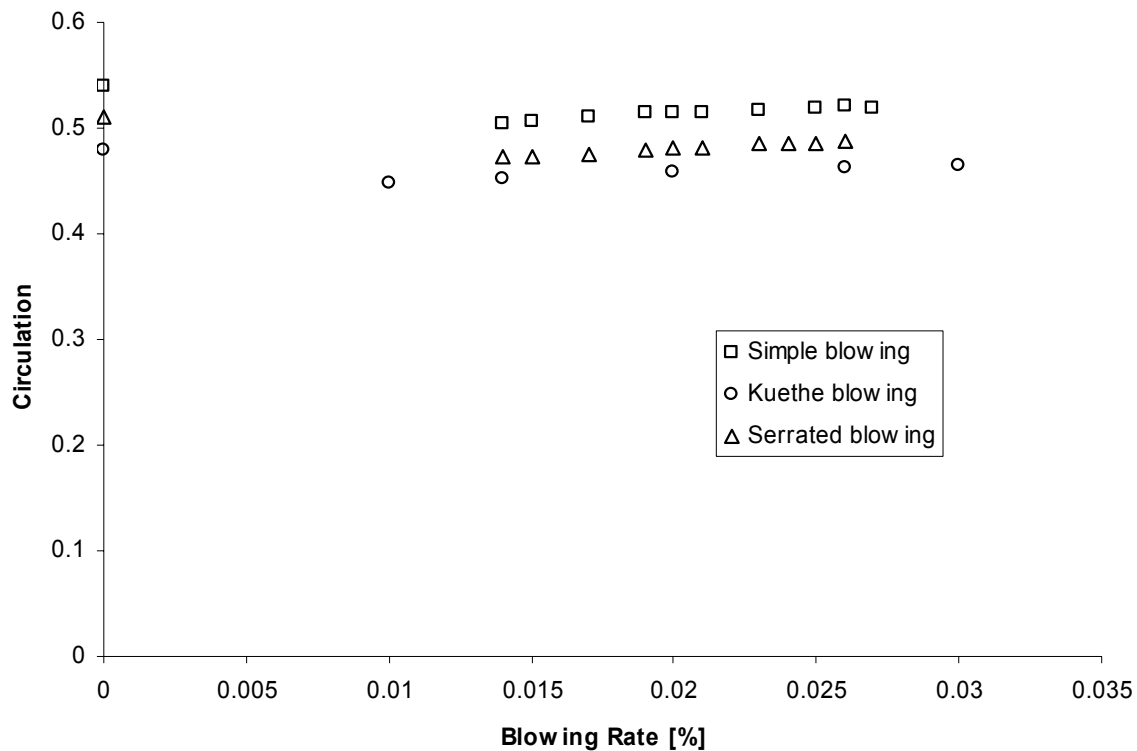


Figure 5.6 Variation of the blade circulation with blowing rate for the simple, Kuethe, and serrated blowing blades.

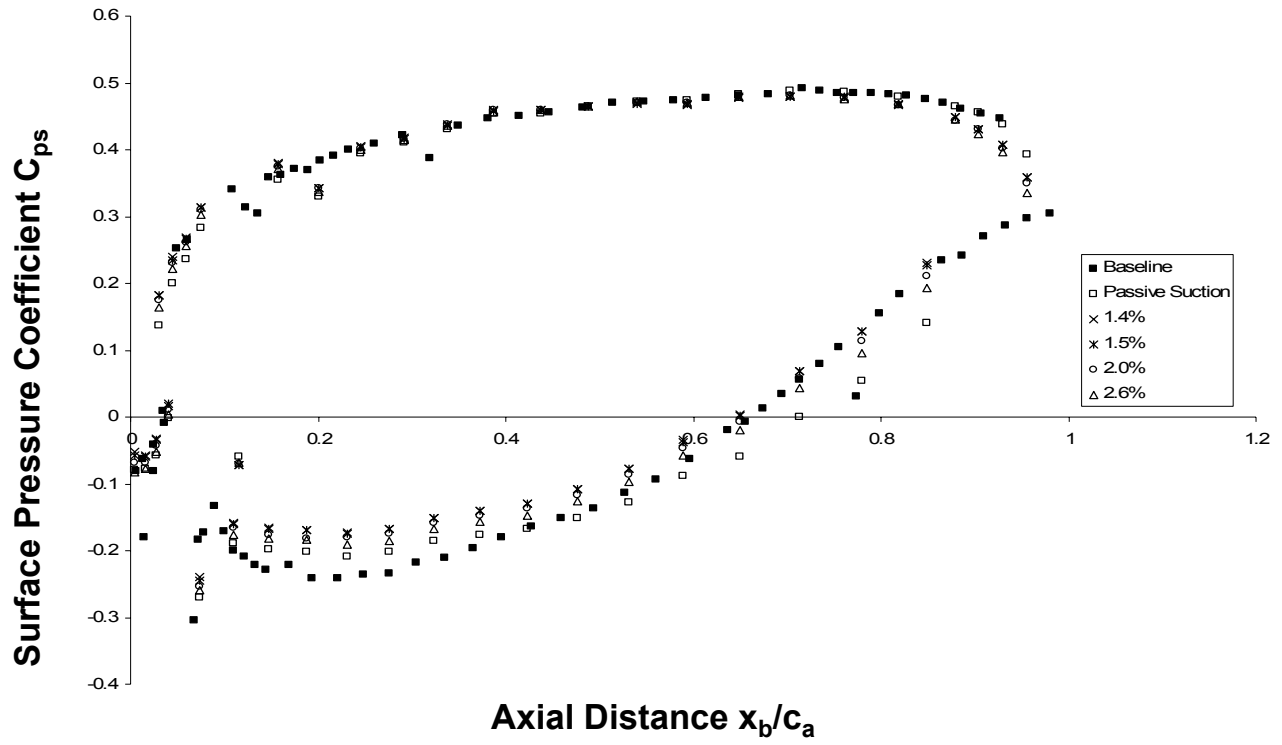


Figure 5.7 Serrated blowing blade loading for various blowing rates (expressed as fraction of the mass flux through the passage).

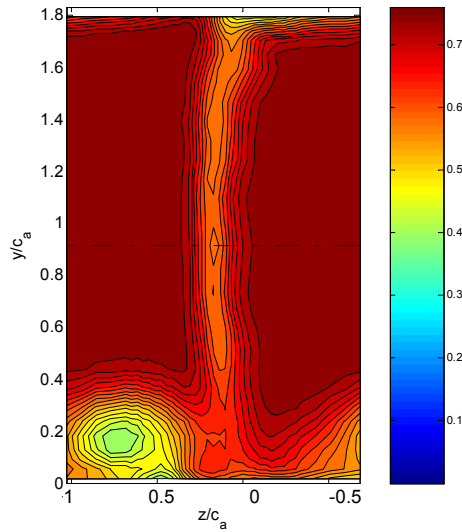


Figure 5.8 Pitot-Static cross-section of the mean streamwise velocity at $x/c_a=0.84$ downstream of the baseline blades. *Note the horizontal axis direction is reversed.*

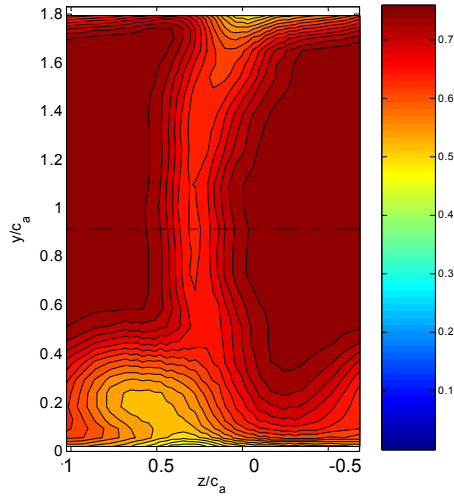


Figure 5.9 Pitot-Static cross-section of the mean streamwise velocity at $x/c_a=1.88$ downstream of the baseline blades. *Note the horizontal axis direction is reversed.*

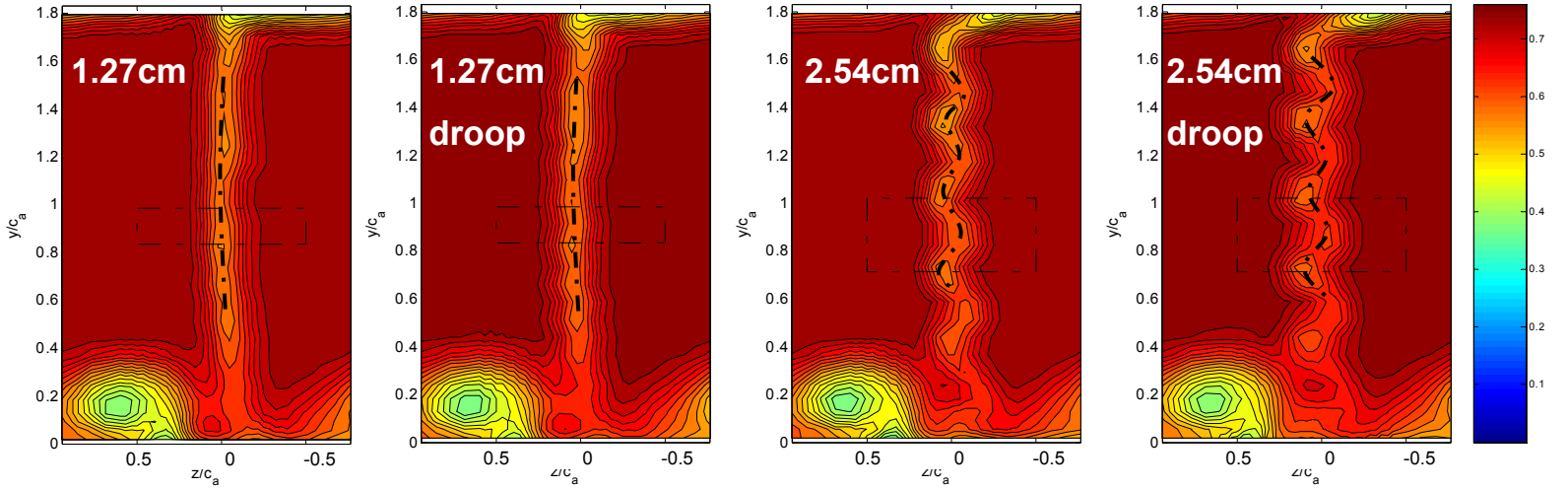


Figure 5.10 Pitot-Static cross-section of the mean streamwise velocity at $x/c_a=0.84$ downstream of the serrated trailing edge blades (From Geiger, 2005). *Note the horizontal axis direction is reversed.*

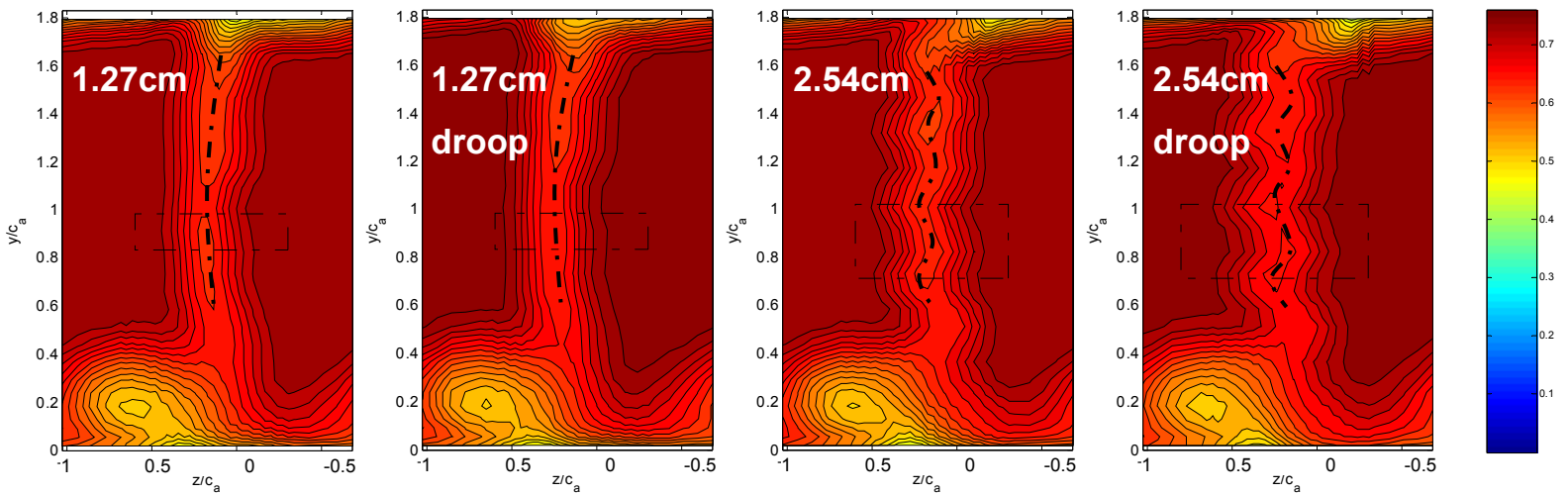


Figure 5.11 Pitot-Static cross-section of the mean streamwise velocity at $x/c_a=1.88$ downstream of the serrated trailing edge blades (From Geiger, 2005). *Note the horizontal axis direction is reversed.*

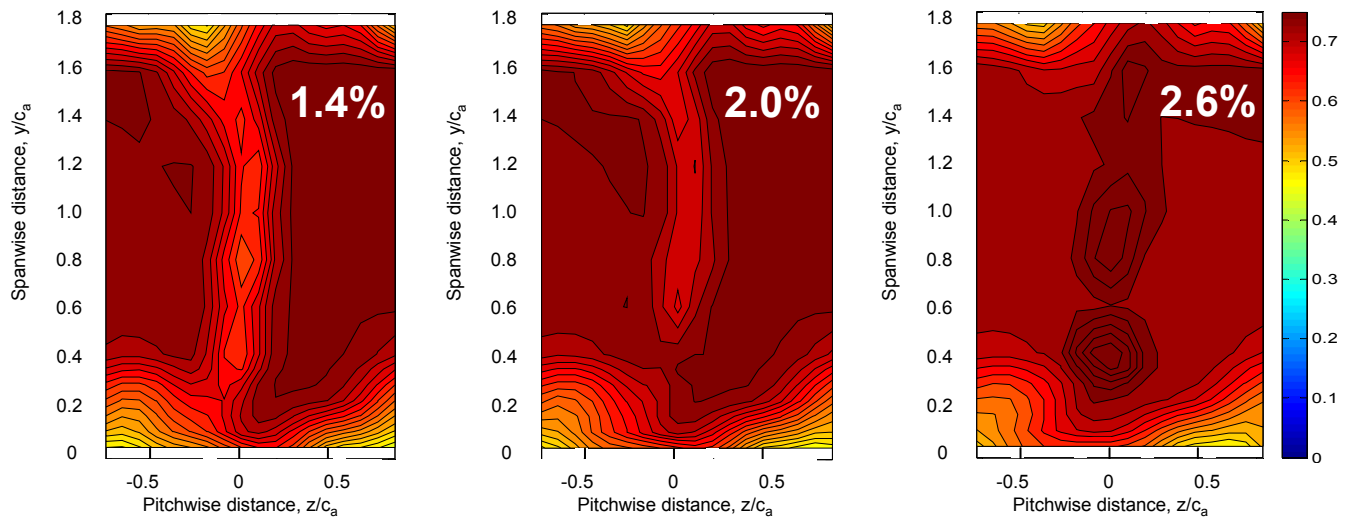


Figure 5.12 Pitot-Static cross-section of the mean streamwise velocity at $x/c_a=1.88$ downstream of the simple blowing blades (From Craig, 2006).

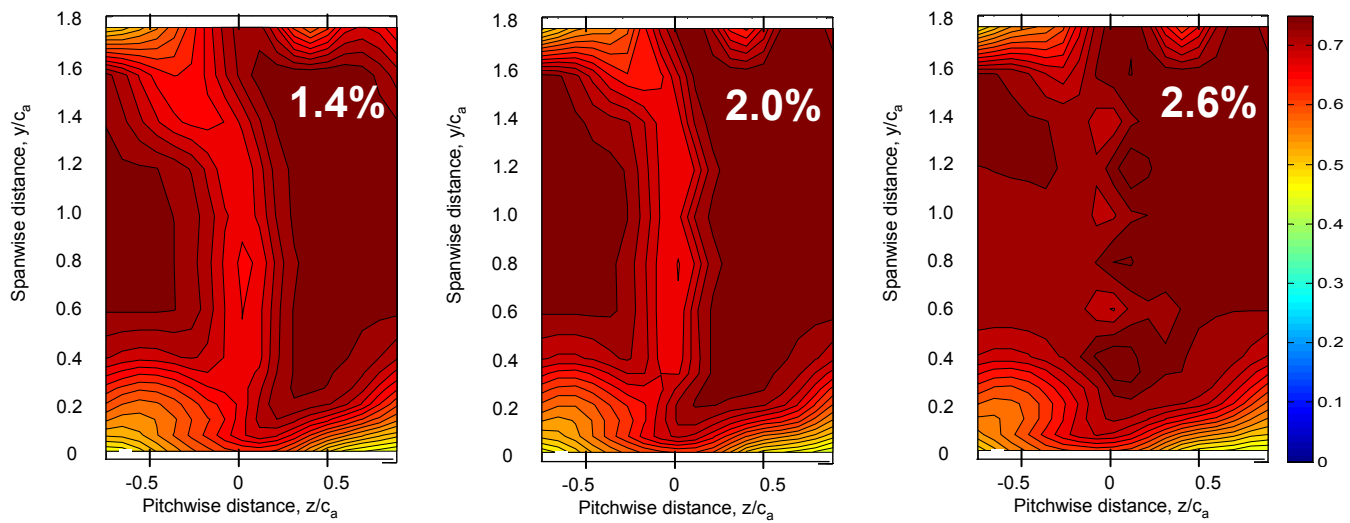


Figure 5.13 Pitot-Static cross-section of the mean streamwise velocity at $x/c_a=1.88$ downstream of the Kuethe blowing blades (From Craig, 2006).

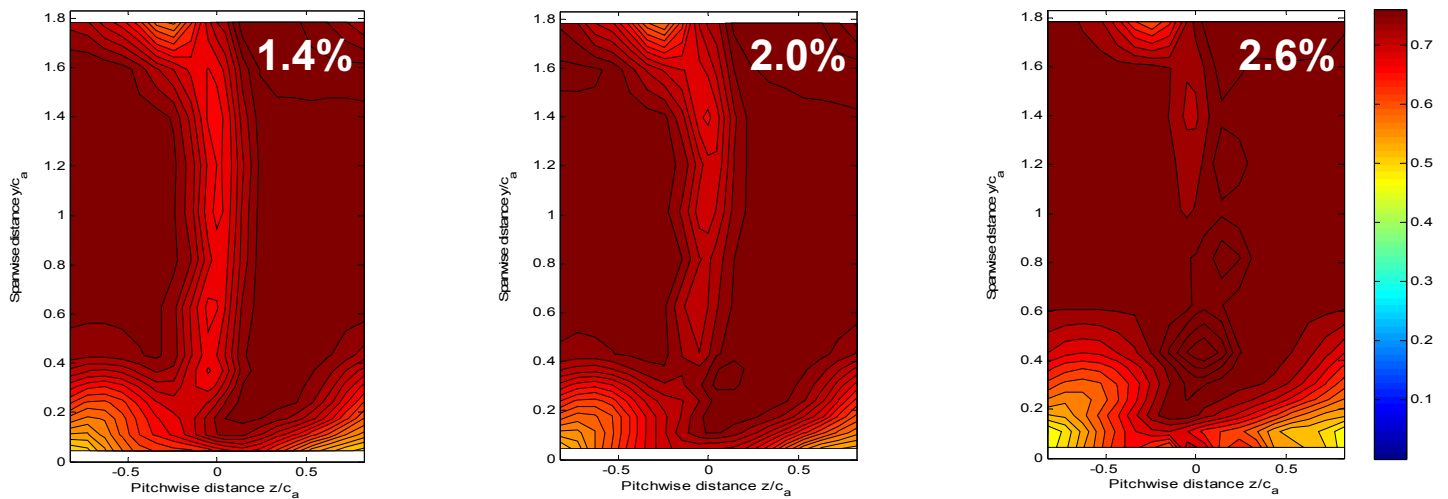


Figure 5.14 Pitot-Static cross-section of the mean streamwise velocity at $x/c_a=1.88$ downstream of the serrated blowing blades.

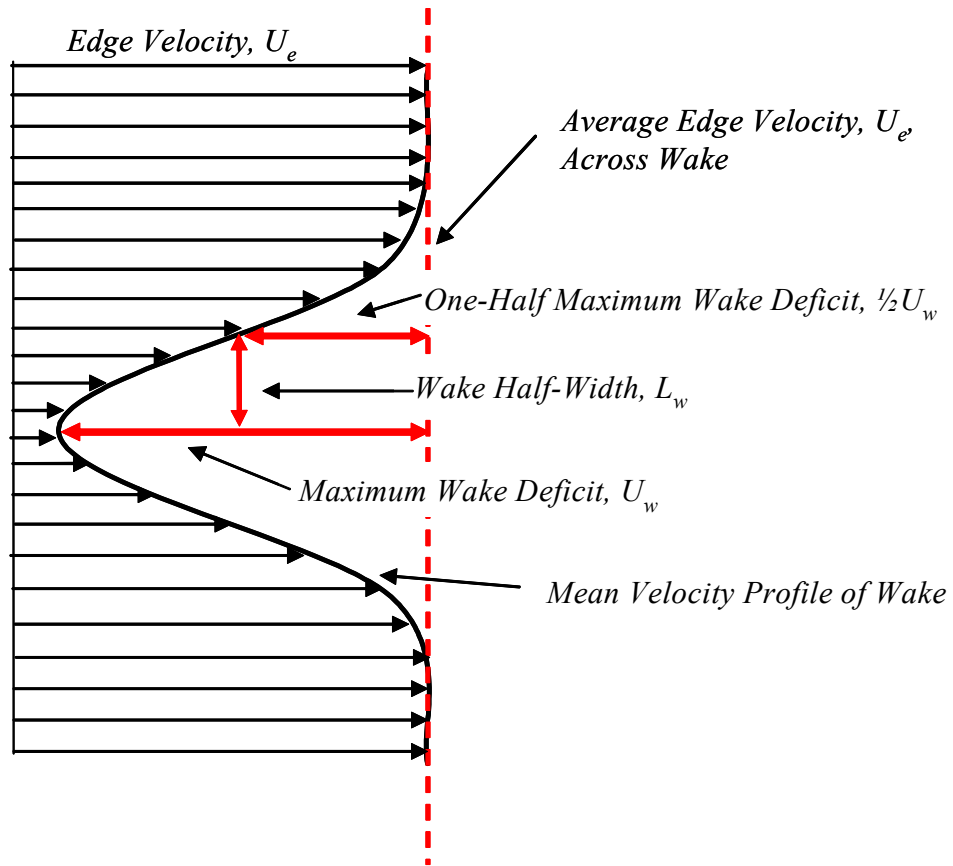


Figure 5.15 Wake parameters definition.

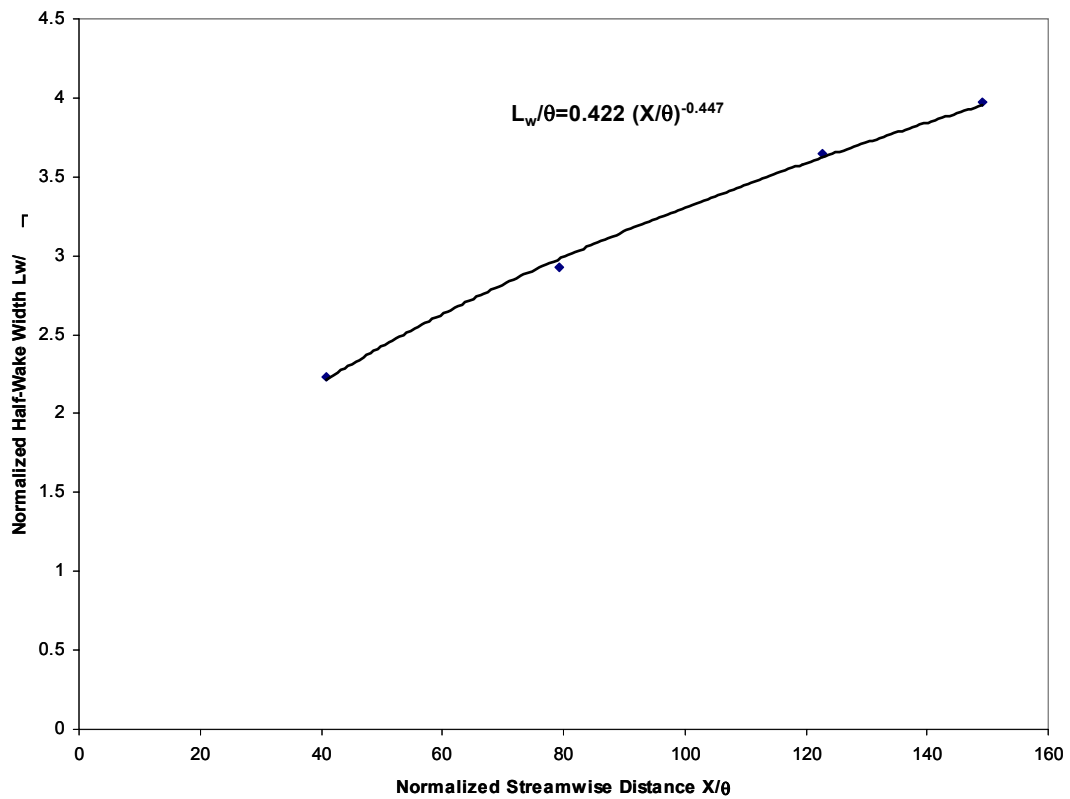


Figure 5.16 Half-wake streamwise variations downstream of the baseline blades.

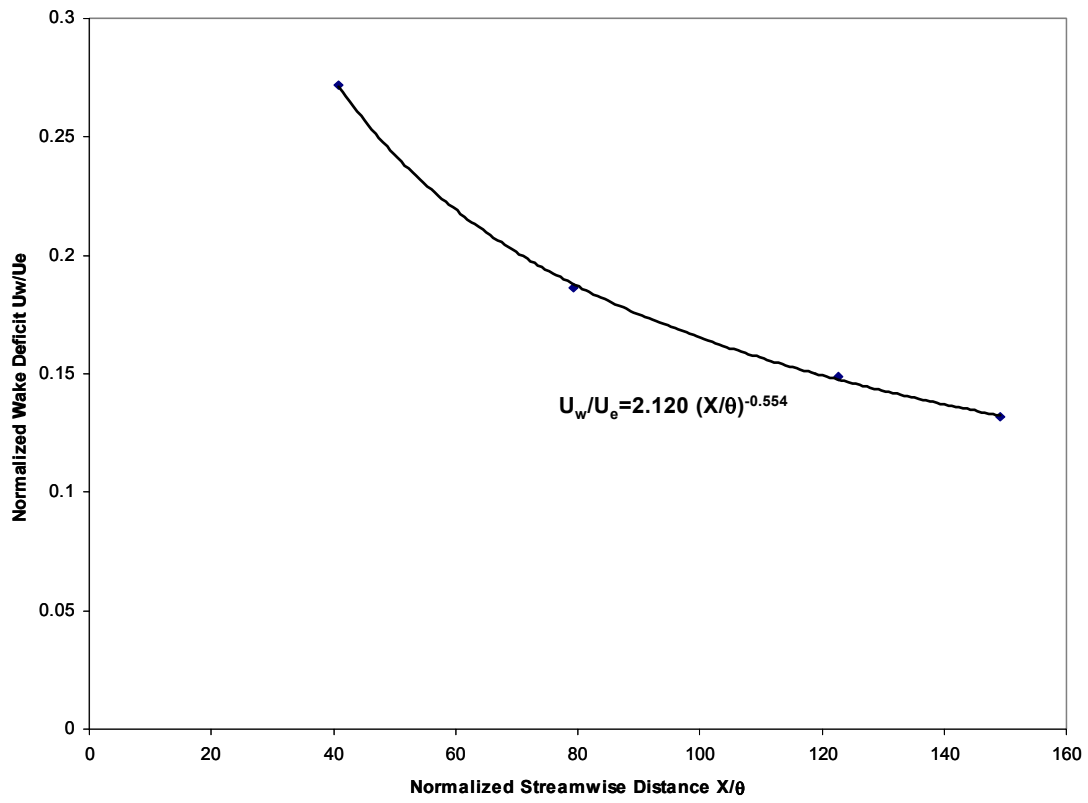


Figure 5.17 Wake deficit streamwise variations downstream of the baseline blades.

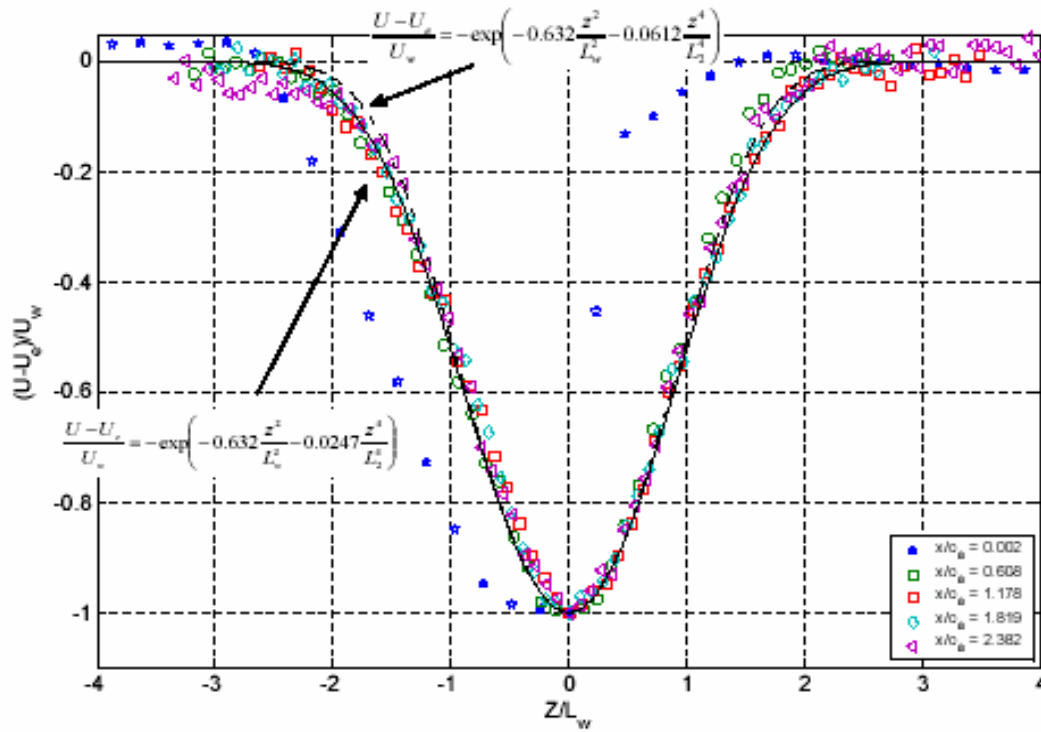


Figure 5.18 Normalized streamwise mean velocity profiles for the baseline blades.

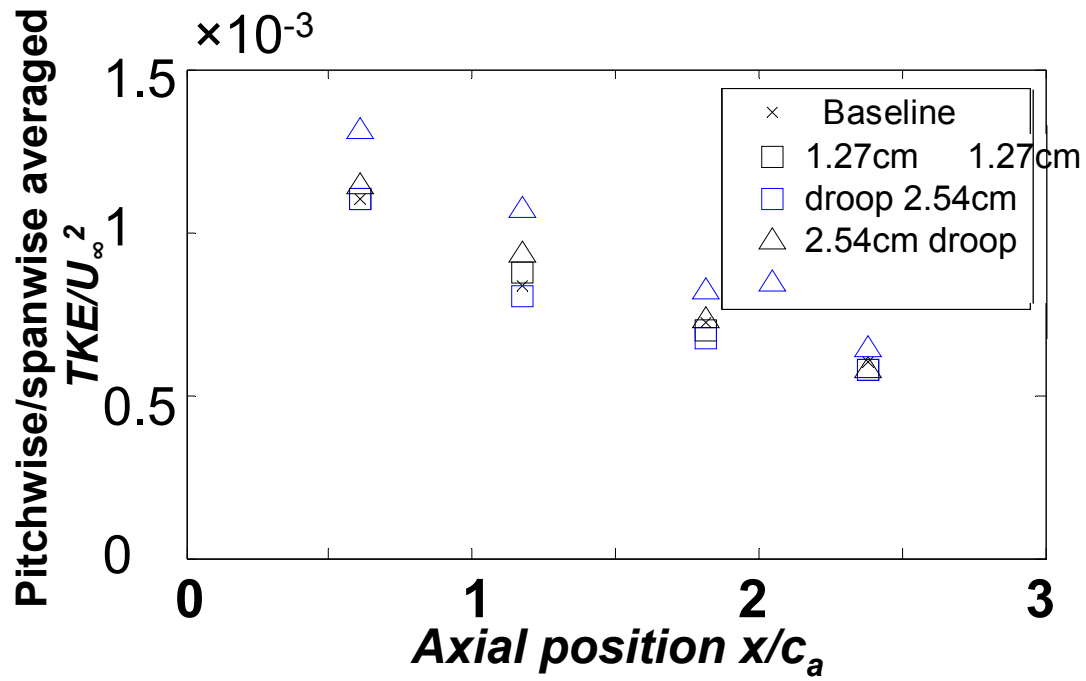


Figure 5.19 Pitchwise and spanwise averaged TKE for the serrated trailing edge blades at $x/c_a=1.88$.

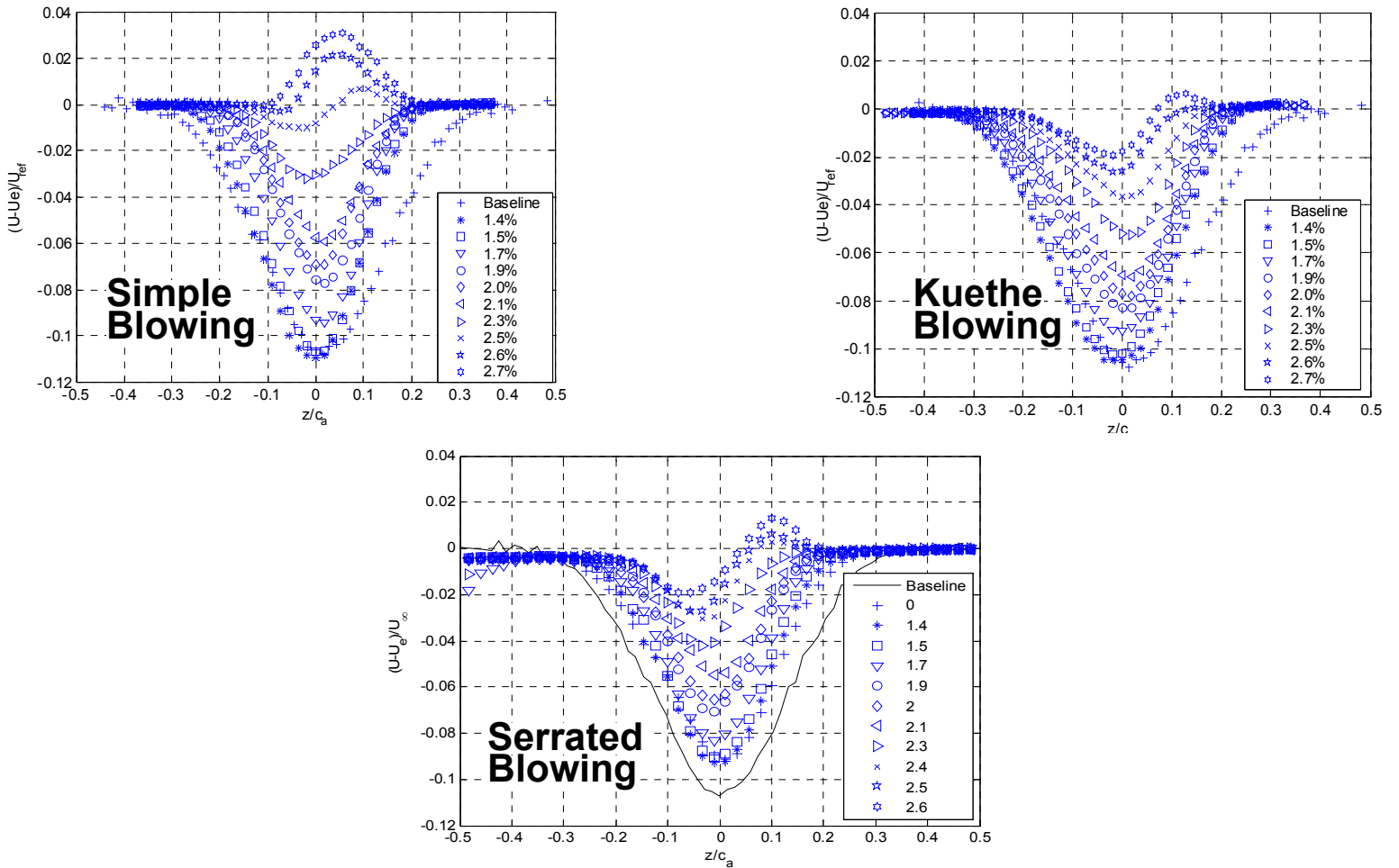


Figure 5.20 Normalized streamwise velocity profiles for the trailing edge blowing blades at $x/c_a=1.88$ plotted for various blowing rates (expressed as % of the mass flux through the passage). Simple and Kuethe blowing data reproduced from Craig (2006).

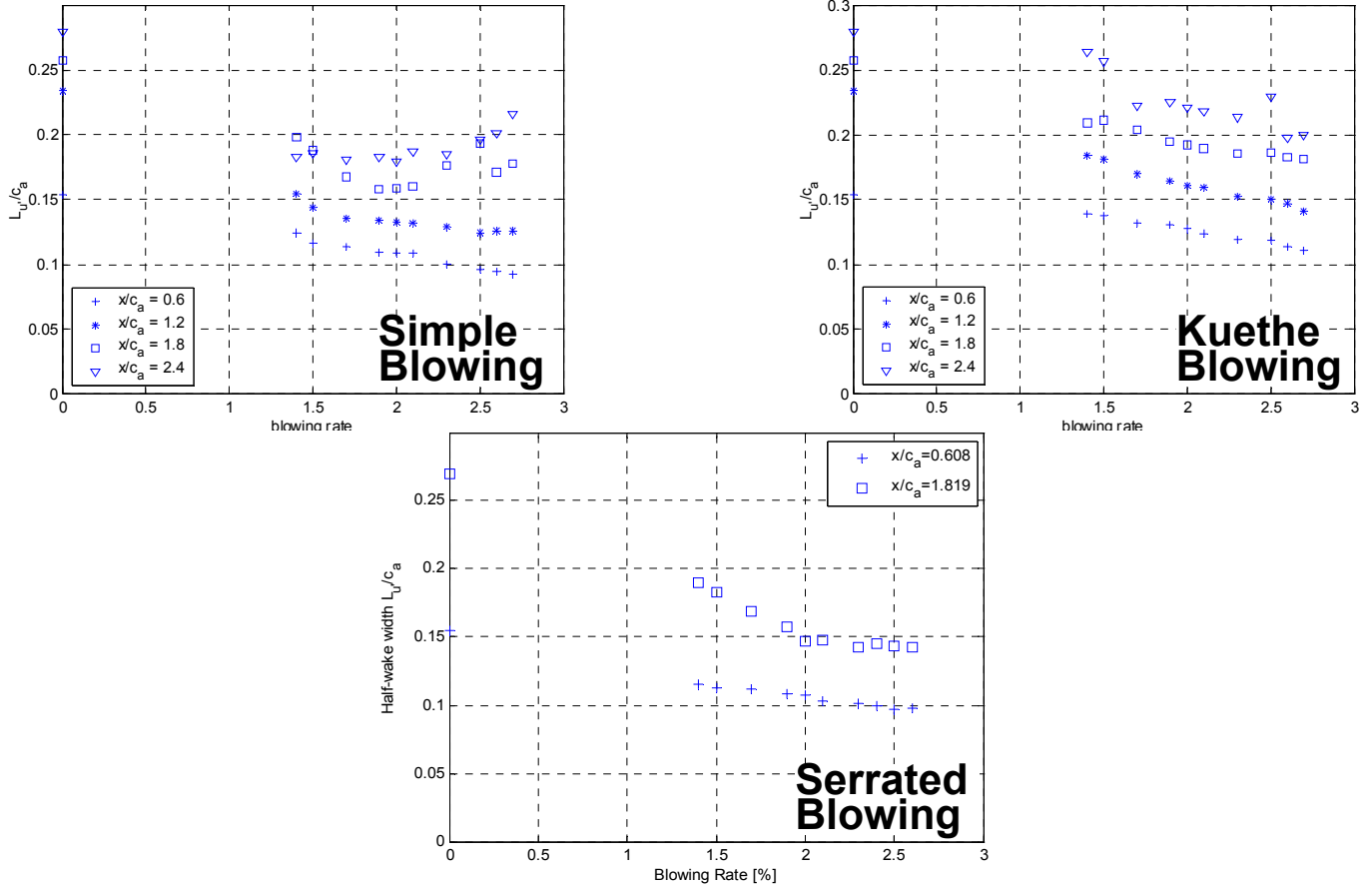


Figure 5.21 Half-wake width variations with blowing rate for the trailing edge blowing blades obtained at different axial locations between $x/c_a=0.6$ and 2.4. Baseline values are indicated at a blowing rate of 0%. Simple and Kuethe blowing data from Craig (2006).

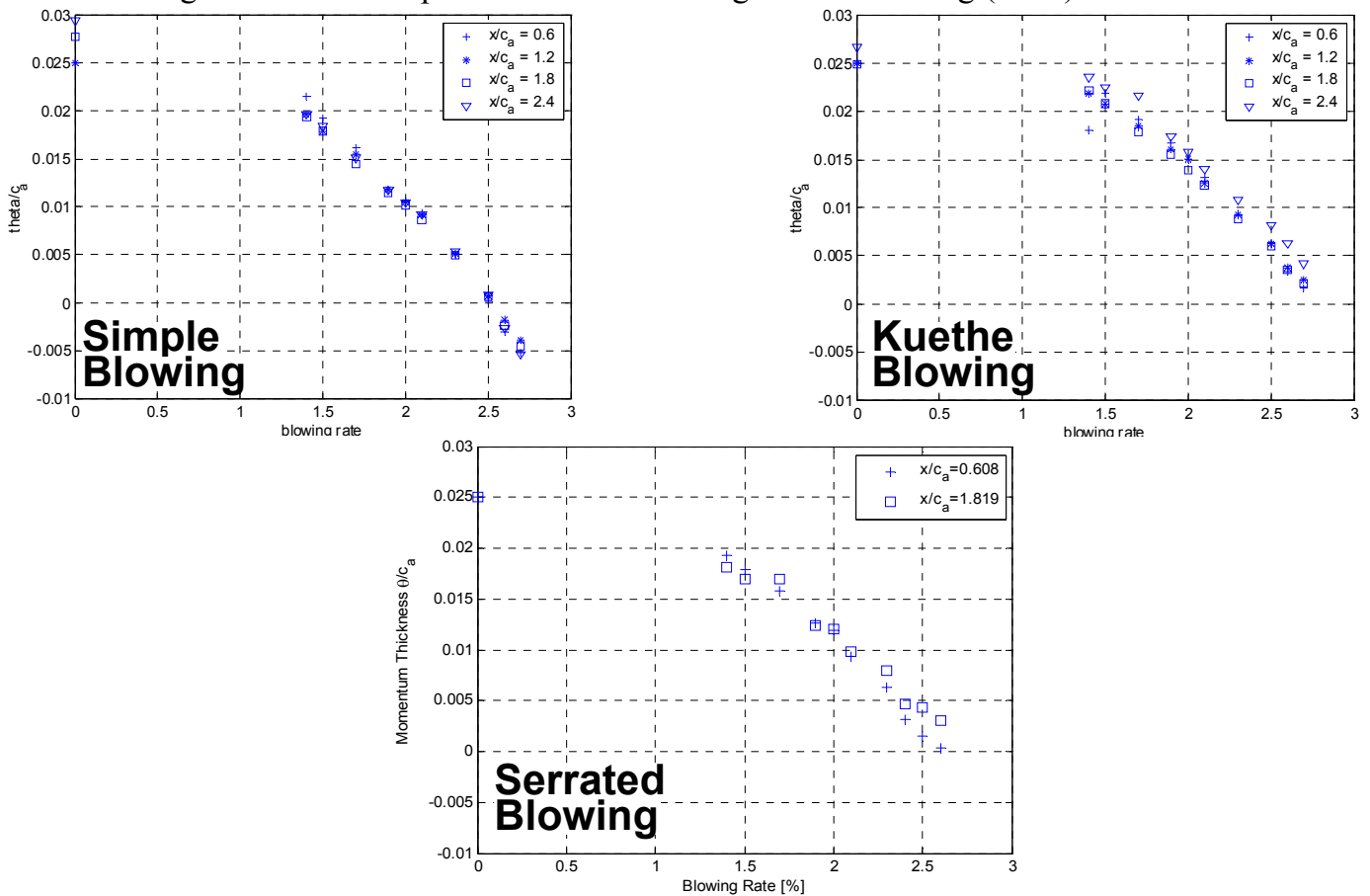


Figure 5.22 Momentum thickness variations with blowing rate for the trailing edge blowing blades obtained at different axial locations between $x/c_a=0.6$ and 2.4. Baseline values are indicated at a blowing rate of 0%. Simple and Kuethe blowing data from Craig (2006).

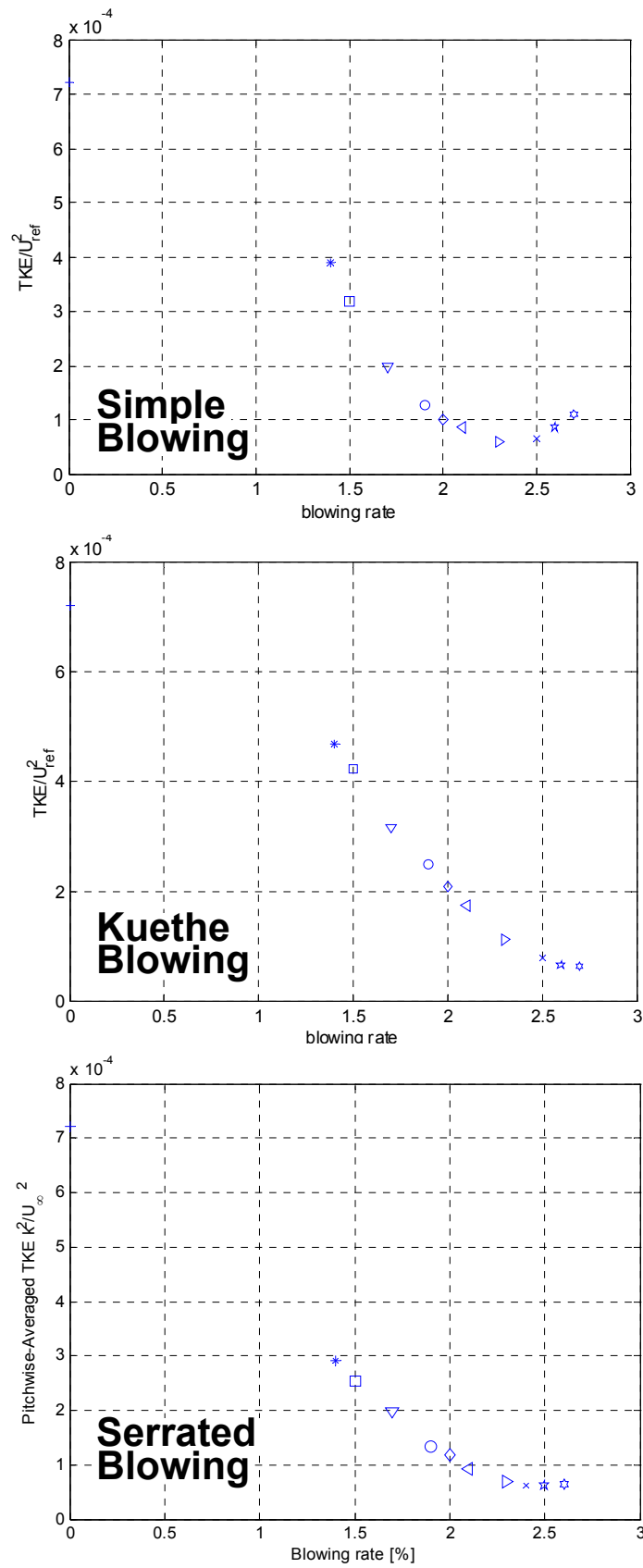


Figure 5. 23 Pitchwise averaged TKE for the trailing edge blowing blades at $x/c_a=1.88$ as a function of blowing rate (expressed as % of the mass flux through the passage).

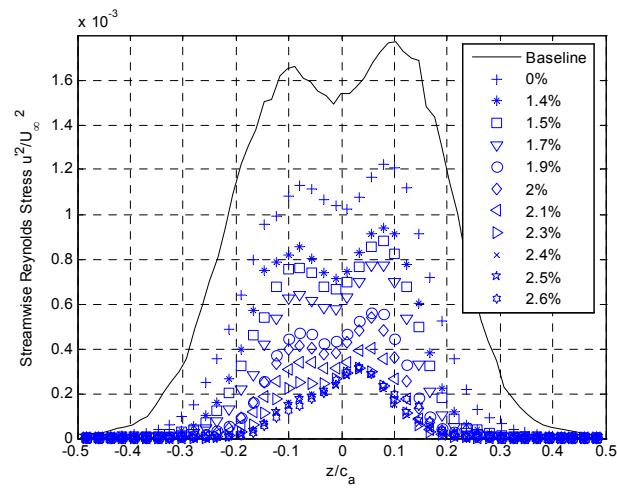


Figure 5. 24 Streamwise Reynolds stress $\overline{u'^2}$ profile downstream of the serrated trailing edge blowing blades at $x/c_a=1.88$ for various blowing rates.

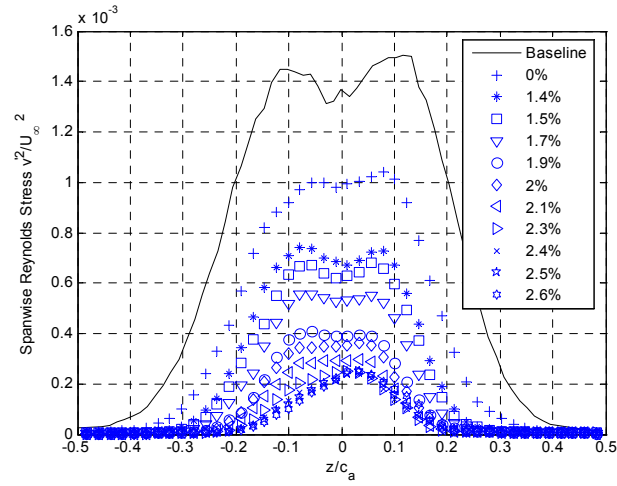


Figure 5. 25 Spanwise Reynolds stress $\overline{v'^2}$ profile downstream of the serrated trailing edge blowing blades at $x/c_a=1.88$ for various blowing rates.

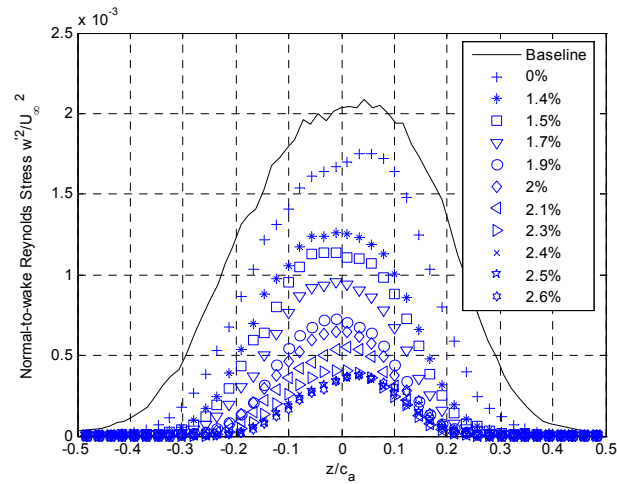


Figure 5. 26 Normal-to-wake Reynolds stress $\overline{w'^2}$ profile downstream of the serrated trailing edge blowing blades at $x/c_a=1.88$ for various blowing rates.

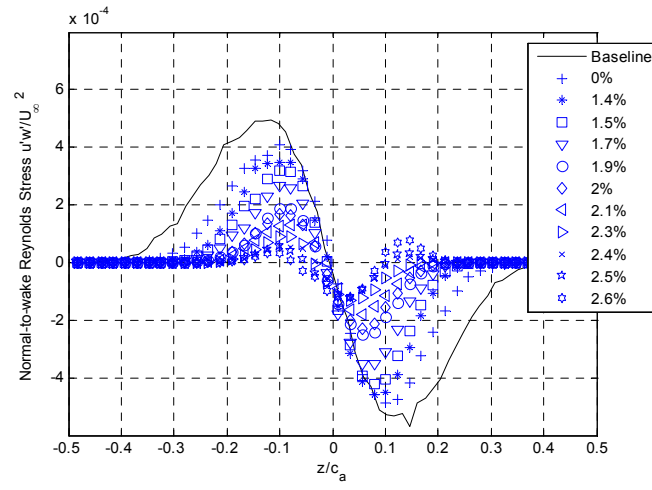


Figure 5. 27 Reynolds shear stress $\overline{u'w}$ profile downstream of the serrated trailing edge blowing blades at $x/c_a=1.88$ for various blowing rates.

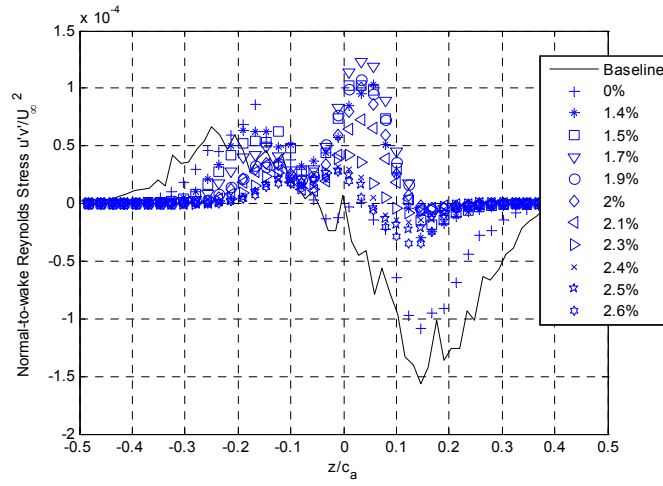


Figure 5. 28 Reynolds shear stress $\overline{u'v}$ profile downstream of the serrated trailing edge blowing blades at $x/c_a=1.88$ for various blowing rates.

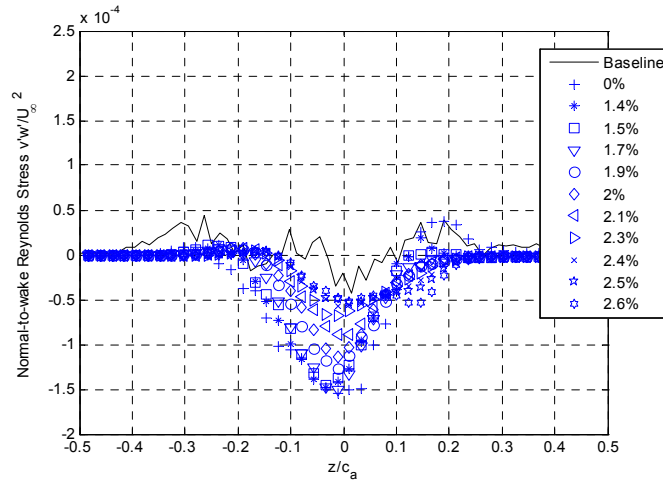


Figure 5. 29 Reynolds shear stress $\overline{v'w}$ profile downstream of the serrated trailing edge blowing blades at $x/c_a=1.88$ for various blowing rates.

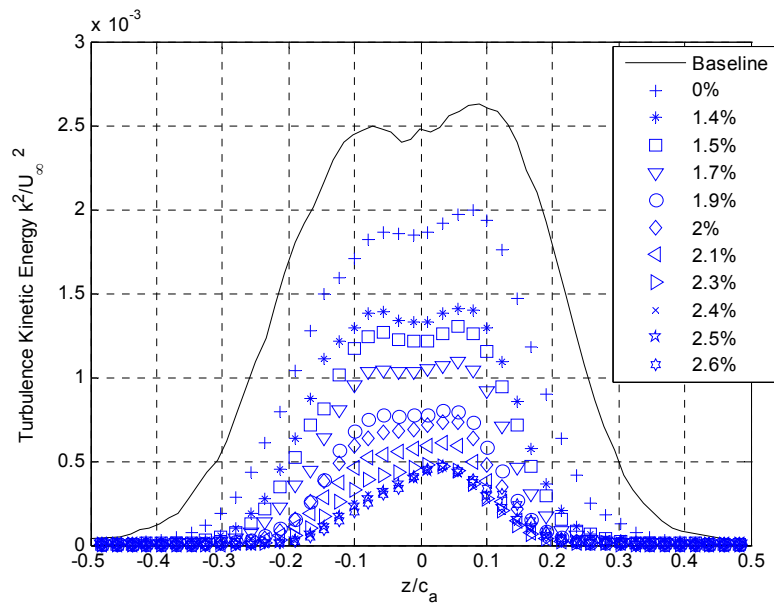


Figure 5. 30 Turbulence kinetic energy profile downstream of the serrated trailing edge blowing blades at $x/c_a=1.88$ for various blowing rates.

Chapter 6 - Two-Point Measurements

The Virginia Tech Low Speed Linear Cascade wind tunnel has been used to experimentally document and investigate the effects of various flow trailing edge flow control strategies on the wake of idealized fan blades. The previous section concerned itself with the study of the mean velocities and turbulence intensities associated with the different strategies (i.e. T.E. serration and T.E. blowing). The investigation of the mean velocity defect allowed estimating the impact of the strategies on the tonal component of interaction noise. The turbulent stress profiles of the modified wake can be used to hypothesize on the possible broadband noise benefits of the various strategies tested. However, as mentioned earlier, the generation of broadband noise is not only dependent on the magnitude of the turbulence inside the rotor wake but also on the scale of that turbulence. To determine both the scale and the magnitude of the wake turbulence, it is required to measure the velocity correlation between two points in the wake at various locations across the wake. Measurements of the velocity correlation were utilized to determine the organization of the coherent structures in the wake as well as obtain descriptions of representative eddies associated with the velocity correlation. This chapter is therefore dedicated to describe how these measurements were taken and how they can be used to obtain information about the coherent structures present in the wakes.

6.1. Theoretical background

6.1.1. Two-Point Velocity Correlation

This chapter focuses on extracting information about the organization of the coherent structures from the two-point velocity correlation tensor. The two-point velocity correlation tensor is defined as the expected value (or ensemble average) of the product the velocity fluctuations in two directions as a function of space and time:

$$R_{ij}(\mathbf{r}, \mathbf{r}', \tau) = \overline{u_i(\mathbf{r}, t) u_j(\mathbf{r}', t') } \quad (6.1)$$

where i and j are indices running from 1 to 3 and corresponding to the streamwise, spanwise, and normal-to-wake directions respectively, $\mathbf{r}$ and $\mathbf{r}'$ are the position vectors of two points in space, and t and t' the times corresponding to the two velocity fluctuations so that $\tau = t - t'$.

Note that the correlation function defined in Eq.(6.1) has the following symmetry property:

$$R_{ij}(\mathbf{r}, \mathbf{r}', \tau) = R_{ji}(\mathbf{r}', \mathbf{r}, -\tau) \quad (6.2)$$

Additionally, the correlation function at zero-time delay ($\tau = t - t' = 0$) and zero-separation ($\mathbf{r} = \mathbf{r}'$) reduces by definition to the Reynolds stress tensor since

$$R_{ij}(\mathbf{r}, \mathbf{r}, 0) = \overline{u_i(\mathbf{r}, t) u_j(\mathbf{r}, t)} \quad (6.3)$$

This study concerns itself with the impact of different strategies on the normal-to-wake Z and spanwise Y velocity correlation. The measurements described in section 6.2.1 and discussed in section 6.4.1 can therefore be expressed in terms of the wake-aligned coordinate systems as $R_{ij}(Z, Z', \tau)$ for the normal-to-wake measurements and $R_{ij}(Y, Y', \tau)$ for the spanwise measurements.

By analyzing how the velocity correlates between several points across the wake, it is possible to obtain information about the organization of the coherent structures. While the level of correlation provides information about the scale of the coherent structures, the shape of the correlation will offer a simple way to extract information about the spatial organization or distribution of the structures across the wake. Such analysis forms the bulk of the analysis of the present chapter (see section 6.4.1).

6.1.2. Statistical Methods for Turbulent Wakes

Two methods are used to obtain a representation of the characteristic eddies implied by the correlation function. These methods are the Proper Orthogonal Decomposition (POD) and Compact Eddy Structures (CES).

6.1.2.1. Proper Orthogonal Decomposition

The orthogonal decomposition of a fluctuating velocity field can be expressed in the normal-to-wake direction as

$$u_i(Z) = \sum_n a_n \phi_i^{(n)}(Z) \quad (6.4)$$

where n denotes the mode number, a_n a set of coefficients and $\phi_i^{(n)}$ are the POD modes.

The POD modes are obtained by optimization the projection of the velocity field onto the mode functions $\phi_i^{(n)}$. As such, they represent the most probable instantaneous velocity profiles and are therefore basis functions of the instantaneous velocity field. As implied by its name, the POD modes are orthogonal and uncorrelated (Lumley, 1968) so that

$$\frac{1}{\zeta} \int_0^\zeta \phi^{(n)}(Z) \phi^{(m)}(Z) dZ = \delta_{nm} \quad (6.5)$$

where ζ is the range of integration in the normal-to-wake direction, and δ is 1 when $n = m$ and zero otherwise.

Lumley shows that the modes were eigenfunctions of the two-point correlation tensor. It follows that the proper orthogonal modes can be obtained from the two-point correlation tensor by solving the Fredholm integral equation (Lumley, 1967):

$$\int R_{ij}(Z, Z', 0) \phi_j^{(n)}(Z') dz' = \lambda^{(n)} \phi_i^{(n)}(Z) \quad (6.6)$$

where $\lambda^{(n)}$ are the eigenvalues.

The magnitudes of the eigenvalues correspond to the proportion of kinetic energy associated with instantaneous fluctuations in the amplitude of the corresponding eigenfunction or mode. This is easily proven by noting that the average kinetic energy of a fluctuating velocity field is given by

$$E \equiv \frac{1}{\zeta} \int_0^\zeta \frac{1}{2} \overline{u(Z)^2} dZ \quad (6.7)$$

Using the decomposition in Eq.(6.1) along with the orthonormality condition of Eq.(6.5), it follows that the energy contained in the first N modes is proportional to the sum of the first N eigenvalues:

$$E_N \sim \sum_{n=1}^N \lambda^{(n)} \quad (6.7)$$

The eigenvalue spectrum (i.e. the variation of the magnitude of the eigenvalues against mode number) can therefore be used to select the first few modes that contain enough energy to obtain an accurate description of the flow.

Since each mode represents the best fit, on average, to the instantaneous velocity field, POD can provide a description of the main eddies with the minimum number of modes.

6.1.2.2. Compact Eddy Structures

For the present purposes, POD can only provide one-dimensional information on the structure and intensity of the turbulence motions, namely in the inhomogeneous direction normal to the wake. In homogeneous directions (such as in time and spanwise across the wake) POD reduces to a simple Fourier decomposition that does not provide much useful information about the types of eddies present in the wake. To generate compact representations of the typical eddy structures responsible for the turbulent motions Glegg and Devenport (2001) suggested obtaining the velocity field in the streamwise direction associated with each proper orthogonal mode by making a linear stochastic estimate of the field based on the modal profile. The resulting velocity fields, termed ‘Compact Eddy Structures’ (CES), turn out to be given by the inner product of the correlation function and the proper orthogonal mode. In the present case:

$$\kappa_i^{(n)}(Z, \tau) = \frac{1}{\lambda^{(n)} \zeta} \int_{-\zeta/2}^{\zeta/2} R_{ij}(Z, Z', \tau) \phi_j^{(n)}(Z') dZ' \quad (6.8)$$

To obtain this relation, Glegg and Devenport suggested obtaining the POD modes to describe the flow in the inhomogeneous direction and combine these modes with Linear Stochastic Estimates (LSE) in the homogeneous direction to obtain the complete velocity field. LSE seeks to minimize the error between the turbulent fluctuations and their linear estimates based on the modal produced (Glegg and Devenport, 2001). The best linear estimate of the instantaneous velocity field at a given position $u^{LSE}(Z')$ can be

obtained from the measured velocity at another point $u(Z)$ and the correlation function between these two locations:

$$u_j^{LSE}(Z') = A_{ij}(Z)u_i(Z) \quad (6.9)$$

The estimation coefficients $A_{ij}(Z)$ are chosen so that they minimize the mean square error between the estimated and the measured velocities. This minimization then leads to an equation of the form:

$$\overline{u_j(Z)u_k(Z)}A_{ik}(Z') = \overline{u_j(Z)u_i(Z')} \quad (6.10)$$

Equations (6.9) and (6.10) shows that the estimated velocity at a given point is obtained from the measured velocity at another location, the correlation tensor between these two locations (the term on the right of Eq.(6.10)) and the Reynolds stress tensor at that location (the left hand term in Eq.(6.10)). It then follows that the estimation coefficient are in essence the correlation coefficients.

As noted by Glegg and Devenport (2001), the CES do not necessarily occur in the flow as specific features, but they do represent average structures (since they are based on the most probable velocity profiles obtained from the POD). While the CES are not basis functions of the instantaneous velocity field like the POD modes are, they are basis functions of the space-time correlation function. Therefore phenomena that depend upon the correlation function (like the broadband radiation resulting from the rotor-stator interaction) can be decomposed using CES.

6.2. Measurements Strategies

Two-point velocity measurements were made both pitchwise and spanwise for the various sets of blades. The direction (pitchwise or spanwise) and location of the two-point measurements varied based on the blade geometry. The measurement direction and location are therefore detailed in the following sections for each type of blade.

6.2.1. Measurement Schemes

6.2.1.1. Pitchwise Measurements

The velocity correlation has to be measured in order to identify the variety of coherent structures present in the wake. The velocity correlation is obtained by

simultaneously measuring the velocity at two different points inside the wake and repeating the measurement at various locations across the wake. For the pitchwise profiles, a chasing probe scheme was selected. Let n_z be the index of a given pitchwise location and N_z be the maximum number of distinct locations. The “fixed” probe would be measuring at point n_z while the “moving” probe would be recording data at points n_z+1 up to N_z . Then the fixed probe would move to n_z+1 and the moving probe would traverse points from N_z to n_z+2 , and so forth until the fixed probe reaches the $N_z - 1$ location. Assuming 41 evenly distributed distinct points across the wake, such method leads a measurement grid populated with 820 total measurement points. Due to the nature of the chasing probe scheme and the traverse system, the correlation can only be measured for those points where the location of the fixed probe z_{fixed} is always strictly greater than that of the moving probe z_{moving} . However, the complete correlation function could be obtained from the symmetric nature of the function described in Eq.(6.2). As described later, the correlation where $z_{fixed}=z_{moving}$ is obtained by averaging the single-point correlation information from each of the two (fixed and moving) probes. Therefore, measurements performed at $N_z(N_z - 1)/2$ points (820 here) effectively permitted to populate a grid of N_z^2 (1681 points total).

Performing three-component velocity measurements (with two probes) at each of these points would result in unreasonable measurement time and data file size. The grid was consequently reduced to 616 points by eliminating some of the data points at larger probe separation. A comparison between the fully populated and reduced measurement grid can be seen in Figure 6.1. For these measurements both probes lie at the same spanwise location.

6.2.1.2.Spanwise Measurements

Spanwise measurements use the same type of scheme as the pitchwise measurements. In the spanwise measurements, the “fixed” probe rests at one spanwise location while the “moving” probe moves through various spanwise locations between the fixed probe and the lower end-wall. For these measurements, both probes lie at the same pitchwise location (corresponding to the wake center location at the spanwise

location of the fixed probe). The minimum theoretical probe separation used for the spanwise profiles is the same as the one used for the pitchwise profiles.

6.2.1.3. Sampling Scheme

Both pitchwise and spanwise measurements used the same sampling scheme for the data acquisition. Three-component velocity was measured using a sampling rate of 51.2kHz. 50 records of 2048 samples of data were taken at each point at a rate of about 3 records per second. High-pass anti-aliasing filters with a cut-off frequency of 25kHz were used to sample the two-point velocity data.

6.2.2. Measurement Locations

6.2.2.1. Baseline Blades

The measurement of the velocity correlation inside the wake of the baseline blades has two purposes. The first is to provide an understanding of the organization and development of the coherent structures present in the wake. The second is to provide a reference against which the modified T.E. blades are compared. To fulfill the first purpose, two-point velocity correlation measurements were taken at a location of $x/c_a=1.8$. Both pitchwise and spanwise measurements were taken. The second purpose is fulfilled by using the data (both pitchwise and spanwise) at $x/c_a=1.8$ as the reference against which the measurements of the different strategies are compared. The axial location of $x/c_a=1.8$ was selected as the reference location because it is representative of the typical axial spacing between rotor and stator in an aircraft engine.

Since the wake of the baseline blades was shown to be nominally two-dimensional near the midspan (see Chapter 5), the pitchwise two-point measurement downstream of the baseline were made at the midspan location of $y/c_a=0.92$. At $x/c_a=1.8$, the pitchwise profile was centered at $z/c_a=-2.52$ with an amplitude of $\pm 0.73c_a$, resulting in a step size of 5mm. The step size (minimum distance between the fixed and moving probes) was kept identical for the pitchwise profiles measured downstream of the serration and blowing blades. The spanwise profile at $x/c_a=1.8$ was measured at $z/c_a=-2.52$ and between $y/c_a=0.02$ and 0.92 (using the same step size as the pitchwise profile).

The wake parameters used to normalize the data presented in this chapter, namely the half-wake width L_u , and the wake deficit U_u , defined in Chapter 5, are $0.270c_a$ and $0.045U/U_\infty$ respectively.

6.2.2.2. Serrated Trailing Edge Blades

To evaluate the impact of the trailing edge serration on the coherent structures, the two-point velocity correlation was measured at the axial location of $x/c_a=1.8$ so it could be compared to the baseline results at the same location. As shown on the Pitot-static cross-sections, the trailing edge serrations produce some large spanwise variations in the wake. The transport of fluid from the pressure side through the serration valley results in under-turning of the flow downstream of the serration valley compared to the serration peak. This turning differential resulted in the convoluted wake shape displayed in the Pitot-static cross-section of Chapter 5. Additionally, single-point profiles of the TKE across the serration period showed the difference in turbulence levels between the flow downstream of the serration peak and valley. This differential in the turbulent structure of the wake was therefore taken into account when selecting the spanwise locations of the two-point measurements. To obtain information about the coherent structures associated with this differential in turbulence levels, pitchwise measurements of the velocity correlation were taken at two spanwise locations for each of the four serrated trailing blade sets. The two spanwise locations correspond to the locations of the serration peak and serration valley closest to the blade midspan. Due to the various serration spanwise periods, the spanwise location of the two-point pitchwise profiles is a function of the blade geometry. The measurement locations of the pitchwise profiles of the velocity correlation downstream of the serrated trailing edge blades are given in Table 6.1.

The pitchwise location of the spanwise measurement was selected as the mean pitchwise location of the wake center (averaged over one serration period). The fixed probe was located at the spanwise location of the serration peak. The measurement locations of the spanwise profiles of the velocity correlation downstream of the serrated trailing edge blades are given in Table 6.1. An error during the spanwise measurements of the 2.54cm drooped blades prevented any meaningful analysis to be performed.

Table 6.1 Two-point measurement locations for the serrated trailing edge blades (see figure 5.11 to visualize positions)

Serration Configuration	Measurement Direction	Measurement Purpose	Reference Point			Measurement range	
			<i>x/ca</i>	<i>y/ca</i>	<i>z/ca</i>	<i>y/ca</i>	<i>z/ca</i>
1.27cm	pitchwise	serration valley	1.819	0.91	-2.52	0	-3.25,-1.79
	pitchwise	serration peak	1.819	0.99	-2.52	0	-3.25,-1.79
	spanwise	spanwise flow	1.819	0.92	-2.52	0.18,0.92	0
1.27cm droop	pitchwise	serration valley	1.819	0.91	-2.53	0	-3.26,-1.80
	pitchwise	serration peak	1.819	0.99	-2.52	0	-3.25,-1.79
	spanwise	spanwise flow	1.819	0.92	-2.52	0.18,0.92	0
2.54cm	pitchwise	serration valley	1.819	0.87	-2.54	0	-3.27,-1.81
	pitchwise	serration peak	1.819	1.02	-2.51	0	-3.24,-1.78
	spanwise	spanwise flow	1.819	0.92	-2.52	0.18,0.92	0
2.54cm droop	pitchwise	serration valley	1.819	0.87	-2.55	0	-3.28,-1.82
	pitchwise	serration peak	1.819	1.02	-2.50	0	-3.23,-1.77
	spanwise	spanwise flow	1.819	0.92	-2.52	0.18,0.92	0

The half-wake width L_u and wake deficit U_u used to normalize the data presented in this chapter are given in Table 6.2.

Table 6.2 Half-wake width L_u and wake deficit U_u downstream of the serrated trailing edge blades.

	1.27cm		1.27cm droop		2.54cm		2.54cm droop	
	<i>valley</i>	<i>peak</i>	<i>valley</i>	<i>peak</i>	<i>valley</i>	<i>peak</i>	<i>valley</i>	<i>peak</i>
L_u/c_a	0.276	0.262	0.280	0.232	0.309	0.306	0.338	0.336
U_u/U_∞	0.046	0.043	0.043	0.062	0.040	0.042	0.042	0.042

6.2.2.3. Trailing Edge Blowing Blades

The possible benefits of trailing edge blowing were evaluated by measuring the two-point velocity correlation at the axial location of $x/c_a=1.8$ for 3 different blowing rates. The flow downstream of the different blowing blades was shown to be nominally two-dimensional near the midspan (see Pitot-static measurements in Chapter 5). Consequently the two-point pitchwise profiles were measured at one spanwise location (i.e. $y/c_a=0.92$, the midspan location). The effects of trailing edge blowing on the midspan wake were evaluated by measuring the pitchwise profiles at 3 blowing rates of 1.4, 2.0, and 2.6% for the simple and serrated blowing blades. These blowing rates (expressed as percentage of the mass flux through one cascade passage) were selected based on the single-point measurements as they are representative of a low, moderate, and high blowing rates respectively. Note that “low”, “moderate”, and “high” rates are used here relatively to their effects on the mean velocity profile, rather than relatively to their absolute value. As discussed in Chapter 5, the amount of air required to produce these kinds of blowing rates is actually too large to be implemented in a full scale engine.

During the serrated blowing data reduction, it became apparent (by comparing the Reynolds stress and mean velocity profiles) that there was a 0.6% difference between the theoretical and actual blowing rates. Consequently, the data measured at blowing rates of 1.4, 2.0, and 2.6% actually were found to actually be taken at rates of 0.8, 1.4, and 2.0%. Accordingly, only the 1.4 and 2.0% results are discussed here.

Physical failure of the Kuethe blowing blades during testing prevented from measuring the two-point profiles at 1.4 and 2.6%.

The spanwise profile of the velocity correlation was measured at the pitchwise location of the wake center downstream the midspan. Spanwise measurements were performed for the three blowing rates described above (1.4, 2.0, and 2.6% of the passage through-flow). Accordingly, the pitchwise location of the spanwise two-point profile was adjusted depending on the blowing rate. Detailed locations of the two-point velocity profiles downstream of the trailing edge blowing blades can be found in Table 6.3.

Table 6.3 Two-point measurement locations for the trailing edge blowing blades (see Figure 5.12 through 5.14 to visualize positions).

<i>Blowing Configuration</i>	<i>Blowing Rate</i>	<i>Measurement Direction</i>	<i>Reference Point</i>			<i>Measurement range</i>	
			<i>x/ca</i>	<i>y/ca</i>	<i>z/ca</i>	<i>y/ca</i>	<i>z/ca</i>
Simple Blowing	1.4%	pitchwise	1.819	0.92	-2.52	0	-3.25,-1.79
		spanwise	1.819	0.92	-2.52	0.18-0.92	0
	2.0%	pitchwise	1.819	0.92	-2.52	0	-3.25,-1.79
		spanwise	1.819	0.92	-2.52	0.18-0.92	0
	2.6%	pitchwise	1.819	0.92	-2.52	0	-3.25,-1.79
		spanwise	1.819	0.92	-2.52	0.18-0.92	0
Kuethe Blowing	2.0%	pitchwise	1.819	0.92	-2.52	0	-3.25,-1.79
		pitchwise	1.819	0.92	-2.52	0.18-0.92	0
Serrated Blowing	1.4%	pitchwise	1.819	0.92	-2.52	0	-3.25,-1.79
		spanwise	1.819	0.92	-2.52	0.18-0.92	0
	2.0%	pitchwise	1.819	0.92	-2.52	0	-3.25,-1.79
		spanwise	1.819	0.92	-2.52	0.18-0.92	0

The half-wake width L_u and wake deficit U_u used to normalize the data presented in this chapter are given in Table 6.4.

Table 6.4 Half-wake width L_u and wake deficit U_u downstream of the trailing edge blowing blades.

	Simple Blowing			Kuethe Blowing	Serrated Blowing	
	<i>1.4%</i>	<i>2.0%</i>	<i>2.6%</i>	<i>2.0%</i>	<i>1.4%</i>	<i>2.0%</i>
L_u/c_a	0.204	0.179	0.132	0.227	0.207	0.166
U_u/c_a	0.036	0.022	0.018	0.028	0.030	0.020

6.3. Data Reduction

6.3.1. Pitch and Yaw Rotations

To obtain the desired minimum pitchwise separation, both two four-sensor hotwire probes had to be yawed relative to each other. Although great care was taken in positioning the probes, it was not possible to obtain the exact intended values (minimum pitchwise separation should be equal to the pitchwise step size which is 5mm at $x/c_a=1.8$). To find the actual minimum separation, the actual yaw angle of the probes had to be computed. To do so, a rotation method based on Euler angles (first about the pitchwise axis z and then around the spanwise axis y) was applied to the data, assuming the probe was not rolled. The pitch and yaw angles of each probe were determined by assuming that in outside the wake the streamlines are aligned with the potential core. Trigonometry was then used, knowing the length of each probe, defined as the distance from probe tip to yaw-axis, and the distance between the yaw-axis of the fixed probe and that of the moving probe to compute the actual minimum pitchwise separation. The probe length (defined above) was adjusted to ensure that the pitch and yaw angles were within the acceptance cone of each probe. Based on the yaw angles, the actual minimum pitchwise separation for the two-point measurements was found to be $5\pm0.59\text{mm}$ at $x/c_a=1.8$.

6.3.2. Single-Point Data Adjustment

Once rotated, the data is compared to previous single-point measurements. Variations in the probes angle calibrations and differences in yaw angle of the two probes result in Reynolds stress profiles that are in good overall agreement with the single-point data but do show some difference between each other (where they should be identical). Consequently, stress data from both fixed and moving probes were compared to the single-point results. The probe producing Reynolds stress profiles closest to the single-point results is selected as the reference probe. These reference stress profiles are then used to establish a correction for the second probe velocity measurements.

In this approach, a first order linear correction for the fluctuating velocity components sensed by the reference probe is obtained from the Reynolds stress profiles and then applied to correct the two-point correlations. The transformation matrix

representing the relationship between the measured and actual fluctuating velocity vector is iteratively adjusted, starting with the identity matrix, using a version of the secant method, to minimize the differences between the fixed and moving probe stress profiles. Applying the transformation to the two-point measurements then results in a two-point data set completely consistent with the single point data, within the uncertainty of measurement.

6.3.3. Formatting the Two-Point Space-Time Correlation Data

During measurements, data was recorded in both time-series and frequency spectra for each data point. Due to the large amount of spectral data collected (639 points resulting in 438Mb binary spectral data files), the data cannot be accessed easily unless it is reduced. To do so, the spectral data was first inverse Fourier transformed, then interpolated to the complete grid (41×41 points). At that point, correlation can be extracted for any time delay or pitchwise location through interpolation. The following is a description of each of these steps.

After data reprocessing, including pitch and yaw rotations and single-point data probe transformation, the two-point space-time correlation tensor is obtained from the velocity spectral data through Inverse Fast Fourier Transform (IFFT). It should be noted that, due to the nature of the pitchwise measurement scheme utilized, the fact that the velocity spectrum matrix lower diagonal terms are the conjugate symmetric of the corresponding upper diagonal terms is used. Generally, the space-time correlation tensor can be extracted from the velocity spectra using:

$$R_{ij}(z, z', \tau) = \int_0^{\infty} G_{ij}(z, z', f) e^{2\pi i f \tau} df \quad (6.11)$$

where R_{ij} is the correlation tensor, τ the time delay, and G_{ij} the velocity spectrum tensor and i is the imaginary unity.

Equation (6.11) can be then discretized as

$$R_{ij}(z, z', \tau) = \frac{f_N}{N_s + 1} \sum_{k=0}^{N_s+1} G_{ij}(z, z', f) e^{\frac{2\pi j(k-1)(n-1)}{N_s+1}} \quad (6.12)$$

where R and G are the correlation and velocity spectra matrices, i and j go from 1 to 3 and are the indices corresponding to each of the three component of fluctuating velocity

(u , v , and w), f_N is the Nyquist frequency (and therefore $f_N=F/2$) and N_s is half the number of samples ($N_s=1024$). Bear in mind that pitchwise data is measured at constant spanwise location.

The fixed probe and moving probe auto-correlations are therefore obtained using Eq.(6.12) along with a standard IFFT algorithm. The $z=z'$ terms of the cross-correlation matrix are obtained by averaging the single-point auto-correlation information from each of the two (fixed and moving) probes.

Subsequently, the correlation matrix was interpolated to the full grid (41×41 points) using a Biharmonic Spline Interpolation method described by Sandwell, 1987. This completes the reduction scheme. Correlation data was saved in easily accessible MATLAB[®] ASCII files of about 20Mb each. For the following discussions, data is accessed at any pitchwise location and time delay through linear interpolation.

In order to validate this reduction method, two checks were performed. First, Reynolds stresses profiles obtained from the reduced correlation matrix, by taking the zero-time delay correlation at $z=z'$, were plotted against the non-processed data. The interpolation is found to have no effect on the Reynolds stresses. A second check consists in plotting the velocity spectra obtained from the correlation matrix by Fast Fourier Transform (FFT) against the non-processed velocity spectra. Here again, the interpolation method is proven to have no effect on the spectra.

As detailed in Chapter 3 and section 6.2.1, the probe traversing set-up enabled measurements of the velocity correlation to be taken in the cascade aligned coordinate system. To simplify interpretation of the correlation functions it is necessary to express them in terms of wake-aligned coordinates (i.e. using distances Z and Z' normal-to-the-wake as opposed to pitchwise positions). Assuming Taylor's hypothesis, this can be done using a linearly varying shift in the time delay across the profile to account for the linearly varying distance between the pitchwise direction and a wake perpendicular (a 36.7° angular difference). When interpreting the present results as space-time correlations perpendicular to the wake (as opposed to pitchwise) it is important to keep this assumption in mind.

6.4. Results and Discussion

This section presents and discusses some of the two-point measurements. First various cuts through the wake-aligned velocity correlation tensor are discussed. Such direct and simple representations of the wake turbulence are very instructive but provide only a limited view of the features enclosed in the correlation tensor. To extract further physical information about the turbulence organization, proper orthogonal decomposition and linear stochastic estimation are then applied to the data to obtain an explicit and compact description of the coherent structures inside the wake. It is then possible to examine the impact of the different strategies on these structures. Proper orthogonal decomposition is of particular interest as it provides a compact representation of the wake turbulence by describing the main eddies with the minimum number of modes. Furthermore such representation is well suited to the computation of the potential of the inhomogeneous wake turbulence to generate broadband noise when interacting with a lifting surface (see Glegg and Devenport, 2001).

6.4.1. Two-Point Time Delay Correlation in the Z-direction

6.4.1.1. Baseline blades

The first method to extract information about the coherent structures present in the wake is to examine the velocity correlation tensor itself. By studying different cuts through this 3-dimensional tensor it is possible to obtain information about the scale and the type of coherent structures at hand and how they evolve in time and space. Once the structures of the baseline flow have been identified, the analysis of the modified wakes will provide a direct assessment of the impact of the different strategies on the coherent structures.

The first cut through the velocity correlation tensor that will be considered is the zero-time delay correlation in the direction normal-to-the-wake (Z). The zero-time delay correlation is obtained by evaluating the normal-to-wake correlation tensor function for zero time lag $R_{ij}(Z, Z', \tau=0)$. As mentioned earlier, the zero-time delay correlation is of particular interest because it reduces to the Reynolds stress tensor for zero probe

separation (for $Z=Z'$, $R_{ij}(Z, Z, 0) = \overline{u_i(Z)u_j(Z)}$). Therefore when each component of the zero-time delay correlation is plotted against the distance across the wake (Z and Z'), the Reynolds stress tensor will appear as the diagonal (bottom left to top right) where $Z=Z'$.

The six independent components of the normal-to-wake zero-time delay correlation, normalized on the peak local turbulence kinetic energy k_{max} , are plotted against the distance across the wake (Z and Z') normalized on the half-wake width L_u , (based on the streamwise Reynolds stress profile, see Chapter 5). This particular normalization was chosen because it will provide information on the relative change in the turbulence structure and intensity from one strategy to the other. The absolute changes, which ultimately will characterize the performance of each flow control strategy, can be then obtained by combining these findings with the single point measurements of the TKE and wake width. This type of figures allows to measure the normal-to-wake scale associated with each velocity fluctuation (computed as the distance between locations where the correlation decays to 10% of the peak local TKE).

The normal-to-wake zero-time delay correlation maps for the baseline blades are plotted on Figure 6.2 for the axial location of $x/c_a=1.8$. As mentioned previously, the diagonal of the streamwise correlation function $R_{11}(Z, Z', 0)$, appearing in Figure 6.2a as the black dashed line, corresponds to the baseline Reynolds normal stress profile (that is plotted as a thumbnail on Figure 6.2a). Following this diagonal starting from the lower left corner, and looking at the corresponding profile, we see that the streamwise correlation first increases to a local maximum, then decreases before reaching the absolute maximum, after which it decays down to zero. The other Reynolds stress profiles can similarly be seen on the diagonals of the other correlation maps (the normal stress profiles for the spanwise and normal-to-wake fluctuations have been reproduced as thumbnails in Figure 6.2b and e).

At $x/c_a=1.8$, Figure 6.2 reveals that the correlation is dominated by the streamwise and normal-to-wake components (as seen in the more intense and wider contours of the R_{11} and R_{33} components in Figures 6.2a and e). The hourglass shape of the streamwise component R_{11} in Figure 6.2a means that the wake tends to correlate more over greater separation near the wake edges than at the center. The R_{11} component reaches a maximum of 73% of the peak TKE on the pressure side at $Z/L_u=0.4$. This is consistent

with the streamwise Reynolds stress reported by Geiger (2005). Near the center, the wake tends to correlate over shorter distances ($0.38L_{u'}$) than at the near the edges (where the maximum extent is $0.58L_{u'}$) as seen in Figure 6.2a. This suggests the presence, near the edge of the wake, of large normal-to-wake structures producing streamwise velocity fluctuations. On the other hand, the normal-to-wake component R_{33} (Figure 6.2e) has more of an eye-shape, demonstrating the tendency of the wake to correlate more at the wake center (where it correlates over $0.96L_{u'}$ as indicated in Figure 6.2e). In other words, the wake is dominated by a large normal-to-wake structure lying near the wake center and generating large normal-to-wake velocity fluctuations. This structure is about twice as large as the structures responsible for the streamwise fluctuations.

The spanwise component R_{22} in Figure 6.2b displays similar features to the normal-to-wake component, but velocity here seems to correlate only over small separations ($0.19L_{u'}$) all across the wake. This behavior implies that the structures responsible for spanwise velocity fluctuations inside the wake tend to be small in the normal-to-wake direction and evenly distributed across the wake. The dominance of the streamwise and normal-to-wake structures is consistent with similar correlation measurements made in a two-dimensional wake (see Devenport *et al.* (2004)). Finally, looking at the cross-terms (R_{ij} with $i \neq j$ presented in Figure 6.2c, d, and f) we see that only the R_{13} (Figure 6.2d) term produces significant correlation (in the shape of one lobe of negative correlation). The R_{13} component correlates up to $0.75L_{u'}$ and reaches a maximum of 20% of the peak TKE. This asymmetry (with respect to the wake center) suggests that more shearing is occurring on the pressure side of the wake (where Z is positive) as the R_{13} component is associated with the streamwise and normal-to-wake velocity fluctuations. This asymmetry is expected as these wakes are shed by a loaded blade. The same asymmetry can be found in the mean velocity profiles reported by Geiger (2005). The remaining two cross-terms (R_{12} and R_{23}) never exceed 10% of peak TKE and are therefore not presented for the modified wakes.

We can now examine the evolution of the coherent structures discovered in the zero-time delay correlation analysis. To do so, cuts through the correlation tensor (similar to those taken at zero-time delay) are obtained at various time delays ($R_{ij}(Z, Z', \tau)$ for various τ 's). Additionally, the time variation of the zero-separation correlation ($R_{ij}(Z, Z, \tau)$

for various τ 's) or auto-correlation are also studied as they provide information on the streamwise evolution of the Reynolds stress components (since $R_{ij}(Z, Z, \tau) = \overline{u_i(Z, \tau)u_j(Z, \tau)}$). The auto-correlation also allows to measure the streamwise scale associated with each velocity fluctuation (computed as the distance between locations where the correlation decays to 10% of the peak local TKE).

The time delay correlation results (for both non-zero and zero probe separation) are presented in Figure 6.3. In this figure, the time variation of each component of the correlation (normalized on the peak TKE computed for zero-time delay) evaluated at various time delays $R_{ij}(Z, Z', \tau)$ is plotted on the top figure. This figure is a collection of plots of one component of the correlation (plotted against Z/L_u' on the vertical axis and Z'/L_u' on the horizontal (not shown)) obtained at various time delays τ (normalized on the ratio of the half-wake width and potential core velocity L_u'/U_e). The bottom figure represents the time variation of the correlation (normalized on the peak TKE computed for zero-time delay) at zero probe separation $R_{ij}(Z, Z, \tau)$ also known as auto-correlation. Here the auto-correlation is plotted against the normalized time delay on the horizontal axis $\tau U_e/L_u'$ and the normalized distance across the wake Z/L_u' .

The time delay correlation results for the baseline blades are presented for the four non-negligible components in Figure 6.3. As observed earlier in the zero-time delay results, the R_{12} and R_{23} cross-components never exceed 10% of the peak TKE and are therefore not presented here. The time variations of the streamwise component R_{11} of the baseline wake are presented in Figure 6.3a. At zero-time delay (the center of the horizontal axis), the time delay correlation contours (top figure) correspond to the zero-time delay correlation results discussed earlier that suggest that the coherent structures responsible for the streamwise fluctuations are located near the wake edges. The spatial organization of these structures does not seem to change significantly over time as the overall hourglass shape is conserved over the entire time delay producing significant correlation. Furthermore, the variations are symmetric with respect to time ($R_{11}(Z, Z', \tau) = R_{11}(Z', Z, -\tau)$) which is a property of the correlation function. The streamwise extent for the R_{11} component (the distance across the wake between the points where the correlation decays to 10% of the peak TKE) is $\pm 0.61 \tau U_e/L_u'$ as shown in Figure 6.3a. This suggests

that the structures responsible for the streamwise fluctuations extend over $1.2L_u'$ or $32\%c_a$ (assuming they convect at the potential core velocity). These structures are therefore 2 to 3 times larger streamwise than they are across the wake (where they range between 0.38 and $0.58L_u'$). The auto-correlation is shown at the bottom of Figure 6.3a. Since the correlation reduces to the Reynolds stress for zero separation and zero-time delay, looking at the normal-to-wake variation of the zero-separation time delay correlation at $\tau = 0$ reveals the Reynolds stress profile. If we start at the bottom of the figure at $\tau = 0$ and describe the variation as we progress upward, we see that a local maximum (63% of the peak TKE) is reached around $Z/L_u = -0.27$ followed by a decrease before achieving the absolute maximum (73% of the peak TKE) at $Z/L_u = 0.4$. These variations are consistent with the streamwise Reynolds stress profile reported by Geiger (2005) and described earlier (see Figure 6.2a). Similarly, one could obtain the Reynolds stress profiles from any corresponding zero-separation time delay correlation plot.

The spanwise component R_{22} of the time delay correlation is presented for the baseline blades on Figure 6.3c. The streamwise variation of the R_{22} component is very similar to the R_{11} component. The overall shape (narrow and uniform across the wake) is conserved throughout the range producing significant correlation. The structures near the wake center seem to dissipate faster than those near the edge of the wake. But most importantly, the overall streamwise extent of these structures is very limited. While the streamwise fluctuations occur over $\pm 0.61\tau U_\infty/L_u'$, the spanwise fluctuations are limited to $\pm 0.24\tau U_\infty/L_u'$. This indicates a streamwise scale of less than $13\%c_a$ or $0.48L_u'$ indicated on Figure 6.3c. However it is interesting to note that the streamwise scale associated with the spanwise fluctuations is 2.5 times the normal-to-wake scale. This is comparable to the ratio of 2 to 3 seen in the streamwise component. The auto-correlation shown below the time delay montage confirms the short life-span of the eddies associated with the spanwise velocity fluctuations as seen in the rapid decay of the contours.

In contrast to the streamwise and spanwise components, the normal-to-wake component R_{33} , seen in Figure 6.3d, exhibits both time variations of its spatial distribution as well as significantly longer life-span. This is evident as the shape of the zero-time delay correlation (the eye shape suggesting larger structures near the wake center) is conserved early (over $\pm 0.04\tau U_\infty/L_u'$). However there are some significant

variations here too. As time is progressively increased first to 0.1 then $0.17\tau U_\infty/L_u$, the contours disappear below about the $Z=Z'$ line (see Figure 6.3d). Such contours imply that the wake at zero-time delay correlates with the wake further downstream only if Z' is less than Z . In other words, the structures responsible for the normal-to-wake velocity fluctuations are moving towards the suction side of the wake (where Z is negative) as they convect downstream. In the process, the scale of these structures is reduced to $0.5L_u$. Inversely for negative time delays, the contours show correlation only below the $Z=Z'$ line suggesting that the structures are originating from the pressure side of the wake. The streamwise scale of the R_{33} correlation is $0.61\tau U_\infty/L_u$. This scale is shown in Figure 6.3d. Therefore, the scales associated with the R_{33} component are 1.5 times as large across the wake as they are streamwise.

Another interesting feature of the R_{33} component is that there is no correlation over $0.27 < |\tau U_\infty/L_u| < 0.47$ as seen in the auto-correlation plot. This region of uncorrelated flow is followed by regions of negative correlation reaching 20% of the peak TKE and extending to $\pm 0.96\tau U_\infty/L_u$. The regions of negative correlation are in turns followed by regions of positive correlation (not shown here as their maximum is less than 5% of the peak TKE). These oscillations in the sign of the correlation are believed to be the manifestation of quasi-periodic structures with a wavelength of $1.42\tau U_\infty/L_u$ (measured between the correlation minima and shown in Figure 6.3d) corresponding to a frequency of 375Hz. These structures could be a major contributor to the potential of the wakes to generate broadband noise as they would stimulate the unsteady surface pressure field on the downstream stator at low frequencies (associated with their period). However, they could simultaneously contribute to reductions in broadband noise at higher frequencies so that one might be willing to conserve these structures if their frequencies can be cut-off.

6.4.1.2. Serrated Trailing Edge Blades

6.4.1.2.1. 1.27cm Serrations

The correlation results for the 1.27cm serrations are presented in Figure 6.4 through 6.7. The 3 normal components of the zero-time delay correlation (R_{11} , R_{22} , and R_{33}) display the same organization as the baseline (whether looking at the serration valley or serration peak seen in Figures 6.4 and 6.6 respectively). As mentioned earlier, the zero-time correlation is presented in normalized form (normalized over the peak TKE and plotted against the normal-to-wake distance normalized on the half-wake width). To provide information variation in the normalizing parameters between the baseline and a given flow control strategy, histograms of both quantity for each configuration are provided at the top of the figure. Looking at Figure 6.4, these parameters (the peak TKE normalized on the inlet velocity and the half-wake width normalized on the axial chord) show that the wake downstream of the 1.27cm serration valley is slightly less turbulent than the baseline and comparable in terms of wake width. Additionally, the normal stress profiles associated with the correlation component are plotted for the baseline (in blue) and the flow control strategy (in red) as a thumbnail. From these thumbnails, it can be seen that the reduction in turbulence levels seen downstream of the 1.27cm serration valley (Figure 6.4) is primarily due to reduction in the streamwise and normal-to-wake stresses (Figure 6.4a and d).

In Figure 6.4a and 6.6a, the streamwise component tends to correlate more near the edges than at the center of the wake. The spanwise component (6.4b and 6.5b) shows small normal-to-wake extent of the correlation all across the wake. The normal-to-wake component (Figure 6.4d and 6.6d) correlates more at the wake center than near the edges. The R_{13} cross-component is also identical to the baseline (with one lobe of negative correlation with a maximum magnitude of 24% of the peak TKE as seen in Figures 6.4c and 6.6c). In other words, in terms of spatial organization, the 1.27cm serration did not produce any significant change in the arrangement of the coherent structures in the wake. There are however some small variations. For example, the normal-to-wake component downstream of the 1.27cm serration valley (Figure 6.4d) has a shape identical to the baseline but the magnitude has been decreased (by 13% of the peak TKE). Downstream

of the serration peak, the extent of the correlation for the R_{33} component (Figure 6.6d) has been increased near the wake center (from $0.96L_u'$ for the baseline to $1.19L_u'$) while the magnitude was decreased by about 10% of the peak TKE. The streamwise and spanwise components of the correlation display very little variation from the baseline. In other words, while the 1.27cm configuration does not affect the spatial distribution of the coherent structures it does lower the turbulence levels (as seen by the lower TKE levels). These results are consistent with the Reynolds stress analysis of Geiger (2005) that showed very little impact of the 1.27cm on the streamwise and spanwise stresses but a small reduction of the normal-to-wake component. Geiger also mentioned that the normal-to-wake stresses downstream of the serration peaks were larger than downstream of the valley. This difference in the turbulence levels is possibly due to the shorter distance the wake can grow on downstream of the peaks (due to the longer chord there).

Figure 6.5 shows that the time variations of the streamwise and spanwise components for the 1.27cm serration blades downstream of the valley are very similar to the baseline. The shapes of the contours downstream of the serration valley and peak remain unchanged except for the expected decay of the magnitude. The time scales associated with these decays are however smaller than the baseline. As seen in the auto-correlation maps, the time scales for the streamwise and spanwise components (figure 6.5a and c) are 1.06 and $0.46\tau U_e/L_u'$ respectively at the serration valley. There is very little change at the peak where these values are 1.04 and $0.42\tau U_e/L_u'$. These values should be compared to 1.22 and $0.48\tau U_e/L_u'$ obtained from the baseline wake. In absolute terms, since the wake widths of both blades are comparable, the same conclusion applies. Therefore, while the small serrations do not affect the streamwise extent of the eddies responsible for the spanwise fluctuations they significantly increase the decay of these structures. It seems therefore that the streamwise vorticity introduced by the serrations has a short life span thus dissipating the wake turbulence faster than the turbulent dissipation of the baseline flow. This is confirmed by observing the auto-correlation results for the R_{33} component seen in Figure 6.5d. The scale associated with the positive lobe of correlation has been reduced to $0.53\tau U_e/L_u'$ (same value as the R_{11} correlation scale). Again, we see the signs of quasi-periodic fluctuations of the normal-to-wake component seen in the baseline results. The time extents of these fluctuations are

however reduced to 1.39 and $1.26\tau U_\infty/L_u$. Interestingly, the faster decay is not associated with a reorganization of the structures. The time delay correlation shows that the same type of changes in the contours (both at the serration valley and peak) of the R_{33} component seen in the baseline. The contours progressively become asymmetric about the $Z=Z'$ line suggesting a shift of the structures from the pressure to the suction side of the wake.

6.4.1.2.2. 1.27cm Drooped Serrations

The correlation maps measured downstream of the 1.27cm serration with droop are presented in Figures 6.8 through 6.11. Just as with the 1.27cm case, the 1.27cm droop produces little change in the overall organization of the coherent structures downstream of the serration valley as seen in Figure 6.8. There, the wake is slightly less turbulent than the baseline while a bit wider (as seen in the histograms at the top of Figure 6.8). The Reynolds stress profiles presented in Figure 6.8a, b, and d show that the reduction in turbulence levels primarily arises from the normal-to-wake fluctuations (Figure 6.8d). There is some reduction in the magnitude of the zero-time delay R_{33} correlation (15% lower than the baseline) as seen in Figure 6.8d, while the difference in streamwise and spanwise components is small (less than 3% of the peak TKE). The flow downstream of the serration peak shows more variation compared to the baseline (Figure 6.10). The normal-to-wake component shows some higher tendency to correlate on the pressure side of the wake (positive Z) than on the suction side. Both the baseline and the 1.27cm blades resulted in eye-shaped contours. This indicates that the structures responsible for the normal-to-wake fluctuations have shifted from the wake center toward the pressure side. It is an important result as it shows that while the 1.27cm serration results only in variations of the velocity fluctuations inside the wake, the addition of the droop actually reorganizes some of the coherent structures in the wake (namely the ones responsible for the normal-to-wake velocity fluctuations). The reason for this behavior could be the creation of stronger coherent structures at the trailing edge of the serration peak as a result of the added serration penetration (droop) on the pressure side. Figure 6.8d shows the added penetration results in a stronger shear layer on the pressure side that can be

seen in the increased magnitude of the negative correlation lobe of the R_{13} component (that is related to the Reynolds shear stress).

Adding droop to the 1.27cm serrations is designed to strengthen the streamwise vorticity injection by increasing the pressure difference between the pressure and suction side of the blade. The stronger vorticity shed from the serrations should therefore further increase the decay of the turbulence. Comparing the auto-correlation results downstream of the 1.27cm drooped serration valley (Figure 6.9) with the baseline, we see that there is indeed some reduction in the streamwise and spanwise components (Figure 6.9a and c) whose extents are reduced to 0.9 and $0.4\tau U_\infty/L_u$. This is a 25% reduction from the baseline and 15% from the un-drooped case for both components. In absolute terms, the scale reductions are comparable since the wake width is little changed. The R_{33} and R_{13} components do not show any significant change in their respective time scale (Figure 6.9d and b). The R_{13} component does exhibit greater magnitude than the baseline and 1.27cm without droop (believed to arise from the stronger shear layer produced by the added serration penetration). Furthermore we can see the quasi-periodic fluctuations of the normal-to-wake component are still present. Their scale ($1.39\tau U_\infty/L_u$) is almost identical to the baseline but the strength of the negative lobe of correlation has actually decreased (to 14% of the peak TKE). As mentioned earlier, the zero-time delay correlation levels for the R_{33} component are 15% lower than the baseline. This suggests that the strength of the lobes of negative correlation associated with the quasi-periodic structures is function of the initial strength of the normal-to-wake turbulence.

The time delay results downstream of the peak show a much different picture (Figure 6.11). The streamwise scale associated with the streamwise component is reduced to $0.8\tau U_\infty/L_u$. This value is lower than the $0.9\tau U_\infty/L_u$ at the valley and $1.22\tau U_\infty/L_u$ for the baseline. However, the extent of the spanwise and normal-to-wake components have now been increased compared to both the undrooped case and the baseline. The streamwise scale of the R_{22} correlation is increased to $0.52\tau U_\infty/L_u$, which is now larger than the baseline ($0.48\tau U_\infty/L_u$). Similarly, the R_{33} component streamwise scale is increased to $0.55\tau U_\infty/L_u$ (a 12% increase over the undrooped case). The auto-correlation plot also shows that this increase in the streamwise scale occurs on the pressure side of the wake (positive Z) resulting in asymmetric contours. This suggests that the addition of the droop

(that increases the serration penetration on the pressure side) results in stronger and larger eddies that remain coherent longer. This is confirmed by the increased scale of the quasi-periodic structures that now spans over $1.58 \tau U_e / L_u$ (a 25% increase from the undrooped case and an 11% increase from the baseline).

6.4.1.2.3. 2.54cm Serrations

The correlation results for the 2.54cm serrated blades are presented on Figures 6.12 through 6.15. The histograms at the top of Figures 6.12 show that the wake is more turbulent and wider than the baseline. The increase in turbulence seems to be primarily due to increase in the streamwise and spanwise Reynolds stresses (thumbnails in Figure 6.12a and b) The zero-time delay maps seen in Figure 6.12 shows that the larger serrations tend to decrease the relative extent and magnitude of the streamwise and spanwise correlation components. However, since the peak TKE and wake width are actually increased, the absolute change turn out to be negligible. The extent of the normal-to-wake component is also little affected by the 2.54cm serrations. The fact that the extent of the correlation is unchanged (compared to the baseline) is very insightful as it shows that the 2.54cm serrations do not affect the spatial organization of the coherent structures across the wake, even though they reduce the turbulence levels (as we will see below). Indeed the magnitude of the R_{33} component is reduced downstream of the peak (where it is 15% of the peak TKE lower than the baseline). Downstream of the valley, the peak correlation is comparable to the baseline results.

This behavior of the normal-to-wake component across the serration period could be explained by looking at the physical mode of operation of the serrations. The serrations are designed to promote the production of streamwise vorticity by allowing flow from the pressure to convey on to the suction side (driven by the pressure gradient between the two sides). The resulting pair of counter-rotating vortices creates a net flow in the negative normal-to-wake direction that is maximum downstream of the valley. The strength of these vortices will be partially dependent on the serration period. Therefore, and assuming these vortices affect the unsteady flow field, larger serrations will result in a stronger normal-to-wake flow downstream of the valley which could translate in

increased normal-to-wake correlation. Interestingly, there is very little variation in the cross-term R_{13} between the serration peak and valley, and the baseline.

The time delay results show that the larger serrations impact is also felt in the streamwise scales of the wake. Looking at the R_{11} component on Figures 6.13a and 6.15a, we see that the streamwise variation of the structures responsible for the streamwise fluctuations suffers little change compared to the baseline. The major difference comes from the streamwise scale associated with this variation. The baseline scale of $1.22 \tau U_\infty / L_u$ has been reduced 0.78 and $0.84 \tau U_\infty / L_u$ downstream of the valley and the peak respectively. The larger serrations have not only decreased the baseline streamwise scale by more than 30% but they have also reduced the 1.27cm serration by more than 20%. This confirms that the stronger streamwise vorticity produced by the larger serration enhances the mixing of the coherent structures in the streamwise direction. Similar reductions can be seen by examining the auto-correlation results for the other components downstream of the 2.54cm serrations. Downstream of the valley, the R_{33} and R_{13} components yield reductions of 30 and 16% from the baseline (Figure 6.13d and b). Interestingly, these reductions are comparable to those seen downstream of the peak (where they are 25 and 18% respectively). These imply that increasing the serration size from 1.27cm to 2.54cm results in 30 and 10% reductions of the streamwise scales of the R_{33} and R_{13} correlations.

The scale of the quasi-periodic structures (still present downstream of the 2.54cm serration valley in Figure 6.13d) has been also reduced to 16% of the baseline scale. The reduction downstream of the peak (Figure 6.15d) is of the same order. The most notable streamwise scale reduction can be seen in the spanwise component of the correlation. The R_{22} streamwise scale is decreased to 0.32 and $0.38 \tau U_\infty / L_u$ for the serration valley and peak respectively. These correspond to scale reductions of 33 and 25% from the baseline results. Maybe more importantly, these reductions show that increasing the serration size from 1.27cm to 2.54cm reduces the streamwise scale of the spanwise fluctuations by 30 and 14% at the serration valley and peak respectively. These scale reductions seen in all the components are however not associated with a re-distribution of the coherent structures. The shape of the auto-correlation, and therefore the spatial distribution of the coherent structures, is conserved for all components except R_{11} . The auto-correlation

shows that the reduction is more pronounced near the wake center ($Z/L_u=0$) resulting in hourglass-shaped contours.

6.4.1.2.4. 2.54cm Drooped Serrations

The zero-time delay correlation maps for the 2.54cm serrations with droop are presented in Figures 6.16 and 6.18 for the serration valley and peak. The addition of the droop to the larger serrations has some significant impact on the wake. The histograms at the top of Figures 6.16 and 6.18 show that the wake is significantly wider. The peak TKE histograms show that while the peak TKE is decreased by 10% downstream of the valley (Figure 6.16) it is increased by 25% downstream of the peak, compared to the baseline. These values are comparable to the 13% increase in the pitchwise and spanwise averaged TKE reported by Geiger (2005). The increase in turbulence at the peak arise from all three Reynolds stresses as seen in the thumbnails of Figures 6.18a, b, and d.

Looking at the streamwise component R_{11} (Figures 6.16a and 6.18a), we see that the combined effects of the added camber (droop) and large serration results increased magnitude and extent of the correlation. Downstream of the serration valley, Figure 6.16a shows that the peak correlation levels are comparable to the baseline (73% of the peak TKE). However, the normal-to-wake scale has been increased by 20%. In terms of absolute variations, this suggests that the streamwise component has lost some intensity but has seen its scale increased by 30% (from $0.16c_a$ for the baseline to $0.21c_a$). In contrast, the peak correlation on the suction side is now 54% of the peak TKE (compared to 64% for the baseline). Similarly, the scale of spanwise component R_{22} (Figure 6.16b) is also increased (from $0.19L_u'$ for the baseline and the 2.54cm serration to $0.46L_u'$ for the 2.54cm with droop). At $0.61L_u'$, the scale of the R_{33} component (Figure 6.16d) is however significantly reduced compared to both the baseline and the 2.54cm serrations (0.96 and $1.01L_u'$ respectively). This behavior is believed to be a direct consequence of the added camber that increases the serration penetration on the pressure side. At the serration valley, the normal-to-wake injection of high momentum fluid from the pressure side into the low momentum fluid near the surface of the suction side re-energizes the boundary layer there. In the process, the added momentum breaks up the coherent structures at their source (the trailing edge boundary layer) leading to lower correlation levels downstream.

On the pressure side, the sudden increase in camber (that occurs over the last 15% of the blade chord at the tip, but corresponding to the last 5% at the serration valley) forces the flow into a sudden increased turn just before leaving the blunt trailing edge. These conditions promote the creation of eddies resulting in higher correlation magnitude and extent.

Downstream of the peak, the magnitude of the R_{11} component (Figure 6.18a) has been amplified. On the suction side of the wake (negative Z), the peak correlation is now 66% of the peak TKE (2% more than the baseline wake). The scale of the correlation is comparable to the baseline there ($0.55L_u$, compared to $0.58L_u$ for the baseline). On the pressure side, the changes are even more evident. There, the peak correlation has risen to 80% of the peak TKE (7% increase over the baseline) and the region of high correlation has expanded to $0.61L_u$. In terms of absolute value, this suggests that the scale of the R_{11} component is increased by 30% (due to the increased wake width) while the turbulence intensity is increased by 25% (as indicated by the peak TKE histogram). This behavior is consistent with the description of the flow downstream of the valley. At the serration peak, the pressure side flow cannot re-energize the low momentum fluid adjacent to the suction side resulting in a thicker boundary layer (consistent with the increased momentum thickness and half-wake width reported by Geiger (2005) downstream of the serration peak). On the pressure side, as mentioned for the 1.27cm droop case, the addition of camber seems to promote the generation of coherent structures by enhancing the strength of the shear layer. Just as in the 1.27cm droop blades, Figure 6.18c shows that this phenomenon is accompanied by an increase in the extent and magnitude of R_{13} shear component (with a maximum correlation of 25% of the peak TKE, compared to the 20% of the baseline).

Figures 6.16b and 6.18b show little variation in the spanwise R_{22} component between the serration peak and valley. The main difference lies in the magnitude of the correlation. The wake downstream of the valley has a maximum spanwise component of 68% of the peak TKE on the pressure side before decreasing as you progress along the zero-separation line toward the suction side. The levels on the suction side of the wake are on the order of 55% of the peak TKE. Downstream of the peak, the spanwise correlation is more uniform across the wake. The maximum occurs on the pressure side

(at 65% of the peak TKE) but the levels remain consistently around 60% of the peak TKE before tapering off near the suction side edge of the wake. Keep in my mind that the TKE levels downstream of the peak are almost 40% greater than at the peak. The extent of the spanwise component, comparable for both the serration peak and valley, is larger than for the baseline ($0.35L_u$ for the 2.54cm with droop against $0.19L_u$ for the baseline). Combined with the increased wake width presented in the half-wake width histograms in Figures 6.16 and 6.18, the absolute scale of the R_{22} component has been increased three fold over the baseline (with turbulence levels 25% greater as suggested by the peak TKE).

The overall increase in the streamwise and spanwise components is associated with a change in the shape of the R_{33} component (downstream of both serration peak and valley). Similarly to what is seen for the normal-to-wake fluctuations downstream of the peak of the 1.27cm droop serrations (figure 6.10d), the structures responsible for the normal-to-wake velocity fluctuations located near the wake center seem to have lost coherency resulting in more uniform contours across the wake. This spatial redistribution is combined with a reduction of the magnitude of the R_{33} component (when compared to the baseline). Downstream of the peak, the normal-to-wake velocity correlation reaches a maximum of 62% of the peak TKE. For comparison, the baseline maximum is 73% of the peak TKE while the maximum downstream of the 2.54cm peak is 60%. Downstream of the valley, the reduction is more significant. The maximum correlation occurs on the pressure side of the wake as mentioned above where it reaches 58% of the peak TKE. On the suction side, the reduction is even larger. There, the correlation maximum is only 45% of the peak TKE. Interestingly, the 2.54cm without droop yields larger correlation levels downstream of the valley (levels comparable to the baseline) than at the peak. This flow behavior is again consistent with the re-energizing of the suction side boundary layer. The added droop promotes the break-up of the eddies inside the boundary layer shed from the serration valley. It seems therefore that the addition of droop to the larger serrations has not only spatially redistributed some of the coherent structures, but it also affected the magnitude of the unsteady flow field. The fragmentation and weakening of the coherent structures suggests some possible reduction of the potential of the wake to generate broadband noise.

The time delay correlation maps seen in Figures 6.17 and 6.19 show that the 2.54cm serrations with droop do not affect how the correlation varies in the streamwise direction, but they do affect how fast it decays. The same type of variations described in the baseline can be seen here where the R_{11} and R_{22} components (Figure 6.17a and c) conserve the same shapes while decaying. We also see the shift of the coherent structures responsible for the normal-to-wake fluctuations from one side of the wake to the other in the R_{33} correlation. The main difference therefore comes from the scale associated with these variations. The streamwise scale of the R_{11} , R_{22} , and R_{33} components have been significantly reduced compared to the baseline. Downstream of the valley, the reductions are 43, 29, and 23% respectively. At the serration peak, the reductions are also significant at 33, 33 and 23%. More importantly, these values represent a 10% reduction from the 2.54cm without droop. These large relative reductions are hampered by the increase in the wake width. In terms of absolute scales, the reductions from the baseline are nevertheless 25, 15, and 25% for the R_{11} , R_{22} , and R_{33} components. This suggests that the addition of the droop reduced the streamwise extent of the coherent structures inside the wake. As the identical auto-correlation contour shapes imply, these reductions compared to the undrooped case are not associated with a re-organization of the structures. The normal-to-wake component (Figure 6.17d) shows more reduction on the suction side of the wake (negative Z/L_u) than on the pressure. This is believed to be a direct consequence of the re-energizing boundary layer on the suction side where the normal-to-wake fluctuations are reduced by the addition of high momentum fluid from the pressure side.

6.4.1.3. Trailing Edge Blowing Blades

The four non-negligible components of the velocity correlation measured 1.8 axial chord downstream of the trailing edge blowing blades are plotted in Figures 6.20 through 6.25, 6.26 to 6.27, and 6.28 through 6.31 for the simple, Kuethé and serrated blowing blades respectively. Each of these figures present for each component the baseline maps (for comparison) along with the results for the blowing rates tested. The same format and normalization used to present the baseline results are applied here.

6.4.1.3.1. Simple Blowing Blades

The histograms of the peak TKE and wake width at the top of Figure 6.20 show that the wake downstream of the simple blowing blades at 1.4% of the through flow is significantly less turbulent and thinner. The peak TKE is 30% lower while the half-wake width is 20% smaller than the baseline. The thumbnails in Figure 6.20a,b, and d show that the reduction in the TKE is primarily caused by reduction in the streamwise and spanwise fluctuations (Figure 6.20a and b). In Figure 6.20, the trailing edge simple blowing can be seen to affect all the components of the zero time-delay correlation. These changes in the structure of the correlation can be best appreciated by first observing the dominant normal components of the correlation. In relative terms, blowing seems to decrease the magnitude and extent of R_{11} correlation while significantly increasing the scales of the R_{22} and R_{33} components. Looking closer at the streamwise component R_{11} in Figures 6.20a, 6.22a, and 6.24a shows that the tendency of the velocity to correlate less near the wake center (hourglass shape) seen in the baseline results is conserved up to a blowing rate of 2.0%. At 1.4% (Figure 6.20a), this type of behavior has actually been amplified so that near the center the wake correlates only over $0.25L_u'$ while correlations up to $0.56L_u'$ can be seen near the wake edges. The baseline R_{11} component is correlated over 0.38 and $0.58L_u'$ at the wake center and edges respectively. The 20% reduction in the wake width results in absolute scale reduction of 50% for the R_{11} component. This suggests that the blowing not only reduces the scales associated with the streamwise component but it also amplifies the differential between the wake center and its edges (while reducing the turbulence intensity by 30%).

Increasing the blowing rate to 2.0% of the mass flux results in very little change of the R_{11} component (Figure 6.22a). The scale and magnitude of the correlation are identical to the 1.4% rate. The histograms of the peak TKE and wake width in Figure 6.22 reveal that the turbulence intensity and wake half-wake width have been decreased by staggering 80 and 30% from the baseline, suggesting a significant break-up of the coherent structures. It is therefore interesting to note that the reduction in turbulence levels is not associated with a change in the spatial distribution of the structures. In absolute terms,

At 2.6% blowing (Figure 6.24a), the R_{II} develops the same shape seen in R_{22} at the same blowing rate. The extent of the correlation is rather uniform across the wake ($0.39L_u$) before decaying at the edges suggesting that the simple blowing has uniformly distributed the structures across the wake. At such a high blowing rate, the peak TKE and wake width histograms at the top of Figure 6.24 show that the wake is as turbulent as it was for 2.0% of the through flow, but is now 50% thinner than the baseline. Consequently, the absolute scale for the R_{II} component is 55% smaller than the baseline.

The time delay results for the simple blowing (Figures 6.21, 6.23, and 6.25) show that this configuration has not only an impact on the streamwise scales of the wake but also on the organization of the eddies inside of it. Looking at the R_{II} correlation shows that the contours of the zero-time delay seem to be conserved as they decay. However, for the 1.4 and 2.0% blowing rates (Figures 6.21a and 6.23a), the streamwise decay of the R_{II} correlation is faster at the wake center than near the edges. This can be seen in the time delay plot (Figure 6.21) as the correlation near the center vanishes for time delays beyond of $\pm 0.2\tau U_e/L_u$, resulting in two separate lobes of positive correlation. This is also revealed in the auto-correlation results by the hourglass shaped contours noticeably thinner near the wake center (where they are 0.62 and $0.6\tau U_e/L_u$ for 1.4 and 2.0% blowing respectively as seen in Figure 6.21a and 6.23a) than at the edges (where the scales are 0.9 and $0.92\tau U_e/L_u$, respectively). The magnitude of these scales is comparable to those measured downstream of the serrated trailing edge blades (ranging between 0.8 and $1.1\tau U_e/L_u$). The significantly smaller wake width associated with the simple blowing therefore results in absolute scales that are 50% smaller than the baseline (and 40 to 50% smaller than the serrated trailing edge).

Two conclusions can be drawn from these values. On the one hand, the simple blowing significantly reduced the streamwise scales of the R_{II} correlation. The scale is 70% of the baseline scale near the wake center and 50% near the edges. On the other hand, the similar values obtained at 1.4 and 2.0% blowing suggest that the streamwise scale of the R_{II} correlation is unaffected by the increased blowing rate, in relative terms. The reduction in wake width yields larger reduction at 2.0% of the through flow. At 2.6% blowing, Figure 6.25a shows that the faster decay near the wake center ceases and the auto-correlation retrieves the contour shapes seen in the baseline. However, the scale has

been decreased to $0.82 \tau U_\infty / L_u$ (32% lower than the baseline), a value similar to the streamwise scales of the R_{11} correlation downstream of the 2.54cm serrations (with and without droop). But here again, the smaller wake width (that is 60% smaller for the simple blowing at 2.6% than the 2.54cm serrations with and without droop) results in significantly smaller scales.

The spanwise component R_{22} appears to be less affected by T.E. blowing. There is some reduction of the peak correlation (on the order of 50% of the peak TKE) but Figures 6.20b and 6.22b show that the scale is little changed (from $0.19 L_u$ for the baseline to $0.24 L_u$ at 1.4 and 2.0%). At 2.6%, the extent and magnitude of the correlation can be seen to be increased (Figure 6.24) with a peak correlation of 66% of the peak TKE and a scale of $0.39 L_u$. The relative scale is almost twice that of the baseline while the magnitude is almost 10% of the peak TKE larger. However, the 50% reduction in wake width results in absolute scales that are almost identical to the baseline. This increase in the spanwise correlation is associated with an increase of the TKE as reported by Craig (2006) possibly suggesting that the structures responsible for the spanwise velocity fluctuations are excited at the larger blowing rate and therefore responsible for the overall increase of TKE.

The streamwise scale of the R_{22} correlation is significantly more affected by the simple blowing. The time delay correlation shows that the R_{22} component (Figure 6.21c and 6.23c) decays faster on the pressure side (positive Z) than on the suction side. As mentioned in Borgoltz *et al.* (2006), this asymmetry, consistent with the asymmetric mean velocity profile reported by Craig (2005), could be due to a misalignment of the trailing edge blowing jet (with respect to the wake propagation axis). This asymmetry becomes most obvious in the pear-shaped contours of the auto-correlation at 1.4 and 2.0% (Figures 6.21c and 6.23c). The streamwise scale of the spanwise correlation is 0.27 and $0.28 \tau U_\infty / L_u$ on the pressure side. On the suction side, the scale is 0.36 and $0.38 \tau U_\infty / L_u$. This shows that just like for the streamwise correlation, the relative scale does not change between 1.4 and 2.0% blowing. At 2.6%, the asymmetry in the auto-correlation disappears resulting in eye-shaped contours (Figure 6.25). At the same time, the streamwise scale is increased to $0.42 \tau U_\infty / L_u$ (a value similar to the scale measured on the suction side at 2.0%). As mentioned above, a large blowing rate is believed to enhance

the generation of eddies responsible for spanwise velocity fluctuations. As a result, the turbulence levels are increased (as seen in the increase in TKE from 2.0 to 2.6%) and spread across the wake (negating the scale reductions observed on the pressure side at 1.4 and 2.0%).

Figures 6.20d, 6.22d and 6.24d show that the normal-to-wake component of the correlation function conserves its shape (synonymous of large structures lying at the wake center) at all blowing rates with some variation. It is interesting to notice that at 1.4% blowing the R_{33} correlation appears to decay faster on the pressure side of the wake (positive Z) as seen in Figures 6.20d. This trend continues up to 2.0% blowing (Figure 6.22d) and is consistent with the asymmetry of the Reynolds stress and mean-velocity profiles described by Craig (2006). It is interesting to note that the blowing slot is located on the suction side of the blade. It follows that the blowing slot is not efficient in breaking up the coherent structures in the wake as it seems to operate preferentially on the pressure side. In other words, the blown wake is a complex flow made of several layers (i.e. the actual wake of the blade and the blowing jet) so that the correlation changes rapidly depending in which region the flow is measured. It follows that the slot design is important as a misaligned blowing jet (with respect to the wake propagation axis) would intensify such asymmetry. That asymmetry can also be observed in the auto-correlation, especially at 2.0% (Figure 6.23) where the streamwise scale is $0.3 \tau U_e / L_u$ on the pressure side and $0.51 \tau U_e / L_u$ on the suction side of the wake. Interestingly, while the asymmetry is less pronounced at 1.4% as seen in Figure 6.21, the streamwise scale of the R_{33} correlation is increased compared to the baseline ($0.63 \tau U_e / L_u$ against $0.61 \tau U_e / L_u$ for the baseline).

The complex impact of the simple blowing is most apparent when observing the variation of the zero-time delay R_{33} correlation against blowing rate. At 1.4% (Figure 6.20d), the normal-to-wake velocity fluctuations correlate over $1.78 L_u$ with a maximum correlation of 95% of the TKE. For comparison, the same baseline components extends over $0.96 L_u$ and contributes 75% of the peak TKE. The large increase in scale over the baseline is not compensated by the wake width reduction. The absolute scale of the R_{33} component is 35% larger than the baseline. Clearly, at a low blowing rate the simple blowing stimulates the creation of coherent structures responsible for normal-to-wake

velocity fluctuations that dominates the flow. While the TKE levels at 1.4% were shown to be lower than the baseline (Craig, 2006), the injection of air amplifies the domination of the normal-to-wake velocity fluctuations. As the flow passes the trailing edge, one envisions spanwise eddies rolling up and grow as they convect downstream (similar to what is seen in a von-Karman vortex street). It is possible that low blowing rates magnify this roll-up phenomenon by entraining the structures created just upstream of the blowing slot on the suction side of the blade thus strengthening them. The stronger spanwise eddies are therefore more resistant to the viscous decay resulting in larger normal-to-wake fluctuations downstream. This is consistent with the increased extent and magnitude of the shear-component of the correlation (R_{13}) that rises to 30% of the peak TKE.

It is also important to note the asymmetry of the R_{13} component (with a large lobe of negative correlation aligned with the Z-direction on the pressure side and a much smaller lobe of positive correlation on the suction side). If the blowing slot does enhance the production of spanwise structures it will also amplify the asymmetry of the wake. Again, this shows how much care should be taken when designing and manufacturing the blowing slot to ensure proper injection direction.

Increasing the blowing rate to 2.0% produces sizeable changes in the R_{33} correlation (Figure 6.22d). The scale of the correlation is decreased to $1.16L_u'$ (lower than the 1.4% case but still larger than the baseline, in relative terms) suggesting that increasing the blowing rate still stimulates the roll-up of spanwise eddies at the trailing edge. In absolute terms however, the scale of the normal-to-wake velocity fluctuations is found to be 20% smaller than the baseline. At 88% of the peak TKE, the R_{33} is still the major contributor to the turbulence levels. As mentioned earlier, the overall TKE levels decrease from 1.4 to 2.0% blowing (Craig, 2006) implying that the increased blowing rate results in smaller and relatively weaker structures (but still dominated by the Z-direction fluctuations). These smaller and weaker structures results in lower shear inside the wake (as seen by the more symmetric contours of the R_{13} component at 2.0%). At 2.6% (Figure 6.24d), the extent of the R_{33} component is further reduced to $0.79L_u'$ (or in absolute term, 60% lower than the baseline) while the maximum correlation reduces to 78% of the peak TKE. The extent of the Z-correlation is also more uniform across the

wake. This can also be seen in the auto-correlation (Figure 6.25d) that displays uniform contours with a streamwise extent of $0.42\tau U_e/L_u$. In terms of relative scales, the streamwise scales for the R_{22} and R_{33} correlations at 2.6% are identical and equal to half of the R_{11} correlation. The scale reduction might suggest that for the larger blowing rate, the large velocity gradient between the injected flow and the suction side boundary layer prevents the roll-up of any large eddy thus eliminating some of the coherent structures at their source. As reported by Craig (2006), these changes are associated with an increase in TKE levels (from 2.0% to 2.6% blowing rate). This suggests that larger blowing rates do break up the coherent structures into smaller eddies (as seen in the lower extent of the correlation) but strengthen them at the same time. Such process could result in stronger broadband interaction noise at higher frequencies.

The impact of the simple blowing on the quasi-periodic structures observed in the R_{33} correlation could also be a key factor in determining the possible benefit of trailing edge blowing. At 1.4%, Figure 6.21d shows that the streamwise scale of these structures is significantly increased to $1.62\tau U_e/L_u$, a 14% increase over the baseline. When compensated for the 25% decrease in wake width, the streamwise scale of the R_{33} component is found to be 15% lower than the baseline. The relative scale increase is also associated to an increase in the magnitude of the negative lobe of correlations to 28% of the peak TKE (compared to 20% for the baseline). This confirms that the magnitude of the negative lobes of correlation depends on the magnitude of the maximum correlation (that is 95% of the peak TKE for the R_{33} correlation at 1.4% as opposed to 74% for the baseline). At 2.0%, the scale of the quasi-periodic structures is down to $1.33\tau U_e/L_u$, with a maximum negative correlation of 15% of the peak TKE (Figure 6.23d), which is 40% smaller than the baseline (in absolute terms). At 2.6%, these structures have almost disappeared from Figure 6.25. They do not appear on the auto-correlation figure since they never exceed a magnitude of 6% of the peak TKE and are therefore considered negligible.

As mentioned previously, the only significant cross-correlation occurs for the R_{13} component. This component is significantly affected by the blowing as it becomes negligible (reduced to less than 10% of the peak TKE at 2.6% blowing rate). The resulting wake (with negligible cross-terms combined with normal components very

similar in shape and correlation levels with each other) suggests that the 2.6% blown wake is tending to nearly isotropic turbulence.

6.4.1.3.2. Kuethe Blowing Blades

The zero-time delay correlation maps for the Kuethe blowing blades can be seen in Figure 6.26. As indicated previously, the Kuethe blowing blades fractured during testing allowing the measurement of the two-point profiles at 2.0% blowing rate only. As with the baseline and the simple blowing case, the R_{12} and R_{23} components are not presented as they never exceed 10% of the peak TKE. The histograms at the top of Figure 6.24 show that the wake is 15% thinner than the baseline, while 60% less turbulent (as indicated by the peak TKE). Interestingly, while the normal-to-wake R_{33} component is still the dominating contributor of the normal components (Figure 6.24d), the spanwise R_{22} correlation (Figure 6.24b) is now comparable in both scale and magnitude to the streamwise component (Figure 6.24a). This is especially true on the suction side of the wake (where Z is negative). We see that both the R_{11} and R_{22} components display significant asymmetry about the wake center. On the suction side of the wake, the extent of the R_{11} correlation is $0.68L_u'$ with a maximum correlation of 70% of the peak TKE. These values are relatively larger than the baseline results of $0.58L_u'$ and 64% of the peak TKE. However, it should be noted that while the maximum occurs on the suction side for the Kuethe blowing it occurs on the pressure side for the baseline. On the pressure side, the streamwise component correlates over $0.46L_u'$. In absolute terms, the scale of the R_{11} component is actually equal to the baseline, while that of the R_{22} correlation is twice as large as the baseline. This suggests that the addition of the Kuethe vortex generators actually increases the scales of the structures on the suction side of the wake as well as their coherency.

The auto-correlation shows however that the relative increase in the normal-to-wake scale is associated with a reduction of the streamwise scale of the R_{11} correlation (a 33% reduction from the baseline). This is the same relative scale that is obtained with the simple blowing at 2.6% suggesting that the Kuethe vanes are more efficient in dissipating the streamwise scale of the streamwise fluctuations. However, when taking into account the variation in wake width, the Kuethe blowing is found to increase the absolute

streamwise scale of the R_{11} correlation. Additionally, the Kuethe blowing is shown to reduce the scale faster near the wake center than at its edges. In the mean time, the streamwise scale of the R_{22} component in Figure 6.27c is actually increased by the Kuethe blowing (compared to the simple blowing) but still lower than the baseline. At $0.42 \tau U_e / L_u$ on the pressure side of the wake, it is 12% lower than the baseline, but 10% larger than the simple blowing at the same blowing rate. The auto-correlation has however adopted the same pear-shape seen downstream of the simple blowing blades and is consistent with the possible magnification of the vortex shedding due to the blowing slot configuration. As mentioned earlier, this could also be the consequence of a misaligned blowing jet. Furthermore, the relatively larger scale of the Kuethe blowing is believed to be a manifestation of the additional eddies shed by the vortex generators on the suction side. In fact, the increased correlation scale of the zero-time delay R_{22} correlation on the suction side ($0.46 L_u$ compared to $0.19 L_u$ for the baseline) combined with the R_{11} results suggest some possible stall occurring near the trailing edge of the blade (on the suction side) as seen in the increased wake width and Reynolds stresses reported by Craig (2006).

Interestingly, the normal-to-wake component R_{33} does not follow that trend. The wake still tends to correlate more near the wake center than at its edges, resulting in eye-shaped contours of the zero-time delay correlation on Figure 6.26d, but does so over a smaller distance ($0.91 L_u$). In absolute term, this scale reduction is comparable to the simple blowing at 2.0% blowing rate and 20% less than the baseline. However, the relative importance of the Z-component has been reduced. The maximum correlation is now 67% of the peak TKE compared to the 73% of the baseline. Craig (2006) reports that this redistribution of the TKE is combined with a significant reduction of the TKE levels. The peak TKE of the Kuethe blown wake at 2.0% is 75% lower than the baseline. Additionally, the auto-correlation map in Figure 6.27d shows that the streamwise scale of the R_{33} correlation has been reduced by 20% compared to the baseline and is consistent with the simple blowing results at 2.0% blowing rate ($0.49 \tau U_e / L_u$ for the Kuethe blowing against $0.51 \tau U_e / L_u$ for the simple blowing). The reduction of the normal-to-wake scale is believed to be to the expression of the increased mixing by the eddies created by the Kuethe vanes. Interestingly, the asymmetry (believed to be due to a blowing jet

misalignment) seen in the auto-correlation contours of the simple blowing case at 2.0% has now disappeared. It seems therefore that while some possible stall could have resulted in a redistribution of the TKE (mainly from the normal-to-wake component in favor of the spanwise fluctuations) there is a diffusion of the coherent structures. Additionally, the small reduction in the streamwise scale of the R_{33} correlation between the Kuethe and simple blowing is associated with a similar reduction of the scale of the quasi-periodic structures (from $1.33 \tau U_e / L_u$ for the simple blowing to $1.29 \tau U_e / L_u$ for the Kuethe blades). Moreover, the size and magnitude of the negative lobes of correlation have also been decreased (the peak negative correlation is down to 11% of the peak TKE against 15% for the simple blowing).

Looking at the R_{22} component in Figure 6.26b, we see that on the pressure side (positive Z) the zero-time delay correlation displays the same characteristics than the baseline and simple blowing (up to 2.0% blowing) where narrow contours suggest small normal-to-wake structures (evenly distributed across the wake) associated with spanwise velocity fluctuations. It seems therefore that the Kuethe blown wake has kept the “wake” characteristics on the pressure side. As mentioned above, the addition of vortex generators has actually increased the correlation on the suction side. In other words, the Kuethe vanes amplify the stratification of the wake by magnifying the difference between the wake component on the pressure side and the jet component associated with the blowing slot located on the suction side. This imbalance could suggest that the Kuethe blowing configuration is not as effective as the simple blowing configuration in reducing the potential of the wake to produce broadband noise (although it could be an improvement over the baseline configuration). Indeed, the reduced TKE levels should lead to lower broadband interaction noise but further analysis of the two-point data is required to validate such statement.

6.4.1.3.3. Serrated Blowing Blades

The zero-time delay correlation maps for the serrated blowing blades can be seen in Figures 6.28 and 6.30 for blowing rates of 1.4 and 2.0%. The histograms at the top of Figures 6.28 and 6.30 show that the wake downstream of the serrated blowing blade is 24% thinner than the baseline at 1.4% of the mass flux and 40% less wide for 2.0%

blowing. The turbulence intensity is significantly decreased by this configuration yielding 50 and 80% reductions for blowing rates of 1.4 and 2.0%. This is also apparent in the Reynolds stress profiles thumbnails of Figure 6.28 and 6.30. Brief observation of Figures 6.28 and 6.30 reveals that all three normal components exhibit good symmetry with respect to the wake center. This can be explained by examining the trailing edge geometry. Instead of having the blowing slot located upstream of the trailing edge on the suction (like the simple and Kuethe blowing configurations), the serrated blowing configuration has a blowing slot located at the trailing edge of the blade (actually reducing the chord by 0.5mm). Such configuration should prevent the stratification of the wake (with a “wake” and “jet” component) by setting identical initial conditions for the wake on the suction and pressure sides.

It is also important to note that all three normal components show the same kind of spatial organization as the baseline for the blowing rates measured. The streamwise component demonstrates tendencies to correlate more near the wake edges than at its center. The spanwise component is narrow across the wake. The normal-to-wake shows tendencies to correlate more at the wake center than at the edges. There are however some noticeable differences.

Figure 6.28 shows that just like for the simple blowing, at 1.4% the difference in the extent of the correlation between the wake center and the edges has been amplified. At the wake center, the streamwise velocity correlates over $0.25L_u$, while the distance increases to $0.6L_u$ at the wake edges. These values are similar to those obtained for the simple blowing (0.25 and $0.56L_u$). The magnitude of the R_{11} correlation for the serrated blowing reaches a maximum of 70% of the peak TKE. This is the exact same value than the baseline and simple blowing. While increasing the blowing rate to 2.0% did not produce significant differences in the shape of the R_{11} component of the simply blown wake, the additional momentum seems to have an impact on the serrated blowing wake. Figure 6.30a shows that the correlation scale is increased at both the wake center and edges (to 0.31 and $0.62L_u$ respectively). In absolute terms, these values are 40% smaller than the baseline. In the mean time, the magnitude of the streamwise correlation has decreased to 64% of the peak TKE. This deviates from the simple blowing case (whose

extent and magnitude remains unchanged from 1.4 to 2.0% blowing) and could possibly result in lower broadband noise levels at low frequencies.

Interestingly, the auto-correlation maps in Figures 6.29 and 6.31 show that the streamwise scale of the R_{11} correlation remains unchanged between 1.4 and 2.0% for the serrated blowing ($0.88\tau U_\infty/L_u$). This behavior is consistent with the simple blowing results suggesting that at low blowing rates (between 1.4 and 2.0%) the streamwise scale is independent of the blowing rate, independently of the blade configuration. Only the value of the scale itself is dependent on the blade configuration (just as the wake depends on its initial conditions). The same conclusion can be drawn for the spanwise auto-correlation that remains constant at $0.36\tau U_\infty/L_u$ between 1.4 and 2.0% for the serrated blowing blades. The corresponding absolute scales are identical to the simple blowing case (at the same blowing rates) and 45 to 55% smaller than the baseline. This is an important result as it implies that if the streamwise scales of the R_{11} and R_{22} correlations are to be targeted in order to reduce broadband noise, increasing the blowing rate between 1.4 and 2.0% will not produce any benefit. Figures 6.28b and 6.30b show that serrated blowing does have some effect on the spanwise correlation. The zero-time delay correlation reaches a maximum of 57% of the peak TKE at both 1.4 and 2.0%. At 1.4%, there is a small asymmetry in the extent of the correlation where the pressure and suction side correlate over 0.25 and $0.4L_u$, respectively. Interestingly, these scales are larger than the baseline, in absolute terms ($0.08c_a$ for the serrated blowing against $0.05c_a$ for the baseline). At 2.0%, this asymmetry has decreased and the correlation extends $0.31L_u$, consistently across the wake. These scales are consistent with the simple blowing results and the baseline.

The normal-to-wake component downstream of the serrated blowing blades shows more difference from the simple blowing case. At 1.4%, the zero-time delay R_{33} correlation shows correlation over $1.25L_u$, with a maximum correlation of 82% of the peak TKE (Figure 6.28d). This demonstrates stronger correlation than the baseline occurring over a larger distance. In absolute terms, this scale is actually identical to the baseline. Furthermore, these values are significantly smaller than the extent and magnitude of the R_{33} component for the simple blowing at 1.4% ($1.78L_u$ and 95% of the peak TKE respectively). The large values of the simple blowing are believed to be the

result of the blowing jet strengthening spanwise eddies separating from the suction side just upstream of the blowing slot. If this is indeed the case, one would expect the serrated blowing slot to prevent this kind of phenomenon from occurring. The serration would encourage the mixing between the high momentum fluid from the injection jet and the low momentum fluid on the suction side, minimizing the roll-up of the spanwise eddies. Secondly, the location of the blowing slot (at the trailing edge instead of upstream of it) combines with the serration to prevent the strengthening of the spanwise eddies detaching from the surface of the blade. Increasing the blowing rate to 2.0% produces little change in the normal-to-wake fluctuations as seen in Figure 6.30d. The extent is still $1.25L_u$, with a maximum correlation of 82% of the peak TKE. This suggests that the normal-to-wake fluctuations downstream of the serrated blowing blade could be independent of the blowing rate (over the range tested). However, the R_{33} auto-correlation on Figure 6.29d shows reduced scale at 2.0%. The streamwise scale of R_{33} at 1.4% blowing is $0.53\tau U_e/L_u$, and reduces to $0.44\tau U_e/L_u$ at 2.0% blowing. These values are a consistent 15% lower than the simple blowing blades (and 50% smaller than the baseline) at the same blowing rates suggesting that the addition of the serration combined with the positioning of the blowing slot have made the serrated blowing blades more efficient in reducing these scales at the same blowing rate.

Finally, the R_{33} auto-correlation shows that the serrated blowing has little effect on the quasi-periodic structures. At 1.4% blowing rate, the scale of these structures (seen in Figure 6.29d) and the magnitude of the negative lobes of correlation are identical to the baseline ($1.42\tau U_e/L_u$, and 28% of the peak TKE respectively), resulting in absolute scale reduction of 25% from the baseline. This streamwise scale is 22% lower than the one measured downstream of the simple blowing blades at the same blowing rate. This result could be confirming that the serrated blowing configuration does not promote the roll-up of spanwise eddies at the trailing edge producing a streamwise scale more consistent with the baseline. Furthermore, if the blowing rate is increased to 2.0%, Figure 6.31d shows that the streamwise scale of the R_{33} correlation decreases (to $1.32\tau U_e/L_u$) possibly because the increased pressure gradient between the blowing jet and the boundary layer combines with the serration to weaken the eddies as they pass the trailing edge.

6.4.2. Two-Point Time Delay Correlation in Y-direction

While the focus of the present study is to investigate the organization of the coherent structures in the two-dimensional wake of idealized fan blades, spanwise measurements of the velocity correlation were taken to evaluate the impact of the different strategies along the blade span. The normal-to-wake measurements can provide information on the scale and magnitude of the turbulence across the wake. Therefore, to extract the potential of these wakes to generate broadband noise, one would need to assume an idealized case where the stator would cut through the rotor wake perpendicular to the rotor span (this is what will be presented in Chapter 7). The spanwise measurements allow to extract similar information for the case of a stator cutting the wake parallel to the rotor span.

To do so, the variation of the spanwise zero-time delay correlation $R_{ij}(\Delta Y, 0)$ is plotted for the various strategies against the baseline as a function of the normalized spanwise separation $\Delta Y/L_u$. The correlation is again normalized on the peak TKE as measured for the normal-to-wake measurements. Additionally, each figure is supplemented by a graph of the spanwise correlation (normalized on the edge velocity U_e) plotted against the absolute spanwise separation $\Delta Y/c_a$. Such plots will allow to determine the absolute impact of the various strategies on the spanwise scale.

Figure 6.32 shows the spanwise variation of the streamwise correlation R_{II} of the baseline (in black) plotted against the serrated trailing edge results (in blue and red). This figure shows that the 1.27cm serrations have little effects on the relative scale of the structures responsible for the streamwise fluctuations. Interestingly, adding droop or increasing the serration size decreases the spanwise scale in similar manners. To quantify this change in scale, the spanwise scale is defined as twice the spanwise separation for which the correlation decays to 10% of the peak TKE of the fixed probe. This definition is therefore consistent with the one used to define the normal-to-wake and streamwise scales introduced in the previous section. Using this definition, the spanwise scale of the R_{II} correlation for the baseline blades is $0.61L_u$ (comparable to the normal-to-wake scale of $0.58L_u$). The 1.27cm scale is slightly reduced ($0.55L_u$). The 1.27cm droop and the 2.54cm blades generate identical scales of $0.44L_u$. It is interesting to note that the relation between these scales and their relative serration periods. Indeed, the scale for the 1.27cm

represents 95% of the serration period, while the 1.27cm with droop is 80% of the period. These scales are on the order of the serration spacing as one would expect. The 2.54cm blades however results in spanwise scale of only 44% of its serration period. The serrations have also done little reduction in the magnitude of the correlation. This can be seen in figure 6.32(b) that shows lower correlation scale for the 2.54cm than for the smaller serrations.

The R_{11} correlation for the blowing strategies is shown in Figure 6.33. The changes here are more apparent. Every blowing strategy yields lower correlation magnitude and scale except for the simple blowing at 2.6% (the largest blowing rate tested). The spanwise scale for this configuration is $0.73L_u$ (20% larger than the baseline). This increased in scale is not due to some possible spanwise periodicity introduced by the five channels of the internal passage as it represents only 25% of the channel spanwise length. This is clearly seen in figure 6.33(b) that shows significant reduction in the spanwise correlation for all blowing rates and configurations. At 1.4%, the simple blowing does reduce the scale to $0.53L_u$. Increasing the blowing rate to 2.0% results in little change in the scale to ($0.49L_u$). The absolute scale is however significantly decreased. Due to the spanwise uniformity of the blowing slot, the serrations are shown to be reducing the relative spanwise scale more efficiently than the simple blowing configuration. However, the lower correlation magnitude of the blowing cases could prove to be beneficial. The Kuethe blades at 2.0% and the serrated blowing at 1.4% produce the greatest scale reductions (0.34 and $0.35L_u$, respectively) suggesting that the serrated blowing is more efficient at targeting the spanwise scale of the streamwise fluctuations. The spanwise scale of the Kuethe blowing wake is only 46% of the Kuethe vane spacing.

The spanwise variations of the R_{22} correlation are shown in Figures 6.34 and 6.35 for the passive and active strategies respectively. Figure 6.34 shows that the serrations do not have any significant impact on the scale of the spanwise velocity fluctuations. The spanwise scale for the R_{22} baseline correlation is $0.51L_u$. The scale is unchanged by the 1.27cm serrations, while the addition of droop and the increase in size results in reduction of 10 and 6% respectively. Interestingly, while the 1.27cm and 1.27cm-droop configuration correlate over 82 to 87% of the serration period, the 2.54cm serrations only

correlate over half of the period (48% to be exact). This is consistent with the spanwise scales of the R_{11} correlation discussed above. The magnitude of the R_{22} correlation is not significantly affected. The blowing blades are shown to have a much wider impact on the spanwise fluctuations as seen in Figure 6.35. As one would expect, the spanwise uniformity of the simple blowing configuration does not reduce the spanwise scales of the spanwise fluctuations (and should yield similar result for the normal-to-wake fluctuations). Interestingly, this configuration is actually found to increase the scales of the spanwise fluctuations at all three blowing rates tested. At 1.4%, the spanwise scale is more than three times the baseline value ($1.86L_u'$ for 1.4% against $0.51L_u'$ for the baseline). This scale corresponds to $0.38c_a$ which is similar to the spanwise length of each vane of the internal passage ($0.37c_a$). Figure 6.35(b) shows that the absolute spanwise scales of the spanwise fluctuations are indeed significantly increased compared to the baseline. This could reinforce the theory that the simple blowing configuration enhances the roll-up of strong spanwise eddies (especially at lower blowing rates) as discussed in the previous section. Increasing the blowing rate to 2.0% and 2.6% results in a significant reduction of this shedding mechanism, so that the scale falls to $0.75L_u'$ (but still 50% larger than the baseline). This confirms that the simple blowing configuration is less effective than the serrated trailing edge strategy at targeting spanwise scales. As one would expect, the secondary flows introduced by the Kuethe vanes and the serrated blowing slot reduce the spanwise extent of the R_{22} correlation. The Kuethe blades (at 2.0% blowing) and the serrated blowing blades (at 1.4%) reduce the spanwise scale to $0.35L_u'$, suggesting again that the serrated blowing blades are the most efficient at targeting these scales.

The spanwise variations of the R_{33} correlation are given in 6.36 and 6.37 for the serrated trailing edge and trailing edge blowing blades respectively. Note that the spanwise range of the horizontal axis has been extended to $2L_u'$ to account for the larger scales involved here. Figure 6.36 shows that the small serrations (with and without droop) augment the spanwise extent of the normal-to-wake fluctuations. The baseline scale for the R_{33} correlation is $0.96L_u'$. That scale is increased to 1.18 and $1.11L_u'$ for the 1.27cm and 1.27cm-droop configurations, suggesting that the normal-to-wake fluctuations correlate over 2 serration periods. The spanwise scale for the 2.54cm

configuration is significantly smaller ($0.57L_u'$ or 60% of the serration period) confirming that the 2.54cm serrations introduce significant secondary flow that disorganize the wake in the spanwise direction. The blowing results presented in figure 6.37 show that trailing edge blowing reduces the spanwise relative scale of the normal-to-wake fluctuations except at high blowing rates. In fact, at 2.6% blowing, the simple blowing configuration is found to increase the spanwise scale to $1.24L_u'$ (compared to $0.96L_u'$ for the baseline). Interestingly, increasing the blowing rate (between 1.4 and 2.0%) seems to have little effect on the spanwise scale for a given blowing configuration. For the simple blowing configuration, the scales at 1.4 and 2.0% are 0.36 and $0.4L_u'$ respectively. Similarly, the serrated blowing blades scales are 0.74 and $0.7L_u'$ at 1.4 and 2.0% blowing respectively.

6.4.2.1. Summary

To summarize the impact of the strategies on the turbulence scales, the normal-to-wake results obtained from the zero-time delay and auto-correlations are plotted in Figures 6.38 through 6.41. The various scales reported in the previous sections and plotted in are listed Figures 6.38 through 6.41 are listed in Tables 6.5 and 6.7 for the serrated trailing edge and trailing edge blowing blades respectively. These scales are also listed in absolute form (normalized on the axial chord c_a) in Table 6.6 and 6.8.

Figure 6.38 presents the normal-to-wake scales (obtained from the zero-time delay correlation) of the serration blades. The scales, normalized over the half-wake width L_u' , are plotted against the serration size (in centimeters). The different symbols define whether the value was measured downstream of a valley or a peak of a serration with either droop or no droop. A color system is used to present the scales of the different components of the correlation (black for R_{11} , blue for R_{22} , and red for R_{33}). The baseline scales are shown as the pentagrams at a serration size of 0cm. From the R_{11} scales (in black), it is apparent that the serration have little effects on the scale compared to the baseline value except downstream of the peak of the drooped blades where it is 15% larger. The R_{22} correlation scales (displayed in blue) show more variation from the baseline. Increasing the serration size when droop is present (represented by the circles and pluses) results in an increase in the R_{22} scales across the wake. Increasing the size of

the undrooped serrations decreases the scale of the R_{22} correlation. Overall, the addition of the serrations increases the spanwise correlation scales (possibly due to the injection of streamwise vorticity). Finally the R_{33} correlation scales are shown to decrease with increased serration size (except downstream of the undrooped valley). Figure 6.38 also shows that small serrations produce R_{33} scales larger than the baseline, while the larger serrations are equivalent or lower. Unfortunately, the largest scales reductions (seen downstream of the larger serrations) are usually associated with an increase in the turbulence levels (as reported by Geiger, 2005) which could potentially negate the scales reduction benefits. The streamwise scales have much simple variations with serration size (figure 6.39). All streamwise scales are decreased with increased serration size.

The analysis of the spanwise measurements showed that the small serrations have little impact on the spanwise scale of the turbulence. Larger serration proved to be particularly effective at breaking up the structures in the spanwise direction (especially those responsible for the normal-to-wake velocity fluctuations).

Table 6.5 Turbulence lengthscales (normalized on half-wake width L_w) generated by the serrated trailing edge blades.

Type	Correlation component	Baseline	1.27cm		1.27cm droop		2.54cm		2.54cm droop	
			<i>serration valley</i>	<i>serration peak</i>	<i>serration valley</i>	<i>serration peak</i>	<i>serration valley</i>	<i>serration peak</i>	<i>serration valley</i>	<i>serration peak</i>
Streamwise	R_{11}	1.22	1.06	1.04	0.90	0.80	0.78	0.84	0.70	0.82
	R_{22}	0.48	0.46	0.42	0.40	0.52	0.32	0.36	0.34	0.32
	R_{33}	0.61	0.53	0.49	0.53	0.55	0.42	0.42	0.33	0.38
Quasi-periodic	R_{33}	1.42	1.39	1.26	1.38	1.58	1.19	1.24	1.09	1.10
Spanwise	R_{11}	0.61	0.55		0.44		0.44		<i>n/a</i>	
	R_{22}	0.51	0.51		0.44		0.48		<i>n/a</i>	
	R_{33}	0.96	1.18		1.11		0.57		<i>n/a</i>	
Normal-to-wake	R_{11}	0.58	0.57	0.59	0.56	0.67	0.50	0.51	0.61	0.61
	R_{22}	0.19	0.38	0.40	0.19	0.22	0.34	0.17	0.46	0.31
	R_{33}	0.96	0.94	1.19	1.11	1.12	1.01	0.85	0.61	0.93

Table 6.6 Absolute turbulence lengthscales (normalized on the axial chord c_a) generated by the serrated trailing edge blades.

Type	Correlation component	Baseline	1.27cm		1.27cm droop		2.54cm		2.54cm droop	
			<i>serration valley</i>	<i>serration peak</i>	<i>serration valley</i>	<i>serration peak</i>	<i>serration valley</i>	<i>serration peak</i>	<i>serration valley</i>	<i>serration peak</i>
Streamwise	R_{11}	0.33	0.29	0.27	0.25	0.19	0.24	0.26	0.24	0.28
	R_{22}	0.13	0.13	0.11	0.11	0.12	0.10	0.11	0.11	0.11
	R_{33}	0.16	0.15	0.13	0.15	0.13	0.13	0.13	0.11	0.13
Quasi-periodic	R_{33}	0.38	0.38	0.33	0.39	0.37	0.37	0.38	0.37	0.37
Spanwise	R_{11}	0.16	0.15		0.12		0.14		<i>n/a</i>	
	R_{22}	0.14	0.14		0.12		0.15		<i>n/a</i>	
	R_{33}	0.26	0.33		0.31		0.18		<i>n/a</i>	
Normal-to-wake	R_{11}	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.21	0.21
	R_{22}	0.05	0.10	0.10	0.05	0.05	0.10	0.05	0.16	0.10
	R_{33}	0.26	0.26	0.31	0.31	0.26	0.31	0.26	0.21	0.31

Trailing edge blowing is shown to have a much larger impact on the coherent structures of the wake than the serration of the trailing edge. The serration effects are focused on the turbulence levels but perform very little spatial re-organization. Their potential to reduce broadband noise is therefore small. The simple blowing was shown to significantly affect the size, the organization and the strength of the coherent structures. These changes were also found to be rather complicated as they do not happen linearly with blowing rate. The addition of Kuethe vanes on the suction side of the blowing blade results in a very complex flow with signs of potential separation. Although the TKE is reduced there, the complex organization of the coherent structures in this flow makes it difficult to estimate the potential to affect broadband noise generation. These two blowing configuration are actually believed to enhance the shedding of strong spanwise eddies near the trailing edge (especially at low blowing rates).

The serrated blowing blades show the greatest potential to reduce broadband noise as they reduce the turbulence levels and scales without creating potentially detrimental structures. In a fashion similar to the scale variation with serration size, we

present the variations of scales with blowing rate for the different strategies tested. Figure 6.40 presents the changes in the R_{11} , R_{22} , and R_{33} correlation scales across the wake against blowing rate using the same format described for Figures 6.38 and 6.39. Figure 6.40 shows that the R_{11} scale is very little affected by the blowing rate. The simple blowing configuration is found to be the most efficient at dissipating these scales. The R_{22} scales are more sensitive to both blowing rate and blowing configuration. The simple blowing is found to increase the R_{22} scale as blowing rate is increased while the serrated blowing configuration dissipates it. In all cases, this scale is larger compared to the baseline. The R_{33} scales were found to be significantly decreased by the blowing rate. However, a low blowing rate results in an 85% increase so that the scale does not go below the baseline value until 2.6% blowing.

The R_{33} correlation scales produced by the serrated blowing configuration were found to be independent of the blowing rate (between 1.4 and 2.0%) and 30% larger than the baseline. Independently of the blowing configuration, trailing edge blowing was found to decrease the streamwise scales of the R_{11} and R_{22} correlations by 25% with little variation with blowing rate as shown on Figure 6.41. Finally, the R_{33} streamwise scale was found to be the most sensitive to blowing rate as it decreases with increased blowing rate while being consistently lower than the baseline. The overall reductions in the turbulence scales combined with the significant reduction in the turbulence levels (Craig, 2006) suggest that trailing edge blowing has great potential to reduce broadband noise levels. Unfortunately, as mentioned earlier, the kind of blowing rate necessary to produce these reductions is too high to be realistic. However, this study is not necessarily aimed at proving the feasibility of such strategy but rather focuses on the fundamental flow physics associated with blowing air into a nominally two-dimensional turbulent wake. Three-dimensional blowing distributions (with variable blowing geometries (like discrete jets or slots) along the rotor span for example) have been found to require less momentum and therefore generate more realistic blowing rates (Langford *et. al.*, 2005)

Due to its spanwise uniformity, the simple blowing configuration was found to promote the coherency (in relative terms) along the span at all blowing rates. Absolute spanwise scales showed that the coherency is truly increased only at 1.4% blowing rate. The other two blowing configurations (Kuethe and serrated blowing blades) reduced the

spanwise scales of all the component of the velocity. This confirms that the serrated blowing strategy has the lowest potential to generate broadband noise.

Table 6.7 Turbulence lengthscales (normalized on the half-wake width L_u) generated by the trailing edge blowing blades.

Type	Correlation component	Baseline	Simple Blowing			Kuethe Blowing	Serrated Blowing	
			1.4%	2.0%	2.6%	2.0%	1.4%	2.0%
Streamwise	R_{11}	1.22	0.90	0.92	0.82	0.82	0.88	0.88
	R_{22}	0.48	0.36	0.38	0.42	0.42	0.36	0.36
	R_{33}	0.61	0.63	0.51	0.42	0.49	0.53	0.44
Quasi-periodic	R_{33}	1.42	1.62	1.33	1.25	1.29	1.42	1.32
Spanwise	R_{11}	0.61	0.53	0.49	0.73	0.34	0.35	0.43
	R_{22}	0.51	1.86	0.76	0.75	0.35	0.34	0.39
	R_{33}	0.96	0.36	0.40	1.24	0.56	0.74	0.70
Normal-to-wake	R_{11}	0.58	0.56	0.58	0.39	0.68	0.60	0.62
	R_{22}	0.19	0.22	0.24	0.39	0.46	0.40	0.31
	R_{33}	0.96	1.78	1.16	0.79	0.91	1.25	1.25

Table 6.8 Absolute turbulence lengthscales (normalized on the axial chord c_a) generated by the trailing edge blowing blades.

Type	Correlation component	Baseline	Simple Blowing			Kuethe Blowing	Serrated Blowing	
			1.4%	2.0%	2.6%	2.0%	1.4%	2.0%
Streamwise	R_{11}	0.33	0.18	0.16	0.11	0.19	0.18	0.15
	R_{22}	0.13	0.07	0.07	0.06	0.10	0.07	0.06
	R_{33}	0.16	0.13	0.09	0.06	0.11	0.11	0.07
Quasi-periodic	R_{33}	0.38	0.33	0.24	0.16	0.29	0.29	0.22
Spanwise	R_{11}	0.16	0.11	0.09	0.10	0.08	0.07	0.07
	R_{22}	0.14	0.38	0.14	0.10	0.08	0.07	0.06
	R_{33}	0.26	0.07	0.07	0.16	0.13	0.15	0.12
Normal-to-wake	R_{11}	0.16	0.11	0.10	0.05	0.16	0.12	0.10
	R_{22}	0.05	0.05	0.04	0.05	0.10	0.08	0.05
	R_{33}	0.26	0.36	0.21	0.10	0.21	0.26	0.21

6.4.3. Characteristic Eddy Decomposition

The previous section showed that a lot of information about the organization of the coherent structures can be extracted from the two-point correlation tensor. It is, however, difficult to obtain a clear representation of these eddies by just examining the velocity correlation. In fact, one is limited to speculate on what such structures could be. It therefore becomes particularly attractive to obtain an objective and efficient methods of extracting physical information about the structure of the instantaneous flow. One such technique is available and consists in combining two methods namely the Proper Orthogonal Decomposition and Compact Eddy Structures.

As mentioned in section 6.1.2, POD is used to obtain the most probable instantaneous velocity field in the normal-to-wake direction by solving the Eigenvalue problem based on the zero-time delay correlation. The eigenvalues and eigenvectors obtained from the zero-time delay correlation can be respectively related to the amount of TKE in the mode and the instantaneous velocity profile associated with the mode. Using

POD enables to also sort the modes according to the amount of the total TKE as shown in Eq.(6.7).

The characteristic eddies induced by the correlation function are then obtained by combining the POD in the normal-to-wake direction with LSE in the streamwise direction. These compact eddy structures (CES) are obtained by taking the inner product of the correlation function and the proper orthogonal mode as shown in Eq.(6.8).

6.4.3.1.Characteristic Eddies associated with the Baseline Blades

The eigenvalue spectrum (plotted against mode number) for the baseline configuration is presented in Figure 6.42 along with the relative cumulative energy spectrum of the eigenvalues. The measurement resolution allows for the calculation of about 120 modes of which the first 40 appear free of any significant aliasing effects. The eigenvalues are plotted for the first 20 modes that contain more than 70% of the total energy. Note that the eigenvalues have been sorted by decreasing magnitude so the first modes will be the most energetic. The spectrum is shown to be dominated by the first 2 modes (that combine for 25% of the total TKE in the wake). This is very similar to the POD decomposition of a plane wake of Devenport *et. al.* (2004). Devenport *et. al.* reported that the plane wake was dominated by the first two modes that combined for 27% of the total TKE in the flow. More interestingly, the amplitude of the remaining modes is seen to decay relatively rapidly with mode number. This is confirmed by looking at the rapid increase of the cumulative spectrum at low mode number. In fact only 9 modes are required to capture more than 50% of the total energy. This is twice the number of modes required to capture the same amount of energy in a turbulent channel flow (Spitz, 2006) suggesting that the turbulence structure of the wake is more complex. Indeed, since each mode is associated with an instantaneous velocity field, the greater the number of modes, the greater the variety of velocity profiles.

The modal profiles associated with the first 3 modes are presented in Figure 6.43. Note that these profiles have been normalized to have a mean square amplitude of unity. The modal profiles of all three components of the velocity are plotted against the normalized normal-to-wake direction Z/L_u . Figure 6.43a shows that Mode 1 (the most energetic mode) is dominated by the streamwise (blue) and normal-to-wake (red)

velocities. The spanwise velocity (green) is negligible. The normal-to-wake velocity is symmetric and dominates the flow. The streamwise velocity is anti-symmetric. This type of motion could be associated with a spanwise eddy moving across the wake and can be associated with streamwise shearing. It should be noted that “spanwise eddy” is used here to describe an eddy whose trace on the X - Z plane is dominated by spanwise vorticity motion. This does not necessarily imply large spanwise coherency (that cannot be deduced from the current set of data). Mode 2 (Figure 6.43b) is also seen to have a negligible spanwise component. Devenport *et. al.* (2004) reported the same type of modal profiles for modes 1 and 2 of a plane wake. Moreover the absence of spanwise fluctuations is important as it suggests that mode 1 and 2 will contribute little to the broadband noise generation if a stator blade were to cut the wake perpendicular to the rotor span (since in this case the upwash seen by the stator blade would be the spanwise component of the wake velocity). The streamwise profile is now almost symmetric while the normal-to-wake velocity is anti-symmetric. This is the opposite of mode 1. This type of motion is associated a spanwise eddy producing normal-to-wake shearing stress. Mode 3 (Figure 6.43c) shows anti-symmetric profiles of all three components. The spanwise fluctuations are not negligible anymore. They are actually comparable to the normal-to-wake fluctuations (which are about half of the streamwise fluctuations). The plane wake data of Devenport et al. (2004) showed no significant spanwise velocity for mode 3.

To ensure that the computational grid is not influencing the energy distribution and modal shapes, a grid independence study was performed on the baseline POD. The eigenspectra for the original 41×41 measurement grid, a 35×35 grid and a coarser 31×31 are presented in Figure 6.45. The spectra are shown to be in good agreement over the first 20 modes where the sparser grids are consistently within 10% of the original eigenvalues up to mode 17. Comparison of the modal profiles associated with the first three modes are also presented in Figure 6.45. They show that while there are some quantitative differences when the grid is reduced to 31×31 points, the qualitative variations are still valid. The solution can therefore be considered as grid independent.

By combining the most probable instantaneous velocity profiles produced by the POD with a linear stochastic estimation of the instantaneous velocity in the streamwise

direction, one can obtain a representation of the eddies implied by the correlation function. As mentioned earlier, these eddies are referred to as Compact Eddy Structures (CES) and are obtained from the inner product of the correlation function and the proper orthogonal mode (see Eq.(6.8)). While these eddies do not necessarily occur in the flow, they do represent average structures since they are based on the most probable instantaneous velocity profiles (i.e. the POD modes).

The CES associated with the first 3 modes of the baseline are presented in Figure 6.44. In such figures, the eddy flow field is represented by the vector plot of the streamwise and normal-to-wake components of the CES along with a contour plot of the spanwise component. These are plotted against the normalized streamwise distance (X/L_u) on the horizontal axis and normal-to-wake distance (Z/L_u) on the vertical. Due to their nature, the magnitude of the CES is arbitrary. Mode 1 (Figure 6.44a) can be seen to be a combination of several small eddies somewhat dominated by a larger counterclockwise structure (centered at $X/L_u=-0.3$ and $Z/L_u=0$). This flow field is associated with a relatively weak spanwise component (a direct consequence of the negligible spanwise component of the POD modal profiles). It is interesting to note that most of the spanwise fluctuations occur in the vicinity of the dominating eddy (suggesting a three-dimensional eddy). Additionally, one can see the oscillations in the sign of the spanwise contours (especially on the suction side of the wake) are direct expression of the quasi-periodic structures seen in the auto-correlation. The scale of the quasi-periodic structures of the auto-correlation was found to be $1.42\tau U_\infty/L_u$, which is comparable to the $1.39X/L_u$ scale of the spanwise fluctuations. This type of spanwise velocity distribution could be beneficial as far as broadband noise potential. If a blade were to cut this flow field in the X - Z plane, the span of the cutting blade would be aligned with the normal-to-wake direction. If so, the normal-to-wake changes in the sign of the spanwise velocity (the upwash felt by the cutting blade) like those seen at $X/L_u=0.4$ could lead to some noise cancellation along the cutting blade span (since in this particular case the suction side of the wake ($Z<0$) is out of phase with the pressure side).

The second mode shows a simpler flow field made of two counter-rotating eddies (centered at $X/L_u=0.5$ and $Z/L_u=-1.3$). This flow also has some three-dimensionality as seen in the mild spanwise contours. Mode 3 shows a flow field similar to Mode 1 where a

series of eddies are convecting around a larger structure. However there are significant differences. To begin with, the secondary eddies are noticeably smaller than the central eddy (located at $X/L_u=0.17$ and $Z/L_u=0.27$). The size of this central eddy ($1.4L_u$) can be seen to closely follow the oscillations of the spanwise contours. It is therefore believed that this dominating eddy is a product of the quasi-periodic structures discovered in the auto-correlation. The phase difference in the spanwise fluctuations between the suction and pressure side of the wake could lead to a lower potential to generate broadband noise if the wake were to interact with a blade cutting perpendicular to it. However, the large region of strong spanwise velocity located near the center of the dominating eddy on the suction side of the wake would certainly overcome the smaller spanwise velocity on the pressure side.

6.4.3.2. Impact of Trailing Edge Serrations on the Characteristic Eddies

The impact of the trailing edge serration on the modal energy distribution can be seen in Figure 6.46 where the eigenvalue spectra have been plotted for all the serration configurations. On these plots, the baseline spectrum is represented by the black circles. The 1.27cm, 1.27cm with droop, 2.54cm and 2.54cm with droop are represented by blue, red, green, and cyan symbols respectively. For each serration size, the spectrum at the serration valley is shown with “+” symbols and the serration peak with “x”.

Let us first consider the spectra for modes 1 and 2 which were identified as the dominant (most energetic) modes for the baseline. The 1.27cm serrations results in very little change in the magnitude of the first 2 modes. The spectra for modes 3 to 20 show that the 1.27cm serrations have little impact on the energy distribution. The spectrum at the valley is slightly greater than the baseline, while at the peak it is just lower. The addition of droop seems to significantly decrease the first 2 eigenvalues at the valley while significantly increasing them at the peak. For modes 3 to 20, adding the droop significantly increases the levels downstream of the peak and therefore the overall energy. This is consistent with the higher TKE levels reported by Geiger (2005) downstream of the drooped serration peak and suggests that the first 2 modes (and the eddies associated with them) could be some of the main contributors to this turbulence intensification.

To confirm this, one can examine the cumulative energy spectrum. This spectra show that while that the 1.27cm serration have decreased the relative importance of mode 1 and 2 by less than 2% of the total TKE. The addition of droop resulted in a slight increase (0.5%) of the amplitude of mode 1 at the peak but left the valley virtually unchanged. Mode 2 contribution to the total TKE is actually decreased compare to the baseline and the undrooped case. For modes 3 to 20, the 1.27cm droop valley produces the same relative energy distribution as the baseline. Starting at mode 3, the rapid increase of the spectrum downstream of the peak suggests that the added serration penetration shifts the energy toward the lowest modes so that the first 20 modes now combine for 78% of the total energy (compared to 72 and 73% for the baseline and the 1.27cm cases). This implies that downstream of the 1.27cm droop peak less modes are required to capture a given amount of energy. In other words, the turbulence structure is simpler (less diverse). These results are in agreement with the description of the zero-time delay correlation presented earlier. This is expected since the POD is based on the zero-time delay correlation and is simply an expression of the eddies information embedded in the correlation.

Increasing the size of the serrations to 2.54cm can be seen to have little effect on the magnitude of mode 1. It does decrease the magnitude of mode 2 both at the peak and valley (where it is 2 and 0.8% lower than the baseline). However, modes 3 to 20 show that the magnitude there is consistently comparable to the baseline. Examination of the cumulative spectra shows that this initial reduction in mode 1 and 2 seen downstream of the serration peaks requires more modes to capture a given amount of energy (compared to the baseline). In fact, the first 20 modes downstream of the 2.54cm serration peak contain 69% of the TKE while the baseline contains 72%.

The addition of droop to the large serrations does not significantly affects the amplitudes of modes 1 and 2 but can be seen to consistently increase the eigenvalue of mode 3 to 20 (at both the serration valley and peak) as detailed in the increased turbulence kinetic energy reported by Geiger (2005). Interestingly, this increase in overall TKE is associated with a lower contribution from modes 1 and 2 (that combine for 23% of the total TKE compared to 24% for the baseline) and an increased contribution of modes 3 to 20. The first 20 modes of the 2.54cm droop blade combine for 79% of the

total TKE, 7% more than the first 20 modes of the baseline. The 2.54cm drooped blades have therefore redistributed the turbulence kinetic energy (possibly from modes 1 and 2 to the higher modes) producing a simpler flow (i.e. a flow that can be described with fewer modes). Unfortunately, this redistribution is associated with an overall increase in TKE.

It is now possible to obtain a visual representation of the eddies associated with the velocity correlation by plotting the modal profiles. As mentioned earlier, these profiles represent the most probable instantaneous velocity profiles. To evaluate the impact of the different strategies on the coherent structures of the wake, the modal profiles for the first three modes are plotted for the serrated trailing edge blades on Figure 6.47 through 6.62 along with the characteristic eddy representations associated with each configuration. To provide some insight on the turbulence intensity associated with the characteristic eddies of each mode, the eigenvalues of the mode (in yellow) and the corresponding baseline mode (in green) are plotted in the lower left corner of the CES. Since each eigenvalue is related to the amount of TKE contained in the mode, such comparison provides a simple mean of assessing the turbulence intensity associated with the eddy motions.

Figures 6.47, 6.49, 6.51, 6.53, 6.55, 6.57, 6.59 and 6.61 show that the serrations have little effect on the velocity signature of the most energetic eddies (mode 1). The profiles are identical for all configurations except for the 1.27cm serration with droop (downstream of the peak) that produces an asymmetric spanwise velocity profile with amplitude comparable to the streamwise velocity. If the wake were to be cut at 90° by a stator blade, mode 1 will contribute to the broadband potential of the wake only downstream of the 1.27cm-droop serration peak (since all the other configuration yield negligible spanwise velocity). The CES associated with mode 1 can be seen to conserve the same organization as the baseline where a series of small eddies convects around a slightly larger structure (Figures 6.48, 6.50, 6.52, 6.54, 6.56, 6.58, 6.60 and 6.62). The small serrations do not produce any significant changes from the baseline. The histograms in Figure 6.48a through c show however that downstream of the 1.27cm serration valley the modes are more turbulent. Increasing the serration size does not change the eddies organization but does reduce the relative size of all the structures

involved (likely due to the increase in half-wake width) as seen in Figures 6.56 and 6.58. Adding droop to the serrations amplifies the spanwise fluctuations downstream of the peak (especially on the pressure side). This is clearly seen for the 1.27cm droop case (Figure 6.54a) where two lobes of strong spanwise velocities are centered near $X/L_u=0$. The maximum spanwise fluctuation on the pressure side is 0.65 compared to 0.52 on the suction side (remember the magnitude of these velocity is arbitrary and is not here related to any reference velocity). The histogram in figure 6.54a also shows that mode 1 is significantly more turbulent than in the baseline flow. These larger spanwise fluctuations are even more apparent for the 2.54cm droop case. There most of the spanwise fluctuations occur on the pressure side (as seen in the absence of contours on the suction side). Such flow field suggests that mode 1 (most energetic) would significantly contribute to the potential of the 2.54cm droop wake to generate broadband noise.

Mode 2 can be seen to be significantly more affected by the trailing edge serrations than mode 1. The modal profiles for the 1.27cm serrations are identical to the baseline (Figure 6.48b and 6.50b). However, adding droop result in a sharp increase in the spanwise component associated with a decrease of the streamwise fluctuations suggesting some significant shear stress (Figure 6.52b and 5.54b). This can also be seen in the intense contours of the spanwise component of the CES for the 1.27cm droop blades. Interestingly, the larger serration size (with and without droop) does not result in such a strong increase of the spanwise fluctuations. This suggests that mode 2 could be a significant contributor to the broadband noise potential for the 1.27cm droop blades.

The serrations seem to be affecting primarily the normal-to-wake fluctuations of mode 3. In the baseline, the normal-to-wake component has an asymmetric profile that is negative on the suction side of the wake, leading to a positive shear stress (since the streamwise profile shape is similar). For most of the serrated blades, the normal-to-wake profile is inverted resulting in negative shear stress as the streamwise (and the spanwise) profiles are conserved. Additionally, the magnitude of the spanwise fluctuations is significantly increased for all configurations. The reduced normal-to-wake fluctuations and increased spanwise velocity can be best visualized from the CES associated with Mode 3. Indeed, figures 6.48, 6.50, 6.52, 6.54, 6.56, 6.58, 6.60 and 6.62 show that the vertical component of the vector field (the normal-to-wake component of the CES) is

reduced thus resulting in less rotation. Even more apparent are the more intense spanwise velocity contours seen for all the serration cases. When no droop is applied, these contours tend to be symmetric about the wake center line ($Z=0$) suggesting that the increase in spanwise fluctuations could be balanced by the phase difference between the suction and pressure side of the wake. The addition of droop however disturbs this symmetry so that the phase difference should not be able to cancel the increase in spanwise fluctuations. This suggests that the serrations have the disadvantage of injecting more energy in a mode that has great potential to produce broadband noise (due to the increased spanwise fluctuations).

6.4.3.3. Impact of Trailing Edge Blowing on the Characteristic Eddies

The impact of trailing edge blowing on the eigenspectra is shown in Figure 6.63. The modal profiles for the first three modes are plotted for the trailing edge blowing blades on Figures 6.64 through 6.75 along with the characteristic eddy representations associated with each configuration.

It is obvious from looking at the eigenvalue spectra (Figure 6.63) that every blowing configuration produces significant reductions in the magnitude of the eigenvalues. This again is expected as the TKE levels discussed in chapter 5 and section 6.4.1 were shown to be significantly lower for the blowing configurations. More importantly, the amplitude of these reductions are about one order of magnitude larger than the changes seen downstream of the serrated trailing edge blades (seen in Figure 6.46). Furthermore these reductions are associated with an important redistribution of the TKE. Except at 2.6% for the simple blowing and 2.0% for the Kuethe blowing blades, every blowing configuration is essentially dominated by mode 1. This becomes apparent by looking at the cumulative spectra where mode 1 is found to contribute 18 and 25% of the total TKE for the simple blowing at 1.4 and 2.0% of the through flow respectively. The serrated blowing relative contribution of mode 1 to the total TKE is 19 and 21% at 1.4 and 2.0% blowing. Interestingly, the modal profiles for mode 1 remain unchanged (Figures 6.64 and 6.66). At low blowing rates the cumulative spectra is shown to be almost independent of the blowing configuration beyond the 5th mode suggesting that the

energy redistribution of the higher modes depends mainly on the blowing rate while the energy is focused in the lower modes.

Figures 6.64 and 6.66 show that this increased importance of the first modes could prove to be greatly beneficial to reduce the broadband potential of the wake as mode 1 is shown to have small spanwise fluctuations (and would therefore contribute little to the overall broadband potential). Additionally, it can be seen that independently of the blowing configuration, trailing edge blowing seems to be primarily targeting the streamwise fluctuations. These are indeed continuously decreasing with blowing rate. Examination of the CES associated with mode 1 shows weak spanwise contours for all the blowing configurations (Figures 6.65, 6.67, 6.69, 6.71, 6.73, and 6.75). It can also be seen that as the blowing rate is increased (independently of the blowing configuration) the flow becomes more vertical on these plots (therefore the streamwise component becomes negligible). Interestingly, at 1.4% blowing, mode 1 for the simple blowing configuration has TKE level comparable to the baseline suggesting that this blowing configuration has little effect on this mode.

Modes 2 and 3 on the other hand can be seen to have a significant spanwise component for all the configuration tested and could prove to be a major broadband contributor. However, this increase in spanwise fluctuations occurs closely out of phase between the suction and pressure side suggesting possible cancellation across the cutting blade span. Additionally, the histograms of the TKE levels show that for all the blowing configurations, the turbulence intensity is dramatically reduced. For mode 3, two configurations evade this trend. At 2.6% of the through flow, the simple blowing can be seen in Figure 6.69c to result in strong velocity fluctuations all across the wake. These are furthermore combined with the quasi-periodic structures revealed in the auto-correlation analysis so that they would increase the broadband potential of the over-blown wake (especially at the low frequency associated to the quasi-periodic structure) if a blade were to cut the wake in a plane parallel to the X - Z plane. Similarly, the Kuethe blowing blades at 2.0% of the through flow (Figure 6.71c) show significantly larger spanwise fluctuations on the suction side ($Z < 0$). Additionally, the TKE levels (as seen in the histogram on Figure 6.71c) reveal that the turbulence intensity associated with this mode is comparable to the baseline. These fluctuations are believed to be a direct

consequence of the addition of the Kuethe vanes on the suction side of the blade. Therefore the increased spanwise fluctuations generated by the addition of the vortex generators could negate the decrease in the turbulence levels measured downstream of the Kuethe blades.

The eigenspectra (Figure 6.63) also show that the effects of the blowing rate are consistent between the simple and serrated blowing configuration. At 1.4% blowing, the spectra produced by both geometries are similar even though the simple blowing displays higher levels. This increased turbulence (compared to the serrated blowing) could be the consequence of the eddies rolling up near the trailing edge as mentioned earlier. At 2.0% blowing, the spectra for both configurations are even closer.

Further increasing the blowing rate to 2.6% (for the simple blowing configuration) does not produce any significant change. It is important to note here how the energy is more evenly distributed at 2.6% blowing. This can be seen on the eigenspectrum, where mode 1 is not clearly dominating the spectrum anymore. The cumulative spectrum confirms this as the first mode contributes only 12% of the total TKE (compared to 15% for the baseline). This trend continues over the first 6 modes so that they combine for the same amount of energy that the first 5 modes of the baseline do (42%). Beyond the 6th mode, the simple blowing at 2.6% cumulative spectrum is consistently greater than the baseline. Therefore, it is shown that the energy distribution occurring at a blowing rate of 2.6% shifts energy from the lower 5 modes toward the higher modes thus resulting in a simpler turbulence structure.

Finally, it is important to note how all the blowing configurations tend toward the same amount of energy over the first 20 modes (82% of the total TKE, compared to 72% for the baseline). Therefore, it is believed that the redistribution of energy within the lower modes (1 through 5) is predominantly a function of the blowing geometry. Meanwhile, the relative amount of energy in the subsequent modes is primarily function of the blowing rate. Lastly, most of the redistribution occurs within the first 20 modes (as all the blowing configurations tend to the same value of 82% of the total TKE by then).

6.4.3.4. Summary

The decomposition of the correlation function in a set of characteristic eddies showed that the serrated trailing edge blades could possibly result in increased broadband potential particularly when droop is added. The serrations do not change the overall turbulence structure. The introduction of streamwise vorticity at the trailing edge of these blades seems to enhance the spanwise velocity fluctuations (especially at the peak of the drooped configurations). The trailing edge blowing was found to primarily reduce the streamwise velocity fluctuations of the average eddies while producing small spanwise fluctuations. Such findings suggest that while the serrations could lead to little to no benefits, the trailing edge blowing could significantly reduce the wake broadband potential.

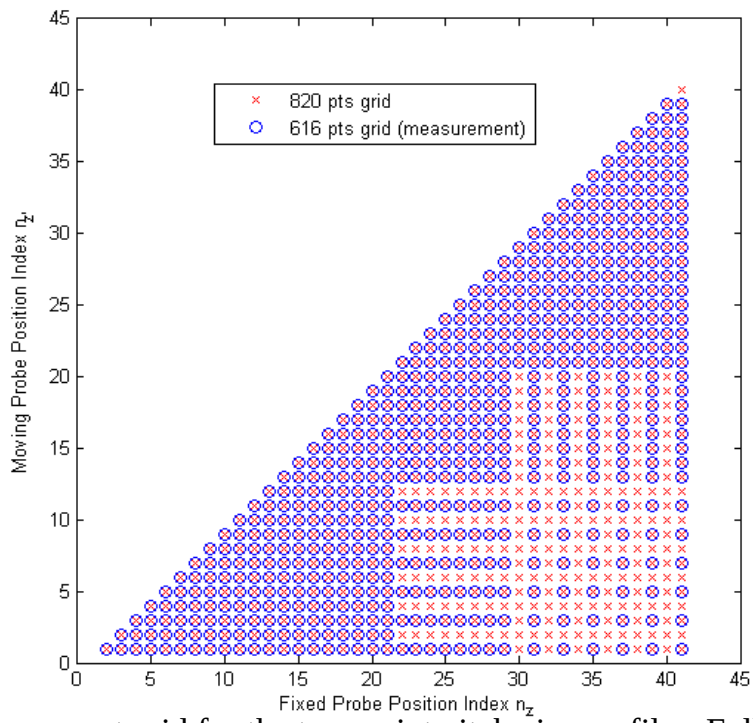


Figure 6.1 Measurement grid for the two-point pitchwise profiles. Fully populated grid is indicated by x and actual measurement grid shown with o.

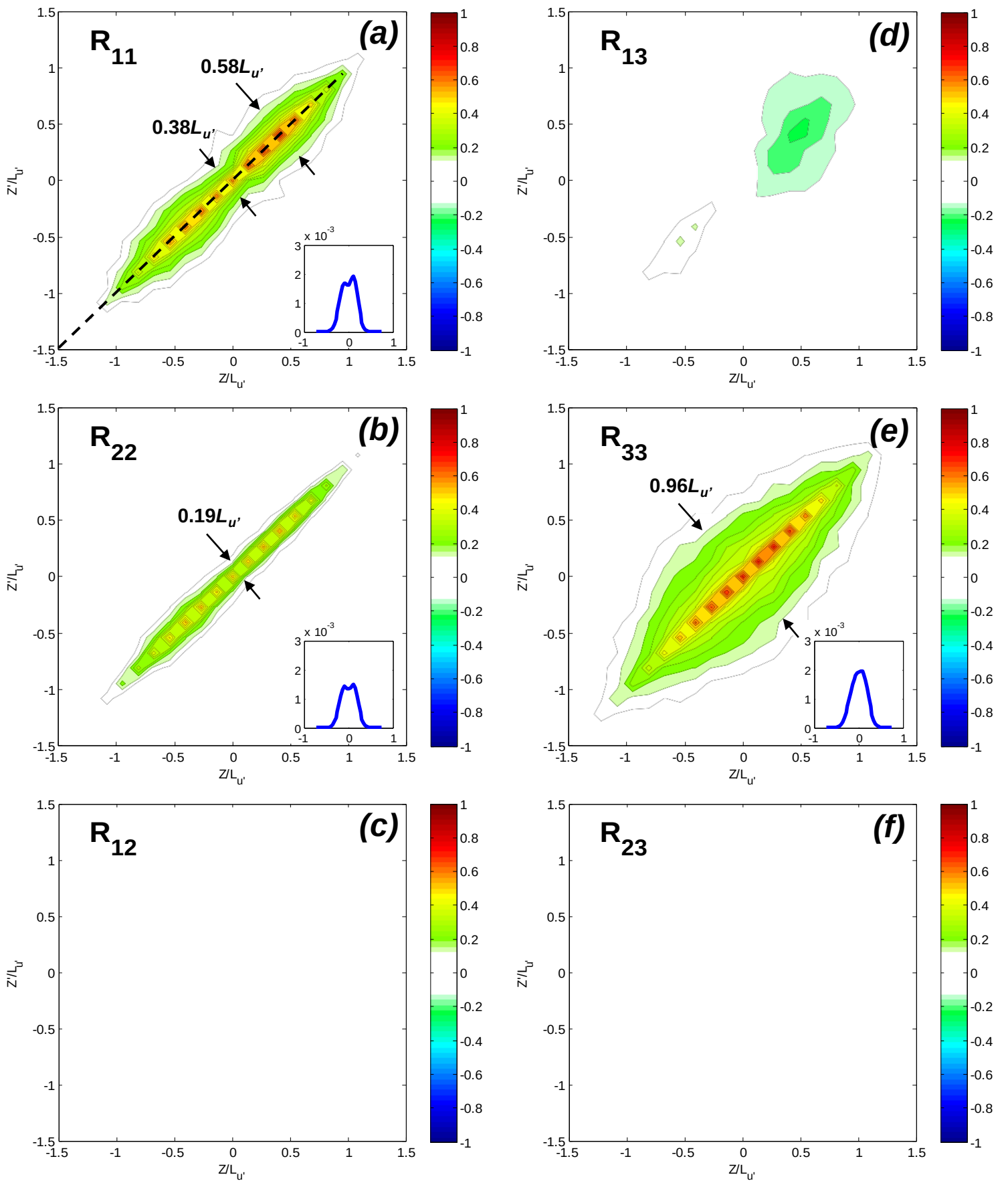
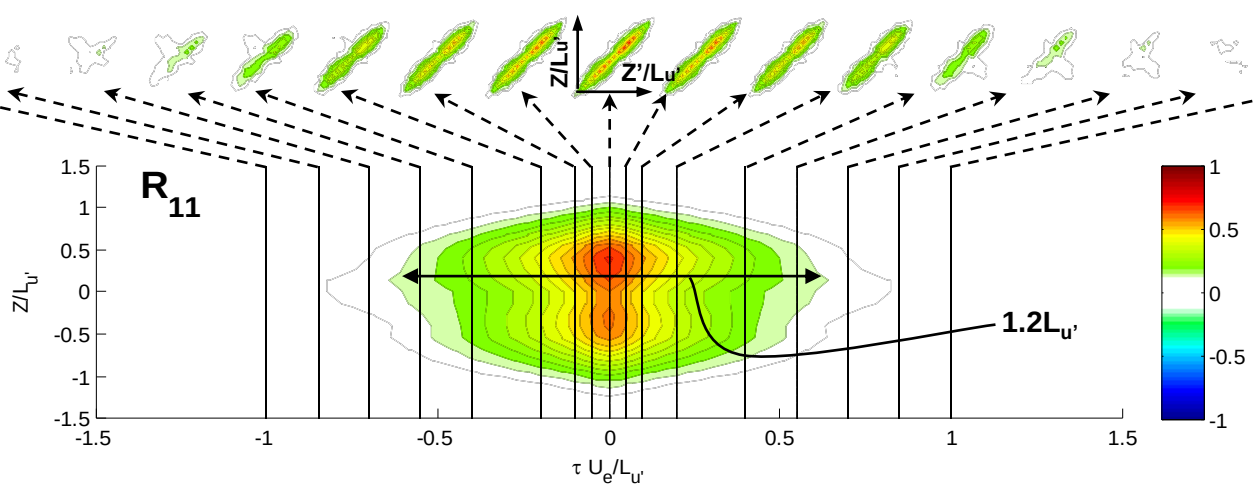
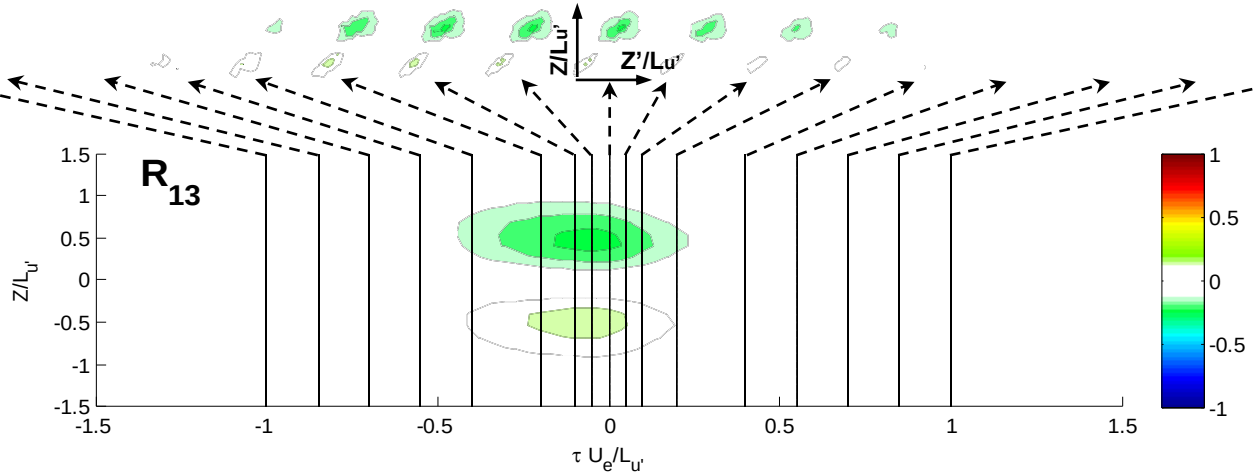


Figure 6.2 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$) normalized on the peak TKE) for the baseline blades, plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$.

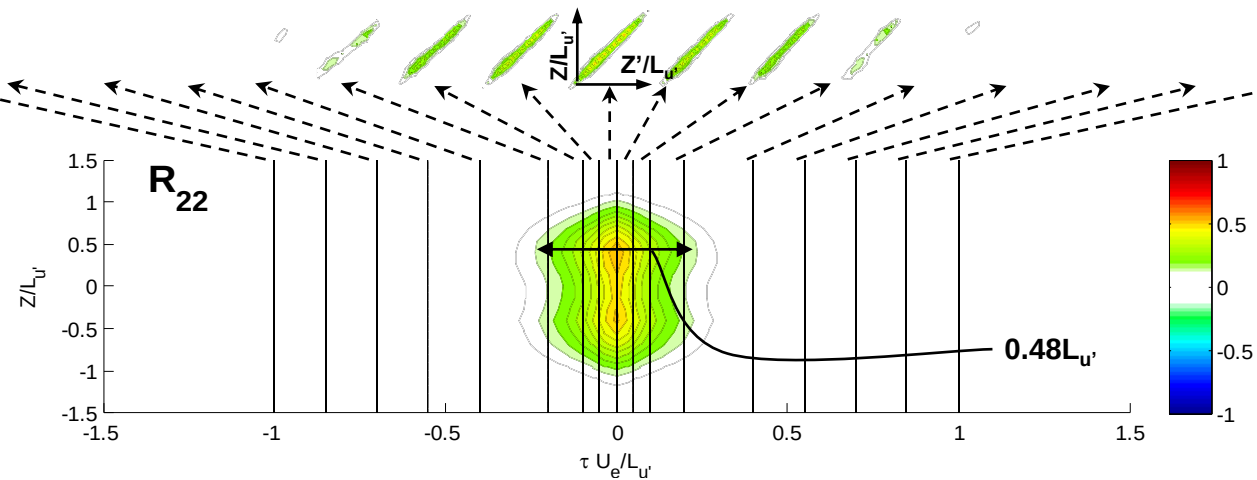
(a)



(b)



(c)



(d)

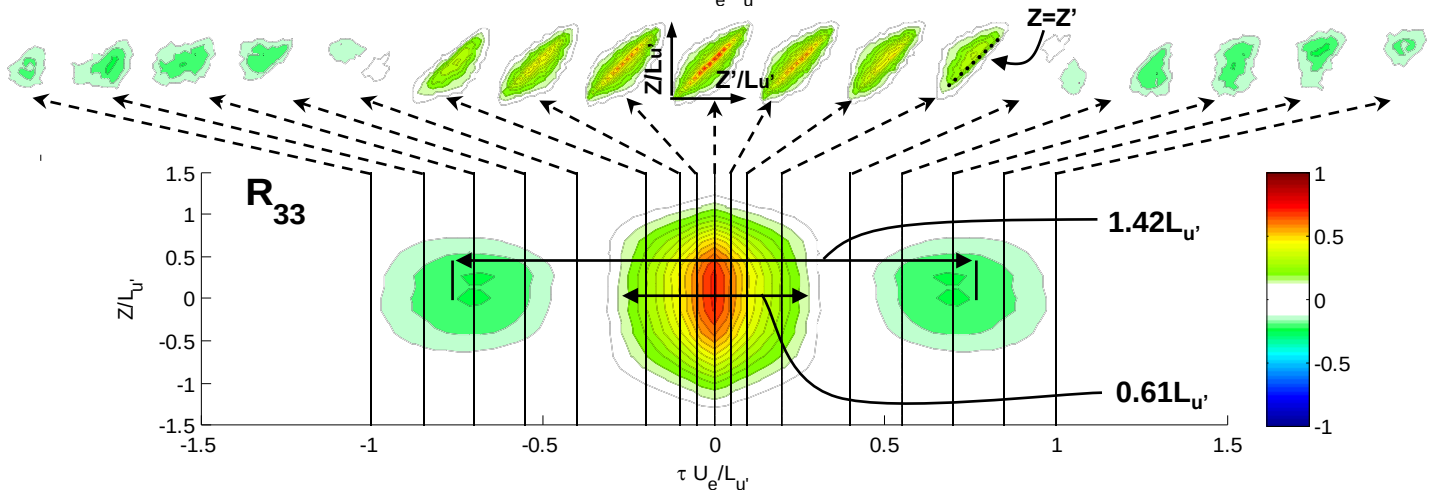


Figure 6.3 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the baseline blades. The auto-correlation $R_{ij}(Z, Z', \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

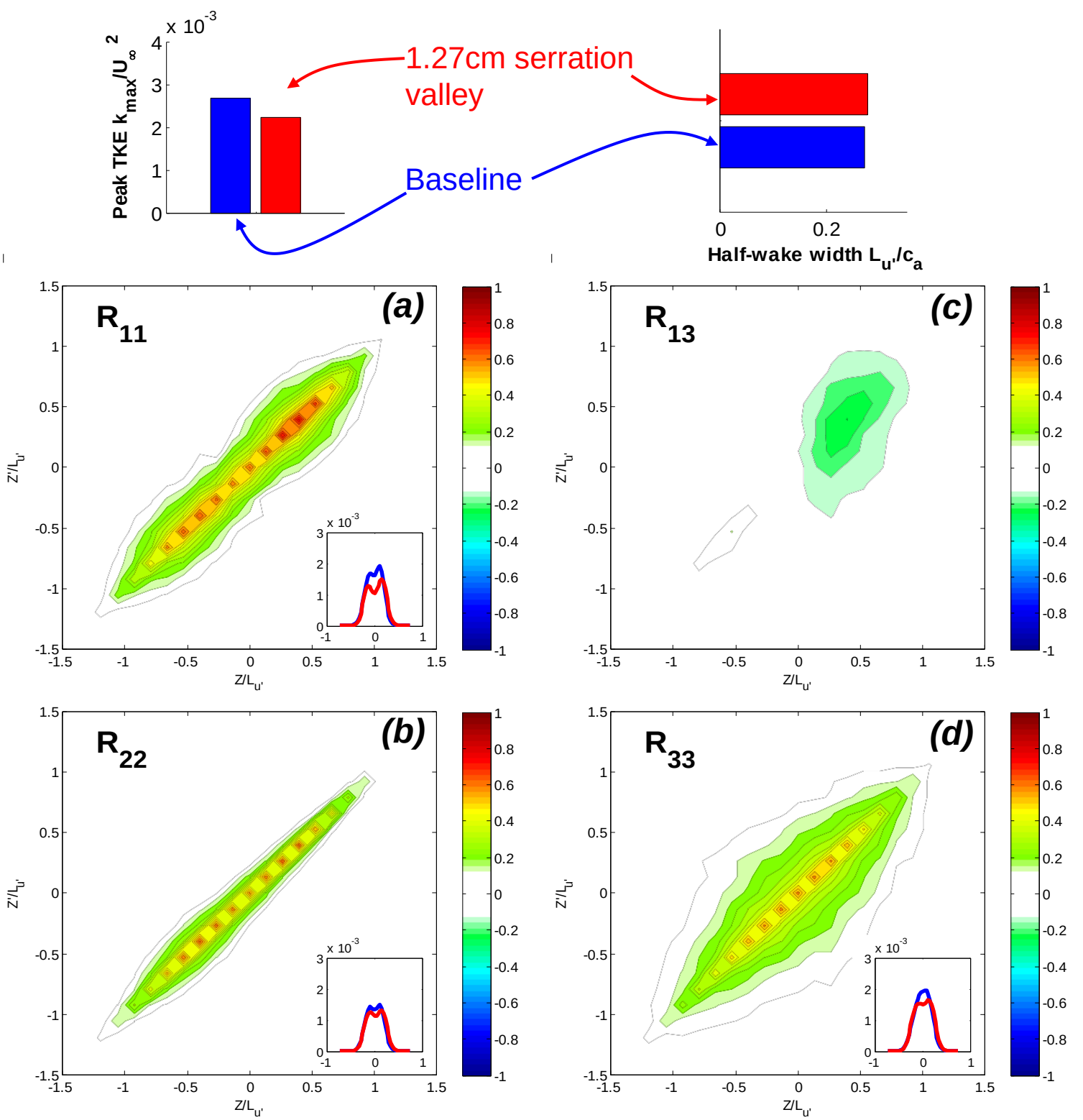


Figure 6.4 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 1.27cm serration blades (serration valley), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$.

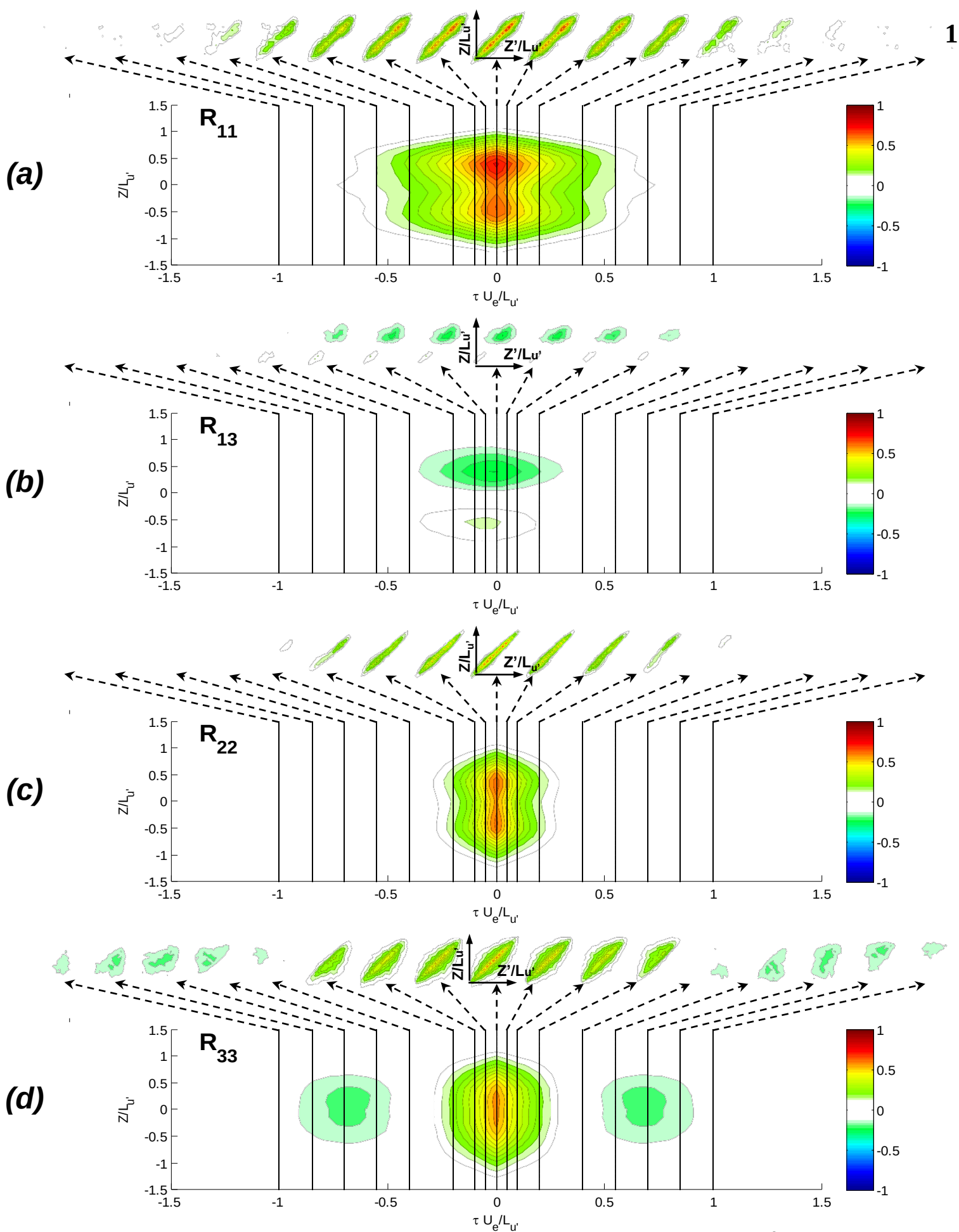


Figure 6.5 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 1.27cm serration blades (serration valley). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

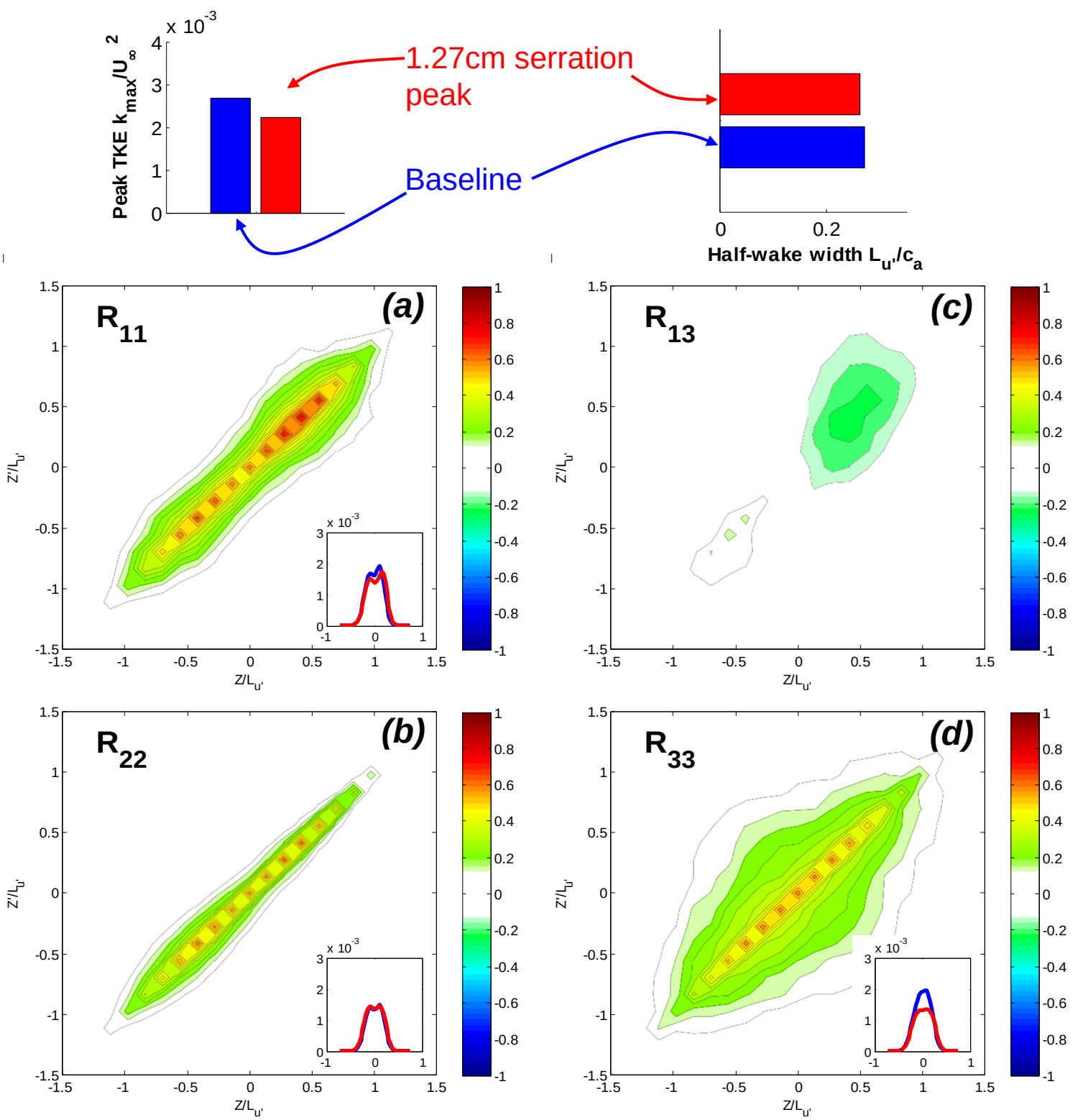
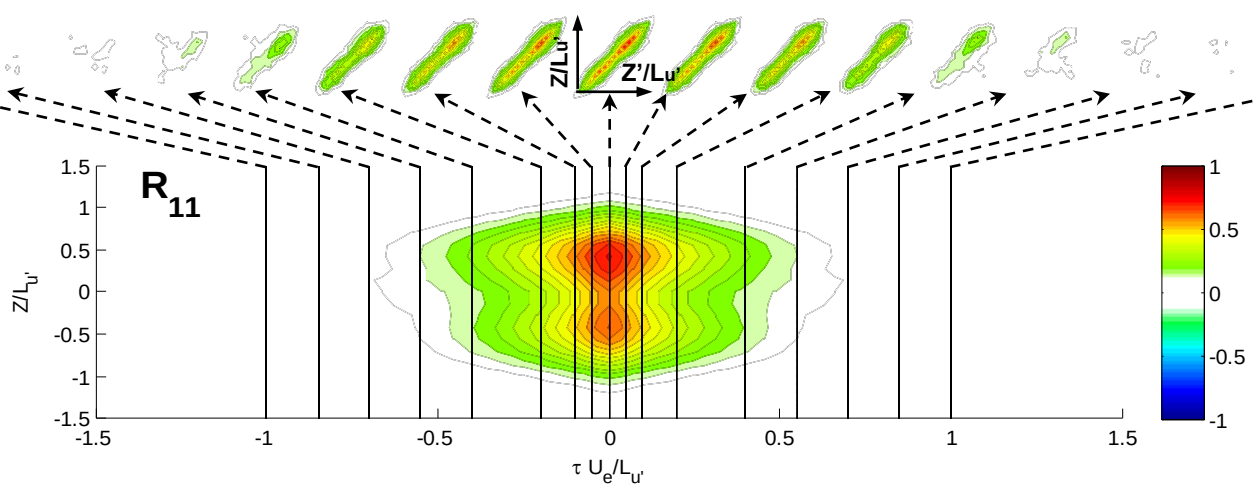
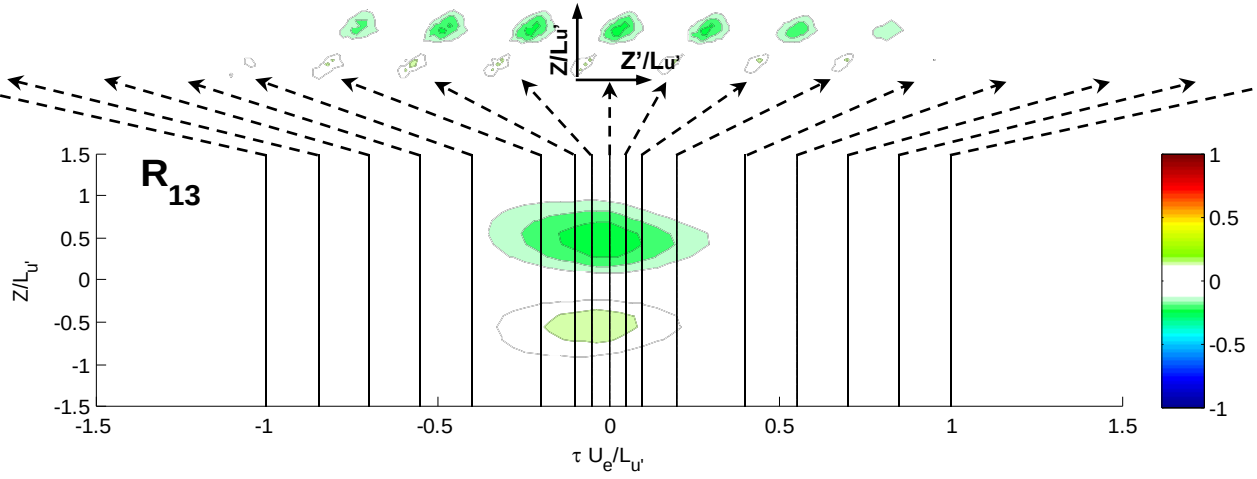


Figure 6.6 Zero-time delay correlation maps ($R_{ij}(Z/Z_{u'}, Z'/Z_{u'}, 0)$ normalized on the peak TKE) for the 1.27cm serration blades (serration peak), plotted against normalized normal to wake directions $Z/Z_{u'}$ and $Z'/Z_{u'}$.

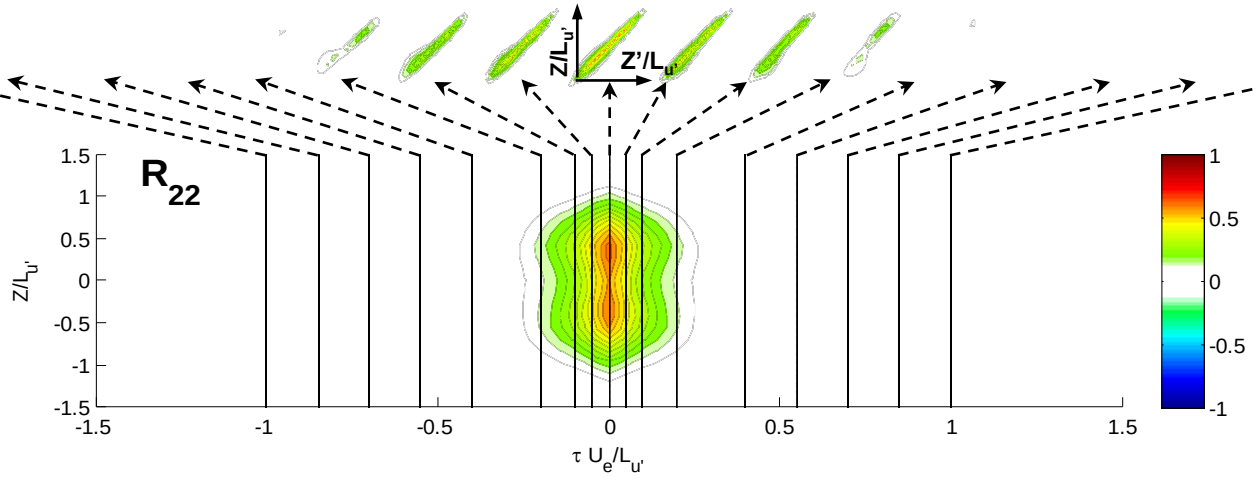
(a)



(b)



(c)



(d)

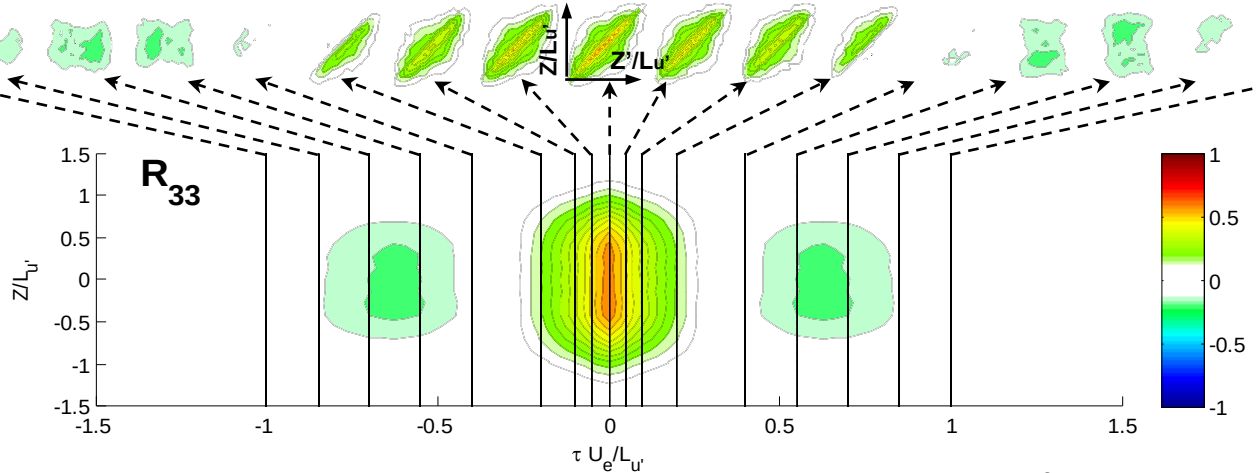


Figure 6.7 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 1.27cm serration blades (serration peak). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$, on the vertical axis and normalized time delay $\tau U_e/L_{u'}$, on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

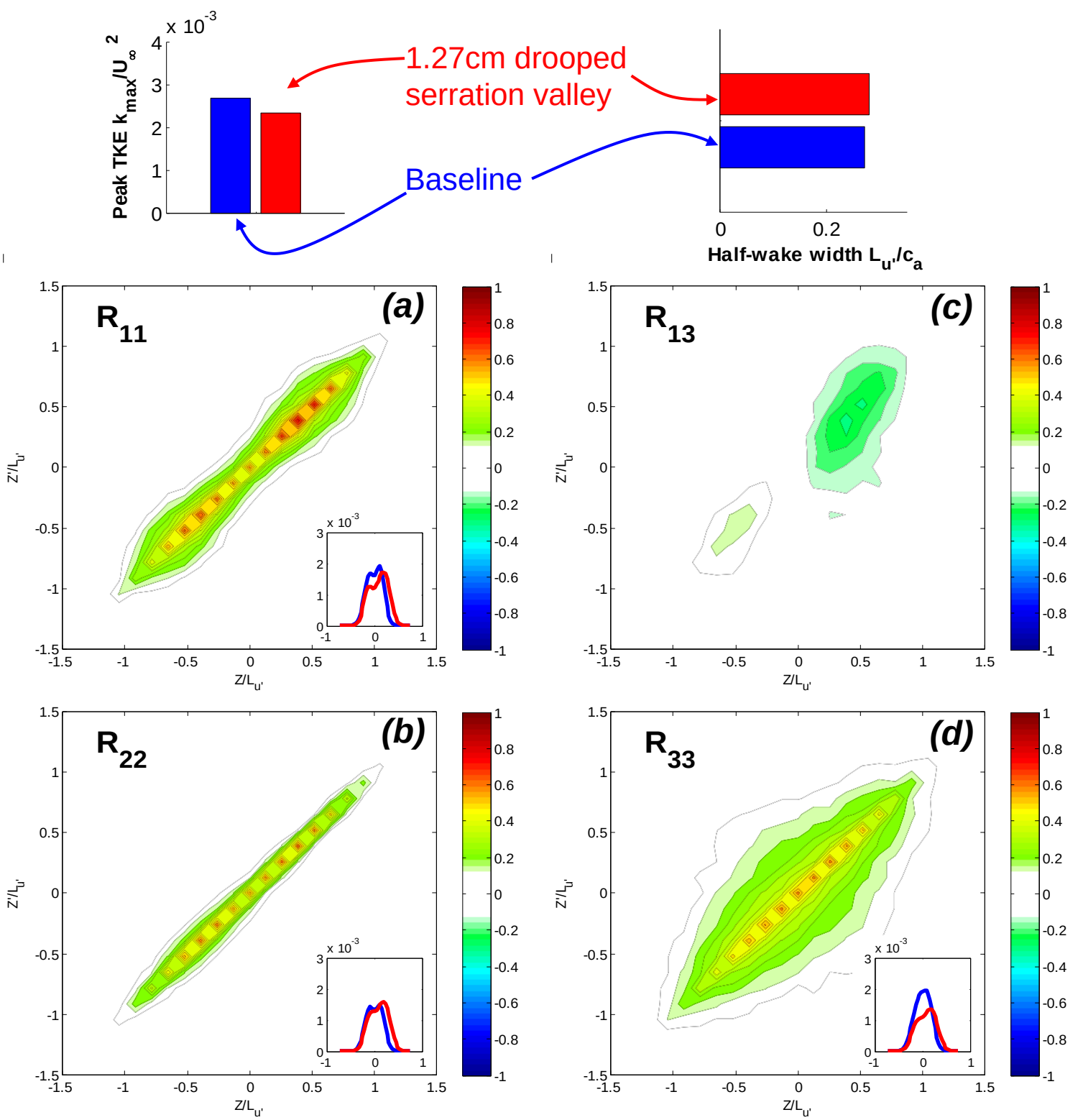
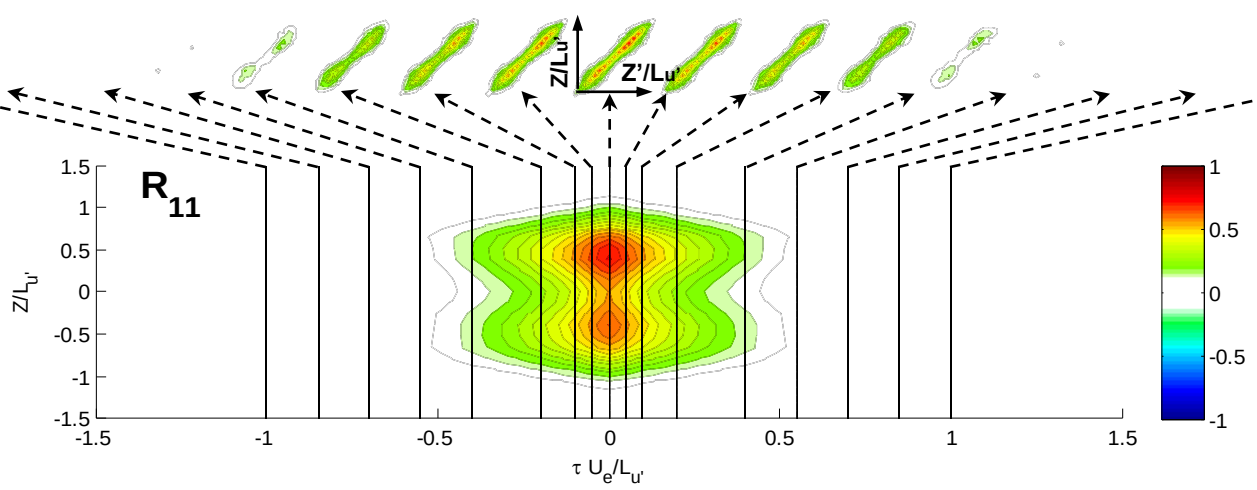
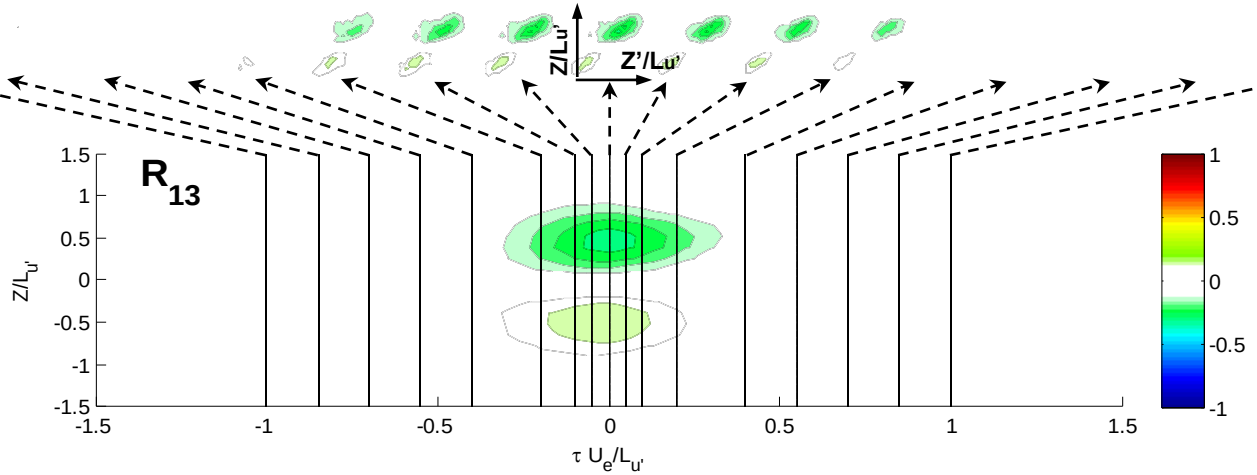


Figure 6.8 Zero-time delay correlation maps ($R_{ij}(Z/Z_{u'}, Z'/L_{u'}, 0)$ normalized on the peak TKE) for the 1.27cm drooped serration blades (serration valley), plotted against normalized normal to wake directions $Z/L_{u'}$, and $Z'/L_{u'}$.

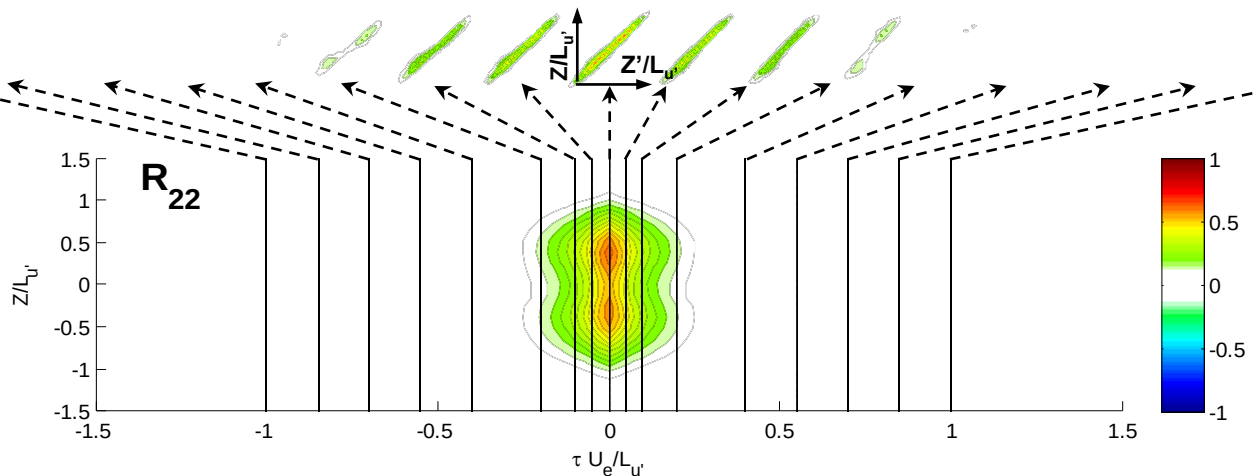
(a)



(b)



(c)



(d)

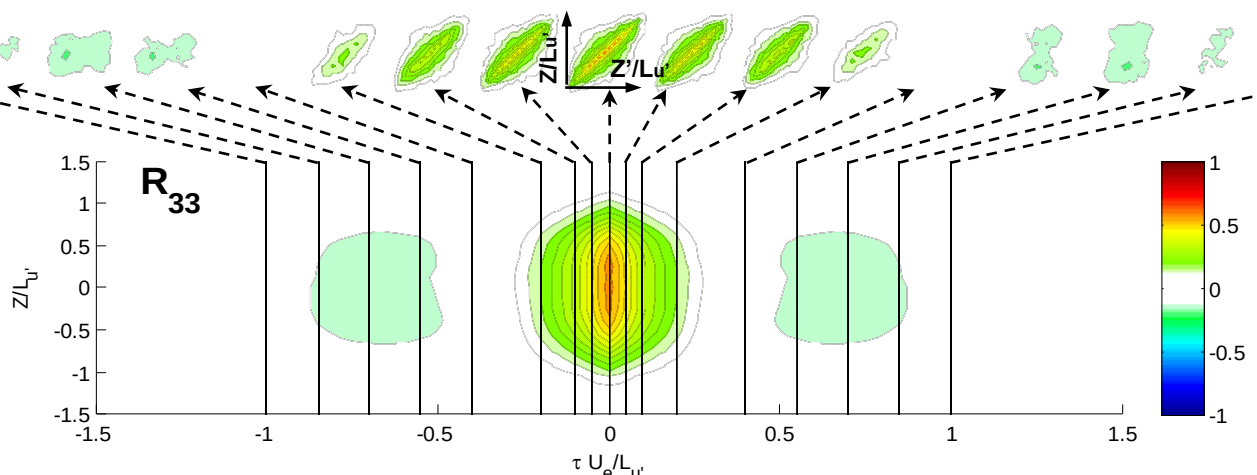


Figure 6.9 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 1.27cm drooped serration blades (serration valley). The auto-correlation $R_{ij}(Z, Z', \tau)$ is plotted against normal-to-wake distance Z/L_u on the vertical axis and normalized time delay $\tau U_e/L_u$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

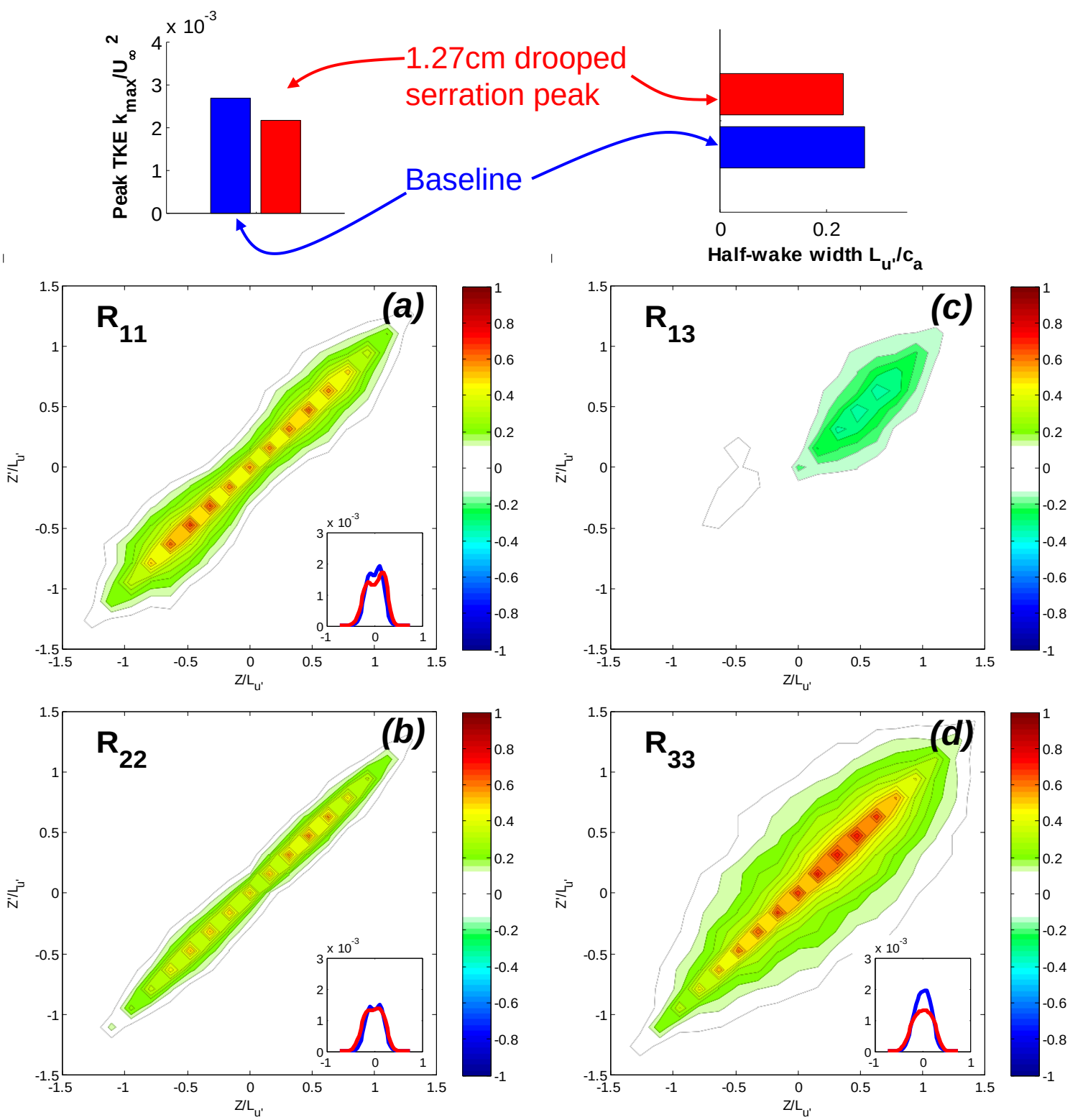
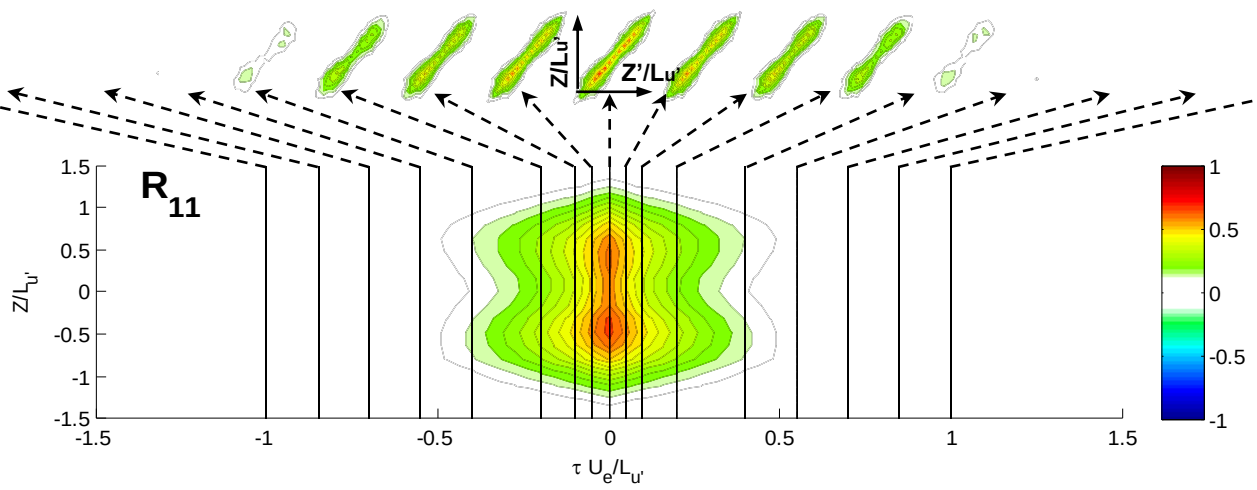
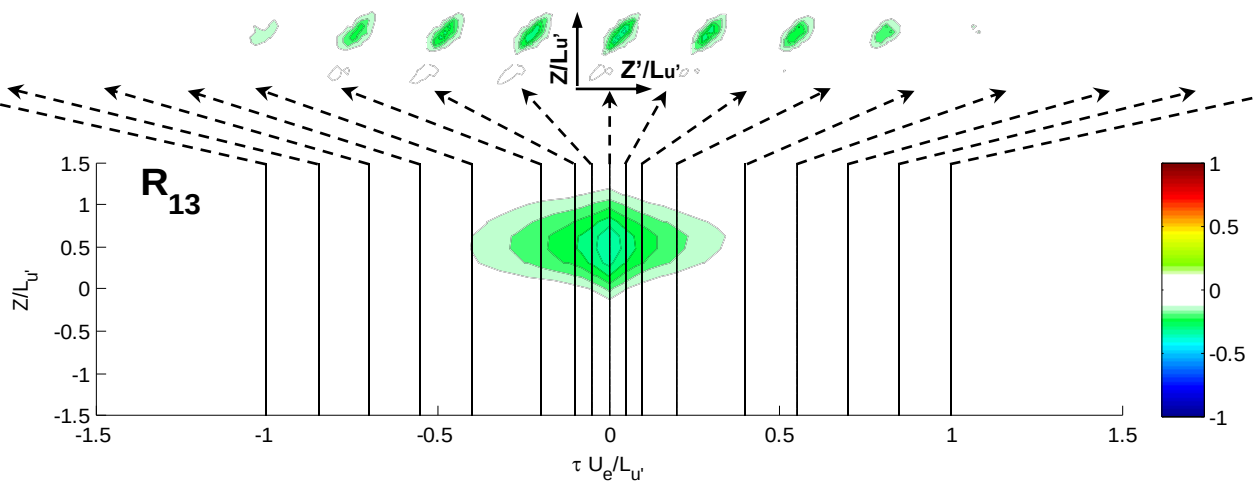


Figure 6.10 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 1.27cm drooped serration blades (serration peak), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$.

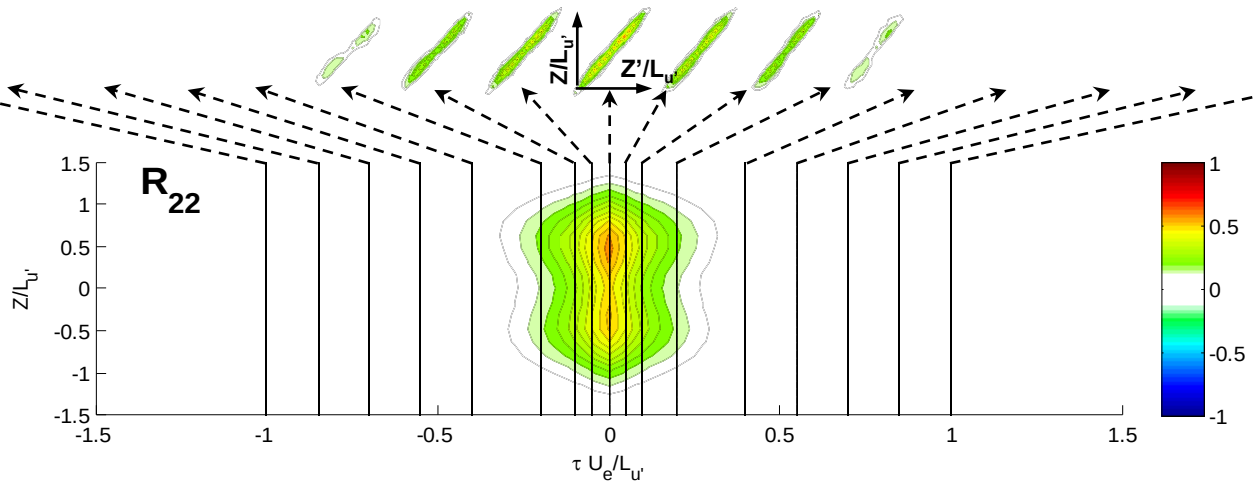
(a)



(b)



(c)



(d)

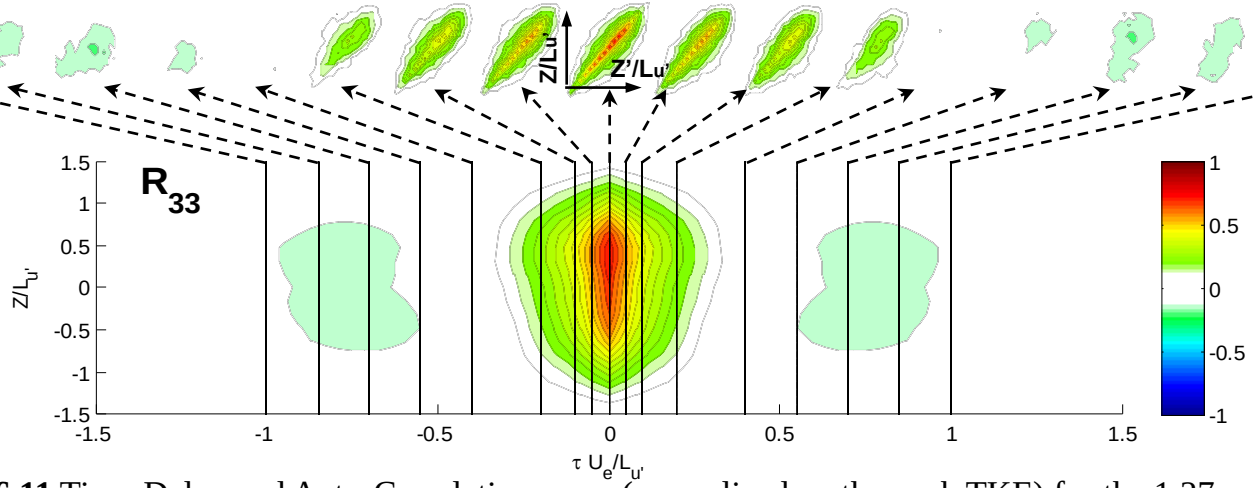


Figure 6.11 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 1.27cm drooped serration blades (serration peak). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

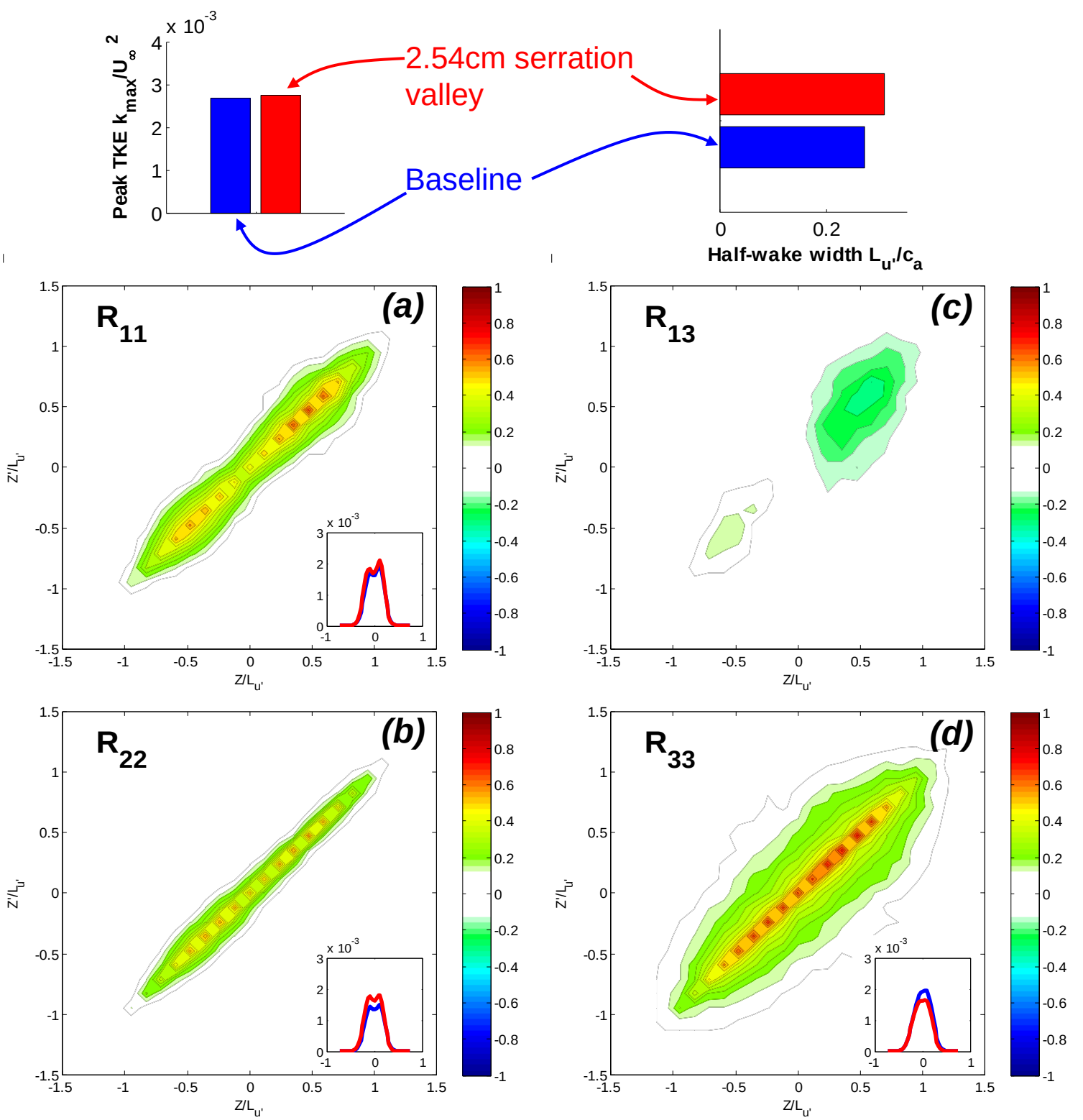
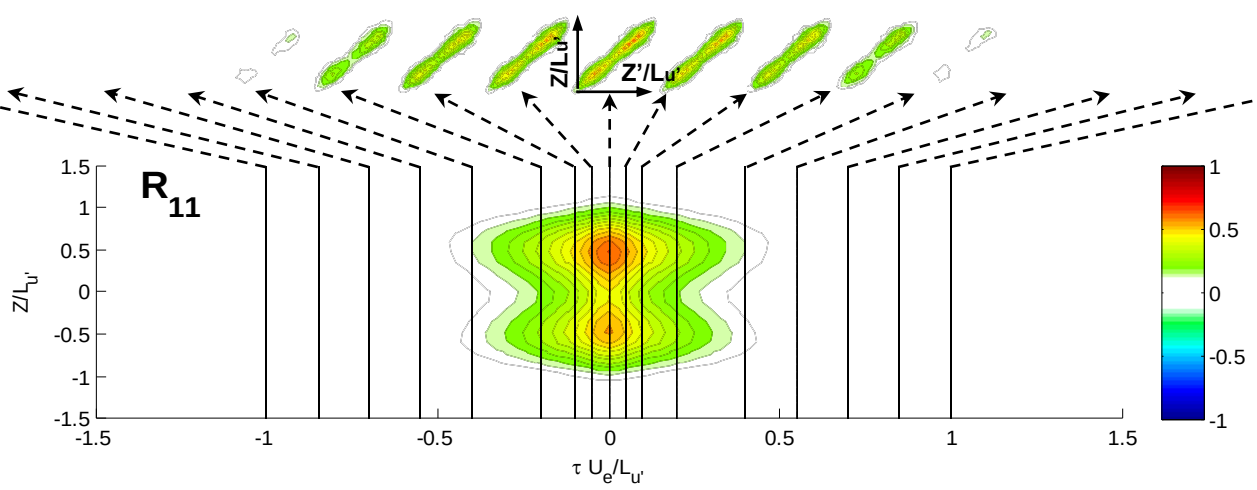
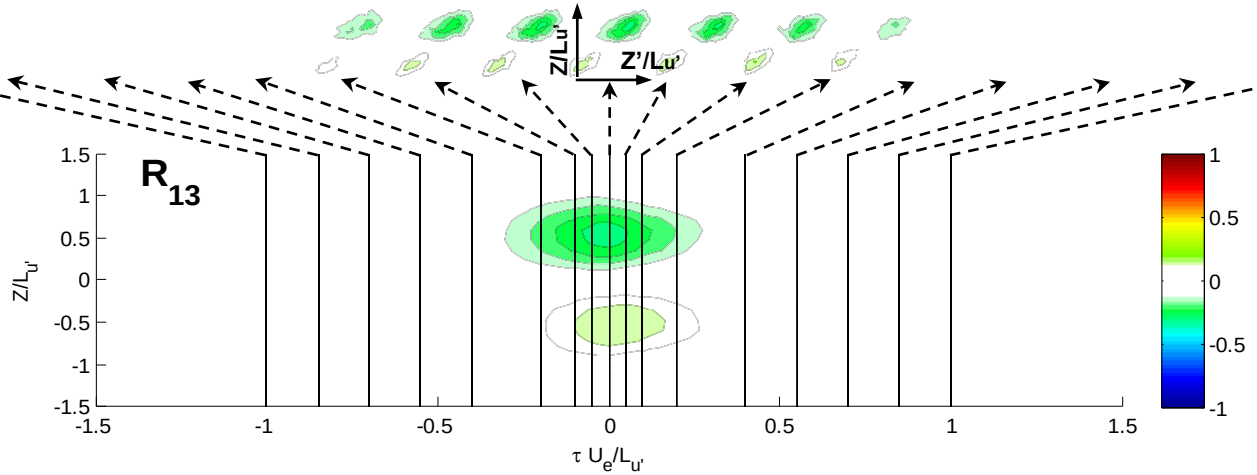


Figure 6.12 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$) normalized on the peak TKE) for the 2.54cm serration blades (serration valley), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$.

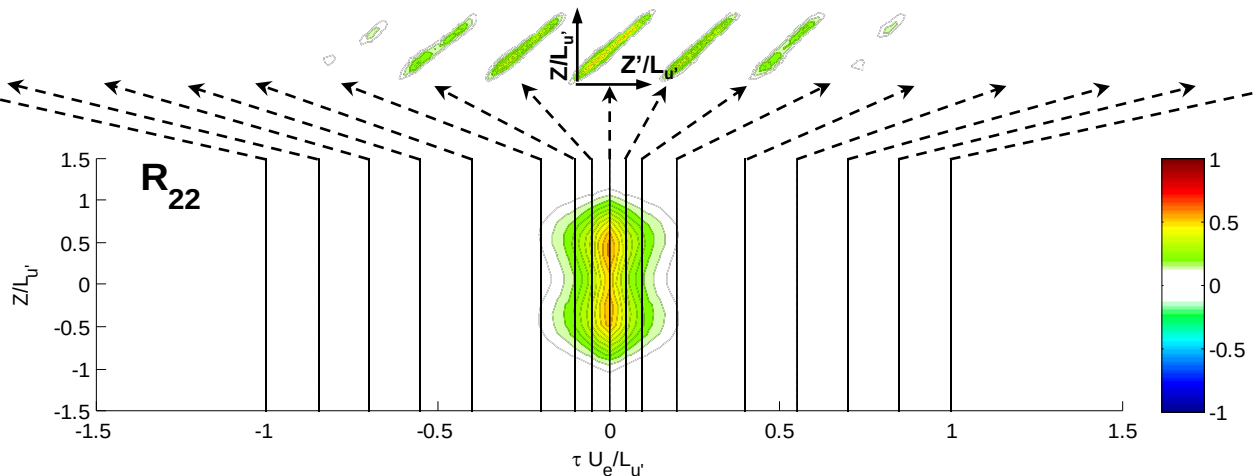
(a)



(b)



(c)



(d)

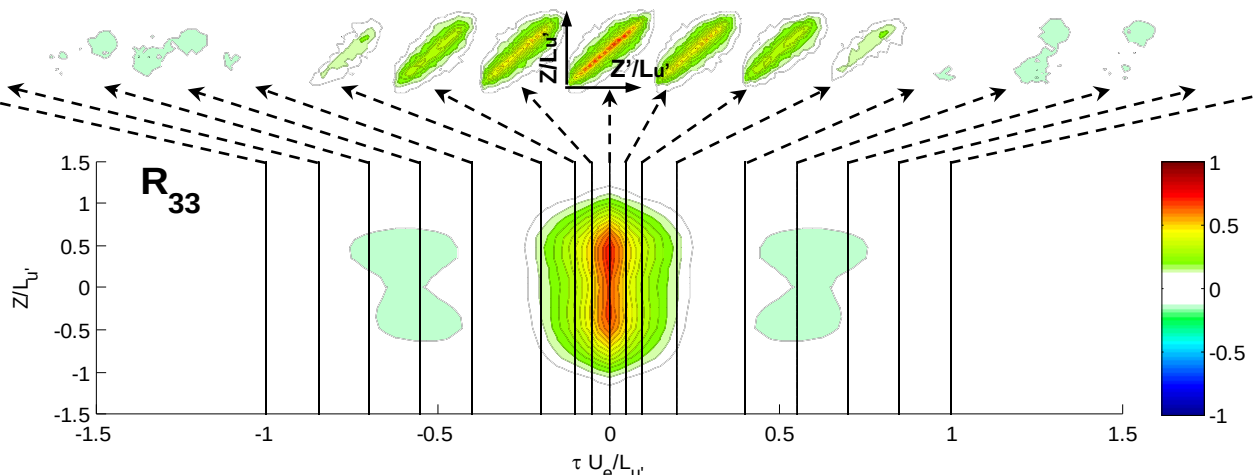


Figure 6.13 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 2.54cm serration blades (serration valley). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

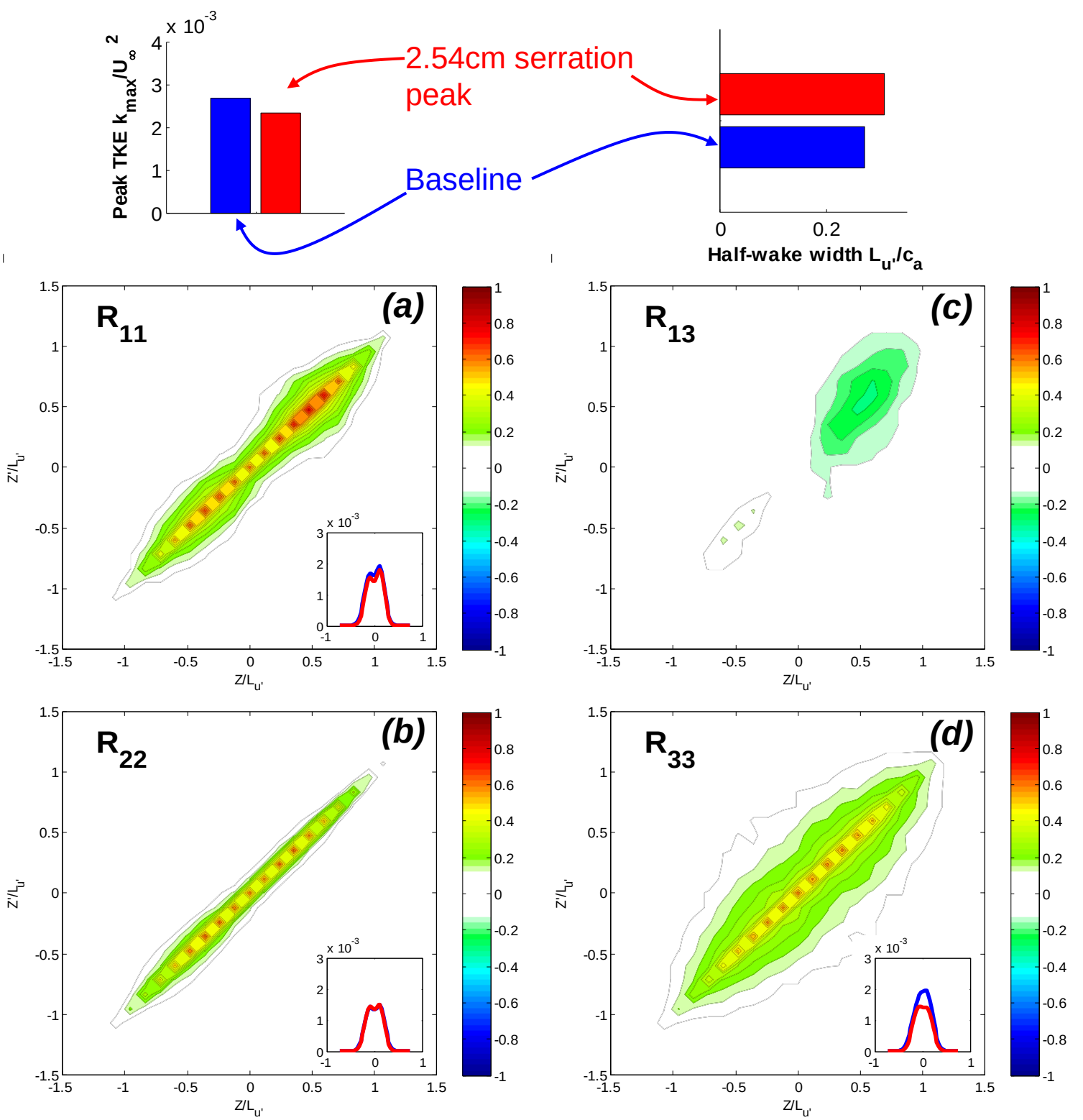
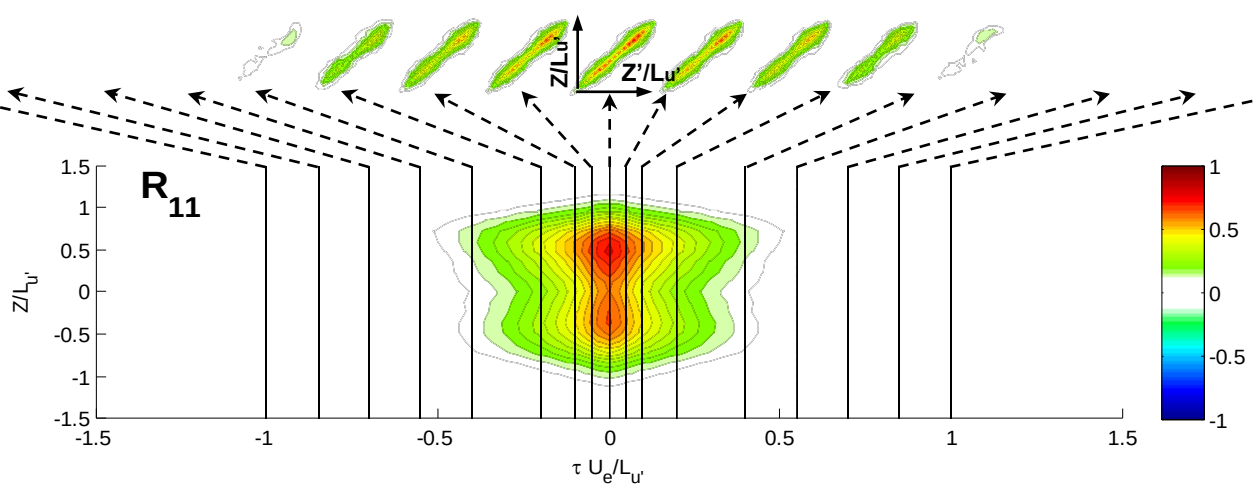
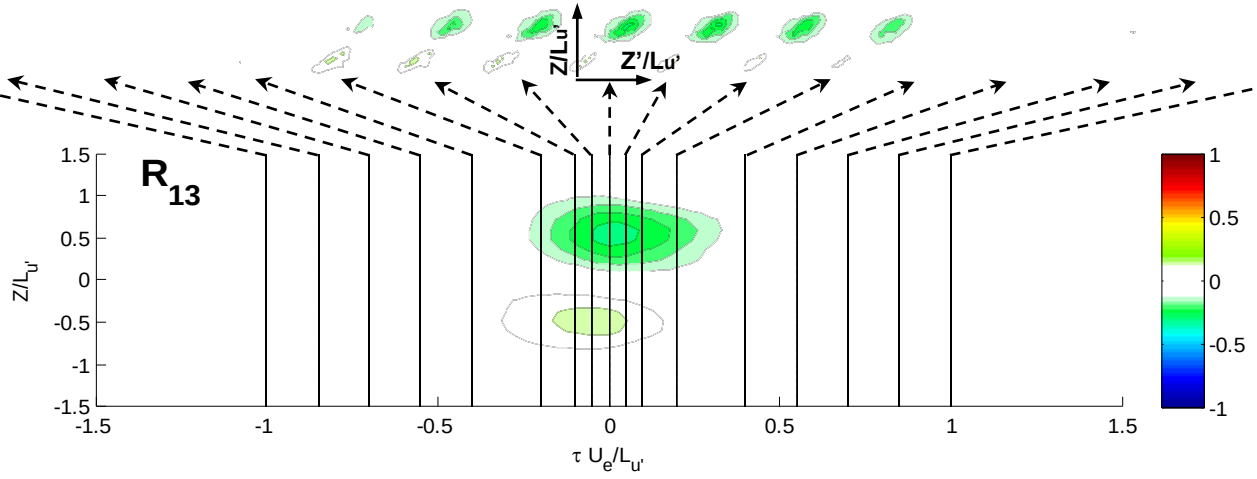


Figure 6.14 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$) normalized on the peak TKE) for the 2.54cm serration blades (serration peak), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$.

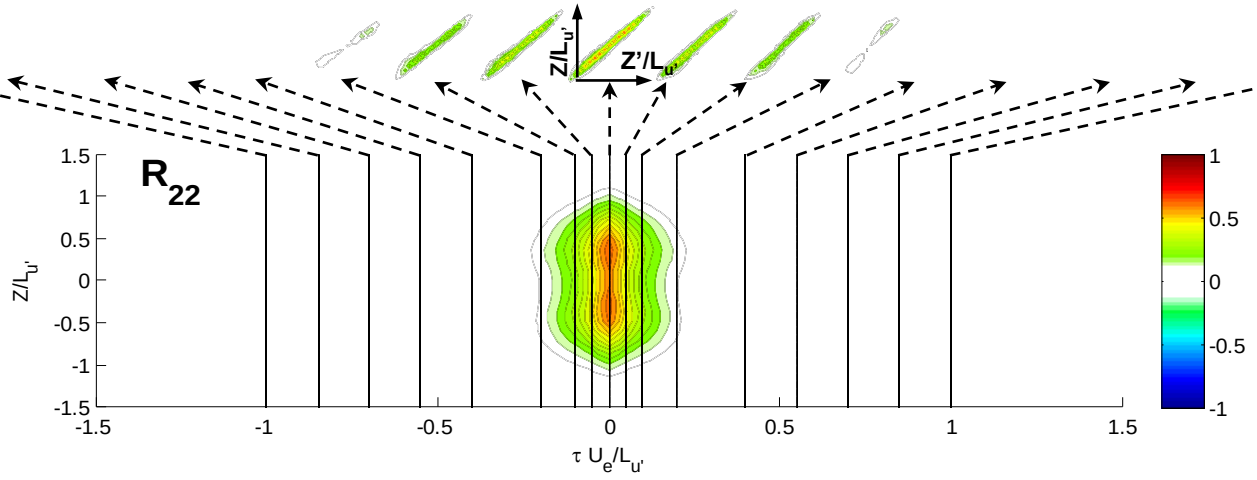
(a)



(b)



(c)



(d)

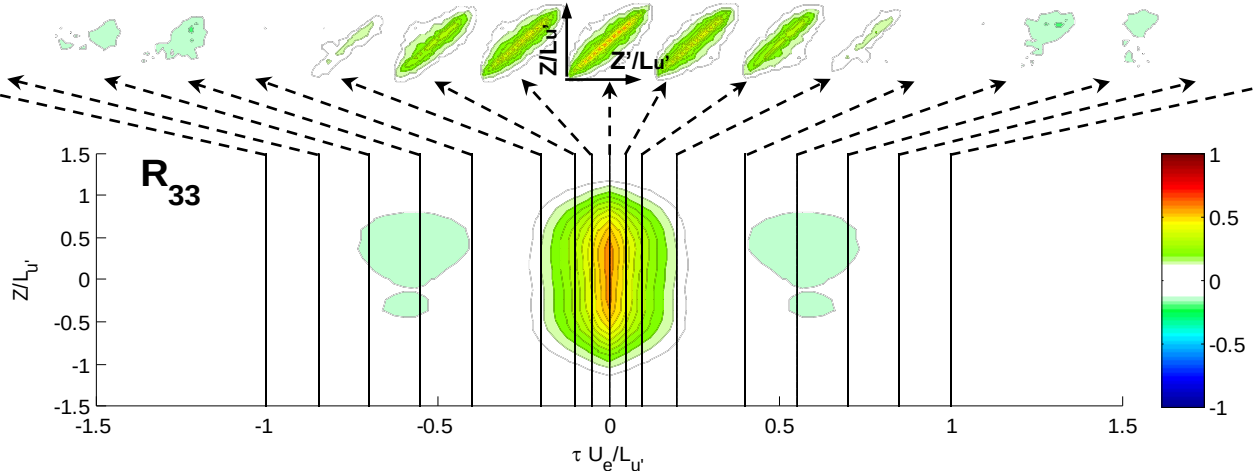


Figure 6.15 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 2.54cm serration blades (serration peak). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance Z/L_u' , on the vertical axis and normalized time delay $\tau U_e/L_u'$, on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

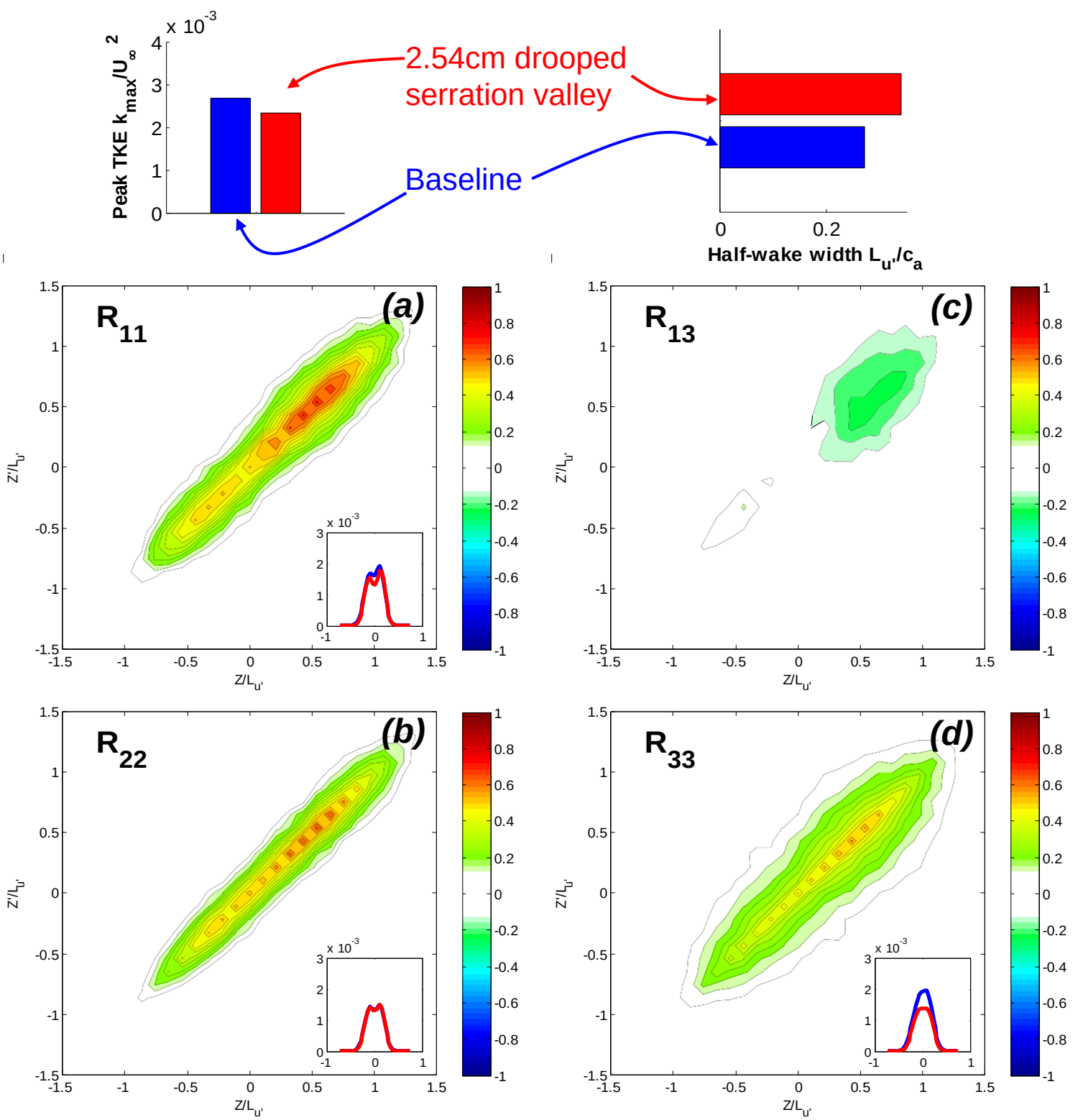
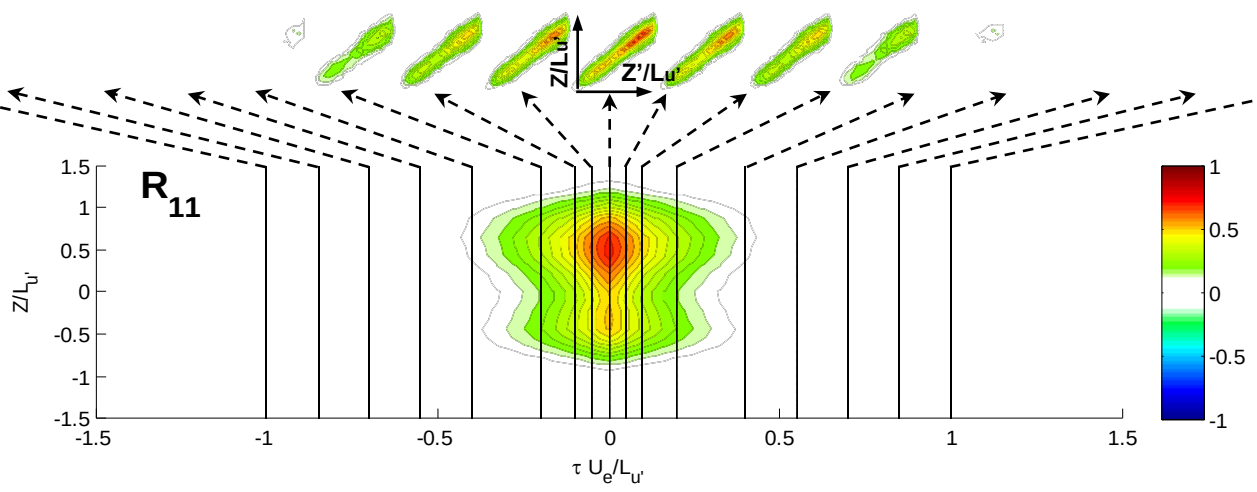
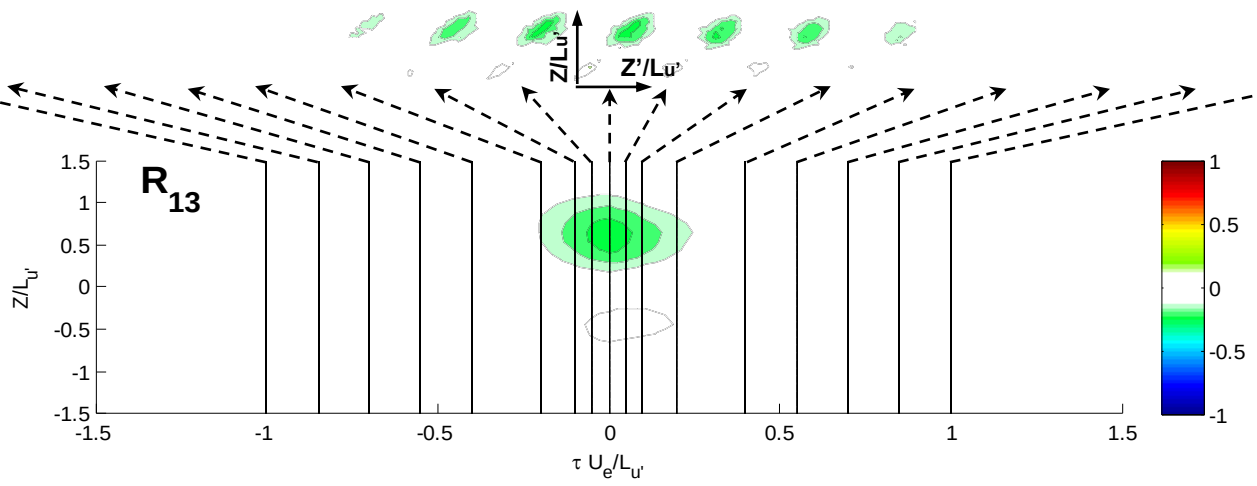


Figure 6.16 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$) normalized on the peak TKE) for the 2.54cm drooped serration blades (serration valley), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$.

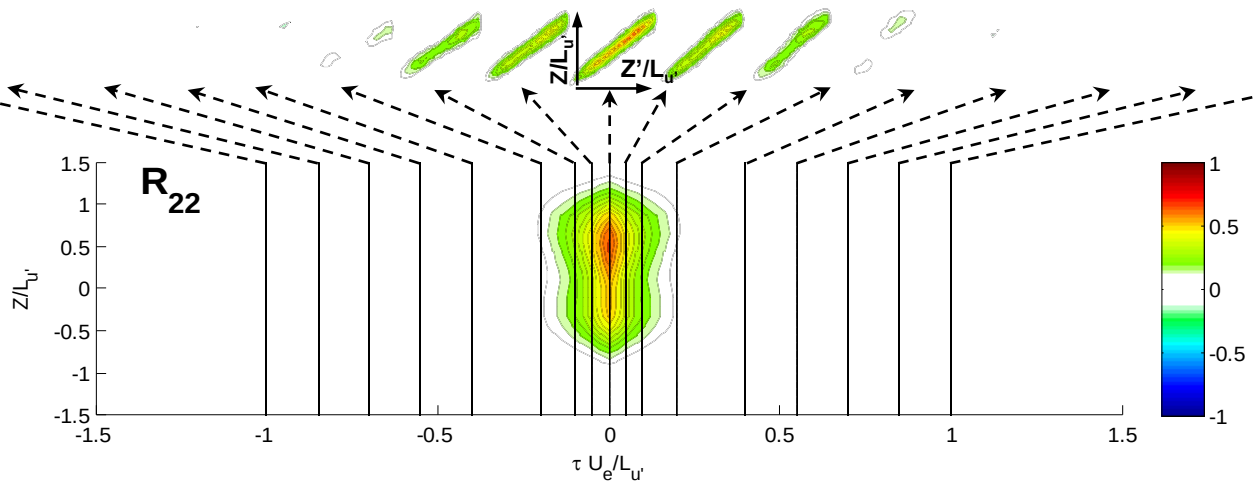
(a)



(b)



(c)



(d)

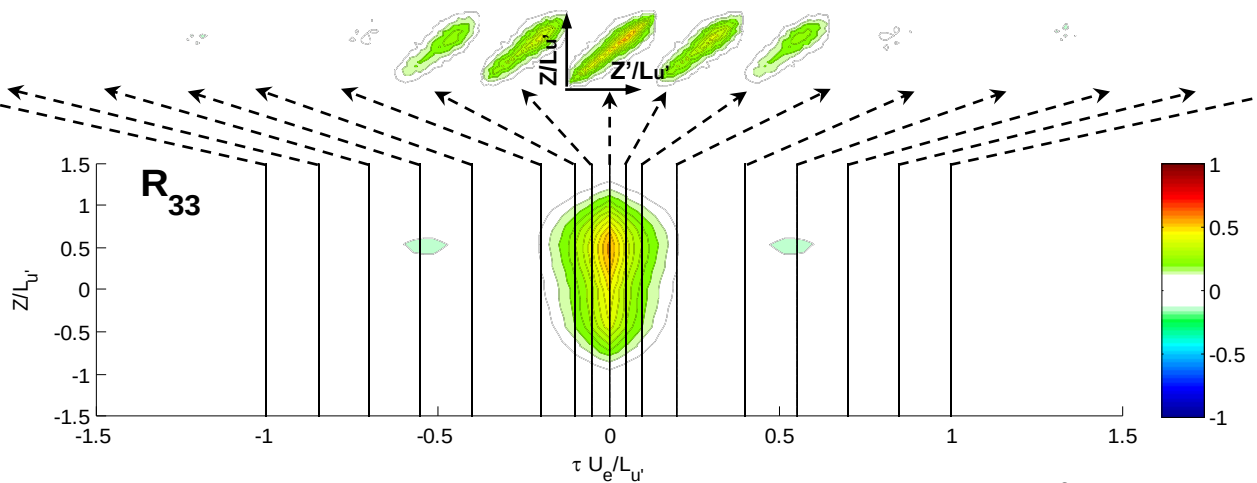


Figure 6.17 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 2.54cm drooped serration blades (serration valley). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

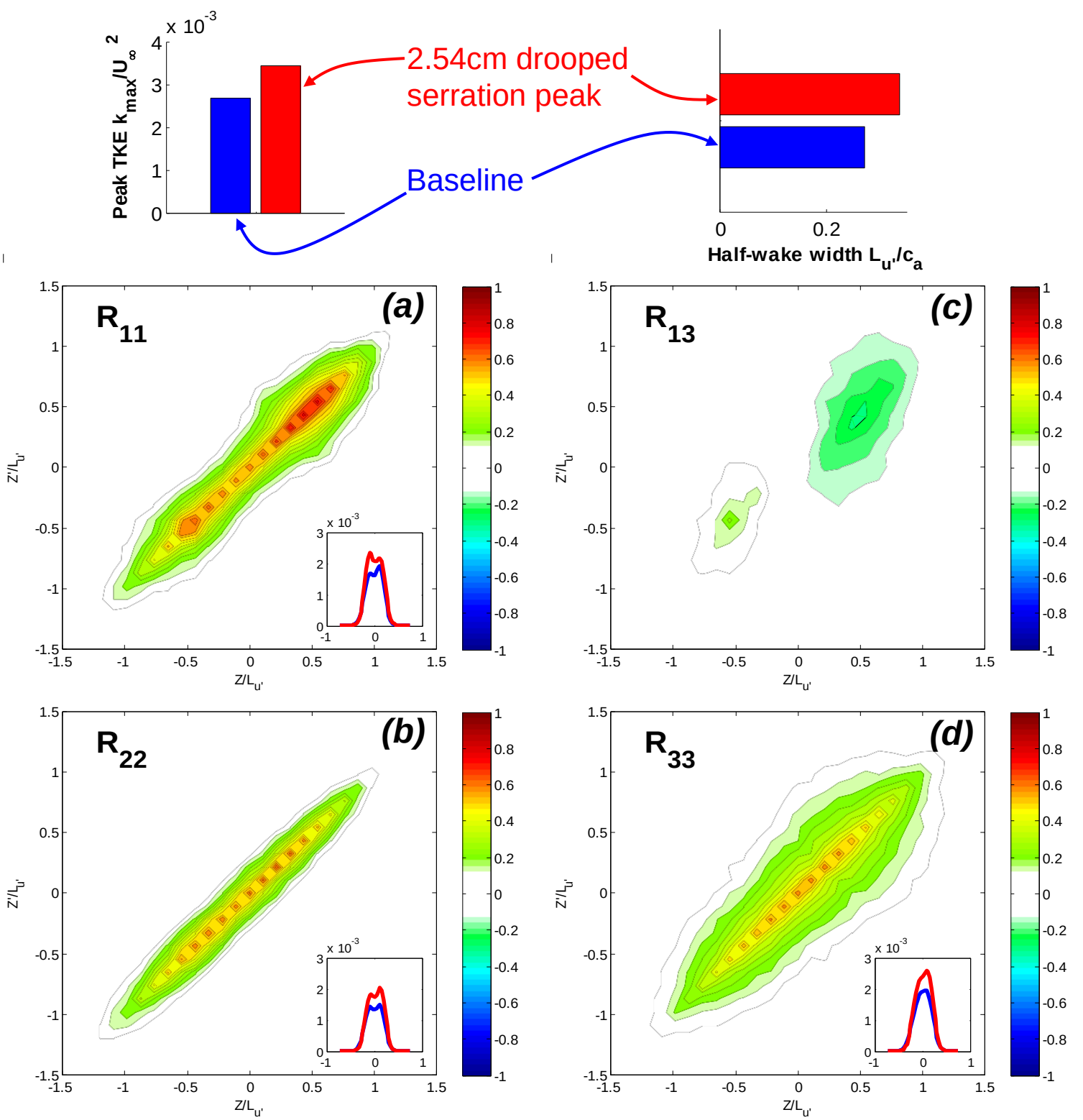


Figure 6.18 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the 2.54cm drooped serration blades (serration peak), plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$.

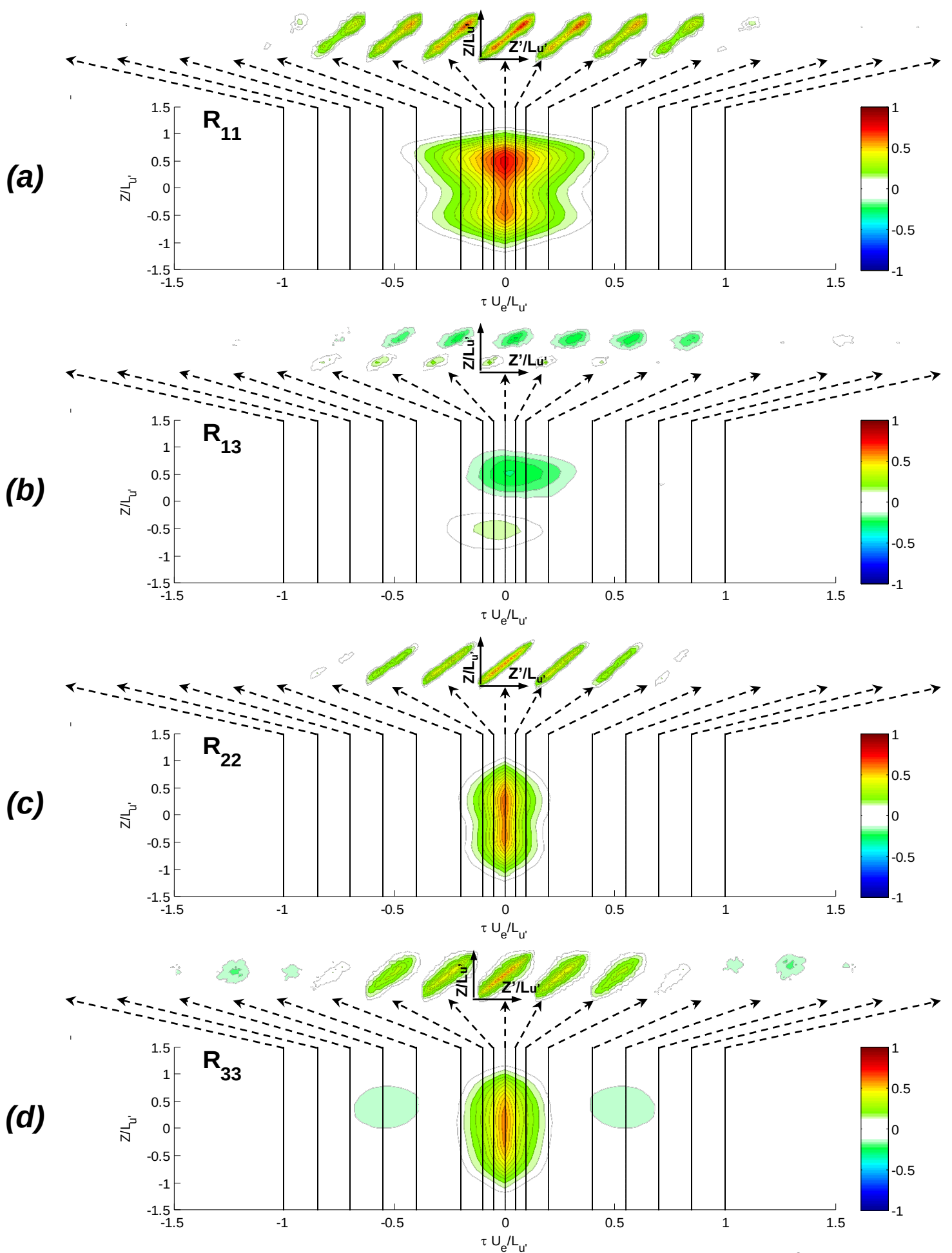


Figure 6.19 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the 2.54cm drooped serration blades (serration peak). The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

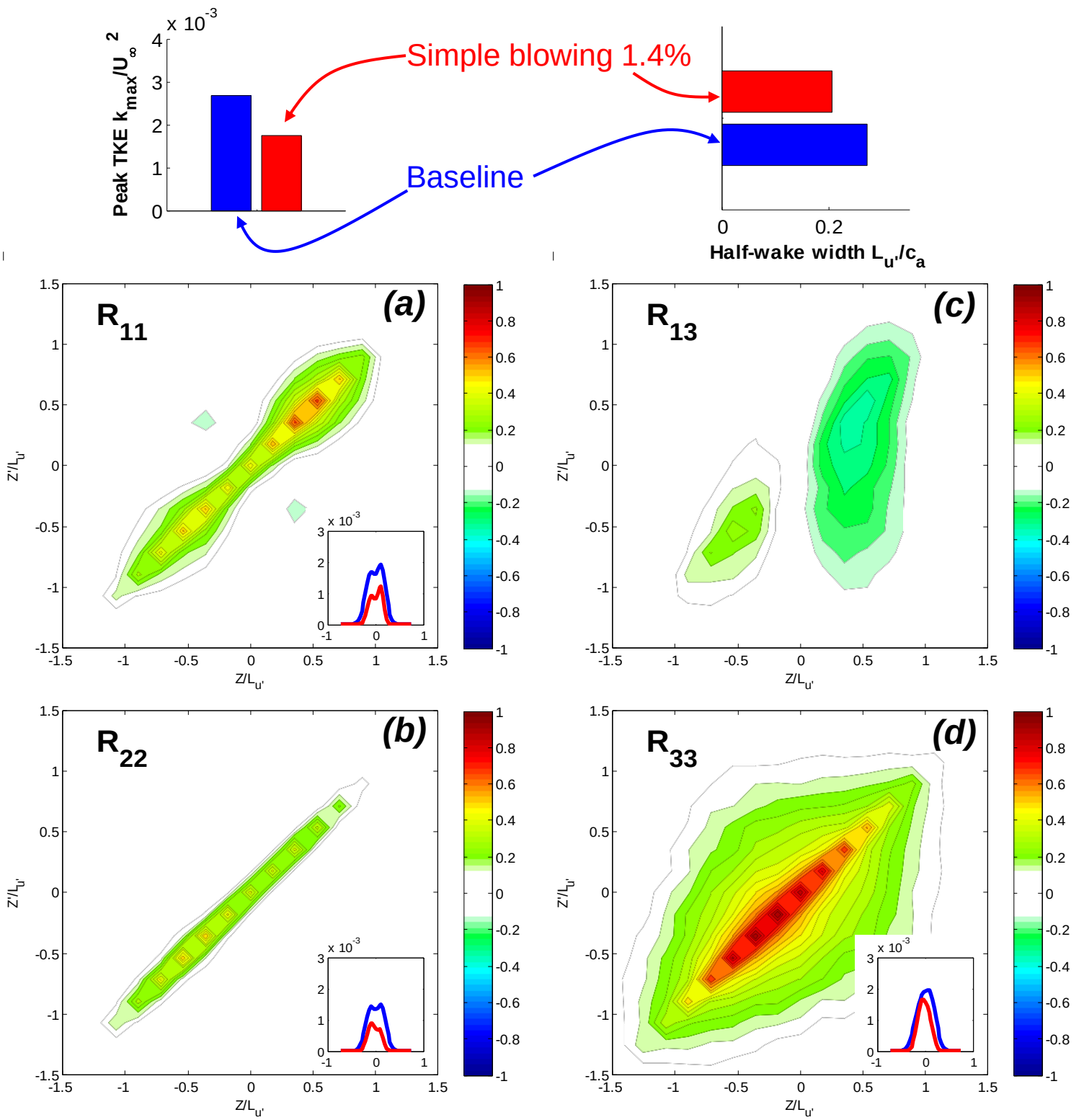


Figure 6.20 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the simple blowing blades at a blowing rate of 1.4%, plotted against normalized normal to wake directions $Z/L_{u'}$, and $Z'/L_{u'}$.

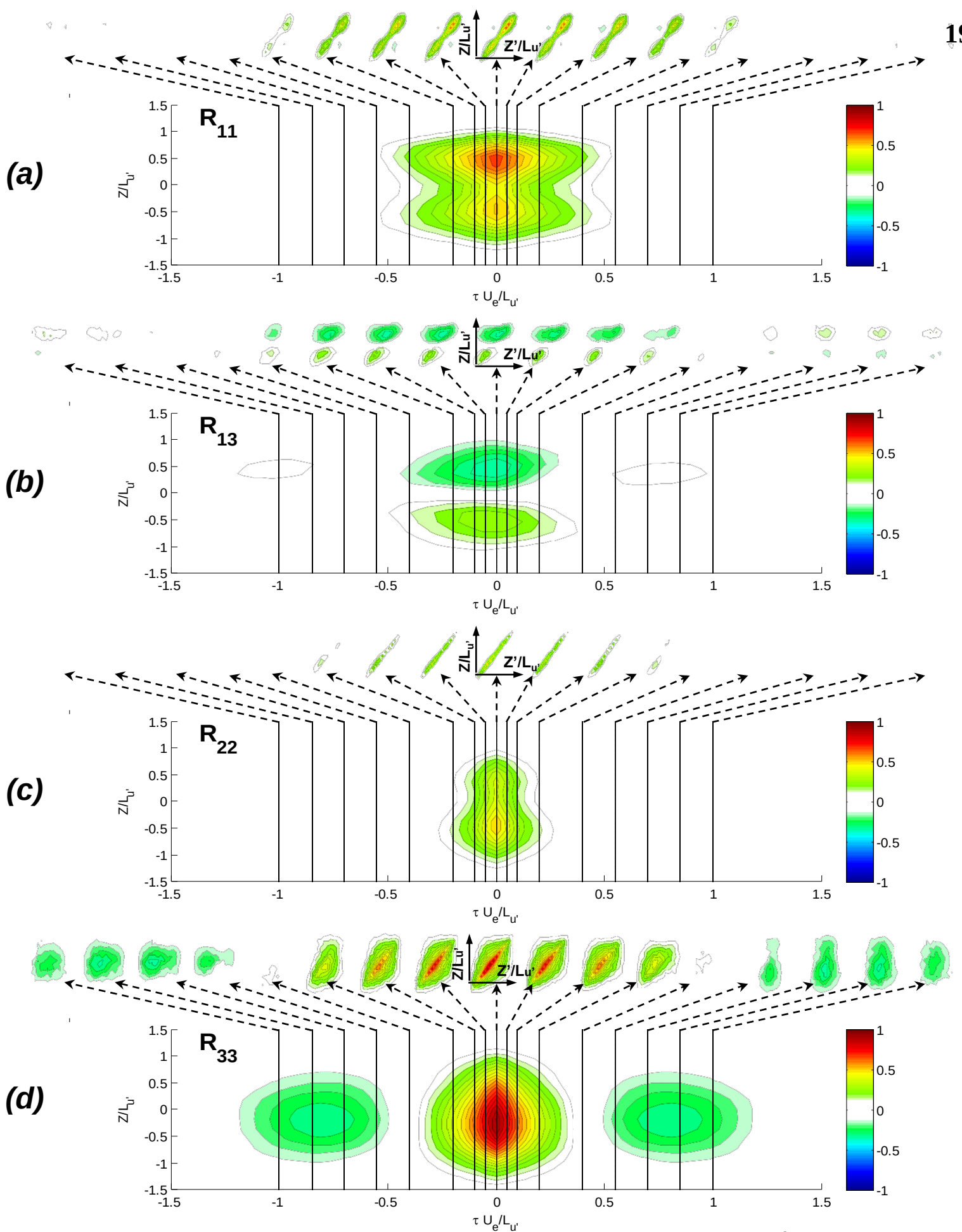


Figure 6.21 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the simple blowing blades at a blowing rate of 1.4%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

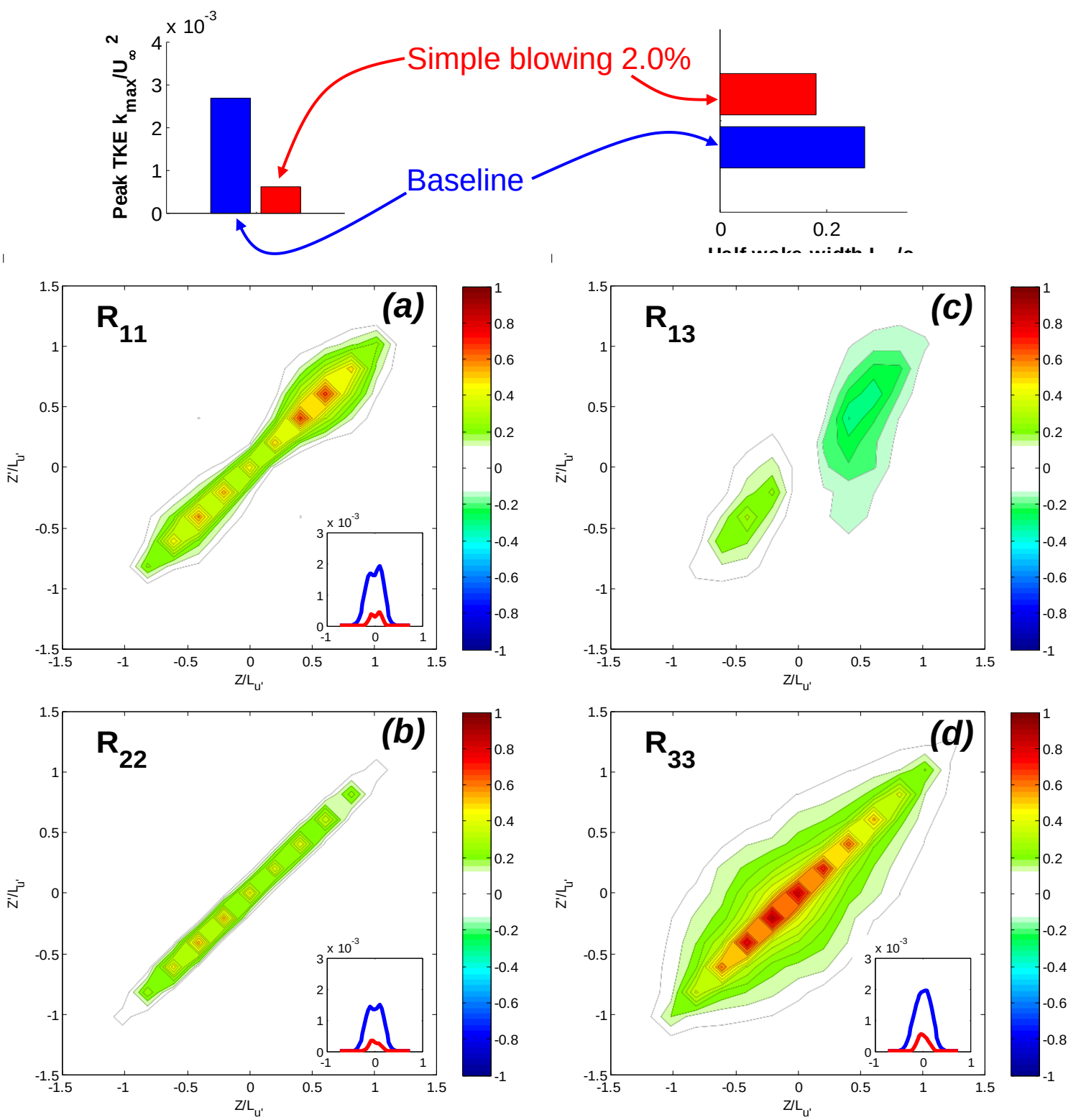


Figure 6.22 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$) normalized on the peak TKE) for the simple blowing blades at a blowing rate of 2.0%, plotted against normalized normal to wake directions $Z/L_{u'}$, and $Z'/L_{u'}$.

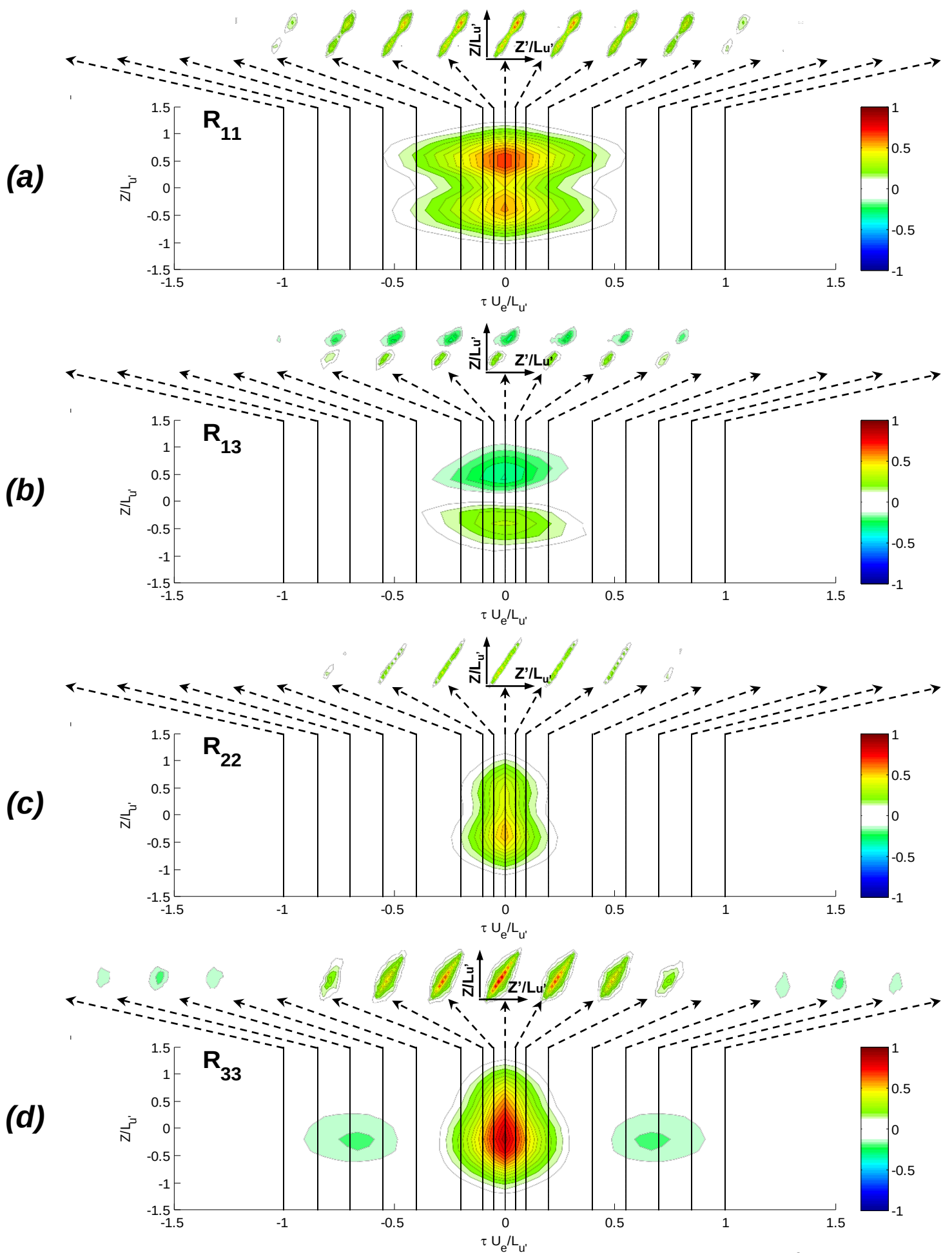


Figure 6.23 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the simple blowing blades at a blowing rate of 2.0%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

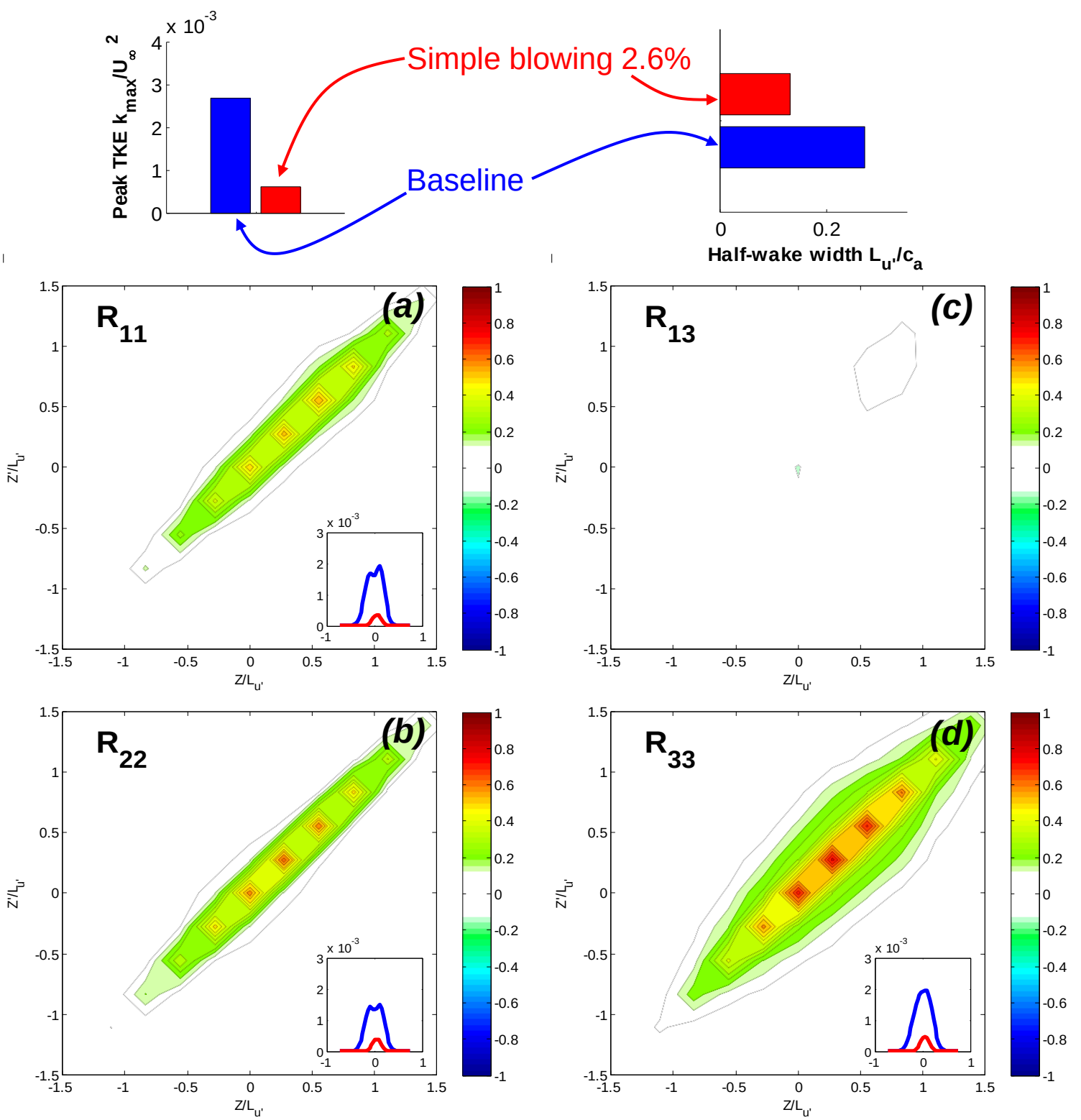


Figure 6.24 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$ normalized on the peak TKE) for the simple blowing blades at a blowing rate of 2.6%, plotted against normalized normal to wake directions $Z/L_{u'}$, and $Z'/L_{u'}$.

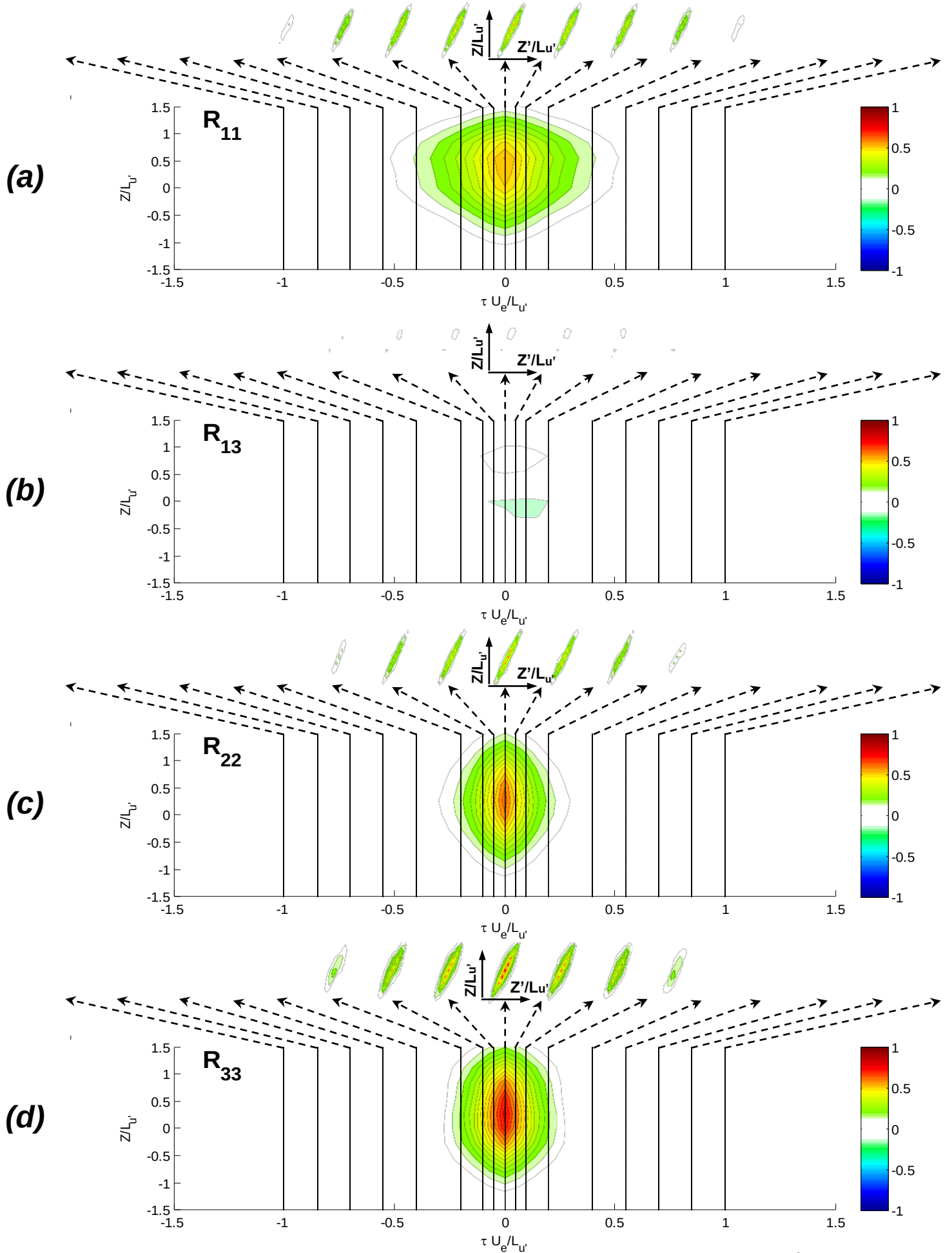


Figure 6.25 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the simple blowing blades at a blowing rate of 2.6%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

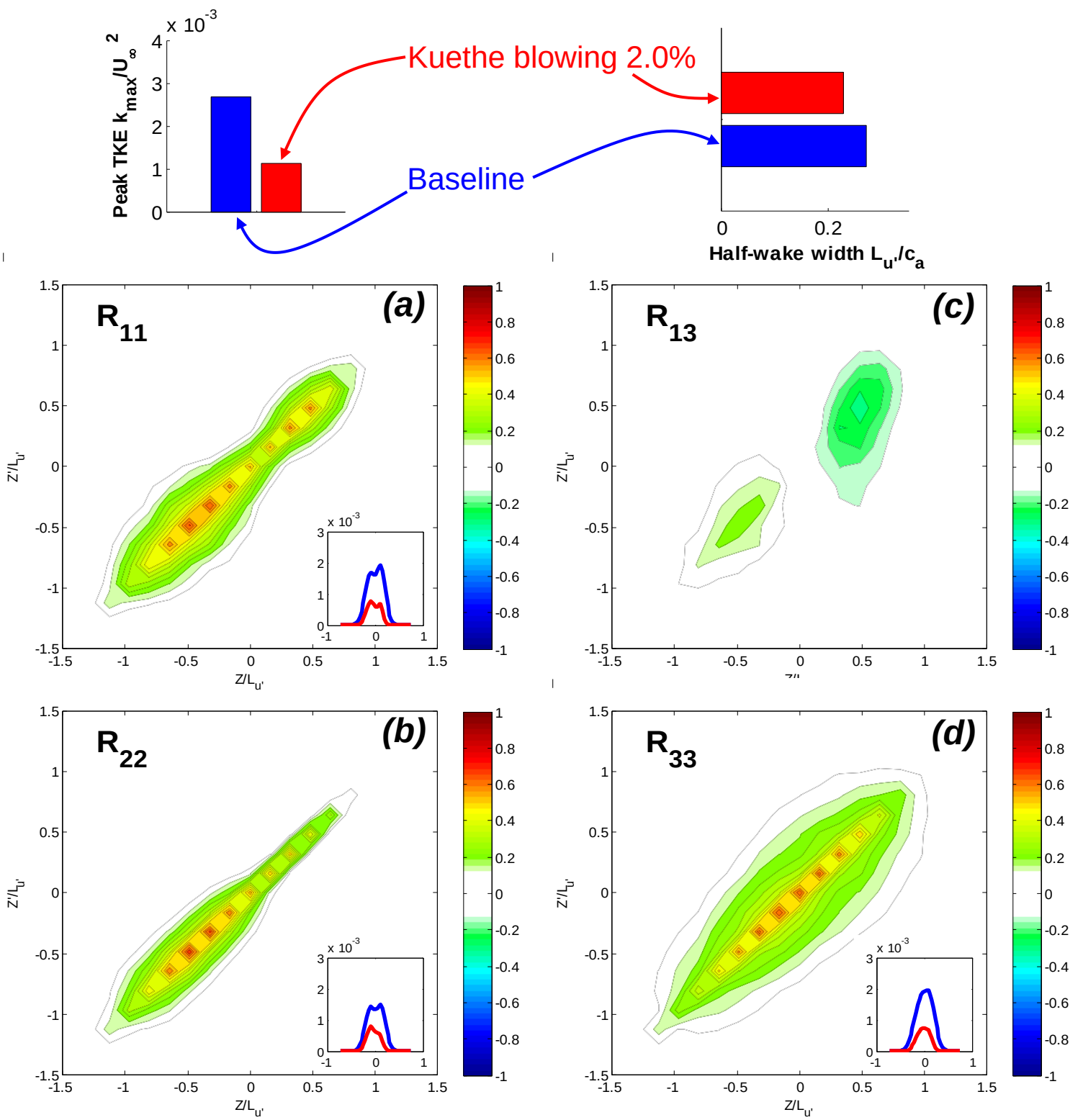
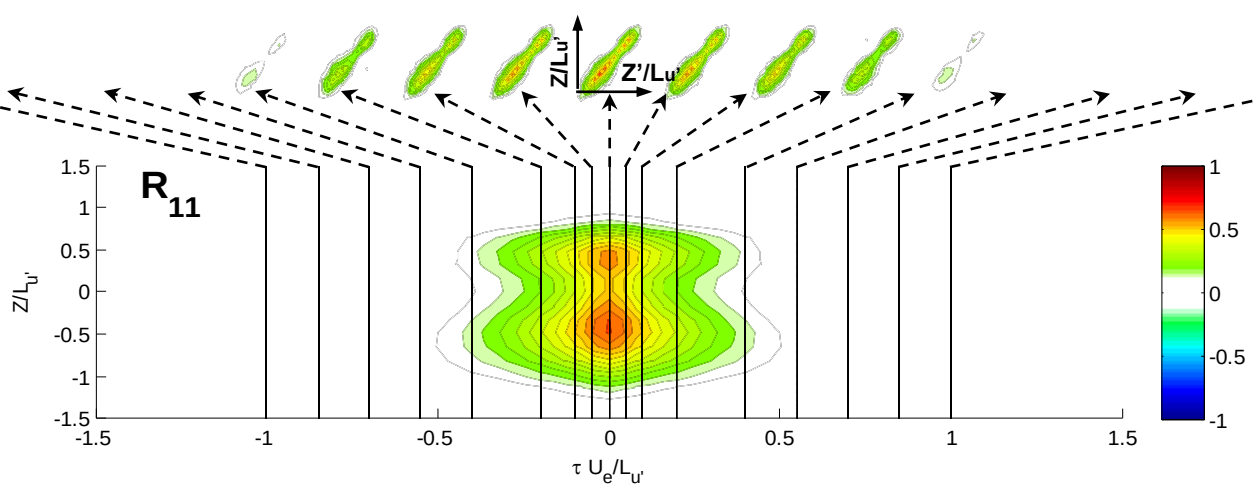
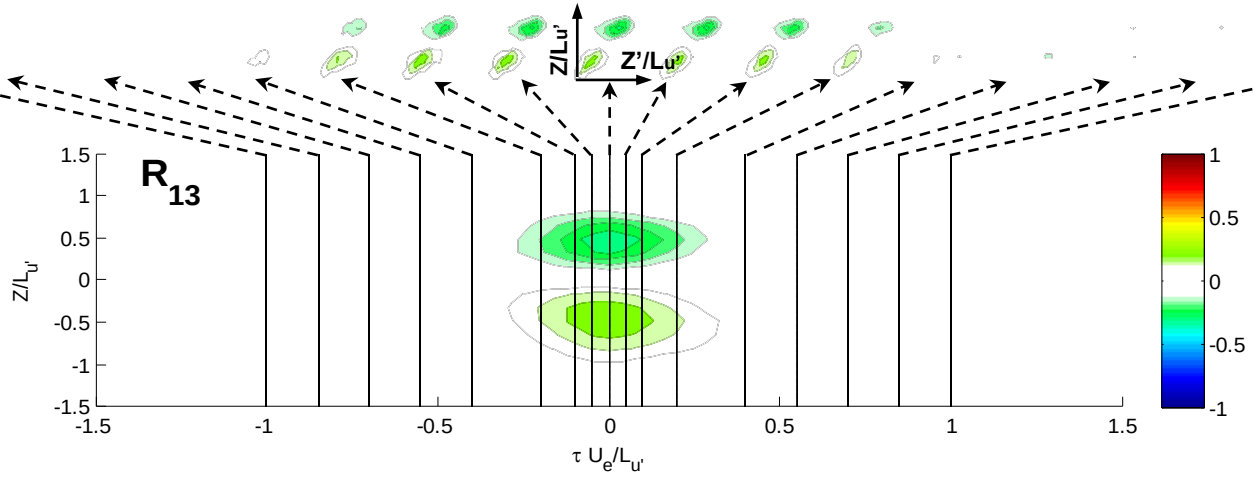


Figure 6.26 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$) normalized on the peak TKE) for the Kuethe blowing blades at a blowing rate of 2.0%, plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$.

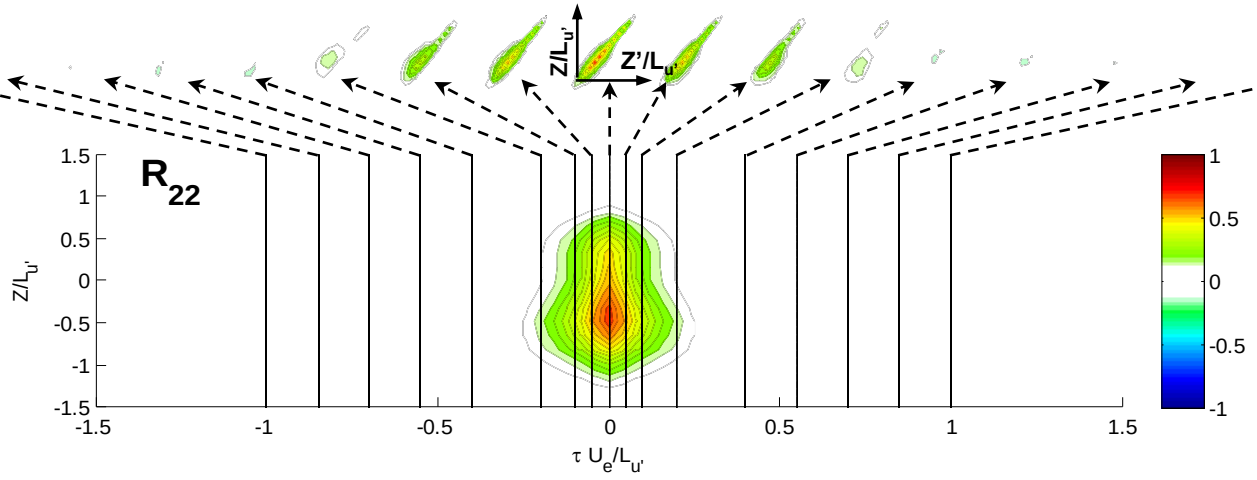
(a)



(b)



(c)



(d)

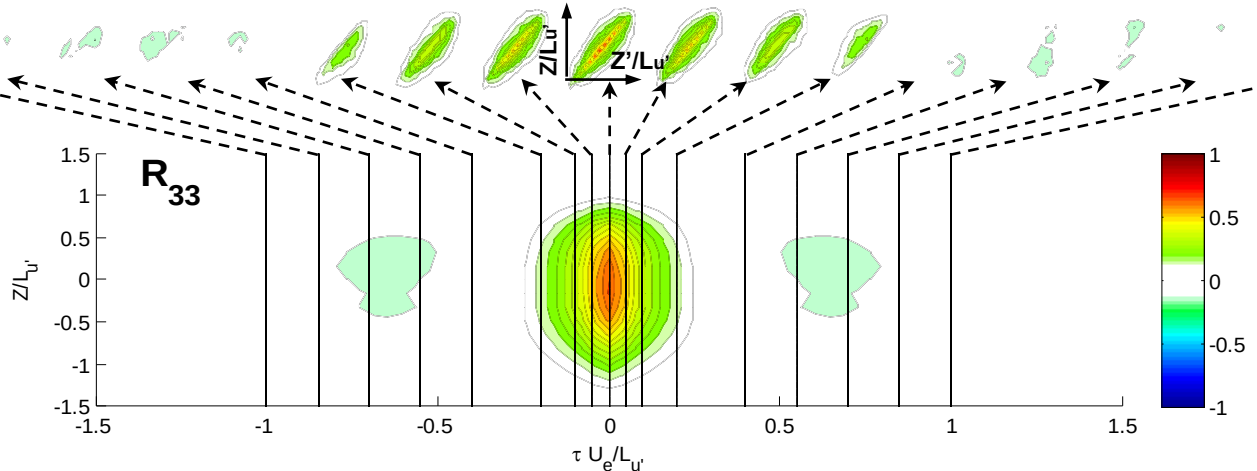


Figure 6.27 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the Kuethe blowing blades at a blowing rate of 2.0%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

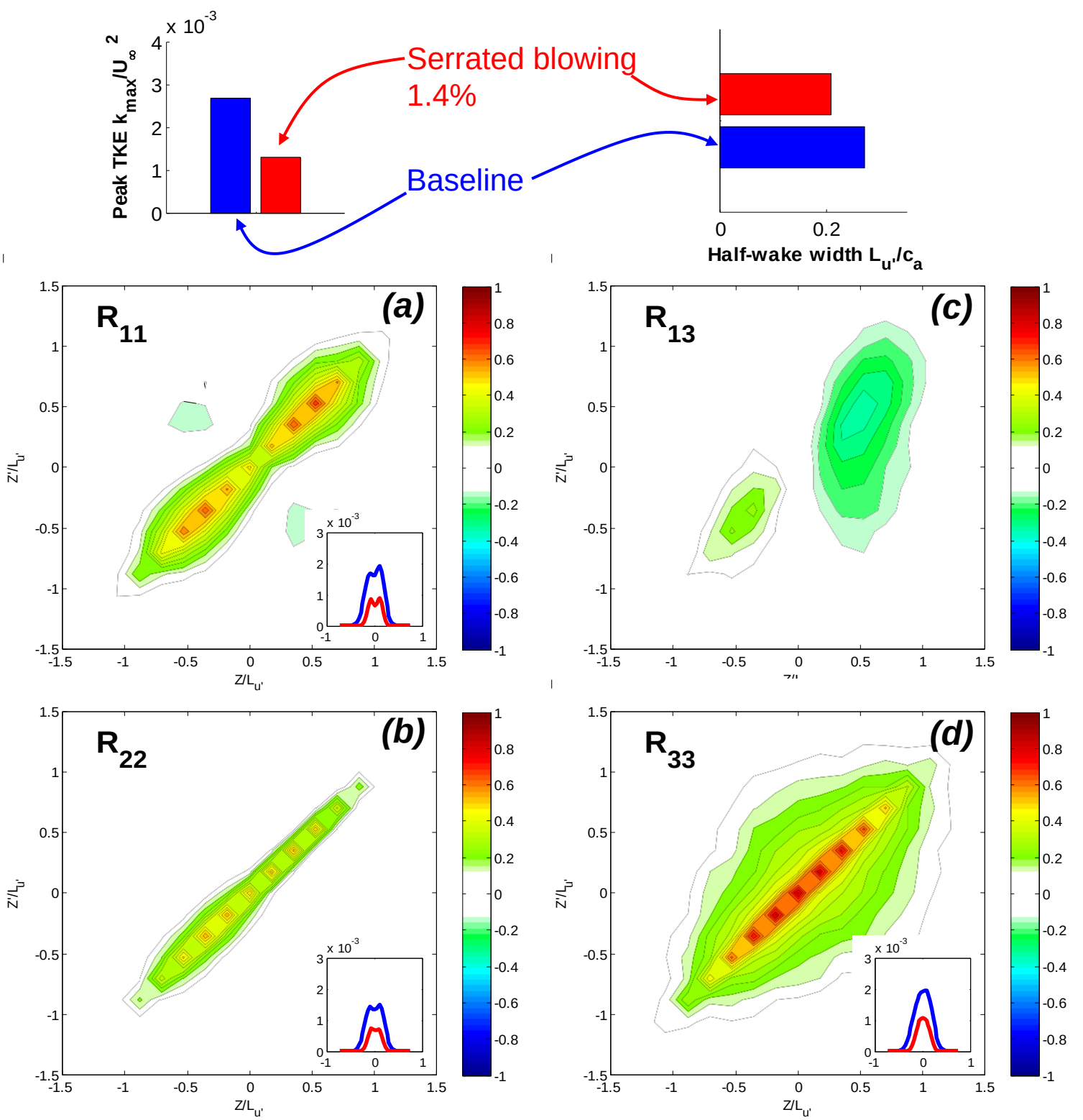
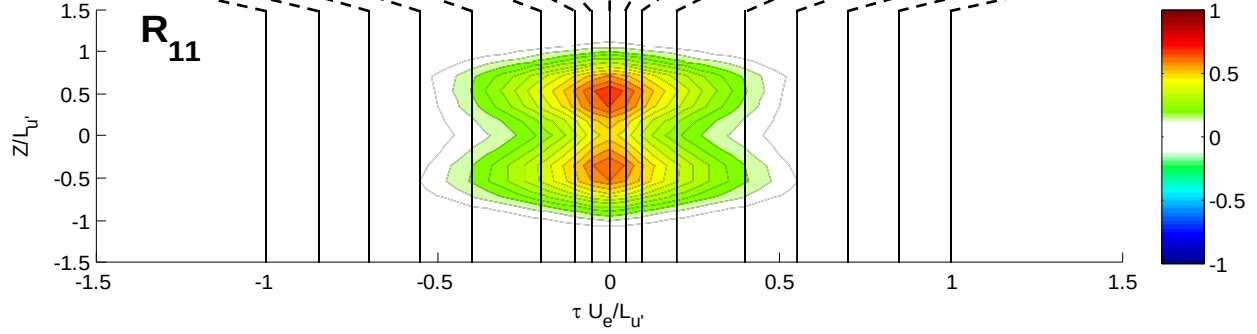
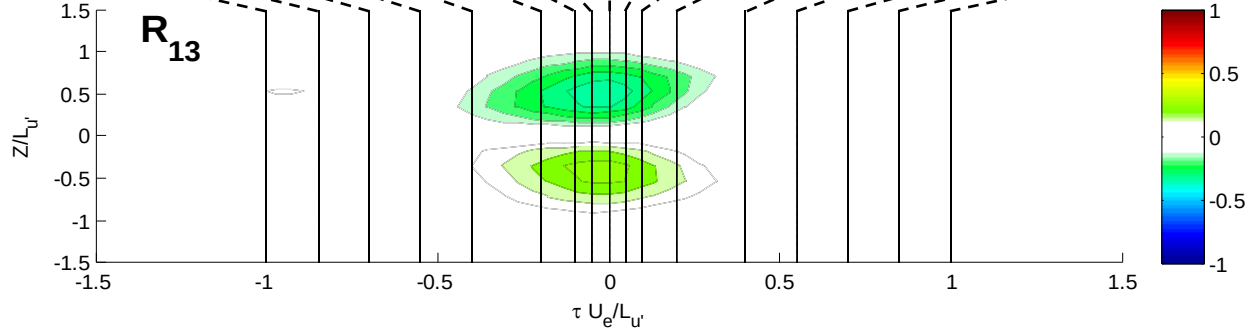


Figure 6.28 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$) normalized on the peak TKE) for the serrated blowing blades at a blowing rate of 1.4%, plotted against normalized normal to wake directions Z/L_u and Z'/L_u .

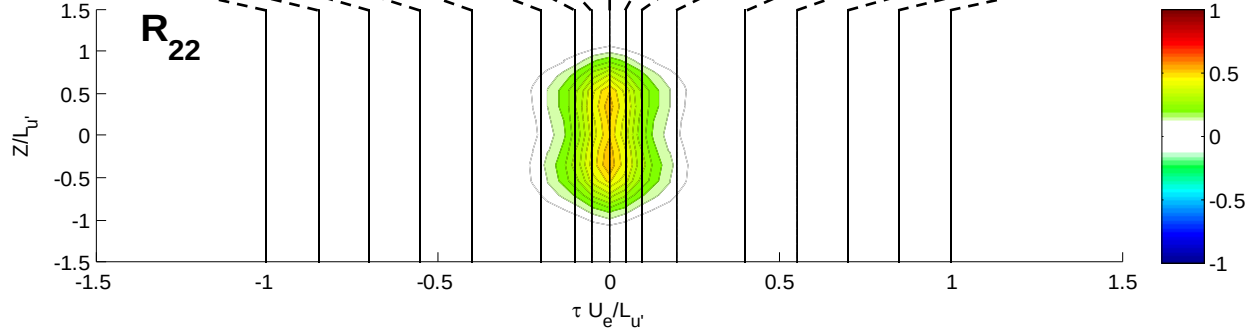
(a)



(b)



(c)



(d)

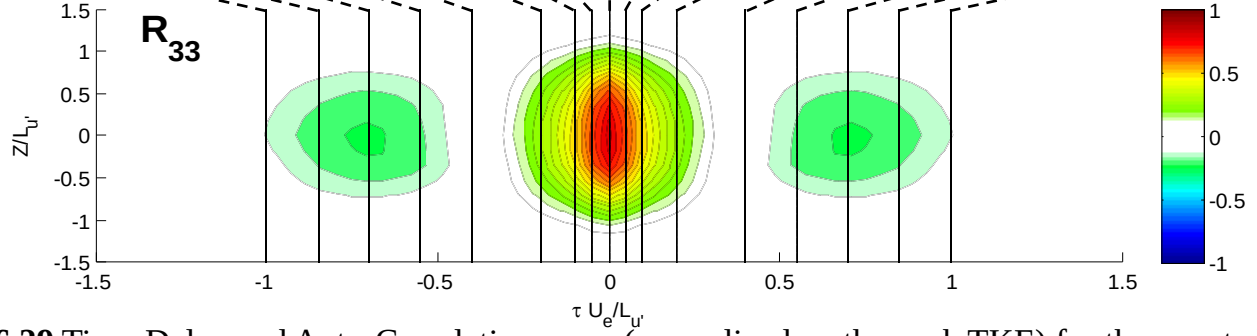


Figure 6.29 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the serrated blowing blades at a blowing rate of 1.4%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

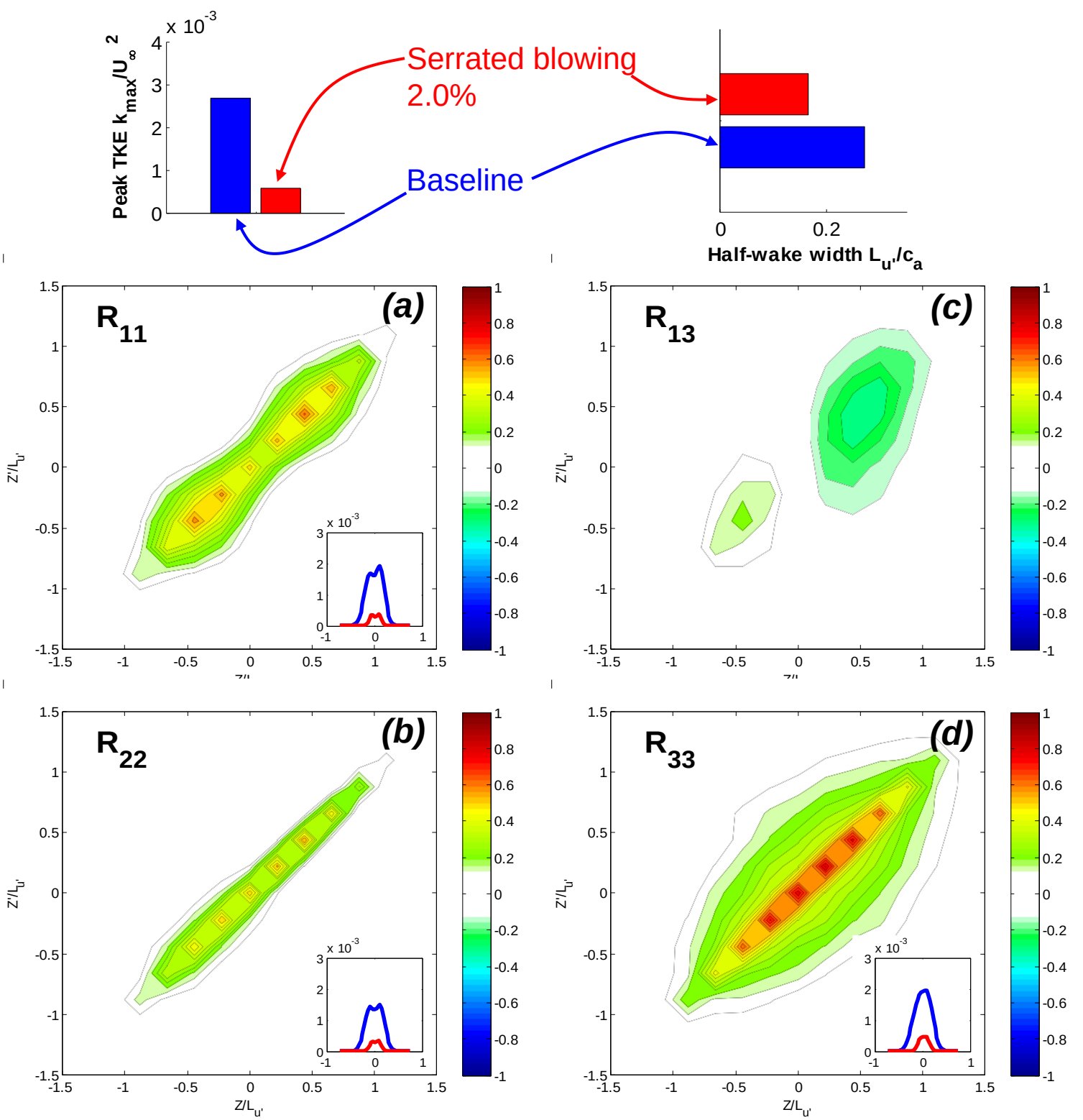
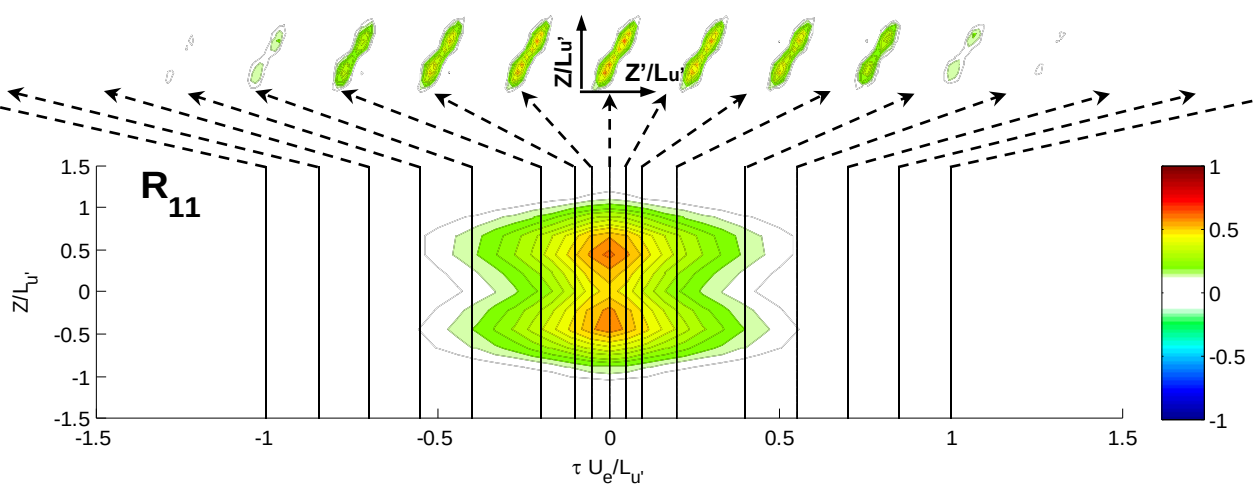
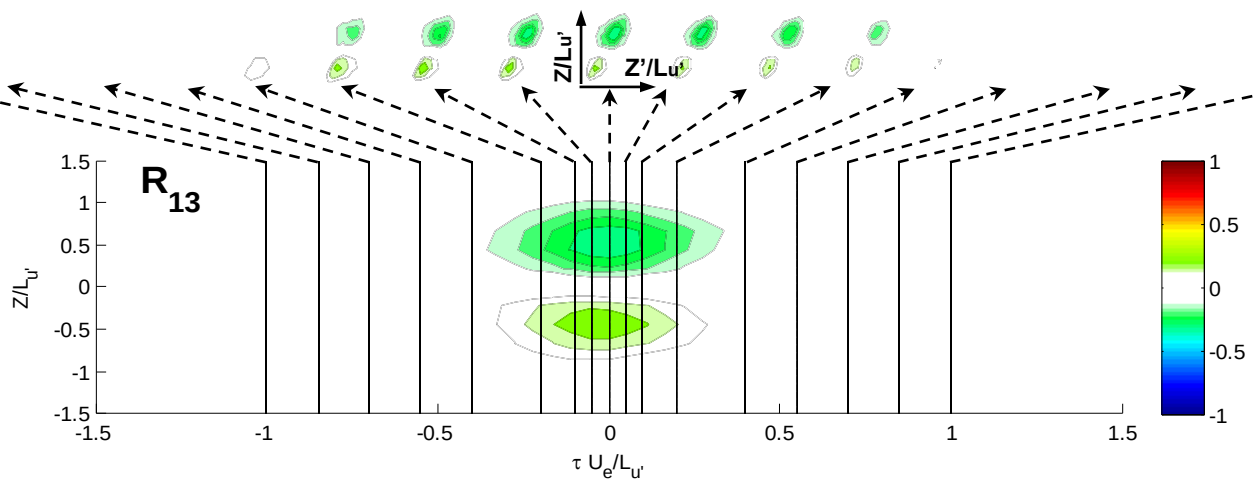


Figure 6.30 Zero-time delay correlation maps ($R_{ij}(Z, Z', 0)$) normalized on the peak TKE) for the serrated blowing blades at a blowing rate of 2.0%, plotted against normalized normal to wake directions $Z/L_{u'}$ and $Z'/L_{u'}$.

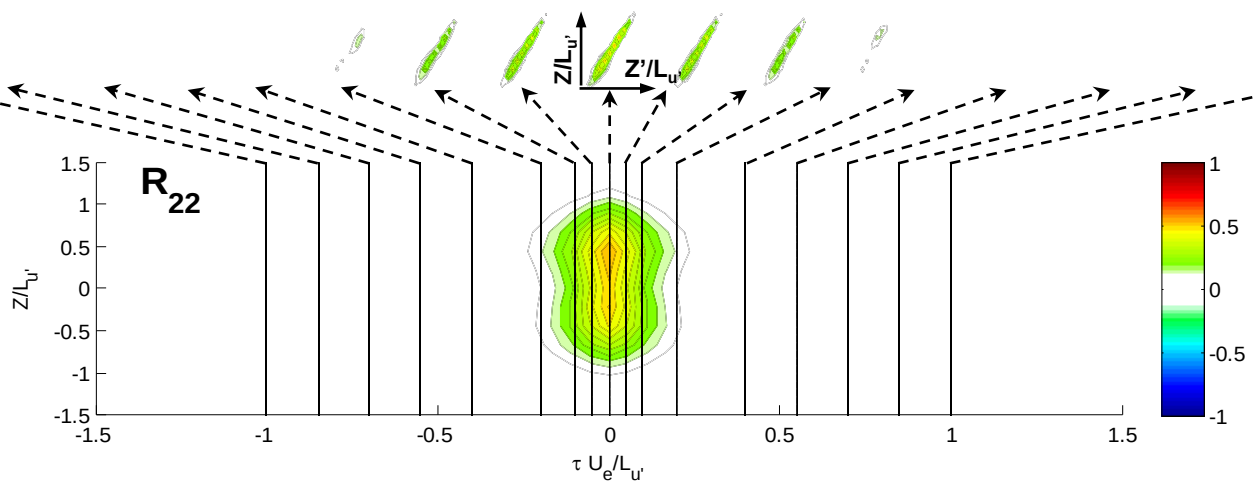
(a)



(b)



(c)



(d)

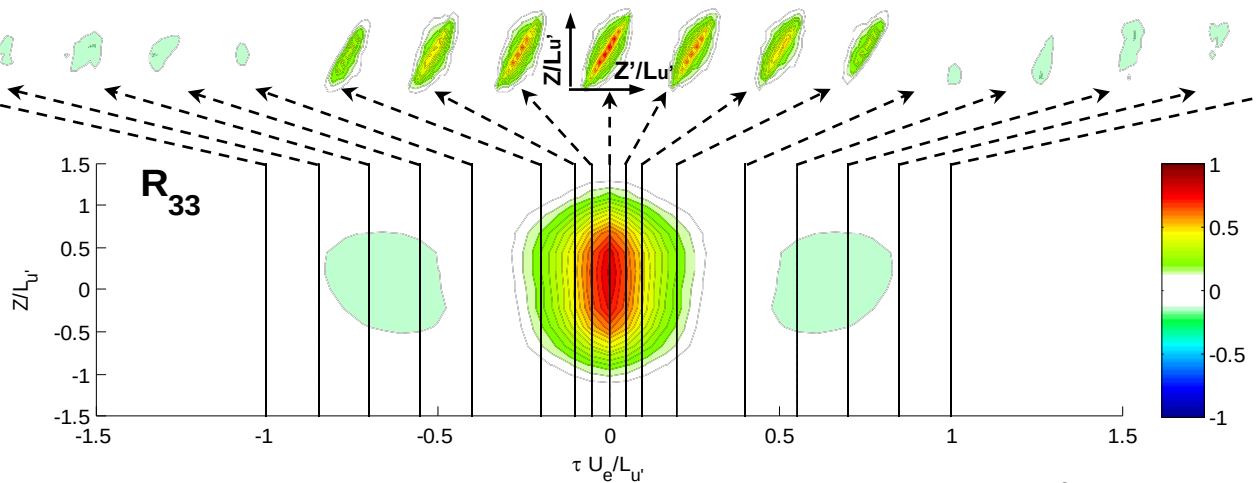
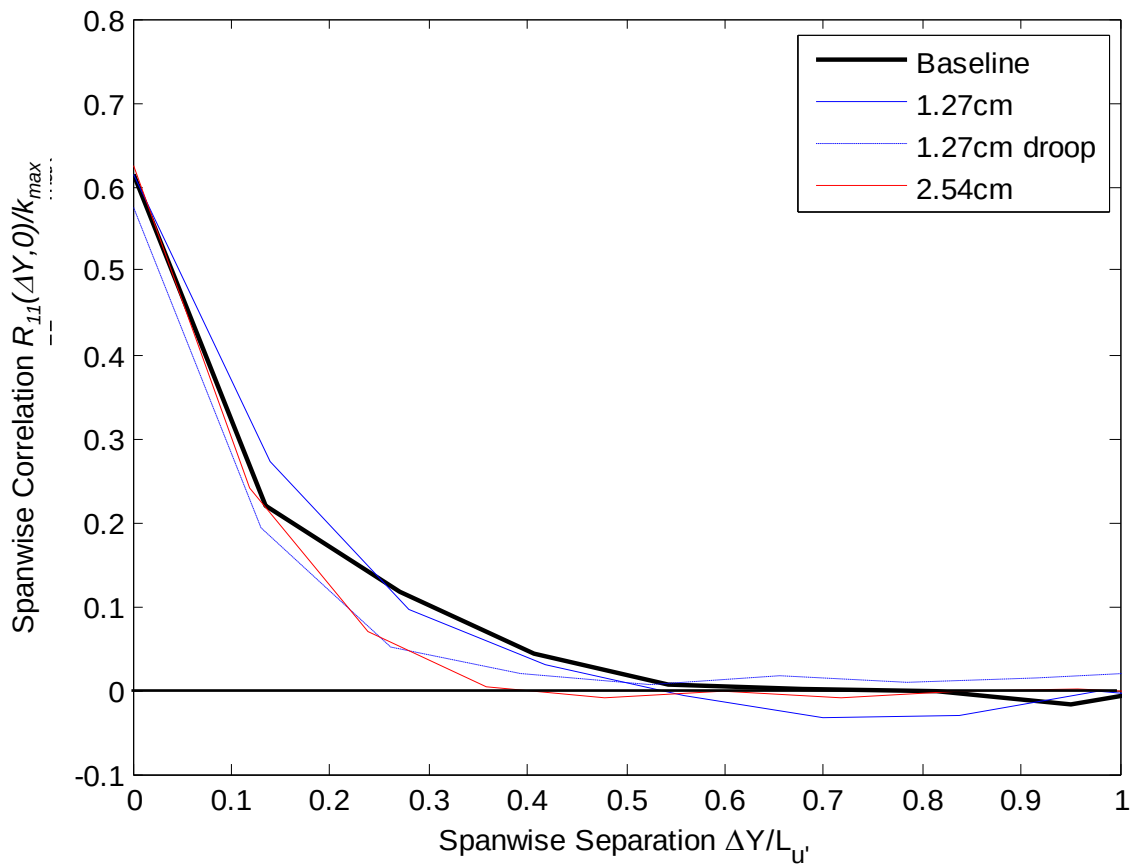
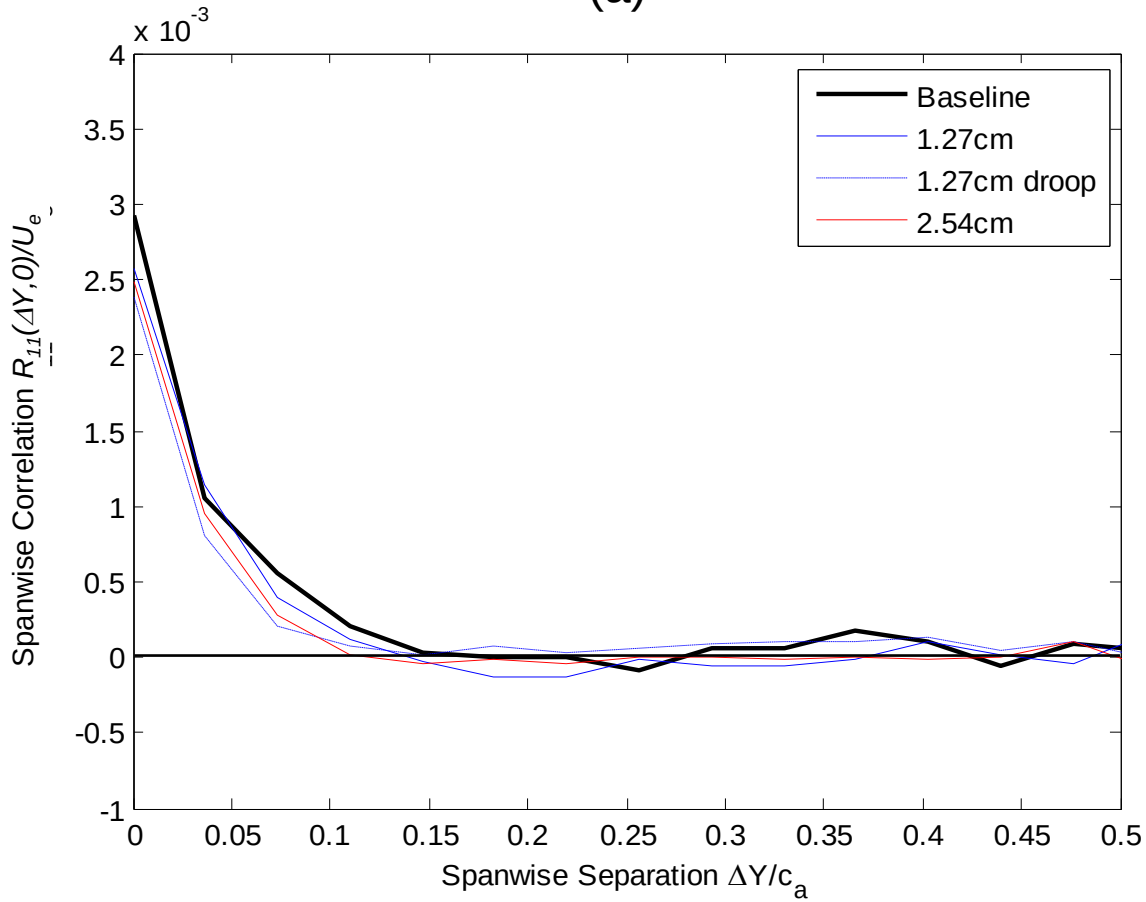


Figure 6.31 Time-Delay and Auto-Correlation maps (normalized on the peak TKE) for the serrated blowing blades at a blowing rate of 2.0%. The auto-correlation $R_{ij}(Z, Z, \tau)$ is plotted against normal-to-wake distance $Z/L_{u'}$ on the vertical axis and normalized time delay $\tau U_e/L_{u'}$ on the horizontal. For each component, the time-delay correlation maps $R_{ij}(Z, Z', \tau)$ evaluated at discrete time delays indicated by the arrows above the auto-correlation plot.

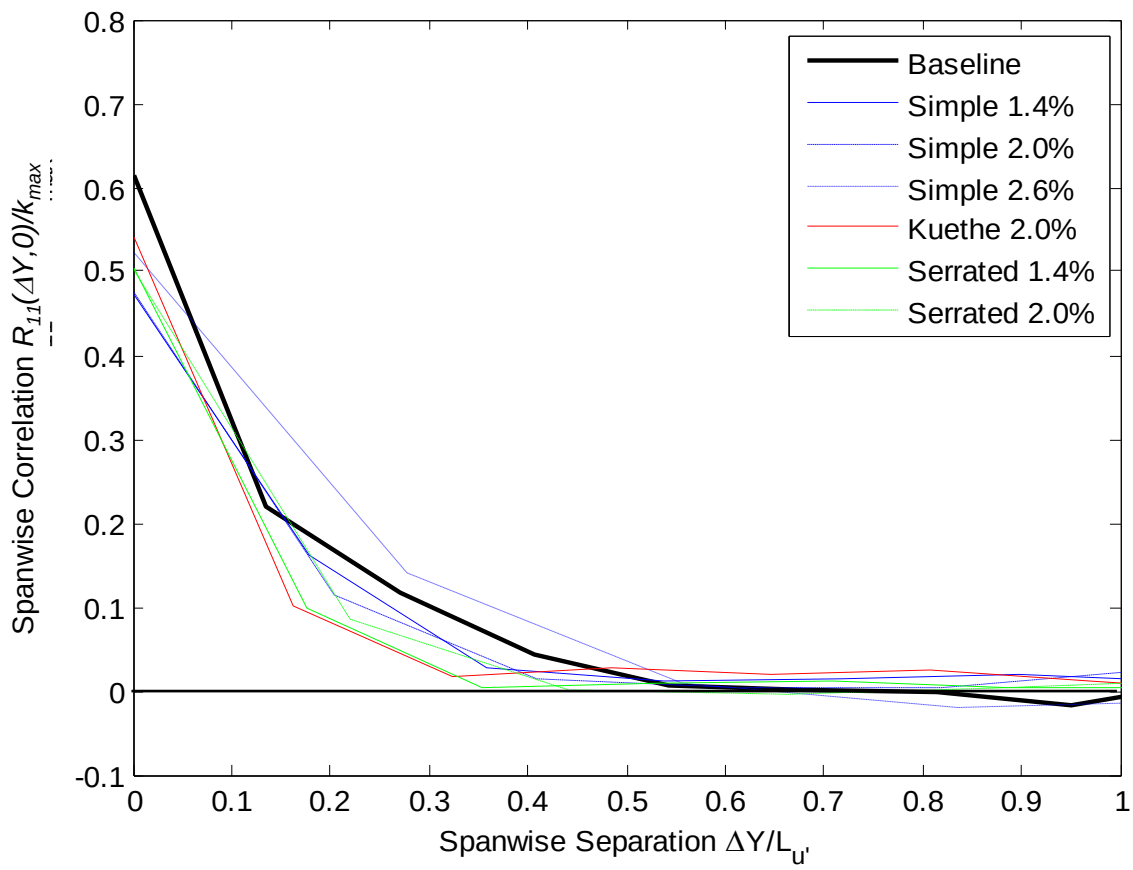


(a)

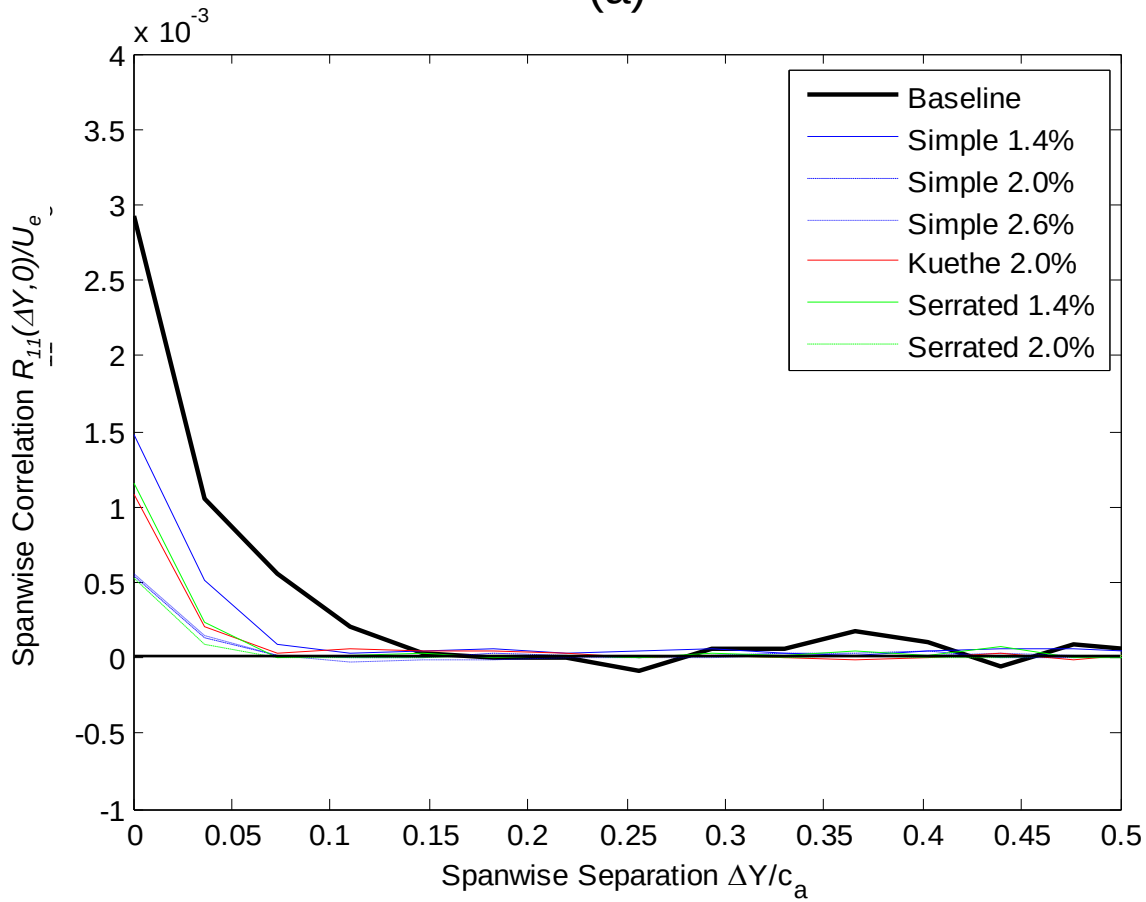


(b)

Figure 6.32 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the R_{11} component for the baseline and serrated trailing edge blades. Correlations are normalized on (a) the peak TKE and (b) the edge velocity.



(a)



(b)

Figure 6.33 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the R_{11} component for the baseline and trailing edge blowing blades. Correlations are normalized on (a) the peak TKE and (b) the edge velocity.

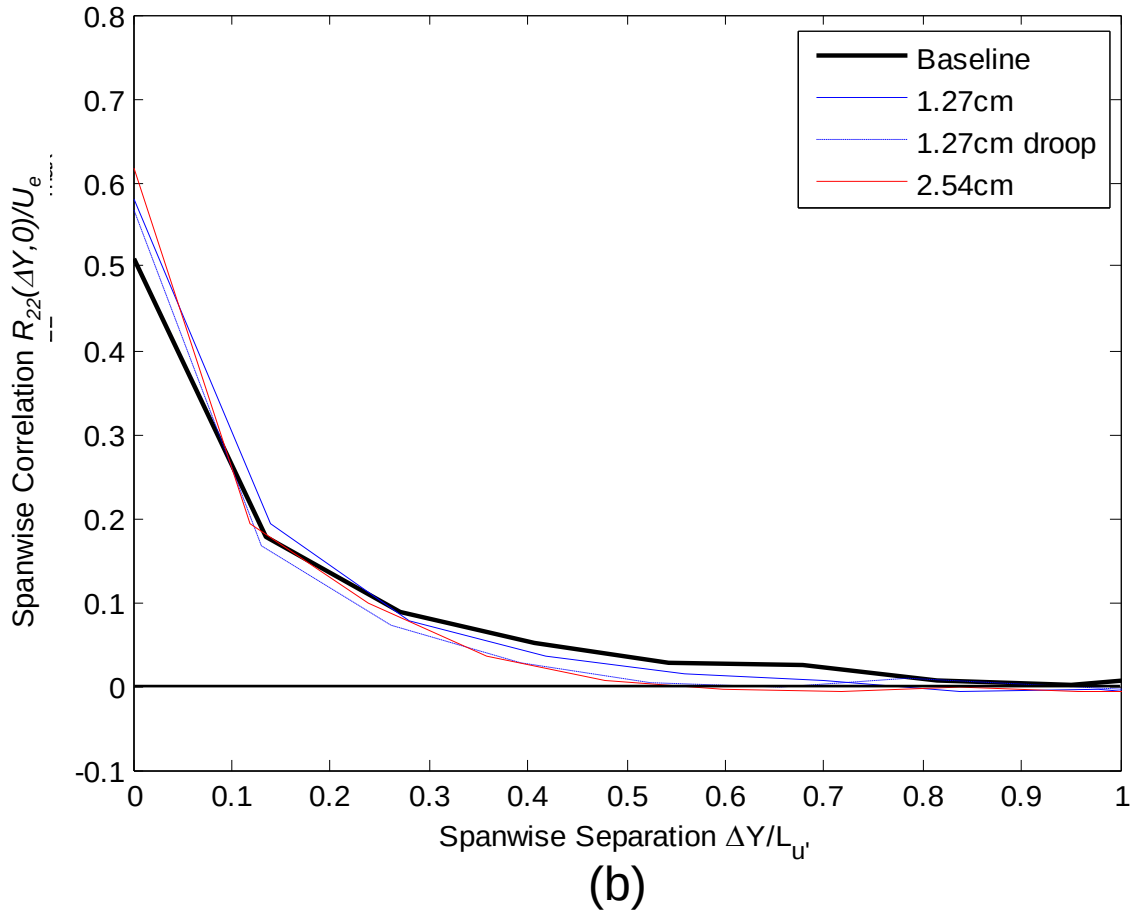
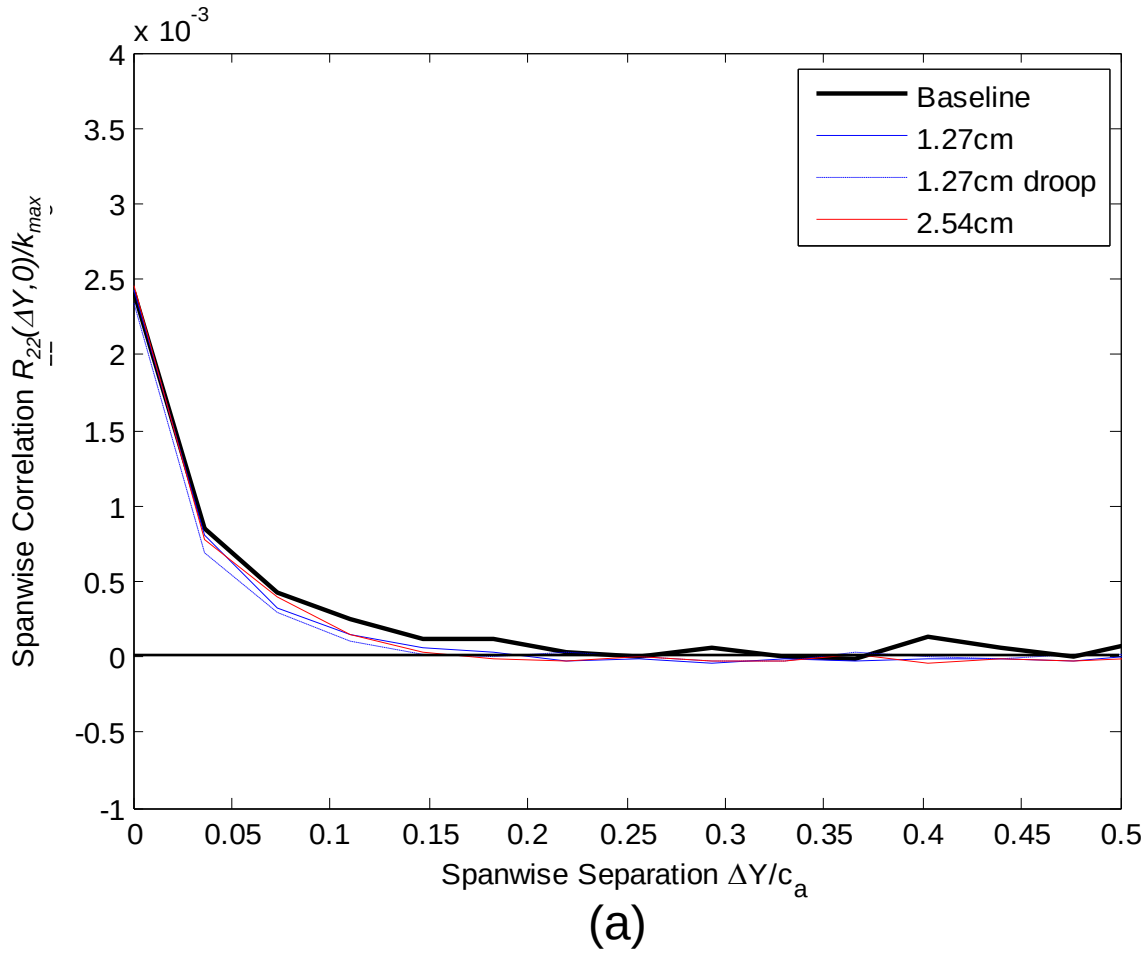
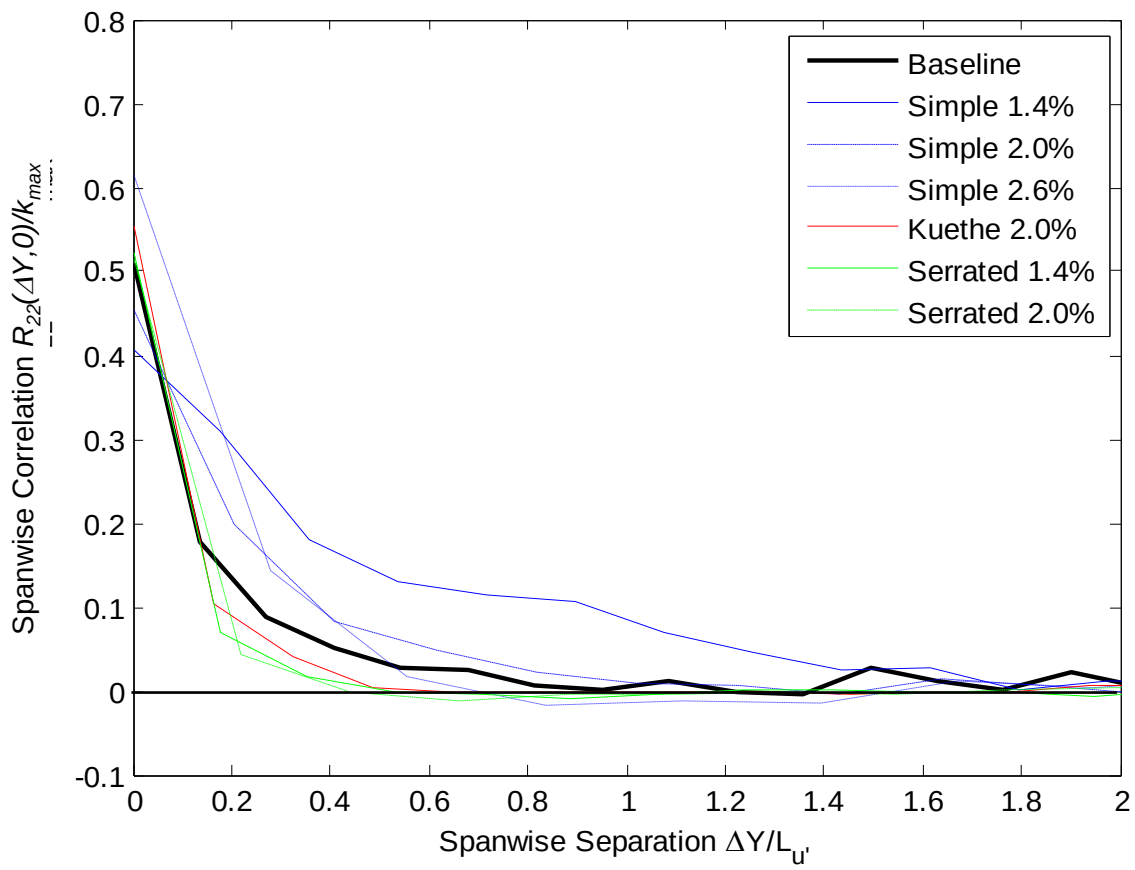
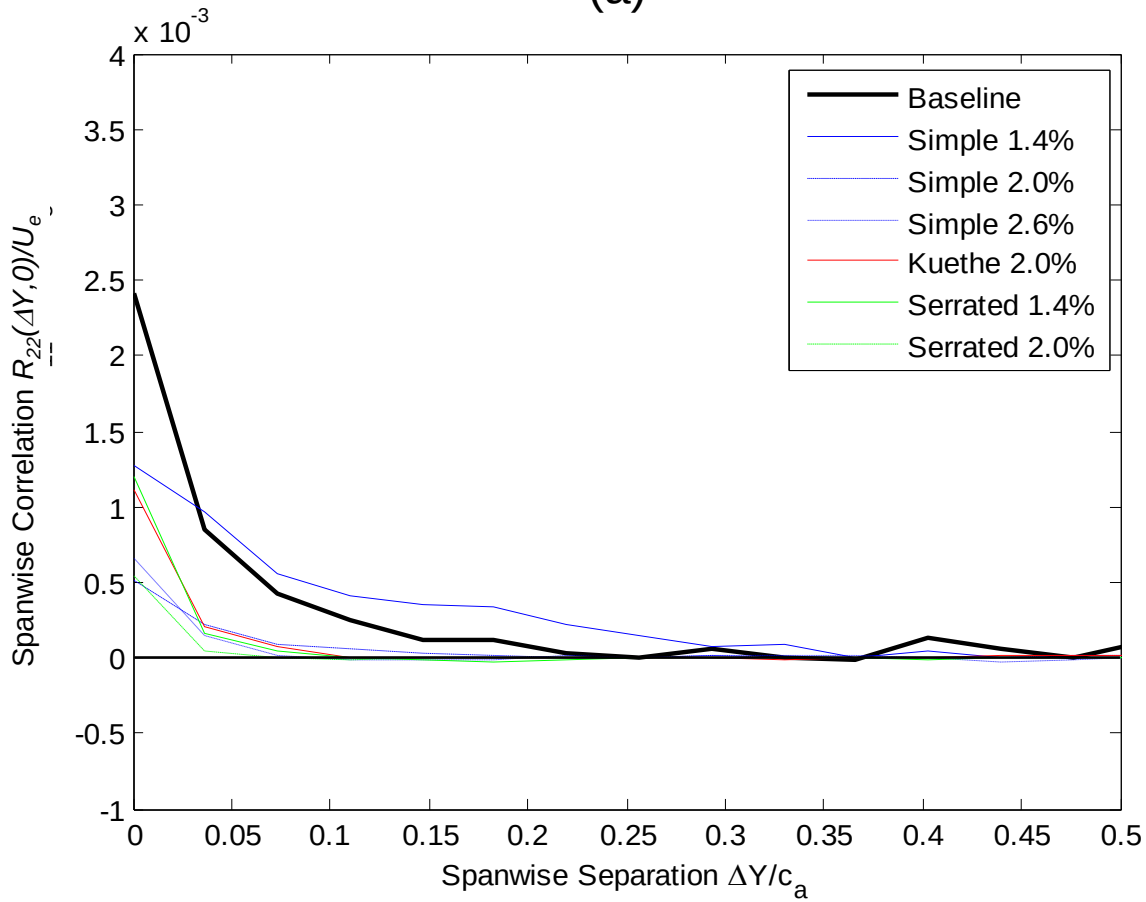


Figure 6.34 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the R_{22} component for the baseline and serrated trailing edge blades. Correlations are normalized on (a) the peak TKE and (b) the edge velocity.

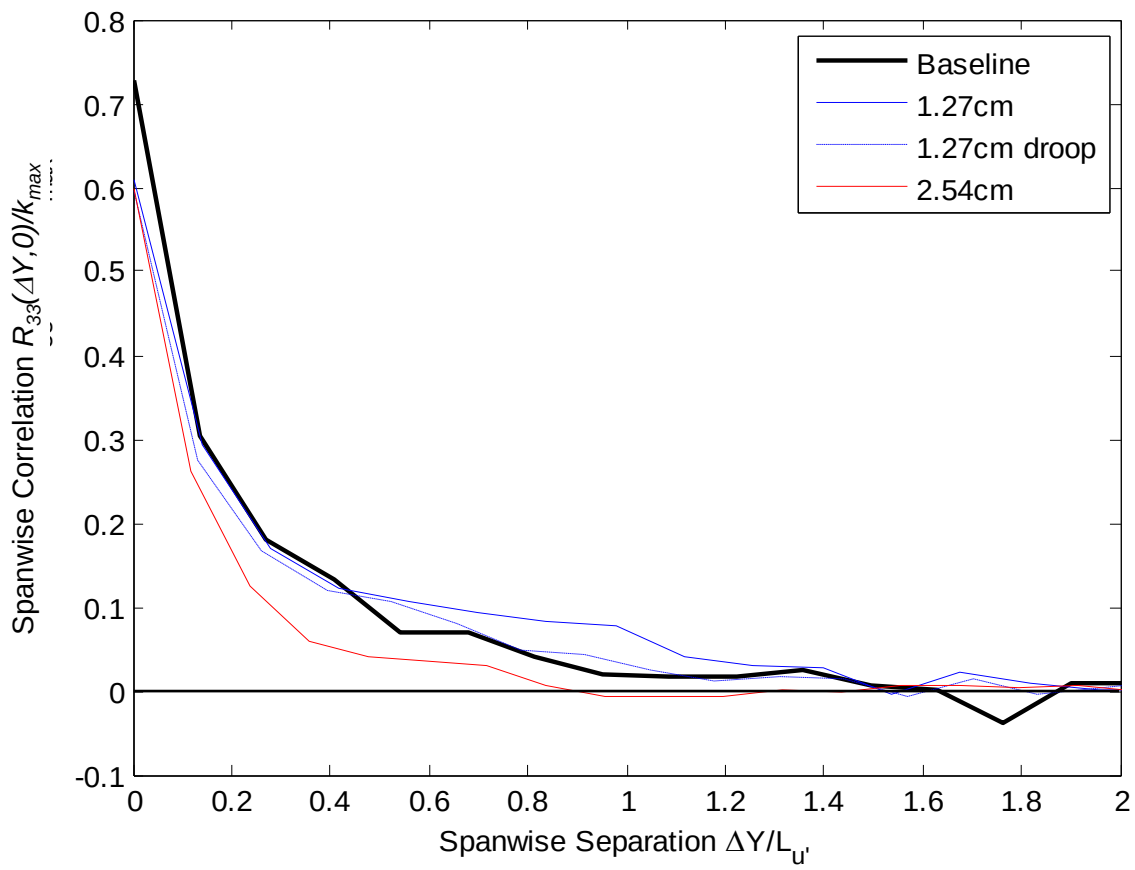


(a)

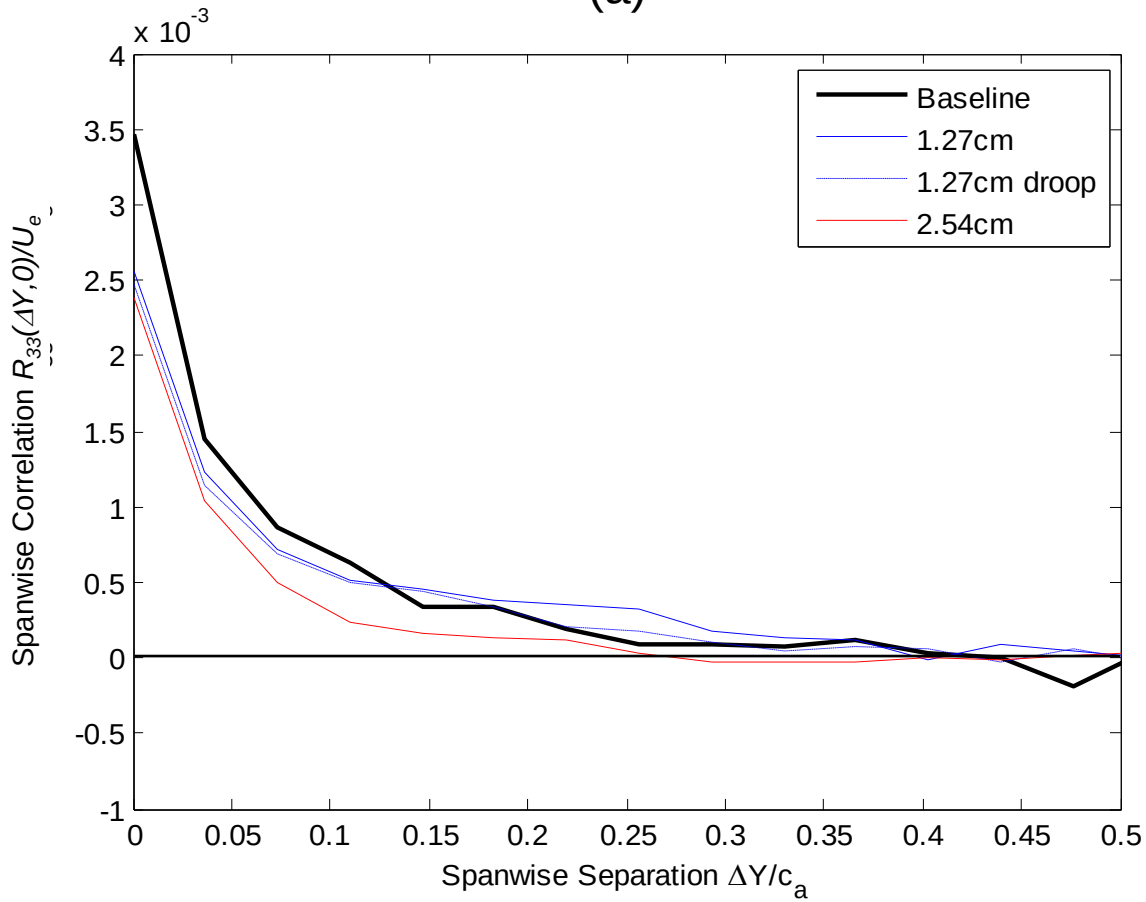


(b)

Figure 6.35 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the R_{22} component for the baseline and trailing edge blowing blades. Correlations are normalized on (a) the peak TKE and (b) the edge velocity.

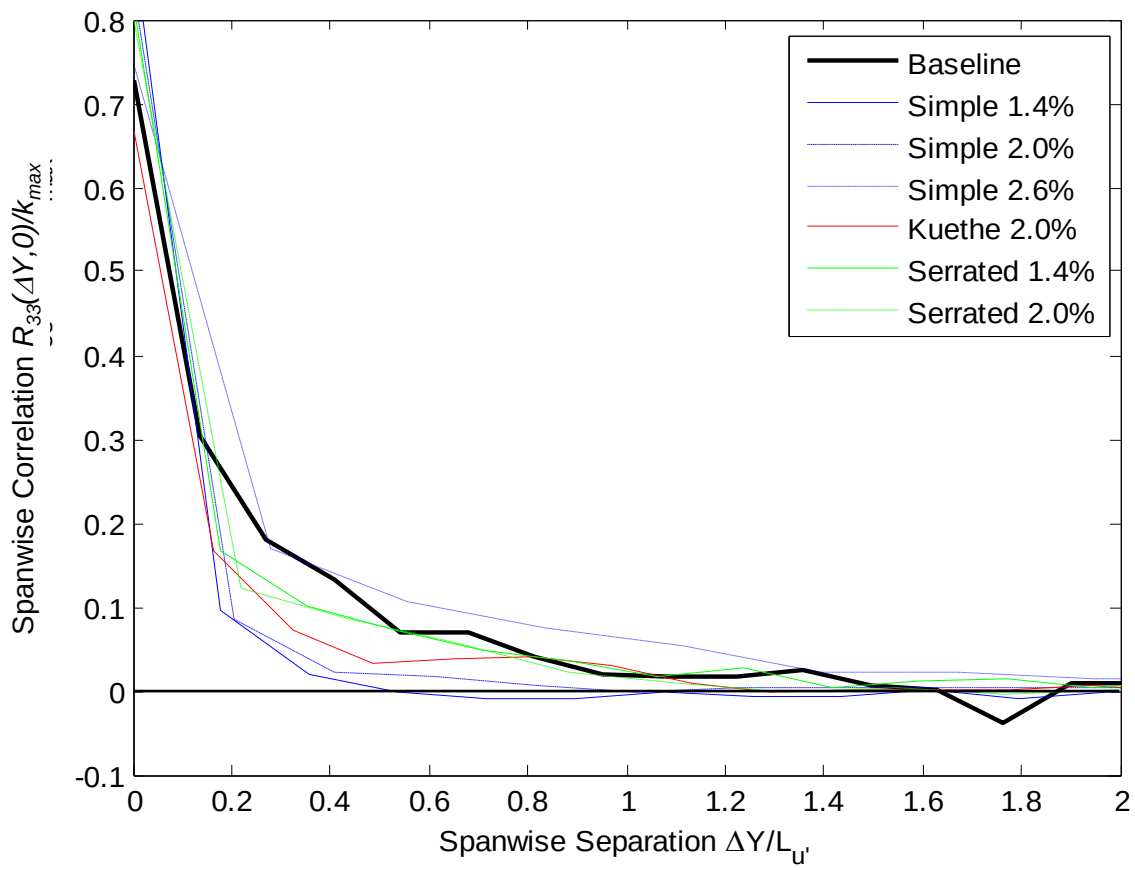


(a)

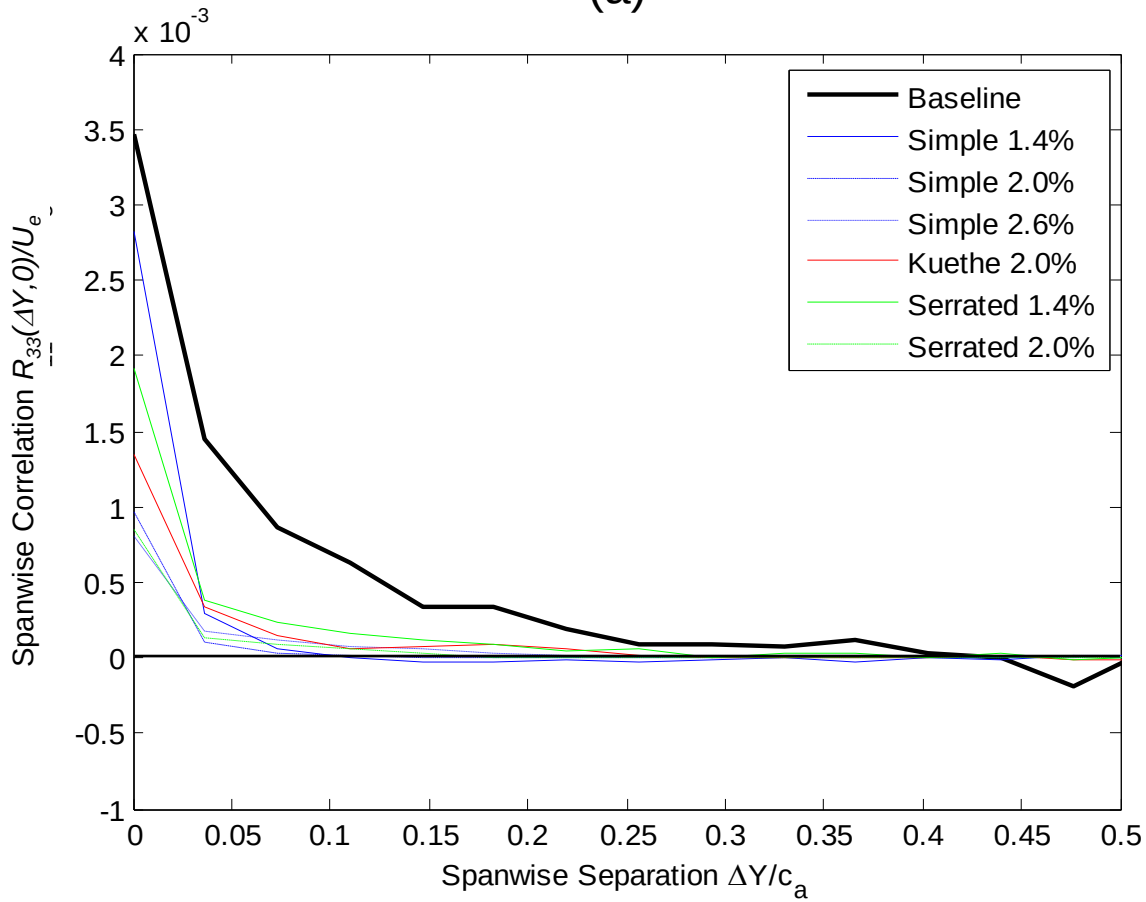


(b)

Figure 6.36 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the R_{33} component for the baseline and serrated trailing edge blades. Correlations are normalized on (a) the peak TKE and (b) the edge velocity.



(a)



(b)

Figure 6.37 Comparison of normalized (a) and absolute (b) zero-time delay spanwise correlation curves of the R_{33} component for the baseline and trailing edge blowing blades. Correlations are normalized on (a) the peak TKE and (b) the edge velocity.

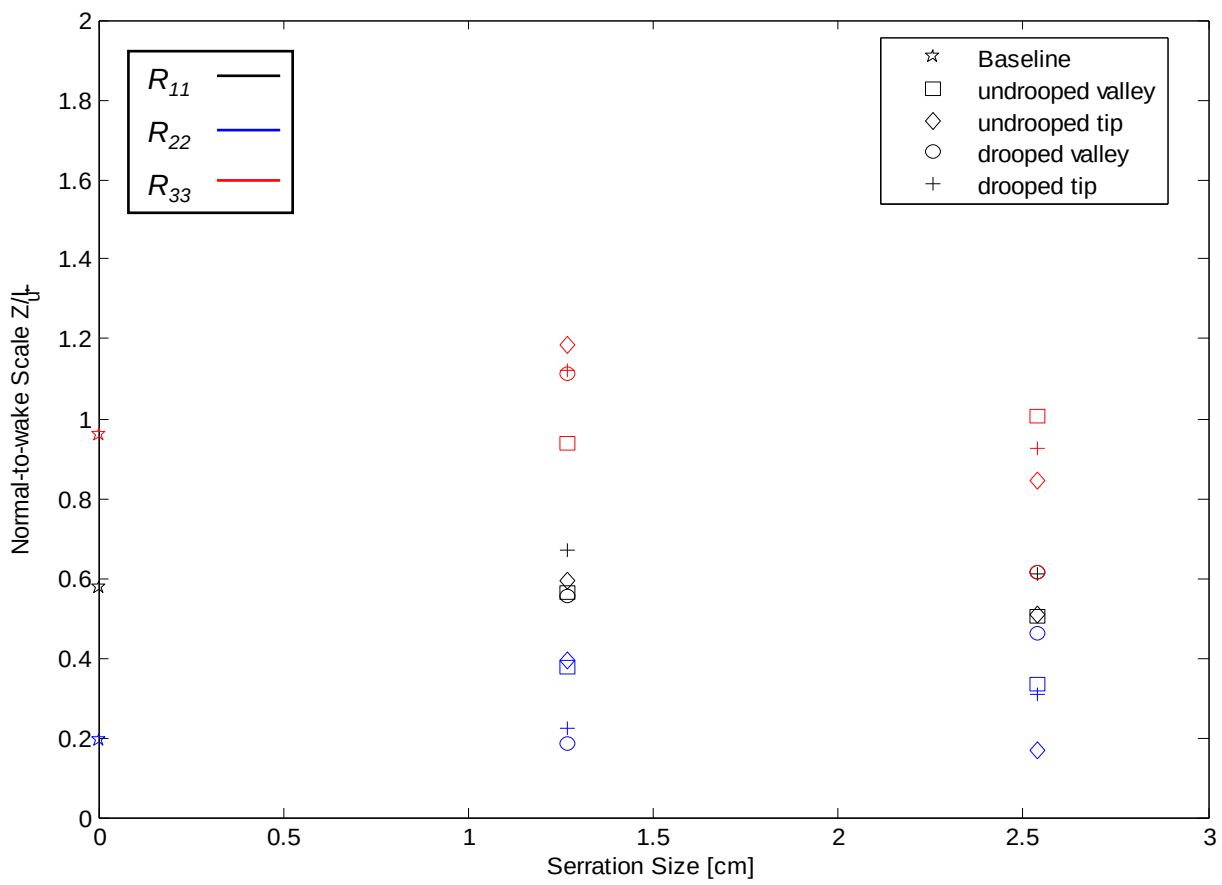


Figure 6.38 Effects of the serration size on the normal-to-wake scales.

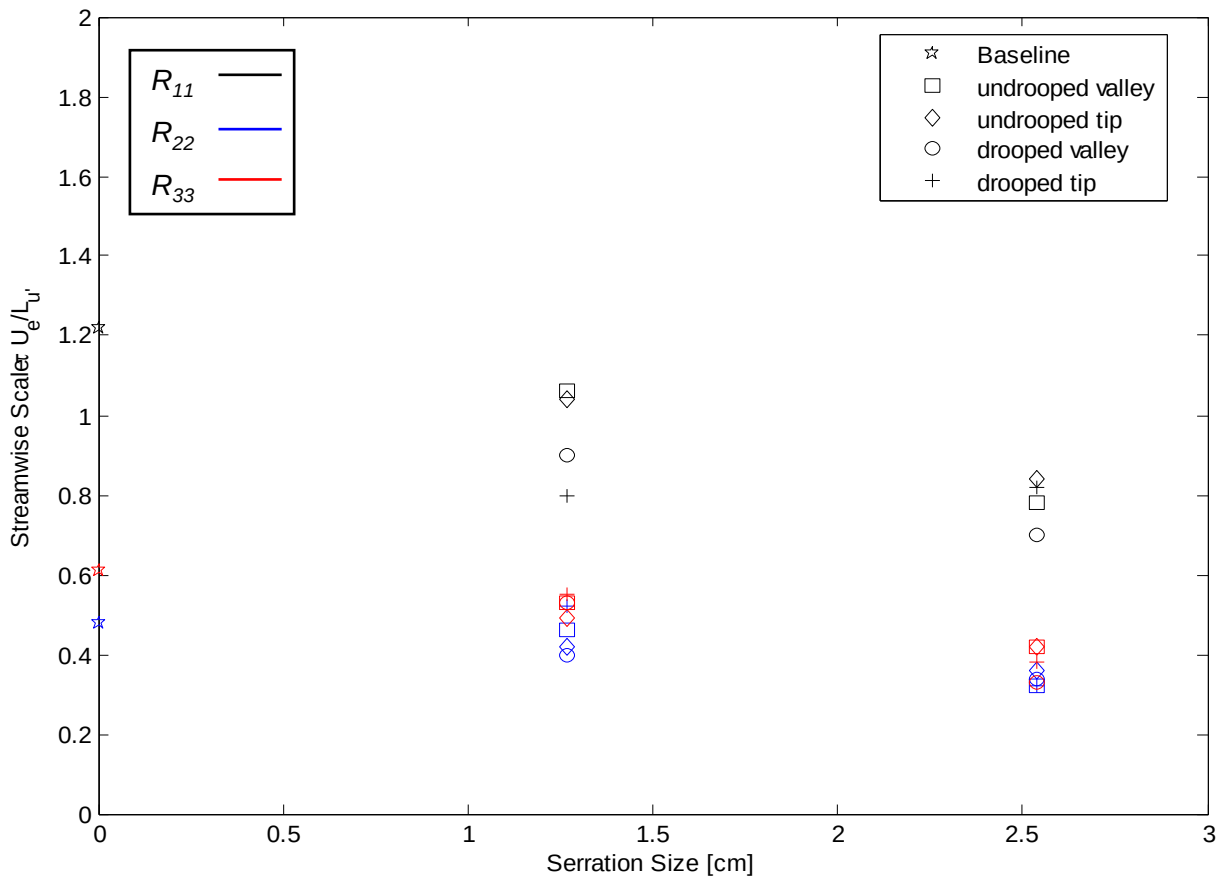


Figure 6.39 Effects of the serration size on the streamwise scales.

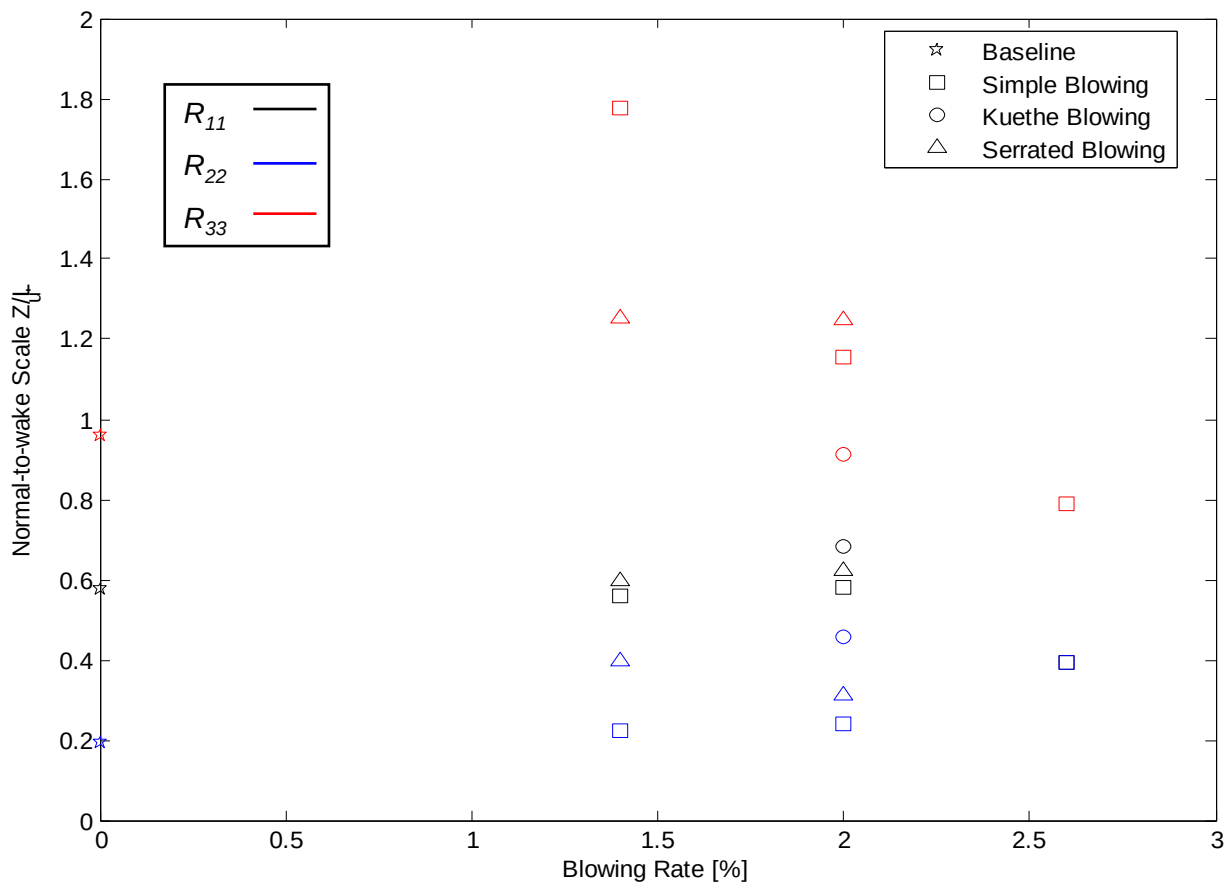


Figure 6.40 Effects of the blowing rate on the normal-to-wake scales.

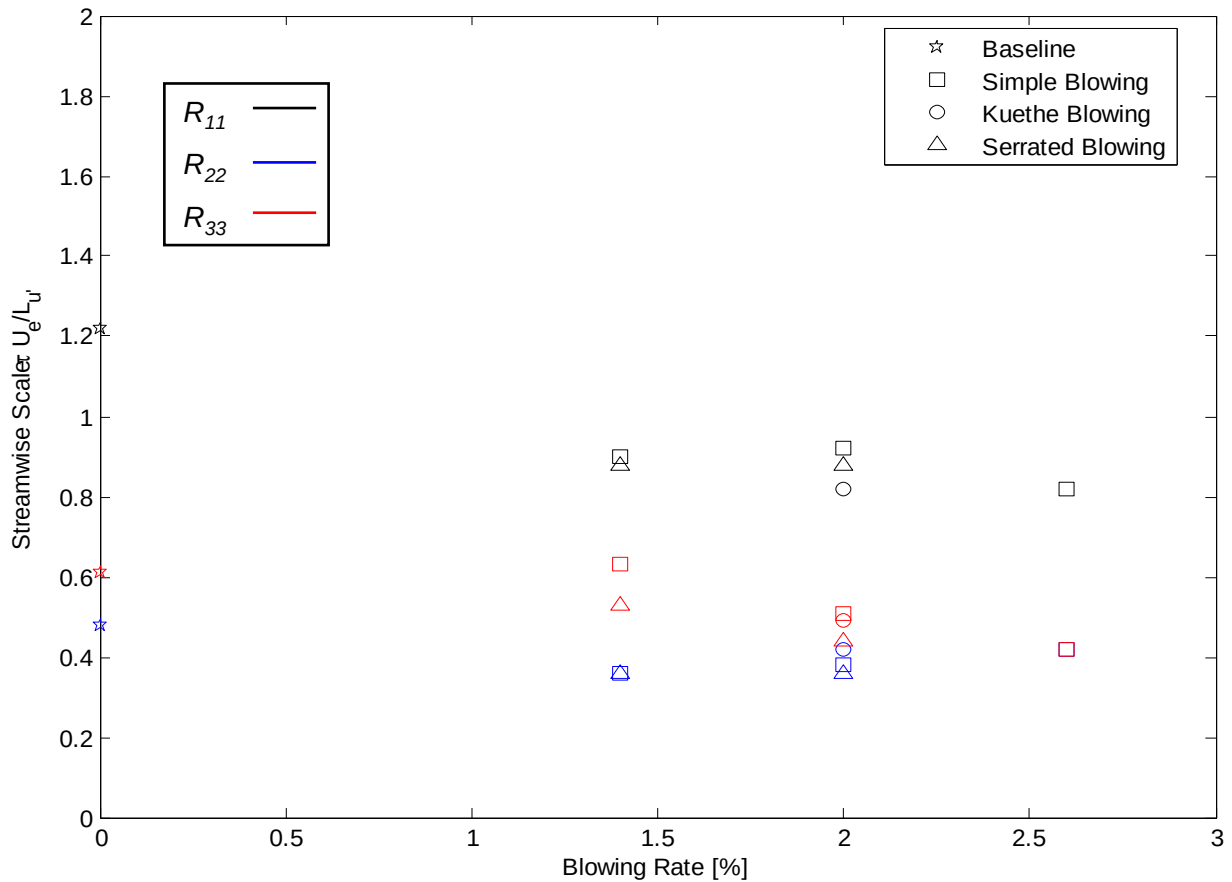


Figure 6.41 Effects of the blowing rate on the streamwise scales.

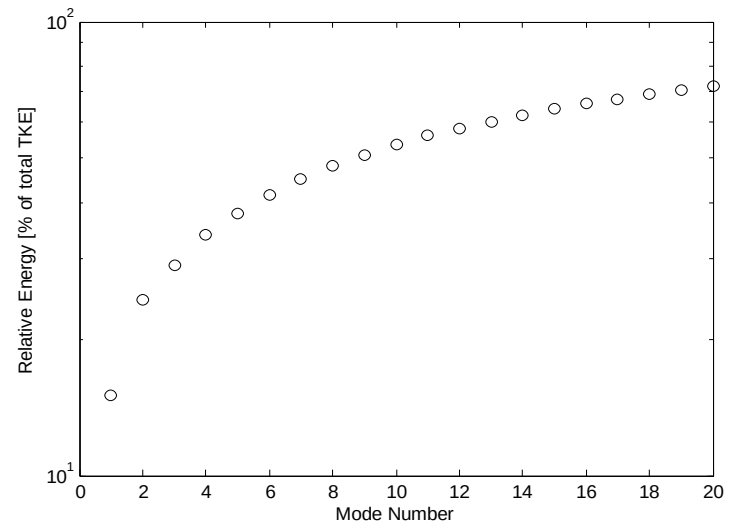
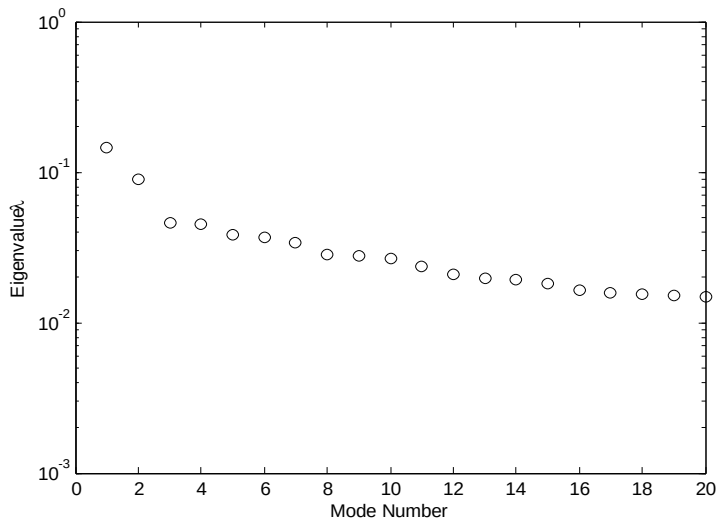


Figure 6.42 POD eigenvalue spectrum of the baseline blades in the Z-direction (left) and cumulative energy spectrum (right).

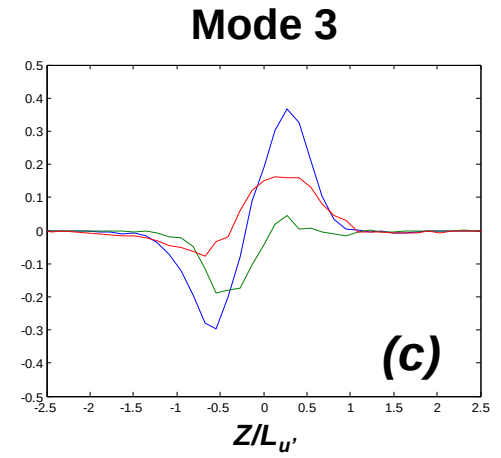
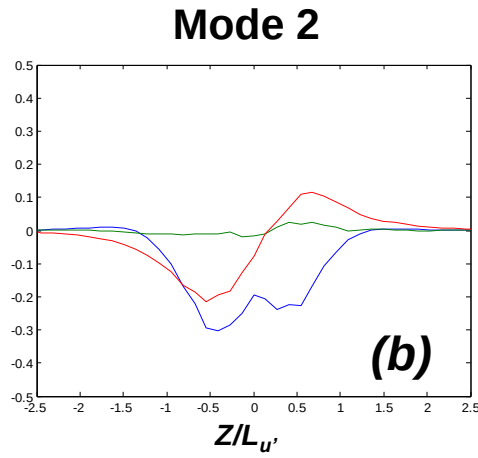
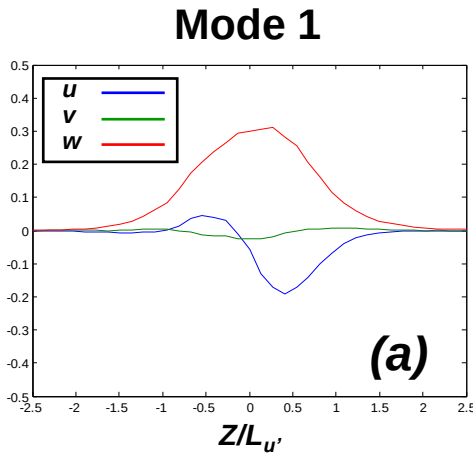


Figure 6.43 Modal profiles of the first three modes obtained from the POD of the baseline blades.

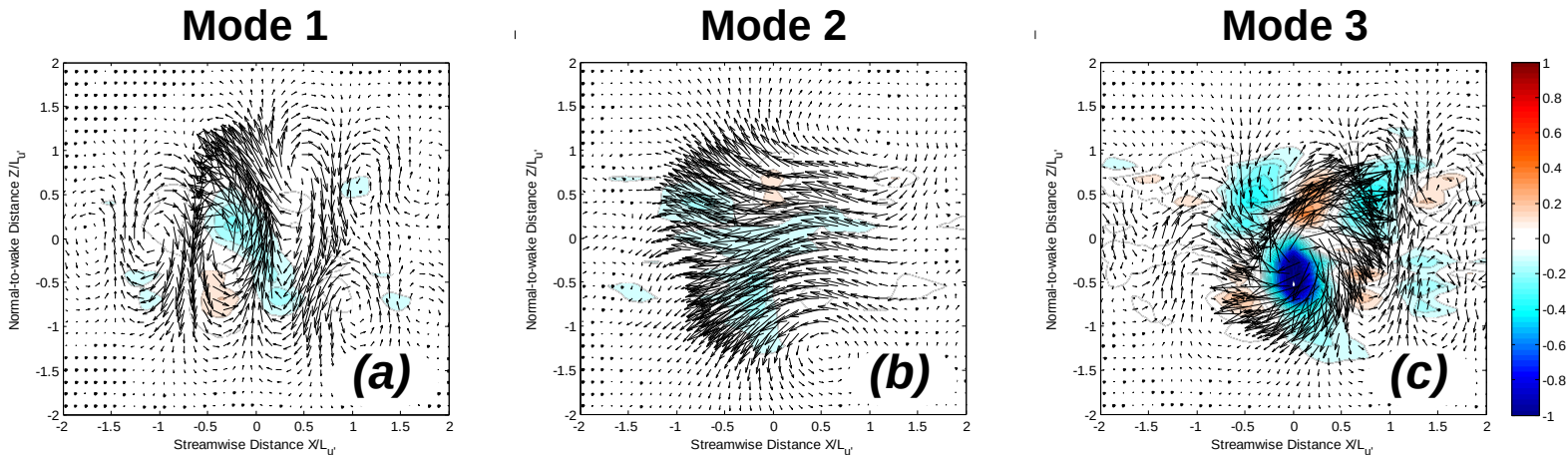


Figure 6.44 Compact Eddy Structures associated with the first 3 modes - Baseline Blades. Contours indicate spanwise velocity component.

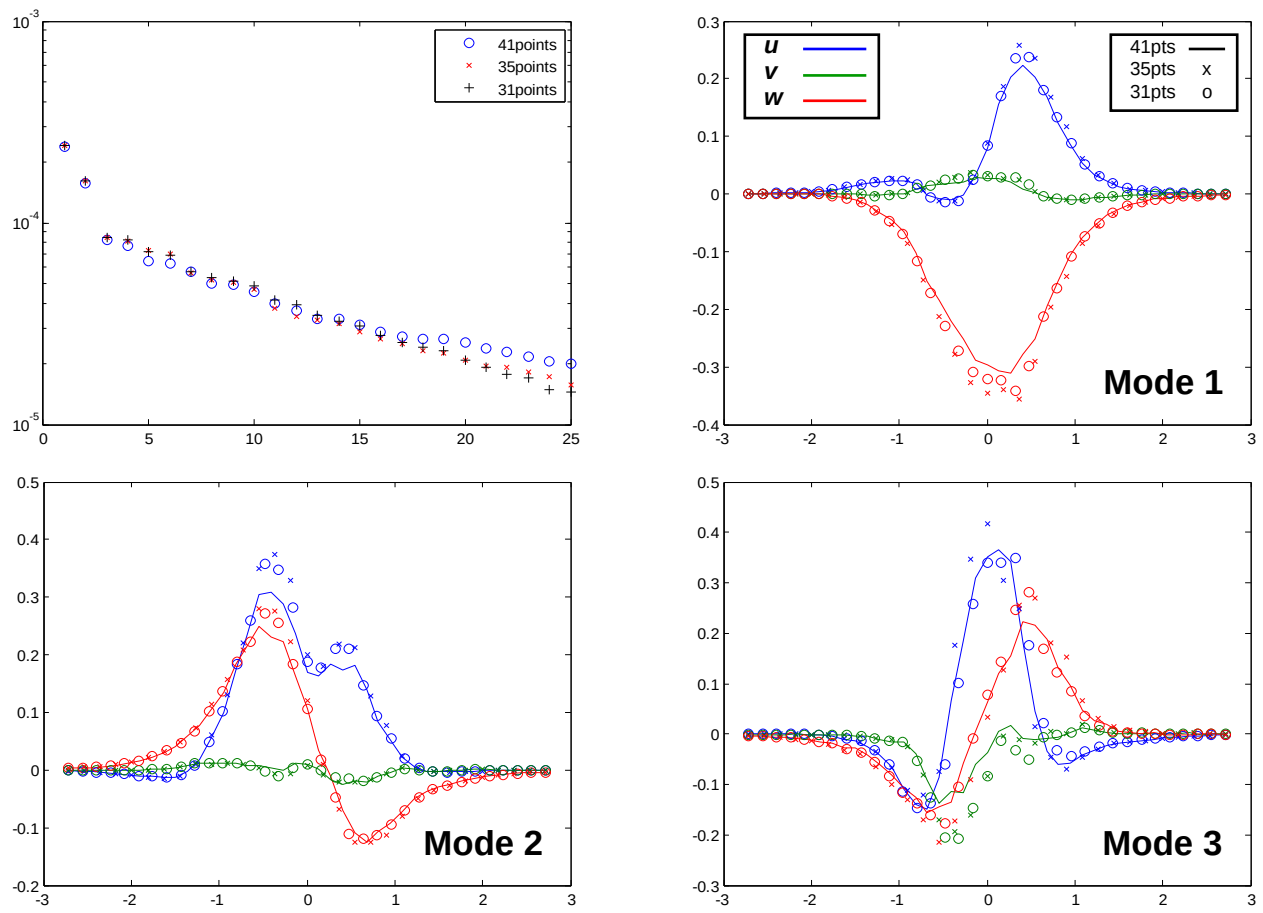


Figure 6.45 POD eigenvalue spectra and modal profiles of the first 3 modes of the baseline blades for different computational grids.

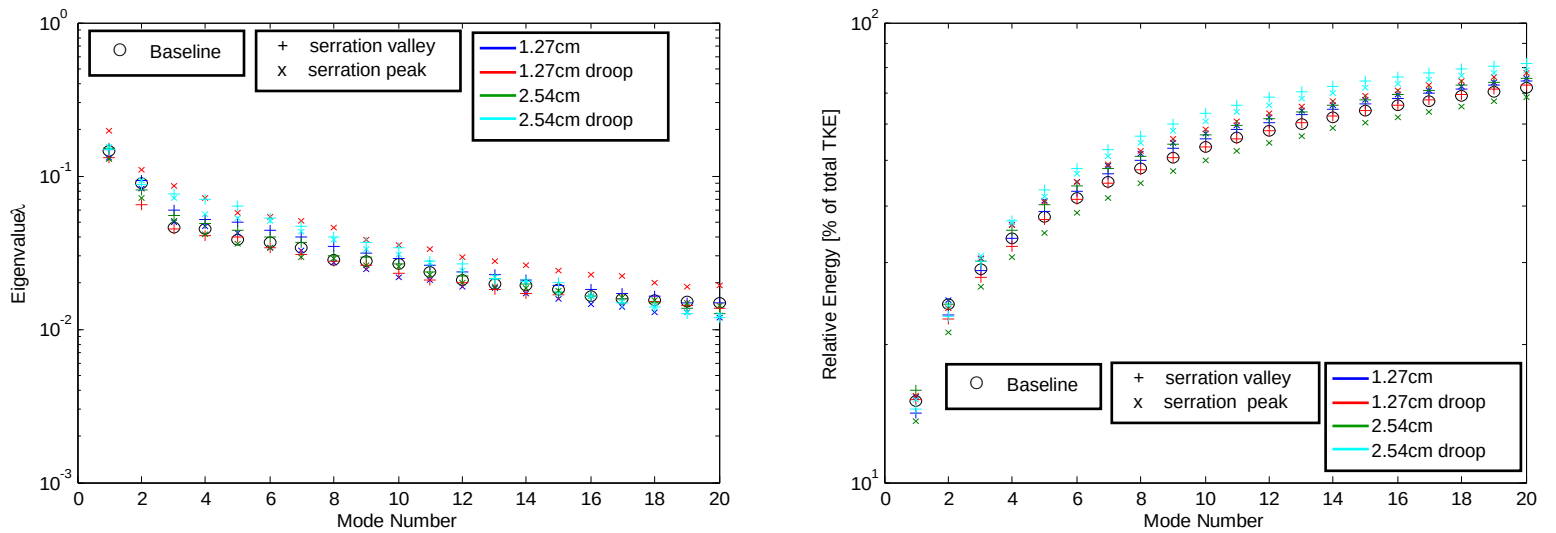


Figure 6.46 POD eigenvalue spectra of the serrated trailing edge blades in the Z-direction (left) and cumulative energy spectrum (right). Baseline values are indicated by black circles.

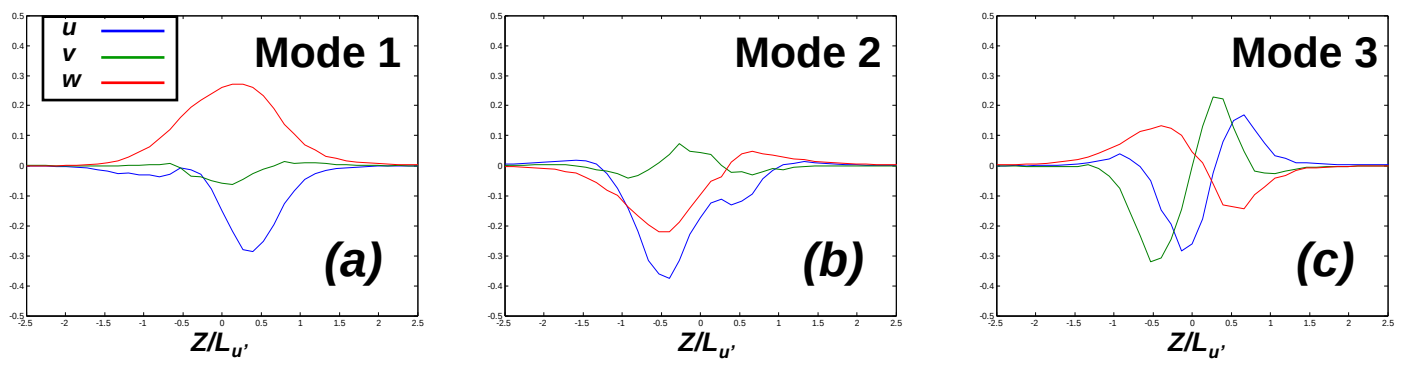


Figure 6.47 Modal profiles of the first three modes obtained from the POD of the 1.27cm serration blades – serration valley.

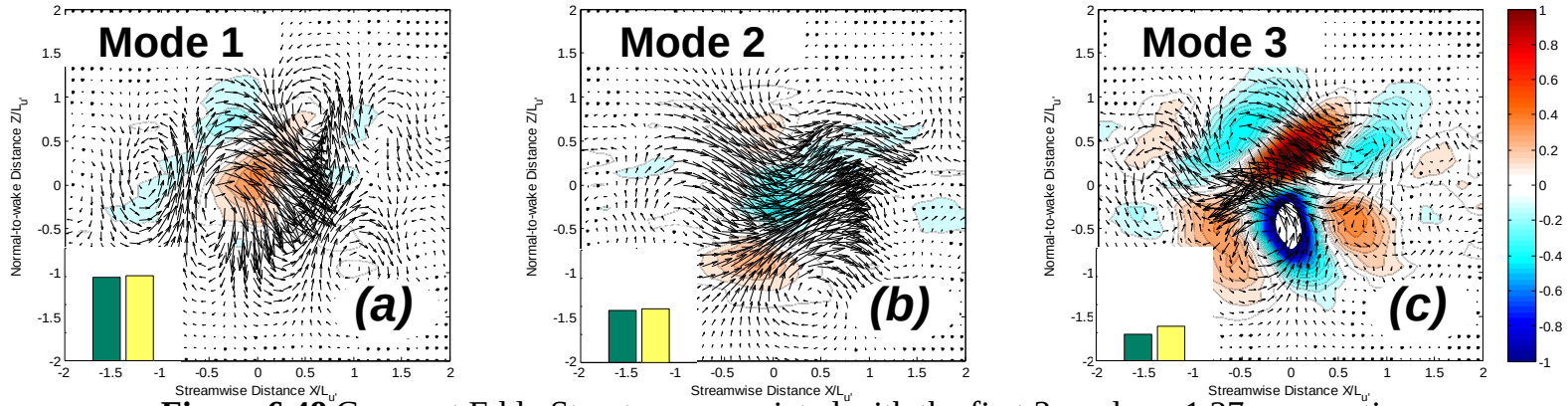


Figure 6.48 Compact Eddy Structures associated with the first 3 modes – 1.27cm serration blades – serration valley. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

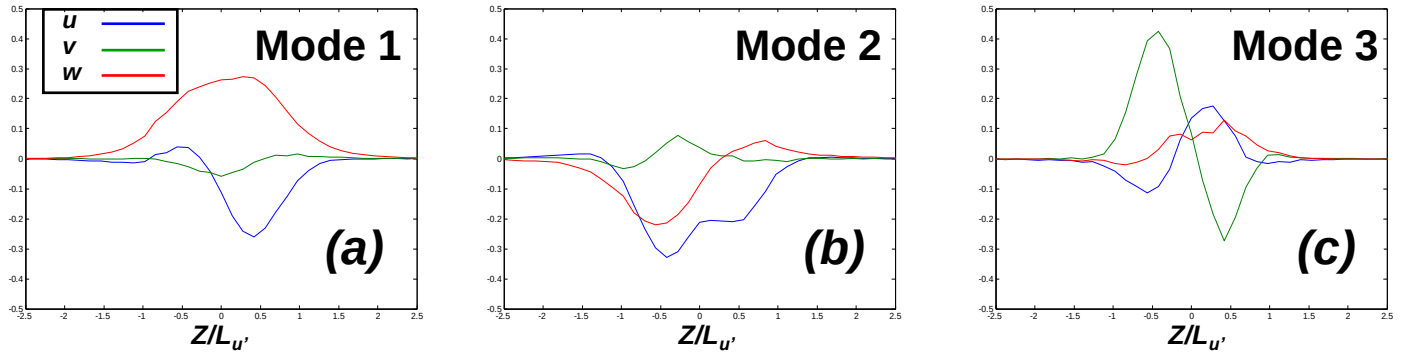


Figure 6.49 Modal profiles of the first three modes obtained from the POD of the 1.27cm serration blades – serration peak.

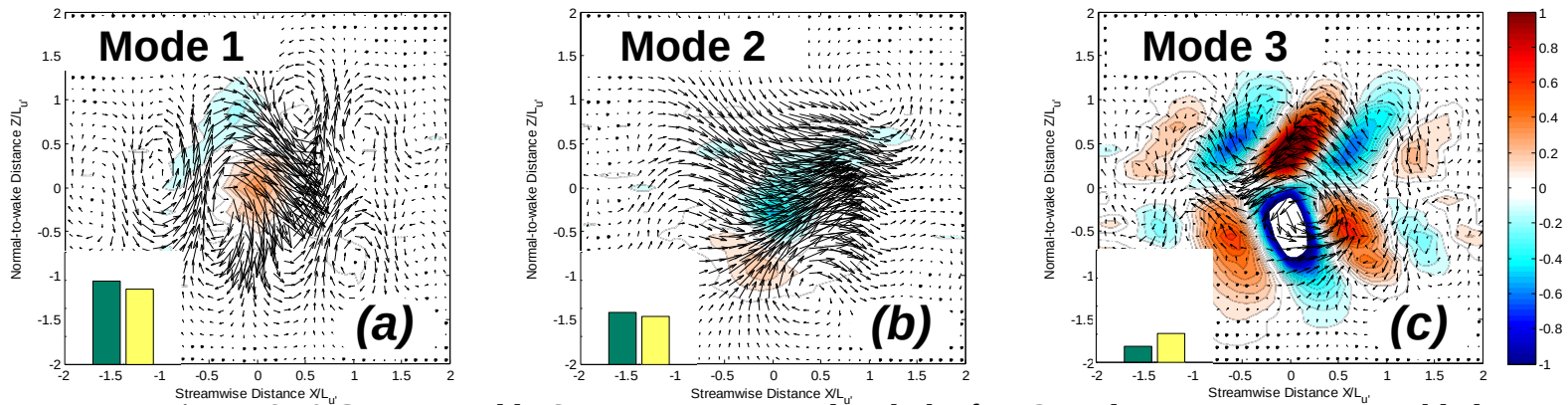


Figure 6.50 Compact Eddy Structures associated with the first 3 modes – 1.27cm serration blades – serration peak. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

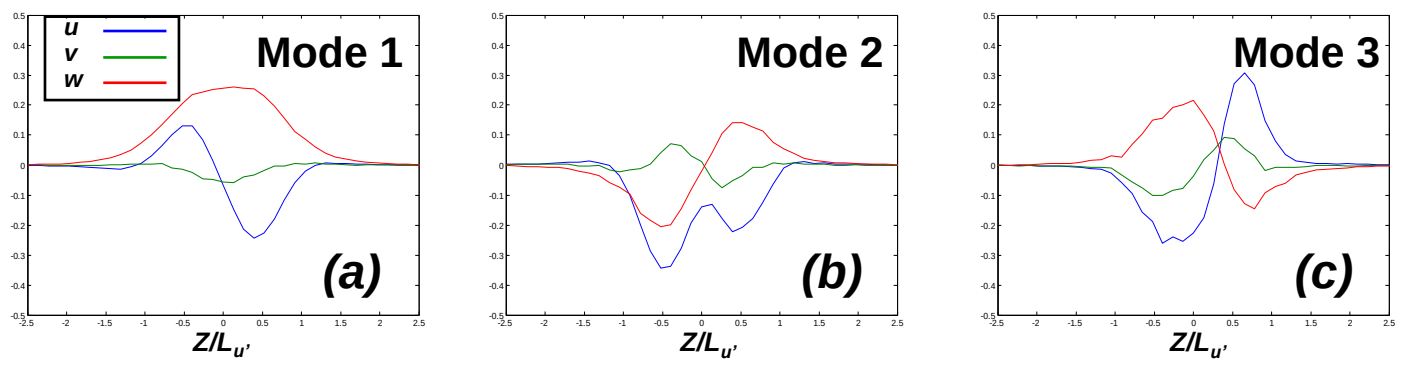


Figure 6.51 Modal profiles of the first three modes obtained from the POD of the 1.27cm drooped serration blades – serration valley.

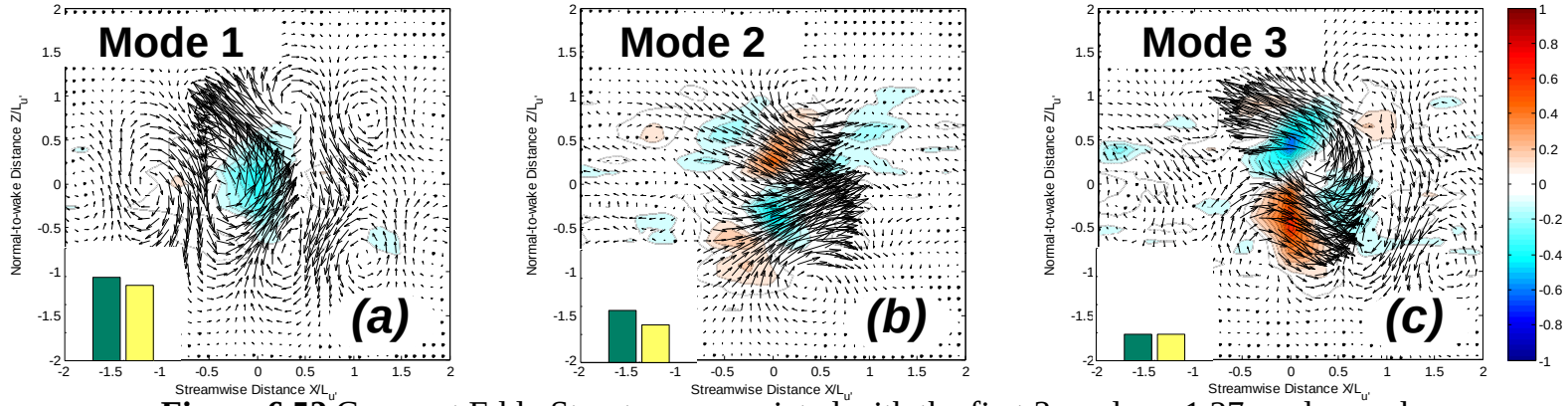


Figure 6.52 Compact Eddy Structures associated with the first 3 modes – 1.27cm drooped serration blades – serration valley. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

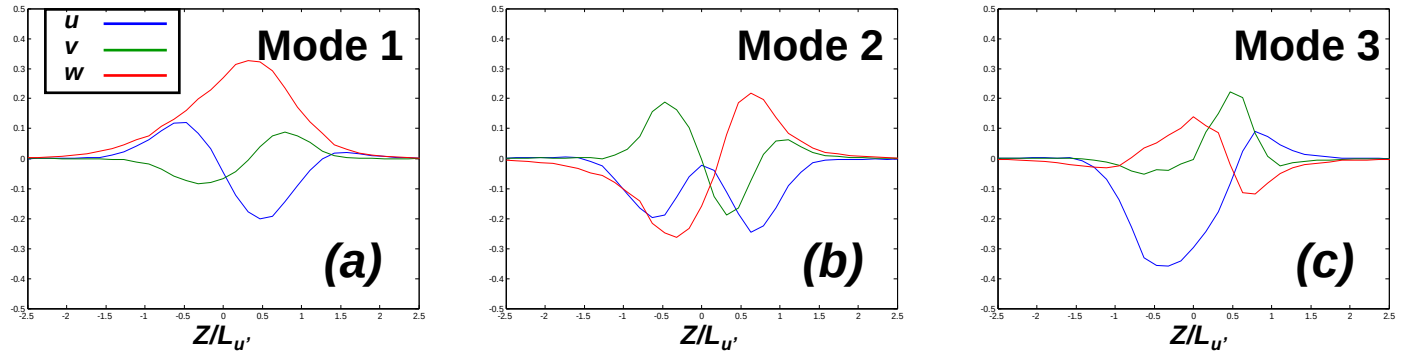


Figure 6.53 Modal profiles of the first three modes obtained from the POD of the 1.27cm drooped serration blades – serration peak.

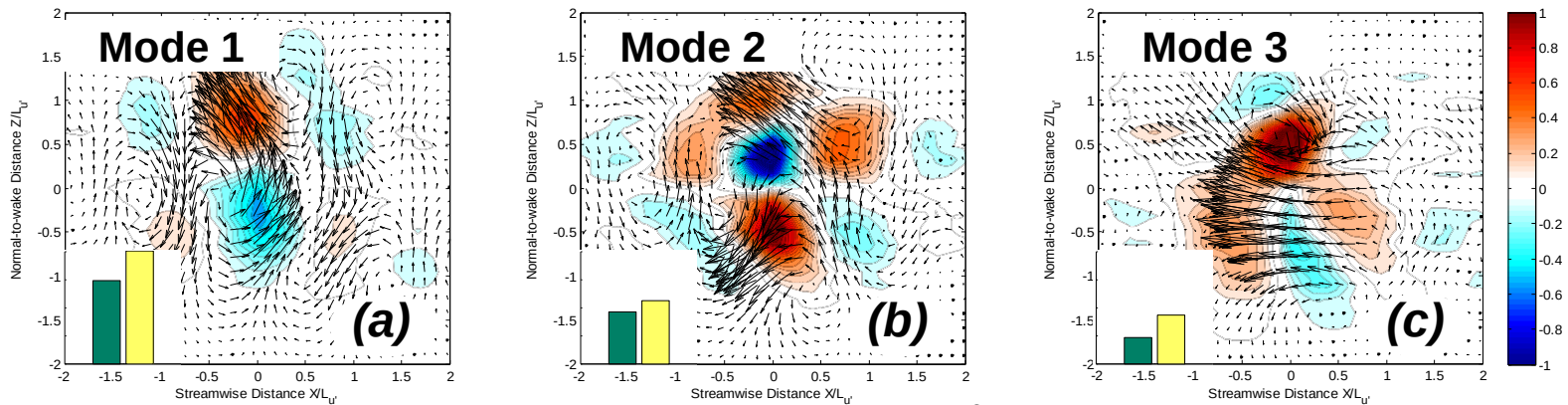


Figure 6.54 Compact Eddy Structures associated with the first 3 modes – 1.27cm drooped serration blades – serration peak. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

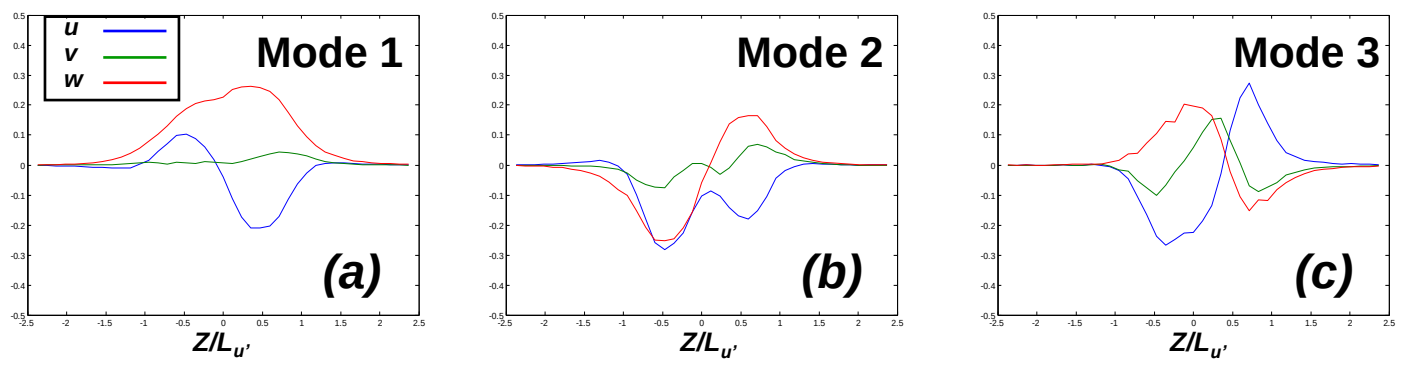


Figure 6.55 Modal profiles of the first three modes obtained from the POD of the 2.54cm serration blades – serration valley.

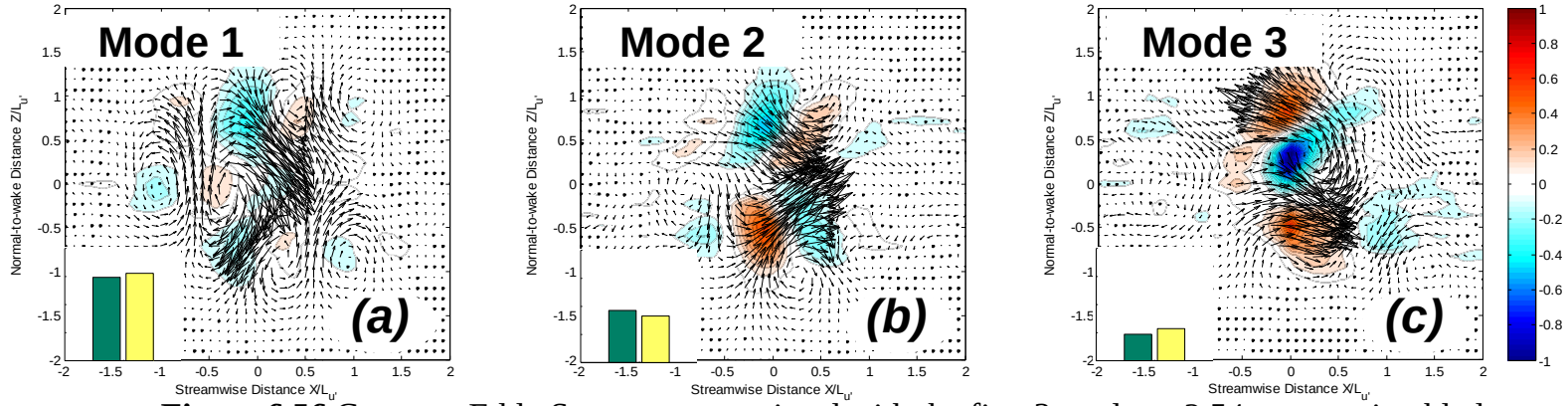


Figure 6.56 Compact Eddy Structures associated with the first 3 modes – 2.54cm serration blades – serration valley. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

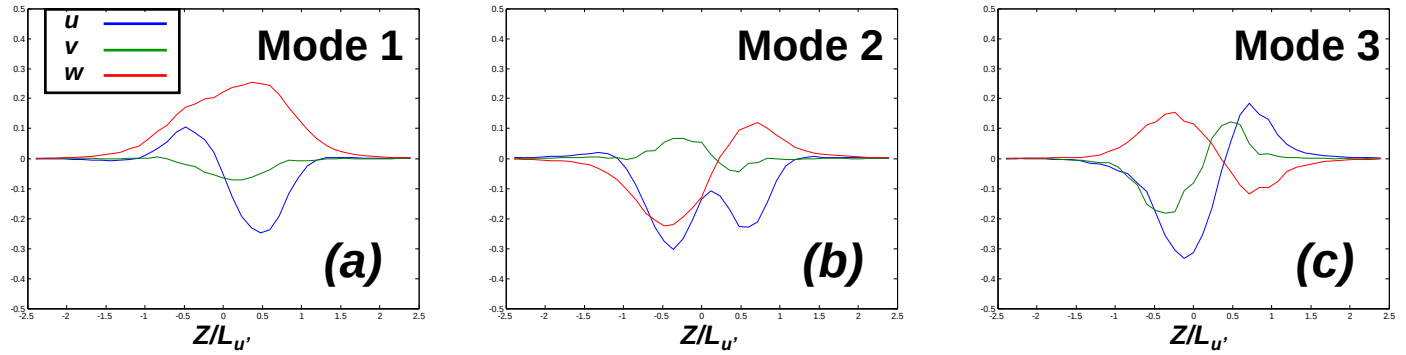


Figure 6.57 Modal profiles of the first three modes obtained from the POD of the 2.54cm serration blades – serration peak.

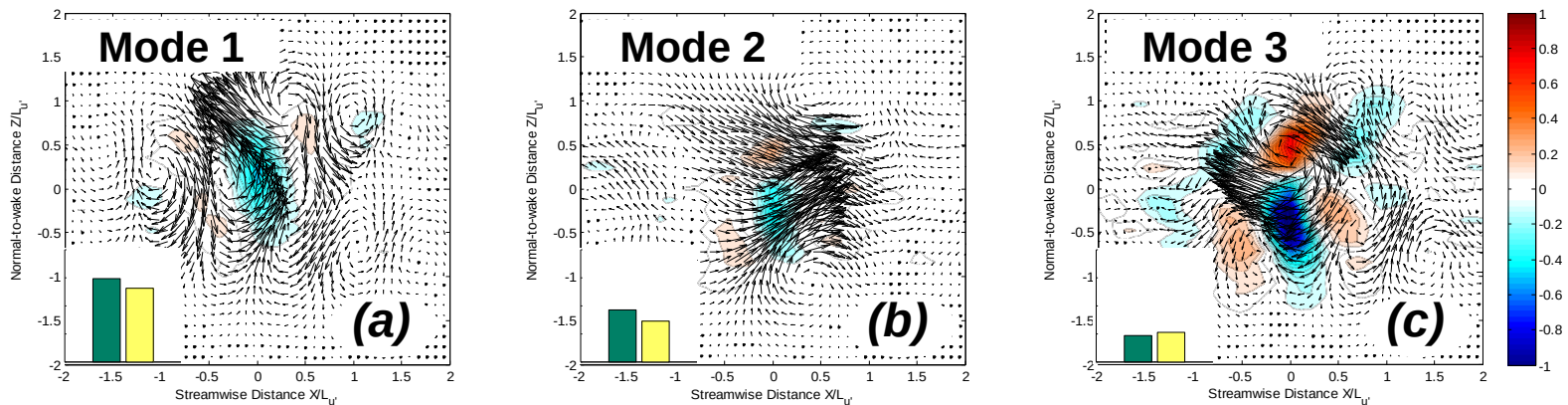


Figure 6.58 Compact Eddy Structures associated with the first 3 modes – 2.54cm serration blades – serration peak. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

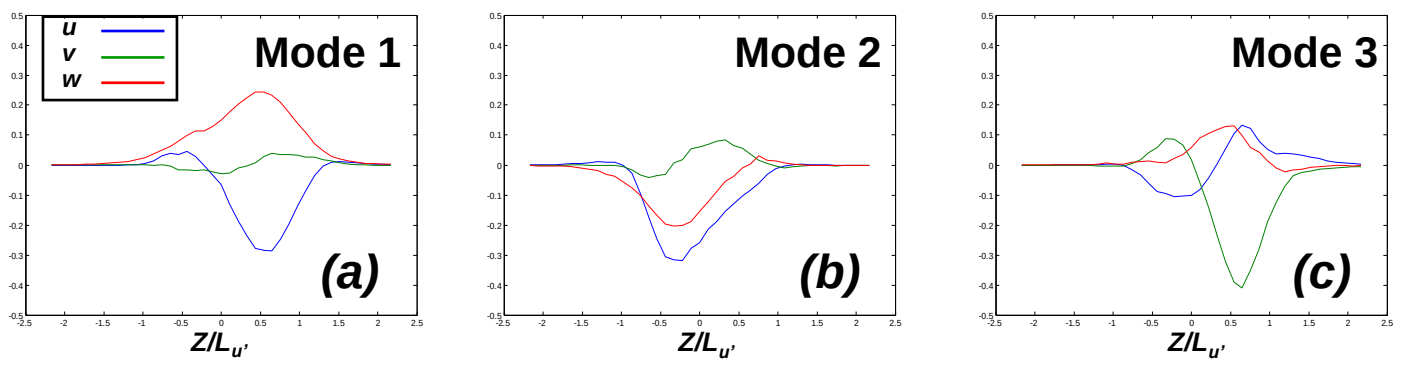


Figure 6.59 Modal profiles of the first three modes obtained from the POD of the 2.54cm drooped serration blades – serration valley.

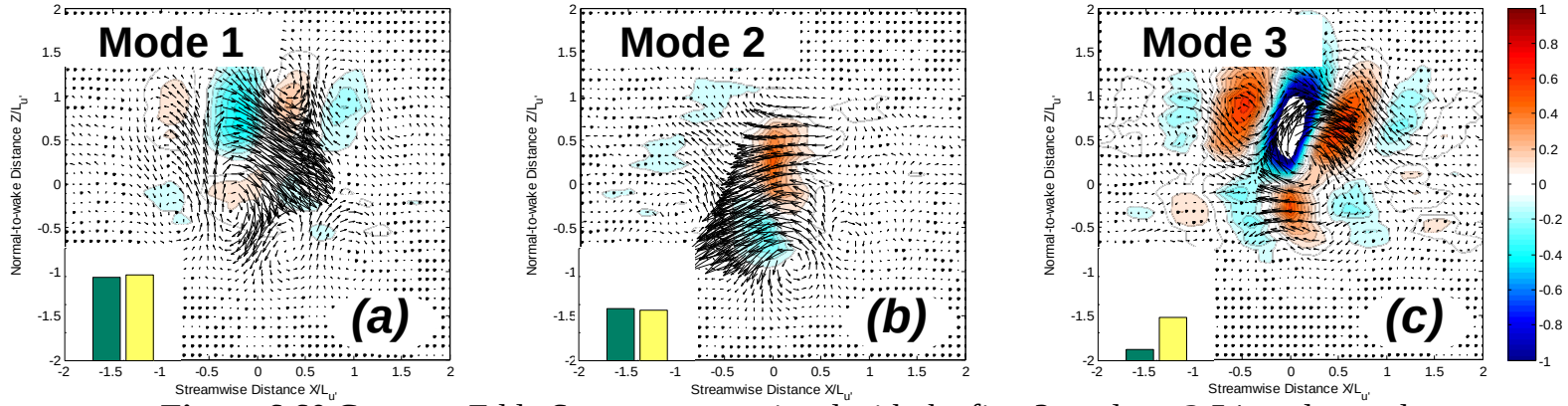


Figure 6.60 Compact Eddy Structures associated with the first 3 modes – 2.54cm drooped serration blades – serration valley. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

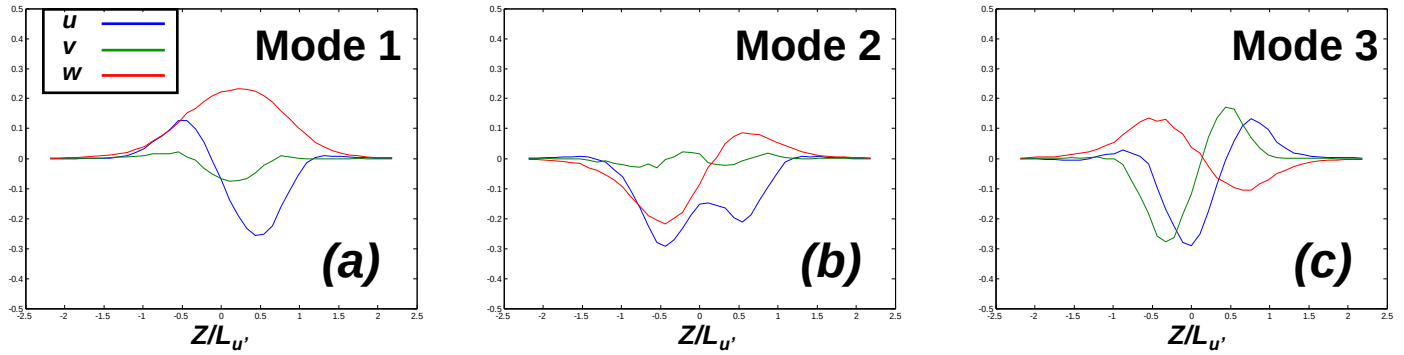


Figure 6.61 Modal profiles of the first three modes obtained from the POD of the 2.54cm drooped serration blades – serration peak.

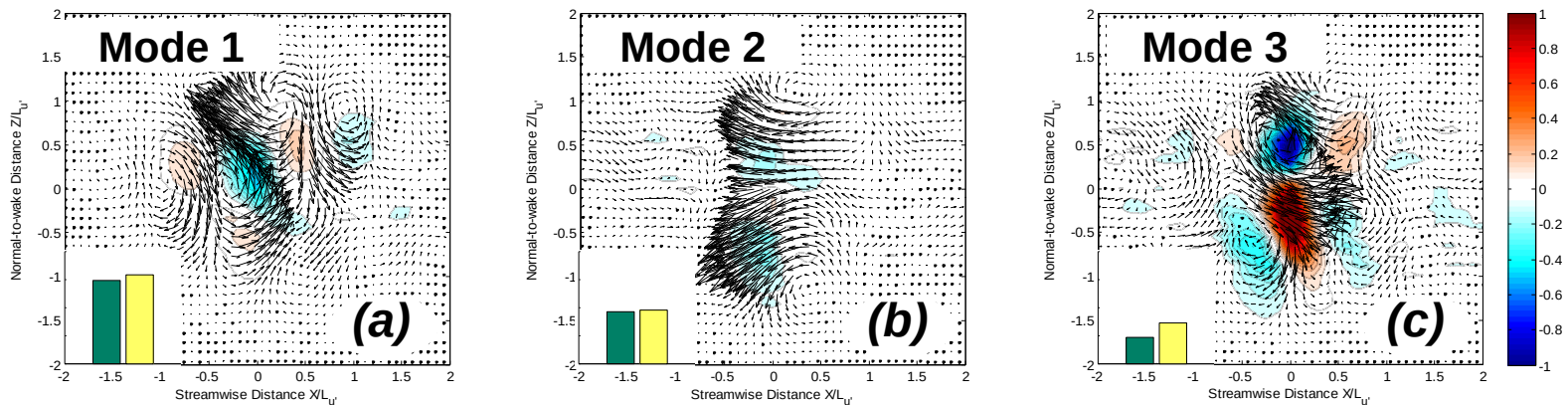


Figure 6.62 Compact Eddy Structures associated with the first 3 modes – 2.54cm drooped serration blades – serration peak. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

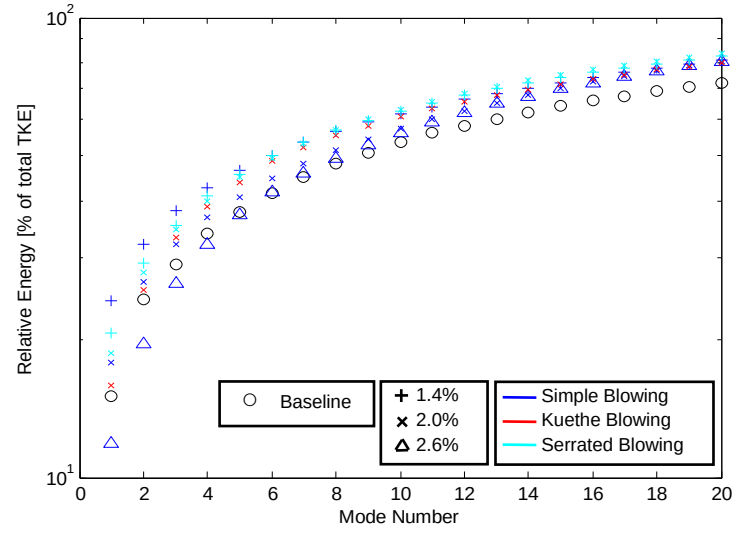
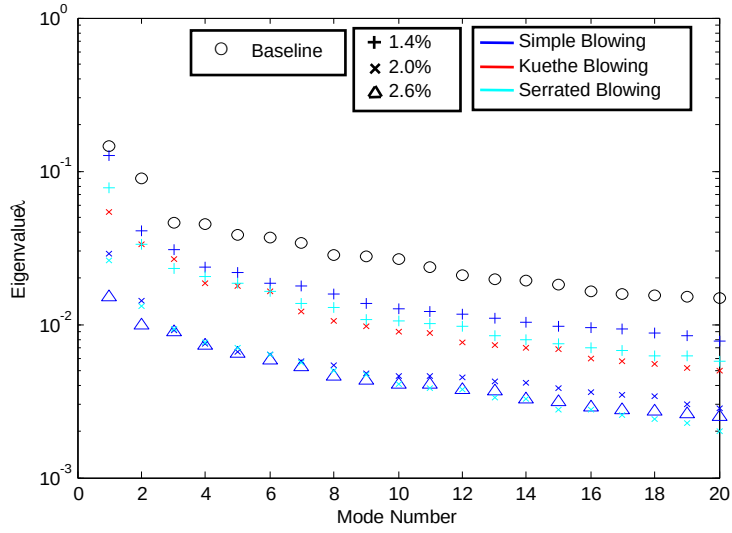


Figure 6.63 POD eigenvalue spectra of the serrated trailing edge blades in the Z-direction (left) and cumulative energy spectrum (right). Baseline values are indicated by black circles.

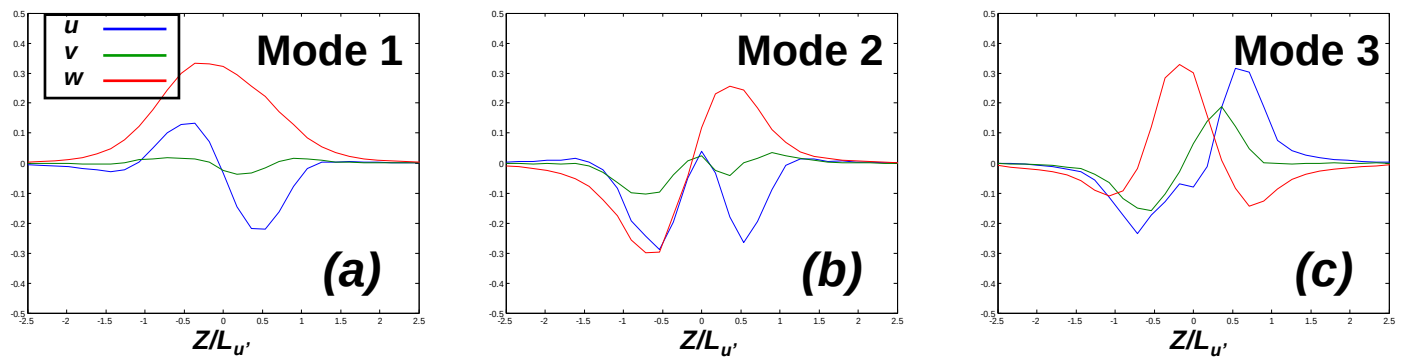


Figure 6.64 Modal profiles of the first three modes obtained from the POD of the simple blowing blades at a blowing rate of 1.4%.

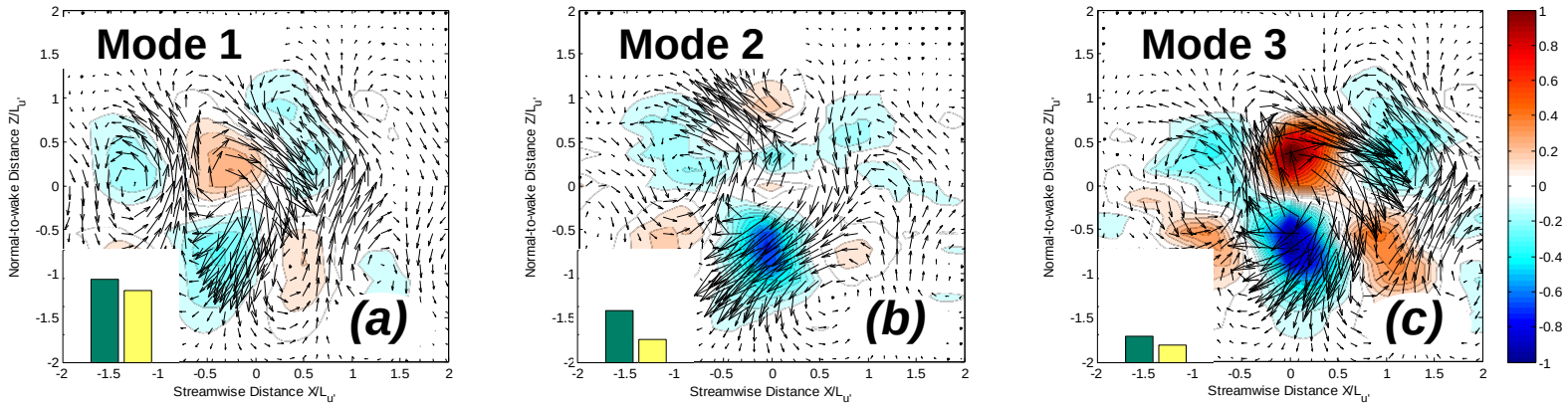


Figure 6.65 Compact Eddy Structures associated with the first 3 modes – simple blowing blades at a blowing rate of 1.4% Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

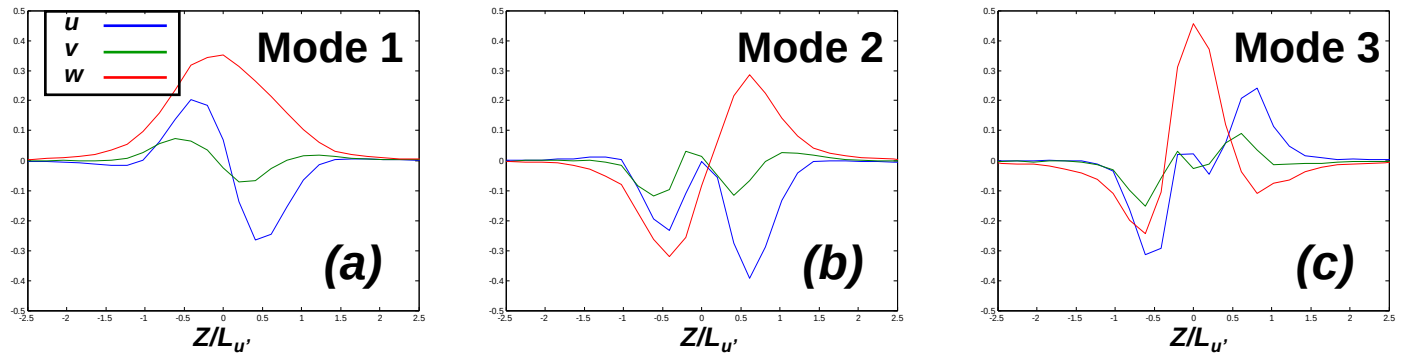


Figure 6.66 Modal profiles of the first three modes obtained from the POD of the simple blowing blades at a blowing rate of 2.0%.

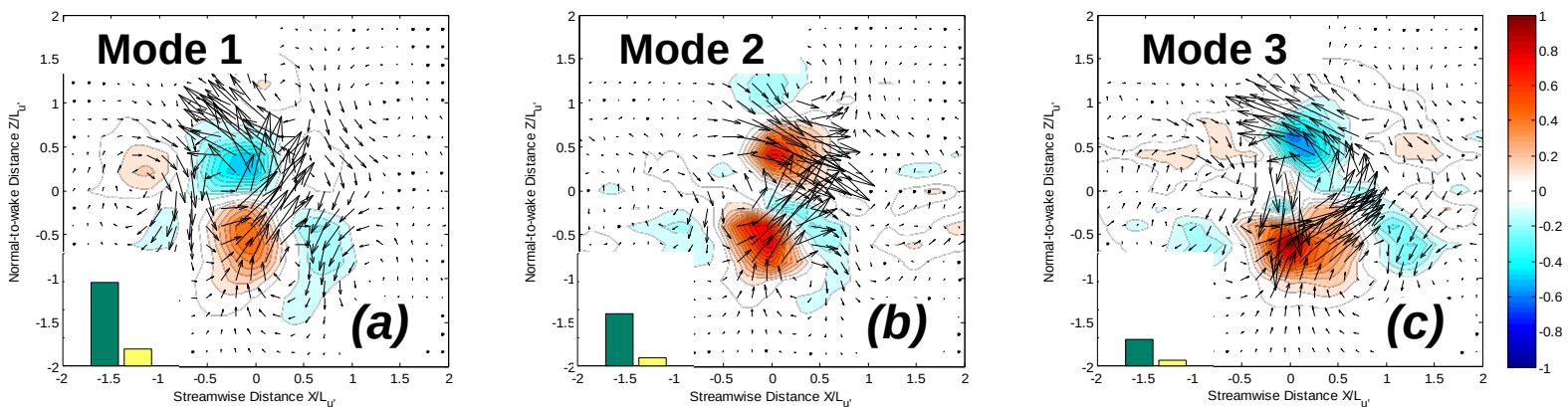


Figure 6.67 Compact Eddy Structures associated with the first 3 modes – simple blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

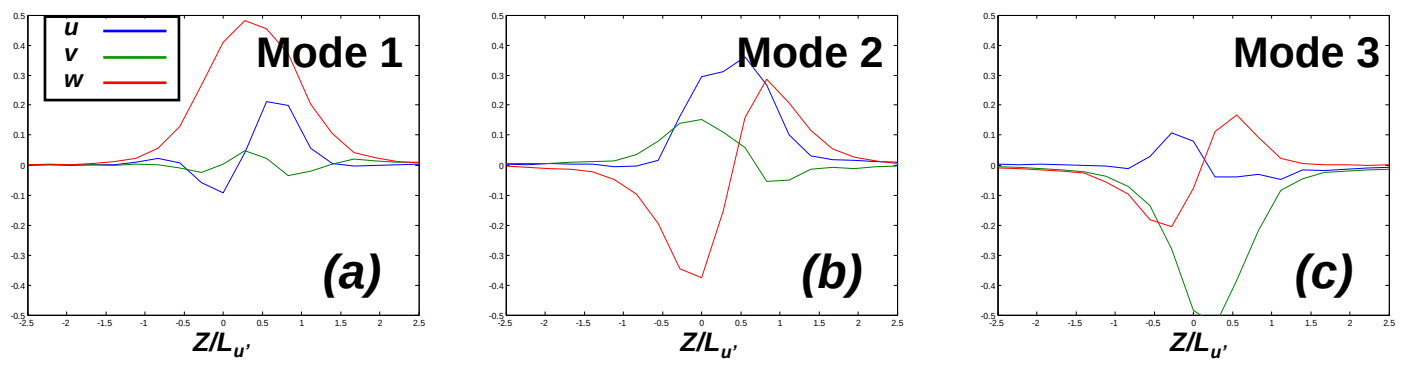


Figure 6.68 Modal profiles of the first three modes obtained from the POD of the simple blowing blades at a blowing rate of 2.6%.

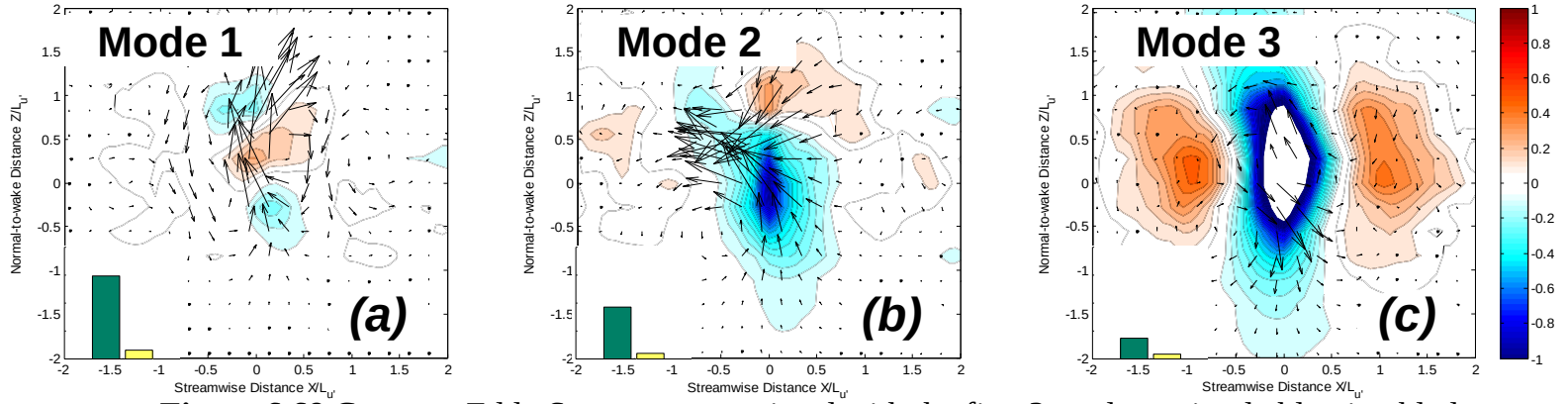


Figure 6.69 Compact Eddy Structures associated with the first 3 modes – simple blowing blades at a blowing rate of 2.6% Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

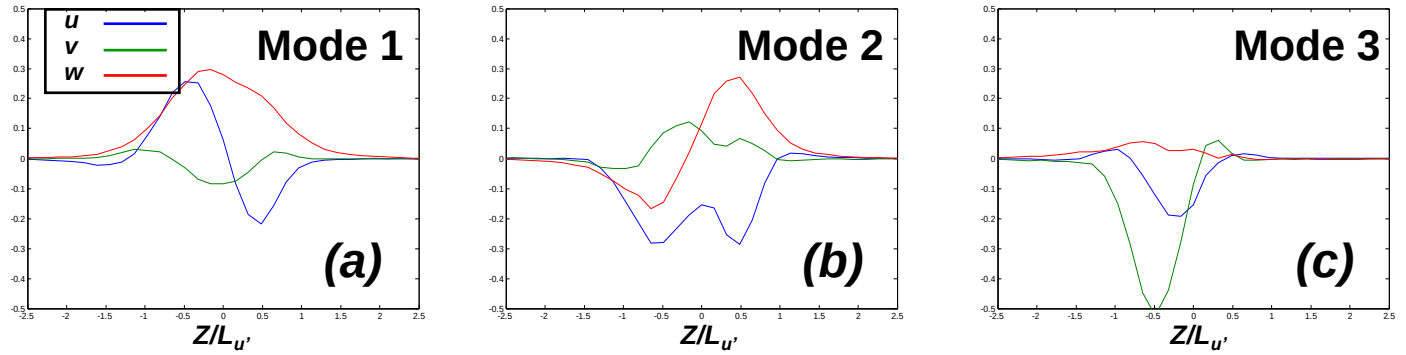


Figure 6.70 Modal profiles of the first three modes obtained from the POD of the Kuethé blowing blades at a blowing rate of 2.0%.

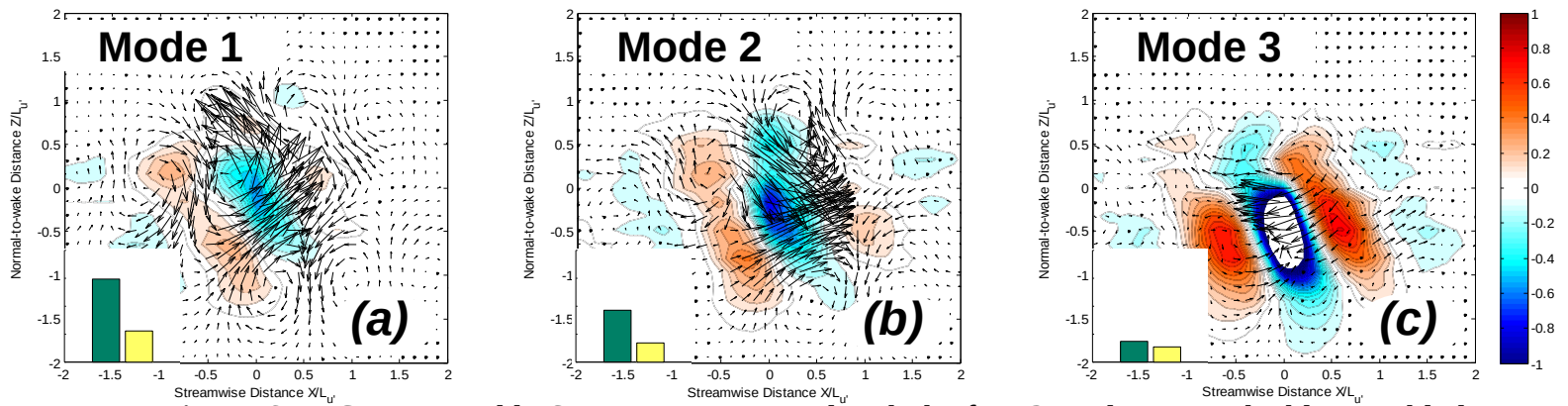


Figure 6.71 Compact Eddy Structures associated with the first 3 modes – Kuethé blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

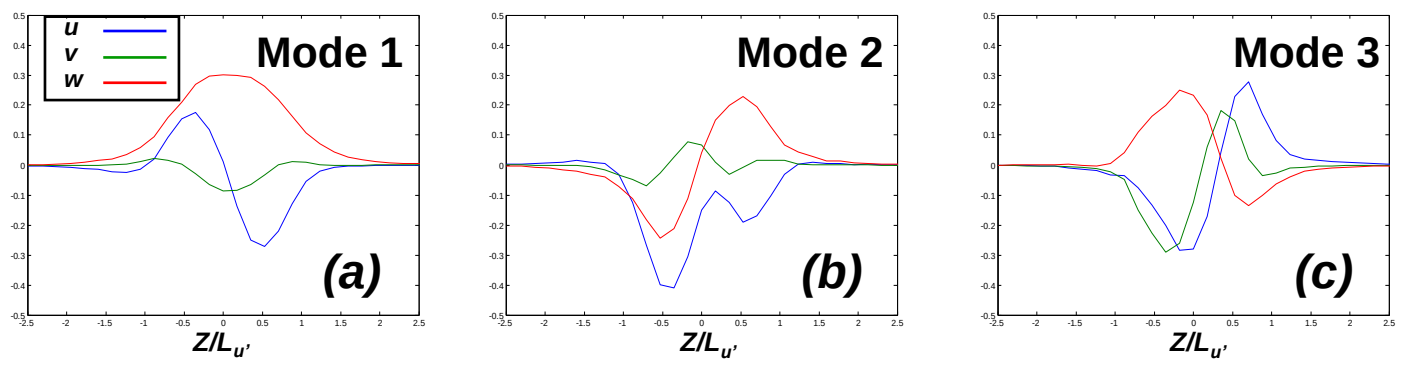


Figure 6.72 Modal profiles of the first three modes obtained from the POD of the serrated blowing blades at a blowing rate of 1.4%.

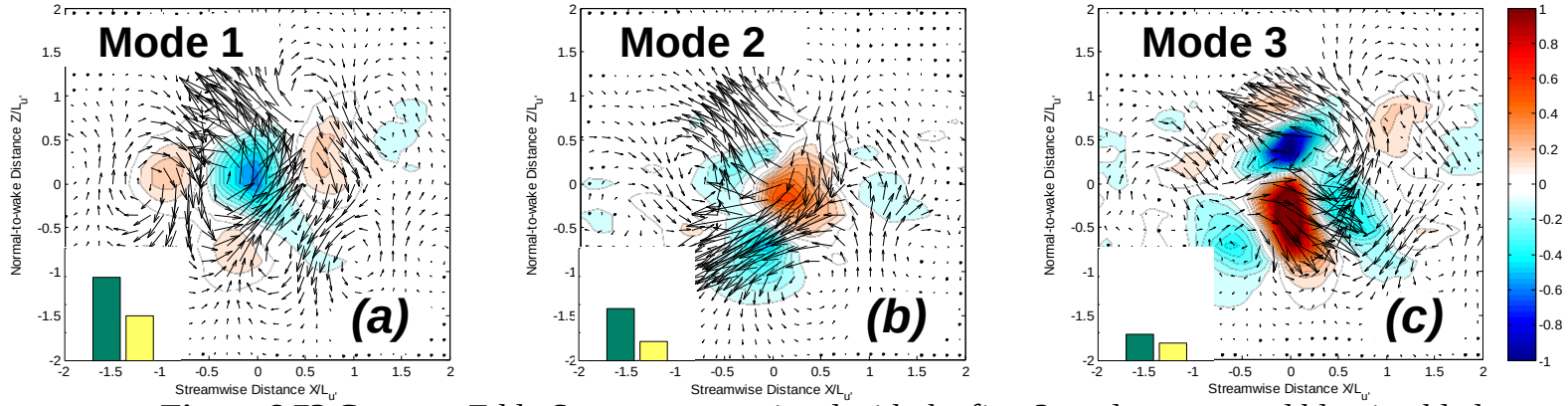


Figure 6.73 Compact Eddy Structures associated with the first 3 modes – serrated blowing blades at a blowing rate of 1.4% Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

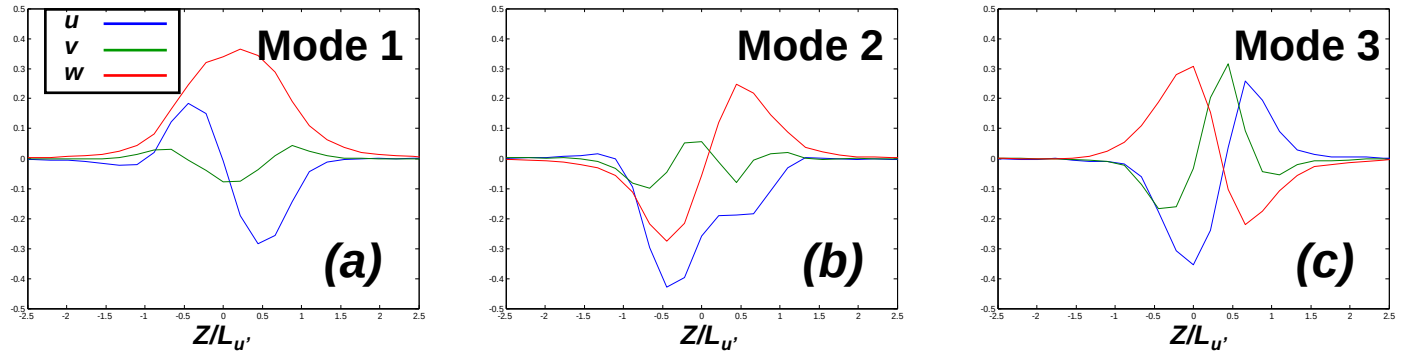


Figure 6.74 Modal profiles of the first three modes obtained from the POD of the serrated blowing blades at a blowing rate of 2.0%.

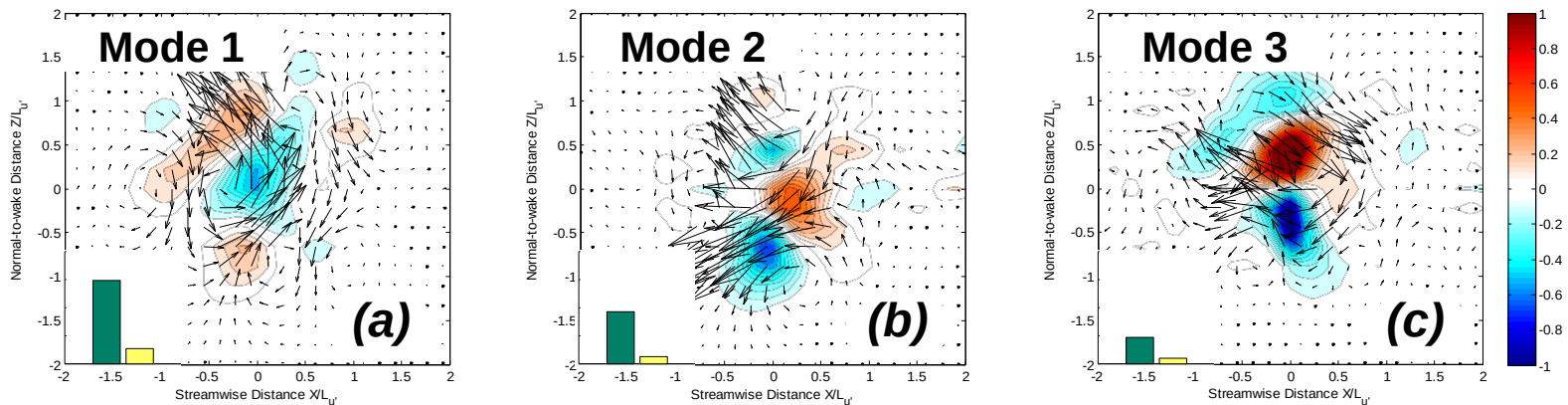


Figure 6.75 Compact Eddy Structures associated with the first 3 modes – serrated blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component. Histograms represent the absolute TKE level in the mode (yellow) and corresponding baseline mode (green).

Chapter 7 - Acoustic Estimations

Chapter 6 described the organization of the coherent structures in the idealized fan-blade wakes and the impact of the different strategies upon them. This analysis provided qualitative clues about possible broadband noise generation if these wakes were to interact with a downstream blade. This scenario emulates the rotor-stator interaction occurring in aircraft turbo-fan engines when the rotor wake impinges on the stator blades. To be able to quantify interaction noise, one could use an anechoic facility and perform acoustic measurement of the far-field radiation when the wake of an upstream blade interacts with a downstream blade. These measurements were not with the present experimental set up. It is however possible to use the present measurements to estimate the potential of a given configuration to generate broadband interaction noise.

To do this, the wake-stator interaction is modeled as a linear system subjected to an excitation force (the wake turbulence) and producing an output signal (the radiated acoustic field). It is then possible to investigate the potential of a given rotor geometry to generate broadband noise by examining the turbulence excitation (or “broadband excitation”) it produces. Due to the experimental set up of the present study, this model assumes that the stator does not perturb the flow field. Performing measurements in a relatively simple environment (such as the linear cascade wind tunnel used for this study) can, therefore, be used as an initial diagnostic tool before further acoustic measurements are performed to validate the design. This chapter aims at describing how the potential of the wakes to generate broadband interaction noise can be obtained using the methods described by Glegg and Devenport (2001) and Amiet (1975) and how the various strategies affect this potential. It should be noted that this study did not perform any acoustic measurements nor reports any acoustic computations. It rather focuses on describing the impact of the various flow control strategies on the broadband excitation.

7.1. Theoretical Background

The interaction between the wake turbulence and the stator blade pressure field results in unsteady surface pressure fluctuations that radiate into the far-field. In a real aircraft engine, the motion of the rotor blades induces significant swirl in the flow downstream of the fan. The ensuing wakes are spiral structures with strong spanwise variations. As a result, they impinge on the downstream stator at a wide range of angles of intersection. The present study of nominally two-dimensional wakes cannot re-create such conditions. However the analysis of the normal-to-wake and spanwise measurements will allow for the use of idealized models to estimate the potential of these wakes to produce broadband noise in the two extreme cases of perpendicular and parallel stator-wake interaction. The normal-to-wake measurements are used to determine the broadband excitation that would result from a perpendicular interaction (figure 7.1a)) with an airfoil of infinite span by combining the far-field radiation of such an airfoil as formulated by Glegg and Devenport (2001) with the characteristic eddy decomposition described in Chapter 6. The spanwise measurements are then used to evaluate the broadband excitation in a parallel cut (figure 7.1b)) using the expression for the far-field radiation of an airfoil subjected to homogeneous disturbance.

7.1.1. Perpendicular Blade-Wake Interaction

To obtain an expression for the broadband excitation, one needs to relate the wake turbulence structure (that was shown to be compactly represented by the two-point correlation function in Chapter 6) to the radiated pressure field. Pressure and acoustic spectrum are the ultimate quantities wanted in noise calculations. The acoustic pressure spectrum $S_{pp}(\mathbf{r}, \omega)$ is defined as

$$S_{pp}(\mathbf{r}, \omega) = \frac{\pi}{T} \text{Ex} \left[p(\mathbf{r}, \omega) p^*(\mathbf{r}, \omega) \right] \quad (7.1)$$

where $\mathbf{r}$ is the position vector relative to the origin, ω the frequency and p the radiated acoustic pressure and the $*$ denotes the complex conjugate.

The radiated pressure field is usually obtained by decomposing the acoustic pressure field in a series of proper orthogonal modes. This technique then allows computing the radiated pressure spectrum by summing the modal contributions.

The radiated pressure field produced by an airfoil of infinite span and chord $2b$ in a subsonic turbulent stream is given by Amiet (1975)

$$p(X, Y, Z, \omega) = \iint \left[\frac{-i\omega Z F(X_0, Z_0, \omega)}{4\pi c_0 \sigma^2} \right] e^{-i\omega(M(X-X_0)-\sigma)/(c_0\beta^2) - i\omega(XX_0 + ZZ_0\beta^2)/(c_0\beta^2\sigma)} dX_0 dZ_0 \quad (7.2)$$

where the observer is located at (X, Y, Z) , the blade chord is aligned with the X -direction, the blade span in the Z -direction, $F(\cdot)$ represents the pressure jump across the blade, c_0 is the local speed of sound, M the Mach number, and $\sigma = (X^2 + \beta^2(Y^2 + Z^2))^{1/2}$ and $\beta = \sqrt{1 - M^2}$.

Glegg and Devenport (2001) then combined Equations (7.1) and (7.2) to obtain the pressure auto-spectrum as a function of the pressure jump across the cutting blade. The pressure jump itself is obtained by calculating the blade response to an upwash velocity in the Y -direction (using the blade transfer function).

Since the CES are basis functions of the space-time correlation, they can be used to reconstruct the velocity spectrum, which in turn can be related to the pressure spectrum of Eq.(7.1). Glegg and Devenport (2001) proved that the radiated pressure power spectral density is then obtained by:

$$S_{pp}(\mathbf{r}, \omega) = \frac{\pi}{T} \sum_n \left| \frac{\pi^2 \omega \rho_0 b g_f(\gamma_1, \gamma_0, \nu_0)}{c_0 \sigma^2} \right|^2 \lambda^{(n)} \left\{ \kappa_2^{(n)}(\gamma_0, \nu_0) \right\}_f \left\{ \phi_2^{(n)}(\nu_0) \right\}_f^* \quad (7.3)$$

where ρ_0 is the flow density (assumed constant), b is the half the blade chord, $g_f(\gamma_1, \gamma_0, \nu_0)$ is the Fourier transform of the blade transfer function expressed in terms of the wavenumbers $\gamma_1 = -\omega X / c_0 \beta^2 \sigma$, $\gamma_0 = -\omega / U_e$ and $\nu_0 = \omega Z / c_0 \sigma$ (where U_e is the convection velocity of the impinging wake) and $\{\}_f$ denotes the Fourier transform operator.

The first term in the summation depends only on parameters that are either constant (like the density or the speed of sound) or properties of the cutting blade (like its chord b). The two other quantities involved in this first term are the frequency ω and the Fourier transform of the cutting blade response function. The remaining terms (the POD Eigenvalue, the corresponding CES, and the POD modal profile) are dependent on the rotor wake flow only. It should be noted that the CES $\kappa^{(n)}$ and POD modal profiles $\phi^{(n)}$

are evaluated along the spanwise direction since the upwash seen by the cutting blade would correspond to the spanwise velocity of the wake. These terms have actually been shown to be obtained from the two-point correlation function (Chapter 6). It should be noted that the CES and POD modal profiles that appear in Eq.(7.3) are actually Fourier transforms of the results presented in Chapter 6. For each mode, the radiated power spectral density can be computed by taking the product of the blade response function and the turbulence excitation. Therefore, at each frequency, it is possible to evaluate the contribution of each mode to the noise radiation in the direction normal to the cutting blade. More importantly, assuming the same cutting blades interacts with all the modified wakes, it is possible to evaluate the impact of the different strategies on the broadband excitation by evaluating the broadband excitation terms (BET) defined as

$$J_n^\perp = \lambda^{(n)} \left\{ \kappa_2^{(n)}(\gamma_0, \nu_0) \right\}_f \left\{ \phi_2^{(n)}(\nu_0) \right\}_f^* \quad (7.4)$$

The frequency variations of $J_n^\perp$ for the different strategies can then be compared to each other to assess the potential of the modified wakes to generate broadband noise. It should be noted that since the cutting blade response is a function of frequency, the overall shape and magnitude of the BET is irrelevant. The magnitude of the BET relative to the baseline levels can however be used to evaluate the impact of the different strategies on the potential of these wakes to generate broadband noise (bearing in mind that the actual broadband levels will be a function of the blade geometry and response function).

7.1.2. Parallel Blade-Wake Interaction

To evaluate the impact of the different strategies on the broadband excitation occurring in a parallel blade-wake interaction (where the cutting blade is parallel to the wake spanwise axis), we will assume that the wake turbulence is homogeneous in the spanwise direction. While this is an idealized model, it will allow providing some insight on another aspect of interaction noise.

This part of the analysis will be based Amiet's theory (1975). The far-field power spectral density, felt by an observer directly above the noise source created by the

interaction of a blade of infinite span $2d$ with an upwash velocity w in the Y -direction, for homogeneous turbulence can be shown to vary as:

$$S_{pp}(X, 0, Z, \omega) \rightarrow \left(\frac{\omega Z \rho_0 b M}{\sigma^2} \right)^2 d |g(X, \gamma_0, 0)|^2 \int_0^\infty R_{ww}(\gamma_0, \Delta Y) d\Delta Y \quad (7.5)$$

where R_{ww} is the cross-spectrum of the upwash velocity fluctuations seen by the cutting blade between two point along its span separated by a distance ΔY . In cascade aligned coordinate, the upwash velocity seen by the cutting blade would be caused by the normal-to-wake fluctuations so that for the present study $R_{ww}=R_{33}$. Note here that we are dealing with velocity cross-spectrum.

Here again, the terms outside of the integral are either constant are dependent on the cutting blade properties. The broadband excitation for a parallel cut can therefore be computed by evaluating the spanwise integral of the wavenumber cross-spectrum of the upwash velocity. Such spectrum can be readily obtained from the spanwise correlation data presented in Chapter 6. We then define the spanwise broadband excitation term as:

$$J''(\omega) = \int_0^\infty R_{33}(-\omega/U_e, \Delta Y) d\Delta Y \quad (7.6)$$

where the fact that $\gamma_0 = -\omega/U_e$ was used.

Similarly to the perpendicular interaction, the impact of a given configuration on the spanwise broadband excitation can then be characterized by studying the change in $J''(\omega)$. It should be noted again that the term excitation is used to represent the potential of the wake to generate broadband noise and not the actual radiation itself (as it is function of the cutting blade response function not taken into account here).

7.2. Broadband Excitation

7.2.1. Perpendicular Blade-Wake Interaction

The broadband excitation terms (BET) for perpendicular blade-wake interaction (defined in Eq.(7.4)) are computed for the first 40 modes (that showed no signs of aliasing effects) of each configuration. The computations are only carried out on the modes that have a non-zero spanwise component. This criterion is enforced by eliminating the modes with RMS spanwise fluctuations lower than 1%. It is then

possible to select the modes that contribute the most to the broadband excitation (that we shall call “driving modes”). To do so, the total broadband excitation is calculated by summing the BET at each frequency. The driving modes are then selected by integrating their respective contribution to the total broadband excitation over the entire frequency range. This implies that the driving modes are the one that contribute the most to the overall energy of the BET spectrum.

Such spectra are shown in figure 7.2. This figure presents the total BET spectrum (in black) that has been normalized on the half-wake width and wake deficit (both based on the streamwise Reynolds stress profile) plotted against the frequency (normalized on the cascade notional blade passing frequency BPF). As mentioned in Chapter 3, the blade row in the Virginia Tech Low Speed Linear Cascade Wind Tunnel is fixed. There is therefore no real BPF involved. However, it is possible to use a notional BPF defined as the ratio of the tangential velocity (along the blade row leading edge line) and the blade passing. This notional BPF is 94Hz for an inlet velocity of 24.5m/s. Care was taken to ensure that the integrand in Eq.(7.4) (implicit in the Fourier transform of the CES and POD modal profile) was adequately resolved over the frequency range presented in Figure 7.2 and subsequent plots. The BET spectra of the first 5 driving modes are also presented. Again, the absolute magnitude and shape of these spectra are irrelevant as they do not include the effects of the blade response function. Figure 7.2 shows two important results. The five driving modes are found to be modes 6, 14, 8, 38, and 3. In Chapter 6, the POD modes were shown to be ordered by decreasing magnitude so that mode 1 is the most energetic. However, mode 1 does not appear among the 5 driving modes (neither does mode 2). This was expected as these two modes were found to be associated with negligible spanwise fluctuations. Mode 3 on the other hand was found to be the most energetic mode with a non-negligible spanwise component. But figure 7.2 shows that mode 3 is only the fifth driving mode. This is a direct consequence of the assumption that the observer is located directly above the intersection of the wake centerline and the cutting blade. Since mode 3 has an almost anti-symmetric modal profile, the integral of the upwash along the span of the cutting blade is small thus limiting its contribution. If the observer were to be located any other angle, the propagation delay along the span would result in some larger contribution. It therefore confirms that the TKE levels alone

do not dictate the potential of a mode to generate broadband noise. Rather, the spanwise modal profile combined with the energy of the mode will determine the excitation potential. This is even more apparent since mode 14 (that contributes only 2% of the total TKE) is actually the second strongest mode.

To quantify the contribution of each of the 5 driving modes to the total broadband excitation, the relative contributions of these modes (expressed as percentages of the total BET at a particular frequency) are plotted as a function of frequency in Figure 7.3. This figure shows that mode 6 contributes about 25% of the total broadband excitation. This is the same amount as the other 4 driving modes combined (modes 14, 8, 28, and 3 respectively contribute 8, 7, 6, and 5.5% of the total excitation). This dominance of mode 6 suggests that the turbulence excitation is relatively simple here. Therefore, if one could target the eddies associated with mode 6, one could argue that the total excitation could be significantly reduced. However to do so, the type of eddies involved needs to be described.

As introduced in Chapter 6, this can be done through compact eddy structures (CES). The CES for mode 6 is presented in Figure 7.4. The flow can be seen to consist in a pair of counter-rotating eddies centered at $(X/L_u, Z/L_u) = (-0.44, 0.14)$ and $(0.17, -0.4)$. The line connecting the two eddies centers is inclined 48° from the leading edge of the cutting blade. The important aspect of this flow is the strong spanwise velocity associated with it (as seen by the large, intense contours). This spanwise velocity distribution is similar to the second driving mode computed from a plane wake data by Glegg and Devenport (2001).

7.2.1.1. Impact of Trailing Edge Serrations on the Broadband Excitation

Now that the baseline excitation has been described, it is possible to evaluate the impact of the trailing edge serrations on the broadband excitation. The technique applied on the baseline wake is used on the modified wakes to not only analyze the changes in the overall broadband excitation but also to reveal the effects of the serrations on the driving modes.

The impact of the serrations on the overall broadband excitation is presented in Figure 7.5. On this figure, the total broadband excitation for each serration configuration (obtained by summing the BET of each mode) has been expressed as a relative change (in dB) from the baseline using the equation

$$[\text{change in dB}] = 10 \log_{10} \left(\frac{J_n^{\text{mod}}(f)}{J_n^{\text{base}}(f)} \right) \quad (7.7)$$

where f is the frequency, and J_n^{mod} and J_n^{base} are the BET spectra of the modified and baseline blades respectively.

Equation (7.7) implies that increased broadband excitation will result in a positive change, while reduced excitation will yield negative values. These changes are shown in Figure 7.5 where the zero-change line (corresponding to a broadband excitation identical to the baseline) has been highlighted by a solid black line. The four serration configurations (1.27cm, 1.27cm droop, 2.54cm, and 2.54cm droop) are plotted in blue, orange, green and magenta respectively. The serration valley measurements are represented by solid lines while peak measurements can be seen as dotted lines. Quick inspection of Figure 7.5 reveals that the serrated trailing edge blades produce no significant reduction of the broadband excitation, they actually tend to increase the broadband excitation. The 1.27cm serrations average an increase of 0.5 and 0.2dB at the valley and peak respectively over the frequency range. This is consistent with the results of Chapter 6 that showed that the small serrations did not have any significant impact on the turbulence structure. It is interesting to note that the relative contributions of the five driving modes are very similar at the peak and valley as seen in figures 7.6 and 7.7. Indeed, while the strongest mode is different (mode 4 at the valley, mode 5 at the peak), the remaining four driving modes are the same (11, 7, 9, and 3) although their order is changed. At the valley, these four modes combine for 30% of the total excitation. At the peak, the combined contribution is up to 43%. Meanwhile, the strongest mode (mode 5) is producing 17% of the total excitation. This is 9% less than at the valley. The eddy structures of the noise producing modes (mode 4 and 5) are shown in Figure 7.8 and 7.9. These figures show while the strongest modes at the peak and valley share the same type of spanwise fluctuations (with a strong lobe near the wake center surrounded by weaker and opposite spanwise velocity), their traces in the X-Z plane are different. Mode 4 at the

valley consists in a series of small eddies while Mode 5 at the peak is clearly dominated by one larger counter-clockwise structure (centered at $X/L_u=0$ and $Z/L_u=0$). This suggests that for the same spanwise fluctuations, it is preferable to have a series of small eddies rather than one larger one.

Addition of the droop reduces the excitation at the valley to 0.3dB but the potential to generate broadband noise is still larger than for the baseline wake. Furthermore the increased penetration of the serration peak results in a 1.6dB increase over the baseline. Interestingly, there is no dominating driving mode downstream of the valley where the five driving modes (5, 7, 12, 24, and 14) all contribute between 7 and 9% of the total excitation as seen in Figure 7.10. Figure 7.11 shows that the dominant driving mode downstream of the peak (mode 12) contains 20% of the total excitation. The CES associated with mode 12 (seen on Figure 7.12) is characterized by two large eddies (a counter-clockwise centered at (0,-0.6) and a clockwise located at (0.7,0.3)). Most importantly, there is a large spanwise region of strong spanwise fluctuations located around $X/L_u=0$.

The 2.54cm serrations can be seen on Figure 7.5 to result in an overall increase of the broadband excitation compared to both the baseline and the 1.27cm serrations. In fact, the increase at the valley is 1.2dB and 0.5dB at the peak. The increase in serration size seems to have amplified the excitation all across the serration period (from 0.5 to 1.2dB at the valley, and 0.3 to 0.5dB at the peak). Figure 7.14 shows that at the valley, the strongest driving mode is clearly mode 10 (that accounts for 33% of the overall excitation). However the other driving modes have significant contributions (modes 7, 4, 5, and 38 represent 13, 12, 7 and 3% for a total of 35%). This means that the driving modes account for almost 70% of the total excitation. Therefore, while the broadband excitation has been increased, the excitation is self has been simplified (since only 5 modes can be used to account for more than two thirds of the total excitation). Additionally, the eddies associated with the driving mode (shown in Figures 7.16 can be seen to have some similar features. While mode 10 and 38 have unique flow fields, modes 7, 4, and 5 share the same type of spanwise fluctuations. These fluctuations are stronger on the suction side of the wake and display the signs of quasi-periodic structures.

Therefore, if this type of motion could be somehow targeted, one could expect to reduce these three modes (that combine for 32% of the total excitation).

Downstream of the peak, figure 7.15 shows that the excitation is more evenly distributed with the strongest driving mode (mode 7) contributing 22% of the total excitation. The other four driving modes (modes 12, 4, 29, and 5) account for 7.8, 7.8, 6.8 and 6% (a combined 28.4% of the overall excitation). This suggests that the excitation downstream of the peak is more complicated than at the valley since the driving modes combine for 50% of the excitation (compared to 70% at the valley). Interestingly, the dominant mode at the peak (mode 7) can be seen (figure 7.17) to have a flow field very similar to the dominant mode at the valley (mode 10). The spanwise fluctuations in both these modes can be seen to consist in successive horizontal V-shape nested contours. Glegg and Devenport (2001) showed that these type of contours were associated with the two driving modes inside a plane wake. It then follows this type of spanwise fluctuations could be critical to the broadband excitation and efforts should be taken to minimize the impact of this type of modes.

Finally, the addition of droop to the larger serrations is found to have contrasted consequences on the broadband excitation. From an absolute point of view, the 2.54cm can be seen in figure 7.5 to be rather unsuccessful at reducing the wake excitation with increases of 3 and 2.3dB at the serration valley and peak. These increases are most likely the results of the increased penetration combined with the blunt trailing edge as discussed in Chapter 6. Study of the relative contributions of the driving modes downstream of the valley shows that there are now 2 driving modes dominating the excitation (modes 5 and 3). These two modes combine for 52% of the total excitation. Furthermore, the five driving modes (5, 3, 8, 7, and 9) account for 72% of the total excitation. This echoes the results seen downstream of the 2.54cm valley where the driving modes combined for 70% of the excitation. It therefore appears that the broadband excitation is somewhat simplified at the valley of larger serrations since only 5 modes are needed to capture at least 70% of the energy. The CES associated with the driving modes downstream of the 2.54cm drooped serration valley can be seen in figure 7.20. Here again, the spanwise fluctuations of the two dominating modes follow the nested V-shape seen in the 2.54cm serrations and reported by Glegg and Devenport (2001).

The contributions of the driving modes to the excitation downstream of the 2.54cm drooped serration peak can be seen to be clearly dominated by mode 4 (see figure 7.19). This mode accounts for 52% of the excitation alone. The spanwise fluctuations associated with mode 4 (seen in figure 7.21) again follow the nested V-shape contours described previously. One could therefore argue that a diagnostic method could be formulated by applying the characteristic eddy decomposition and analyzing the broadband excitation of the resulting modes. The absence of nested V-shaped spanwise fluctuations in the dominating modes could then be used as a design parameter to minimize the broadband excitation.

7.2.1.2. Impact of Trailing Edge Blowing on the Broadband Excitation

The impact of the trailing edge blowing on the overall broadband excitation of a perpendicular blade-wake interaction is given in Figure 7.22. On this figure, the simple, Kuethe and serrated blowing configurations are shown in light blue, red, and dark green respectively. The blowing rate is indicated by dotted, solid, and dash-dotted lines for 1.4, 2.0, and 2.6% of the passage through flow respectively. The same format used to present the serration blades result is applied. These results are quite a contrast from the serrated trailing edge blades data presented in the previous section. Figure 7.22 shows that all the blowing configurations result in broadband excitation reductions.

The simple blowing configuration can be seen to produce significant excitation reductions. More importantly, the variations with blowing rate show that there is an optimal blowing rate that produces the maximum reduction. At 1.4% blowing, the overall broadband excitation is reduced by 3dB from the baseline. The relative contribution of the driving modes to the total excitation (figure 7.23) shows that there is no clearly dominating mode. The driving modes (13, 12, 15, 23, and 6) combine for only 45% of the total excitation and range between 6 and 11%. It follows that at low blowing rate, the broadband excitation is a function of a large number of scales and is therefore quite complex. Additionally, the four strongest modes are higher modes (i.e. lower TKE), suggesting that the blowing generates the lower excitation by eliminating the spanwise fluctuations of the more energetic modes (as seen in the absence of such fluctuations in the modal profile of modes 1 and 2 presented in Chapter 6). The eddies associated with

the driving mode at 1.4% blowing are presented in Figure 7.24. This figure shows the spanwise velocity distribution of most of these modes consist in short oscillations in the sign of the upwash along the $X=0$ line. The wavelength of these oscillations varies from mode to mode from 0.3 to $0.55L_u$ (0.6 to $0.11c_d$). Mode 12 seems to exhibit the nested V-shapes spanwise fluctuations. However, the magnitude of these fluctuations is low. This then combines with the small amount of TKE associated with this mode (2% of the total energy in the wake) to reduce the impact of this type of spanwise fluctuations on the broadband excitation.

Increasing the blowing rate to 2.0%, further reduces the overall excitation by 2.7dB (5.7dB lower than the baseline). This reduction is consistent with the reduction in the scale and magnitude of the correlation described in Chapter 6. Examination of the relative contributions of the driving modes (figure 7.25) reveals that while mode 9 seems to dominate the excitation with 22% of the total output, the 5 driving mode combine for less than 50% of the total. This confirms that the blown wake is a complex flow where several scales and motions are involved. At the same time, the significant reduction in scale and magnitude of the turbulence results in great excitation diminution. Interestingly, the dominant mode (mode 9) seems to display the nested V-shaped contours of the spanwise fluctuations (figure 7.26) although just like for 1.4% blowing the levels are faint. It therefore becomes apparent that this type of spanwise velocity fluctuations is a major contributor to the overall excitation.

At 2.6% of the passage through flow, the overall broadband excitation reduction falls back to 4dB. This behavior is consistent with the variation of the peak TKE reported by Craig (2006) where a blowing rate of 2.3% resulted in the smallest turbulence levels. As a matter of fact, the description of the correlation function at 2.6% blowing showed that the spanwise fluctuations were amplified by the higher blowing rate. In the case of a perpendicular airfoil, the increased spanwise fluctuations translate into stronger upwash for the cutting blade thus amplifying the broadband excitation. Not surprisingly, the dominant driving mode (mode 3), that accounts for 43% of the total excitation, displays strong and large spanwise contours (figure 7.28). Interestingly, there is very little spanwise vorticity associated with this eddy. The amplified spanwise fluctuations are also clearly visible in the CES of the other driving modes

The overall broadband excitation of the Kuethe blowing configuration at a blowing rate of 2.0% can be seen to be significantly higher than the simple blowing configuration at the same blowing rate. The Kuethe blades result in a broadband excitation that is 2.4dB lower than the baseline, but more than 3dB larger than the simple blowing at 2.0%. As mentioned in Chapter 6, the addition of the Kuethe vanes on the suction side of the blades significantly increased the scale of the spanwise fluctuations on the suction of the wake (possibly due to some separation occurring near the trailing edge). Examination of the relative contribution of the driving mode downstream of the Kuethe blades show a distribution very similar to the simple blowing at 2.6% blowing. The excitation is dominated by mode 3 that accounts for 34% of the total output (figure 7.29). The flow field associated with mode 3 (figure 7.30) clearly shows the increased spanwise fluctuations occurring on the suction side of the wake. It can be therefore concluded that the addition of the vortex generators diminished the efficiency of the trailing edge blowing.

The serrated trailing edge blowing results show that the different blowing slot design combined with the serration did not result in a significant change from the simple blowing configuration. The reductions in the overall broadband excitation are 3 and 5.5dB at 1.4 and 2.0% blowing (compared to 3 and 5.7dB reductions for the simple blowing). However, the structure of the turbulence seems to have been simplified. At 1.4% blowing, the relative contribution of the driving modes (figure 7.31) shows that mode 5 (with 22%) contributes the most to the overall excitation. The driving modes combine for 60% of the total excitation. At 1.4%, the driving modes of the simple blowing account for only 45%. It seems therefore that the addition of the serration combined with the blowing slot design resulted in a simpler turbulent structure while maintaining the excitation reduction. It should be noted that the upwash contours associated with mode 5 and 7 (figure 7.32) of the serrated blowing configuration displays some characteristics of the nested V-shape. There is some asymmetry with respect to the wake center line possibly due to the asymmetric nature of the serration described in Chapter 4.

At 2.0%, this simplification of the turbulent structure is conserved. The excitation is dominated by mode 5 (responsible for 32% of the total output) as seen in Figure 7.33.

The 5 driving modes also combine for 60% of the total output (the same amount as the 1.4% blowing). Figure 7.34 shows that the dominant mode at 2.0% has again the nested V-shaped spanwise fluctuations contours.

7.2.2. Parallel Blade-Wake Interaction

The perpendicular blade-wake interaction described in the previous is obviously a highly idealized model for the rotor-stator interaction. As mentioned previously, the actual rotor wakes are spiral-like structures with significant spanwise variations. Furthermore, the motion of the rotor blades results in swirling effects. Consequently, the wake incidence on the stator vane can significantly vary. Analyzing the case of a parallel blade-wake interaction, in addition to the perpendicular cut described above, will provide additional insight on the rotor-stator interaction. In a parallel cut, the stator leading edge would be parallel to the wake spanwise axis (i.e. along the Y-direction for the present study). It then follows that the upwash seen by the cutting blade corresponds to the normal-to-wake velocity (Z-direction) inside the wake. Such analysis will again be modeled as a linear system subjected to a broadband excitation. In this case however, the excitation is based on the expression for the radiated pressure spectrum density of Amiet (1975) derived for homogeneous turbulence (Eq.7.6). While the spanwise homogeneity approximation can be considered valid for the baseline (and some of the blowing configuration), the Pitot-static cross-sections downstream of the serrated trailing edge blades showed significant spanwise variations (in the form of a sinuous wake, especially for the larger serrations). This was further confirmed by the turbulence velocity measurements of Geiger (2005). It is therefore stressed here that the spanwise homogeneity assumption is understandably a substantial simplification of the problem at hand. Nevertheless it can be argued that it will still provide additional understanding of the overall rotor-stator interaction.

The results for the spanwise BET are presented in figure 7.35. This figure uses the same type of format as figures 7.5 and 7.22 where the variations in the spanwise broadband excitation J'' are expressed as changes (in dB) from the baseline (using Eq. 7.6). Here again, care was taken to ensure that the integrand in Eq.(7.6) was properly

resolved over the frequency range presented in Figure 7.35. The resulting spectra are plotted against the frequency (normalized on the notional BPF of 94Hz) for the various strategies tested. As mentioned in Chapter 6, the spanwise data for the 2.54cm droop could not be used and is therefore absent of this figure. The 1.27cm, 1.27cm with droop, and 2.54cm serrated blade results are shown in blue, orange, and green. The trailing edge blowing configurations (simple, Kuethe, and serrated blowing) are presented in light blue, red, and dark green respectively. The blowing rates of 1.4, 2.0, and 2.6% are indicated by dotted, solid, and dash-dotted lines respectively. For comparison purposes, the line of 0dB change (indicating the baseline levels) is shown as a solid black line.

Interestingly, the different strategies seem to be affecting the broadband excitation of a parallel interaction the same way they affect a perpendicular interaction. The serrated trailing edge blades can be seen to have little influence on the excitation. Over the frequency range presented here, the change in the spanwise BET of the 1.27cm serrations from the baseline is 0.4dB. The addition of droop or the larger serration size does not affect the average excitation relative to the baseline. These results are qualitatively comparable to the excitations resulting from a perpendicular interaction. However, close inspection of the 2.54cm spectrum reveals that this zero average change is split between a 1dB reduction at low frequencies (below 5BPF) and 1dB increase at high frequencies. While the shape of the spectrum is trivial here (since the ultimate radiation will be function of the cutting blade response function), such behavior could prove important.

Interestingly, this behavior seems to occur for the trailing edge blowing configurations as well. At low frequencies (below 5BPF here), all configurations seem to exhibit their maximum reductions (that are almost constant until 5BPF). Such frequency is comparable to the frequency of the quasi-periodic structure seen in the R_{33} auto-correlation reported in Chapter 6. As discussed in Chapter 6, the trailing edge blowing was found to significantly affect these quasi-periodic structures which explains the large reduction seen at these low frequencies. Above this frequency, the reductions suddenly decrease and reach a plateau. At a blowing rate of 1.4%, the simple blowing configuration can be seen to reduce the spanwise excitation by about 8dB. At higher frequencies, this reduction drops to 1dB. Increasing the blowing rate to 2.0% of the passage flow increases leads to a 13dB reduction at low frequencies and 4dB at high

frequencies. At 2.6%, the over-blown wake results in smaller reduction at low frequencies (11dB). As the frequency increases, the excitation seems to tend towards the baseline levels. This confirms that over-blowing could be especially detrimental since it would not only require a significant amount of air to be bled from the compressor, but it also shows potential to negate any possible broadband noise reduction. Therefore, there seems to be an optimal blowing rate between 2.0 and 2.6% that would generate the maximum excitation reduction (a conclusion that was also drawn from the perpendicular interaction analysis).

The addition of the Kuethe vane on the blowing blade can be seen to significantly alter the excitation reduction obtained at the same blowing rate (2% of the mass through flow) with the simple blowing configuration. Below 5BPF, the reduction is on the order of 7dB (compared to 13dB for the simple blowing blades). Above 5BPF, the reduction falls to 2dB as opposed to the 4dB reduction of the simple blowing. This result is consistent with the increased spanwise correlation levels described by Kuethe (1972) downstream of such vortex generators. Since the blowing rates involved here are already too large to be realistic, it becomes critical to ensure that the blowing configuration is optimum to maximize the efficiency of the system. Clearly, the addition of the Kuethe vane decreased the efficiency of the simple blowing configuration. This loss of efficiency mirrors that reported for a perpendicular interaction.

The serrated blowing blade results (seen in dark green) show that just like in the case of a perpendicular interaction, the addition of serrations on each side of the blowing slot produces excitation reduction similar to the simple blowing configuration. At 1.4%, the low frequency reduction is on the order of 7dB (a 1dB difference from the simple blowing at the same rate). At high frequencies, the reduction falls to 2.7dB. The simple blowing reduction at high frequencies is 1dB. This suggests that the serrated trailing edge blowing configuration is more efficient at reducing the broadband excitation for a parallel interaction. At a blowing rate of 2.0%, the benefits of the serrated blowing slot disappear so that the excitation levels are comparable with the simple blowing configuration. It is again interesting to note that the behavior of the broadband excitation downstream of the serrated blowing blades is similar for both perpendicular and parallel interactions.

7.2.3. Summary

The interaction between the rotor wake and the stator blade was modeled as a linear system where the wake was treated as an exciting force converted into a radiated pressure field through the cutting blade response function. Assuming a linear process allows to estimate the possible broadband benefits of a particular configuration by evaluating the change in the broadband excitation. As mentioned earlier, one could expect that a reduction in the broadband excitation would lead to a reduction of the broadband noise generation. At the very least, these results can be treated as a preliminary diagnostic tool to predict the potential of a particular configuration to reduce broadband noise. Further acoustic measurements of these configurations would then be needed to confirm the actual radiation reductions.

The analysis of the interaction between the wakes and a hypothetical cutting blade at 90° with the wake spanwise axis showed that the serrated trailing edge blades increased the broadband excitation and therefore the potential of these wakes to generate noise. This is especially true for the larger serrations that resulted in a 1.2dB maximum increase. The addition of droop increased the excitation for both small and large serrations leading to a maximum increase of up to 3dB downstream of the large serrations. In contrast, every trailing edge blowing configuration was found to produce large reduction in the broadband excitation. The simple blowing configuration produces reductions of 3, 6, and 4dB at 1.4, 2.0, and 2.6% of the through flow. It seems therefore that an optimal blowing rate between 2.0 and 2.6% could result in reductions of at least 6dB. The lower efficiency of the simple blowing at the higher blowing rate is believed to be the result of the increased spanwise velocity fluctuations. The addition of Kuethe vanes on the suction side of the blowing blades significantly reduced the reduction to 2.4dB at a blowing rate of 2.0% (possibly due to some late flow separation downstream of the vortex generators). The serrated blowing configuration was found to yield reductions similar to the simple blowing configuration. However, the turbulence excitation was simplified. A comparison of the broadband excitation obtained from the various strategies is given in Figure 7.36.

Most importantly, a specific spanwise velocity fluctuation distribution was found to consistently appear among the driving modes of the broadband excitation. In such a

distribution, the spanwise fluctuations appear along nested V-shaped regions of alternating sign of the velocity. Consequently, if a method could be devised to minimize this type of spanwise fluctuations, sizeable reductions of the broadband excitation could follow. At the very least, it would become particularly interesting to obtain a model of the two-point correlation function that would allow to tune the blade geometry by eliminating the lower modes associated with this type of fluctuations.

The overall comparison of the broadband excitations for a parallel cut downstream of the various strategies tested can be seen in Figure 7.35. The analysis of an idealized parallel interaction between the modified wakes and a hypothetical stator blade revealed that the resulting broadband excitations follow the same trends (for almost all the configurations tested) that appear in a perpendicular interaction. While the parallel interaction analysis is highly idealized (mainly by assuming homogeneity in the spanwise direction) it proved to produce similar results. One could therefore argue that the excitations resulting from intermediate interactions (such as those occurring in a real aircraft engine in which the stator blade leading edge is at an angle between 0 and 90° to the rotor wake local spanwise axis) should follow the trends described by the perpendicular and parallel interactions. Consequently, it appears that a model assuming a perpendicular interaction could be used as a reference to diagnose the rotor-stator interaction.

The trailing edge serration was found to have no positive effects on the broadband excitation of a parallel cut and could actually be increasing it by 1dB at high frequencies (independently of the serration configuration). While the excitation reductions of a perpendicular interaction were found to be relatively constant over the frequency range, the broadband excitation of a parallel interaction was shown to be dependent on the frequency. Since the model used in the present study do not take into account the effects of blade response, their absolute variation with frequency is irrelevant. However, the trailing edge blowing was found to be particularly efficient at targeting the quasi-periodic structures of the turbulence translating into large excitation reductions (up to 13dB) at low frequencies. At higher frequencies, the serrated blowing configuration was found to be the most efficient configuration with high frequency reductions of almost 3dB. The analysis of the simple blowing configuration showed that an optimum blowing between 2

and 2.6% could lead to broadband excitation reductions of at least 4dB at high frequencies. The addition of Kuethe vanes on the suction side was found to decrease the efficiency of the simple blowing configuration. Unfortunately, as mentioned in the previous chapter, the blowing rates involved here (about 2% of the passage through flow) are too high to be realistic. The applicability of such technology will then depend on the capacity to lower the required blowing rates. The study by Langford *et al.* (2005) showed that a distribution of discrete jets along the blade span lead to more realistic blowing rates (on the order of 1% of the through flow).

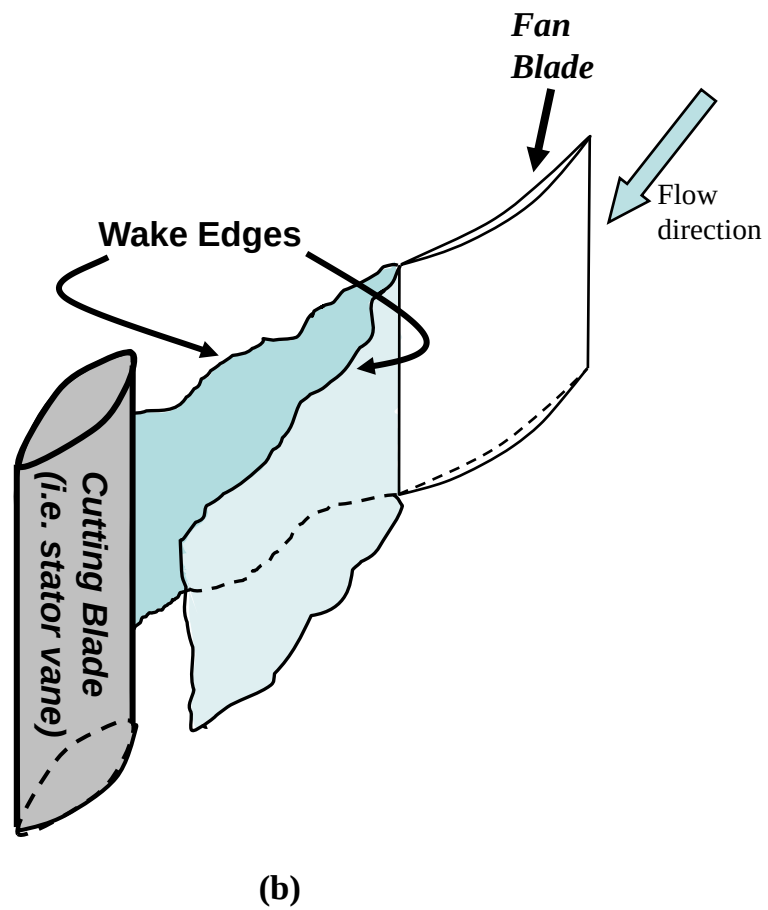
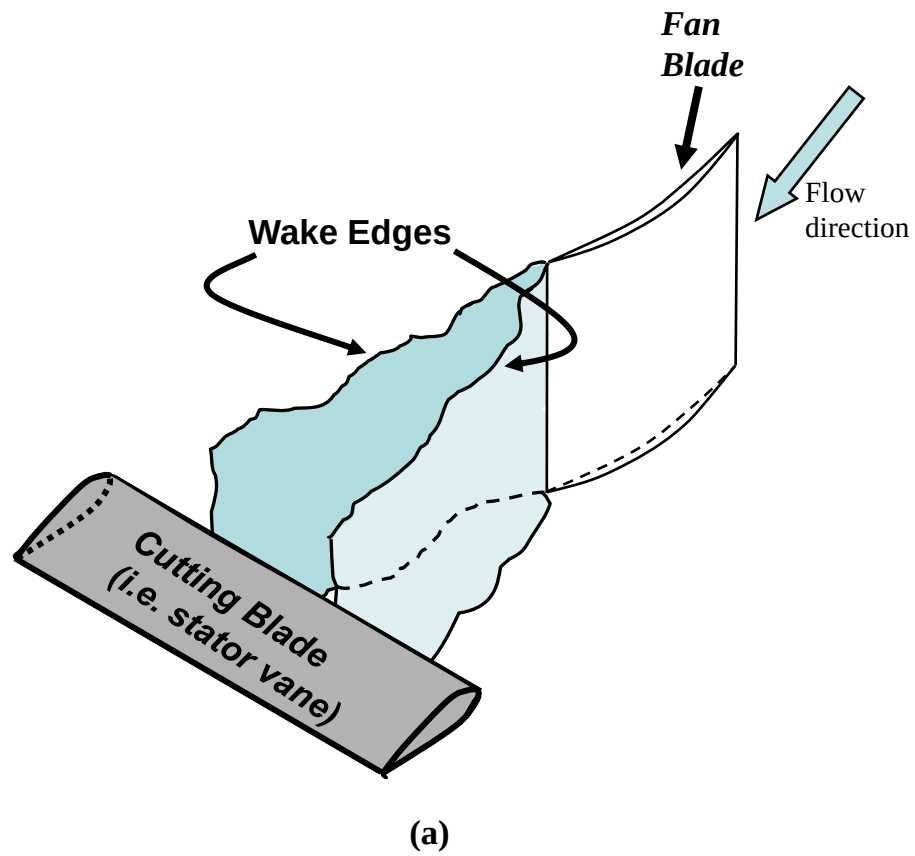


Figure 7.1 Schematic description of (a) perpendicular blade-wake interaction and (b) parallel blade-wake interaction.

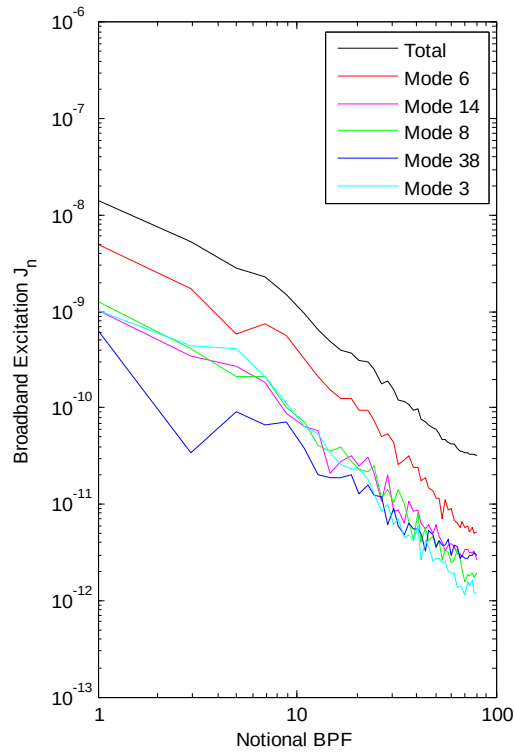


Figure 7.2 Broadband Excitation Term (BET) Spectra for the 5 driving modes – Baseline Blades.

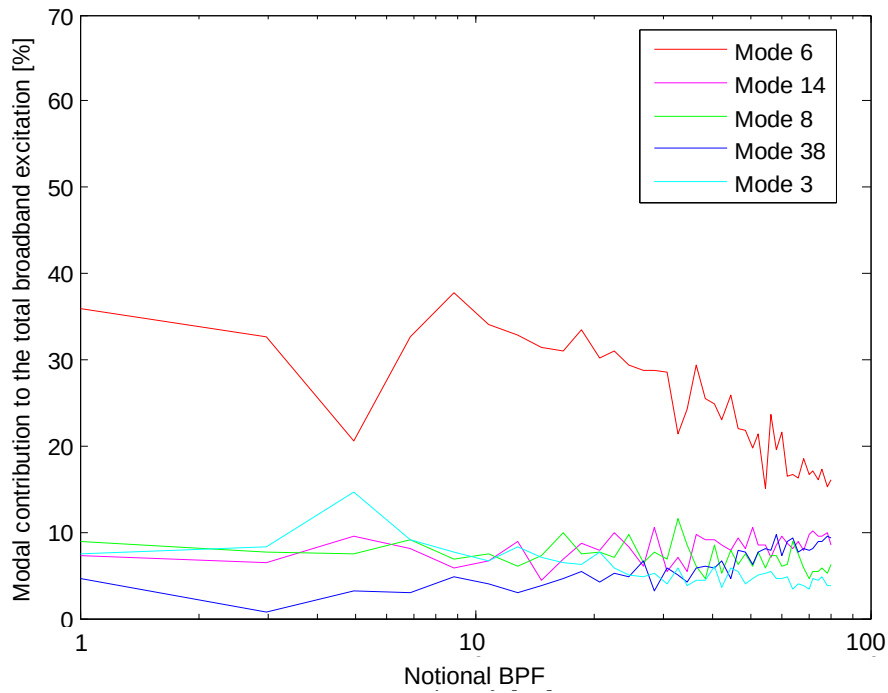


Figure 7.3 Relative contributions of the 5 driving modes to the total broadband excitation - Baseline Blades.

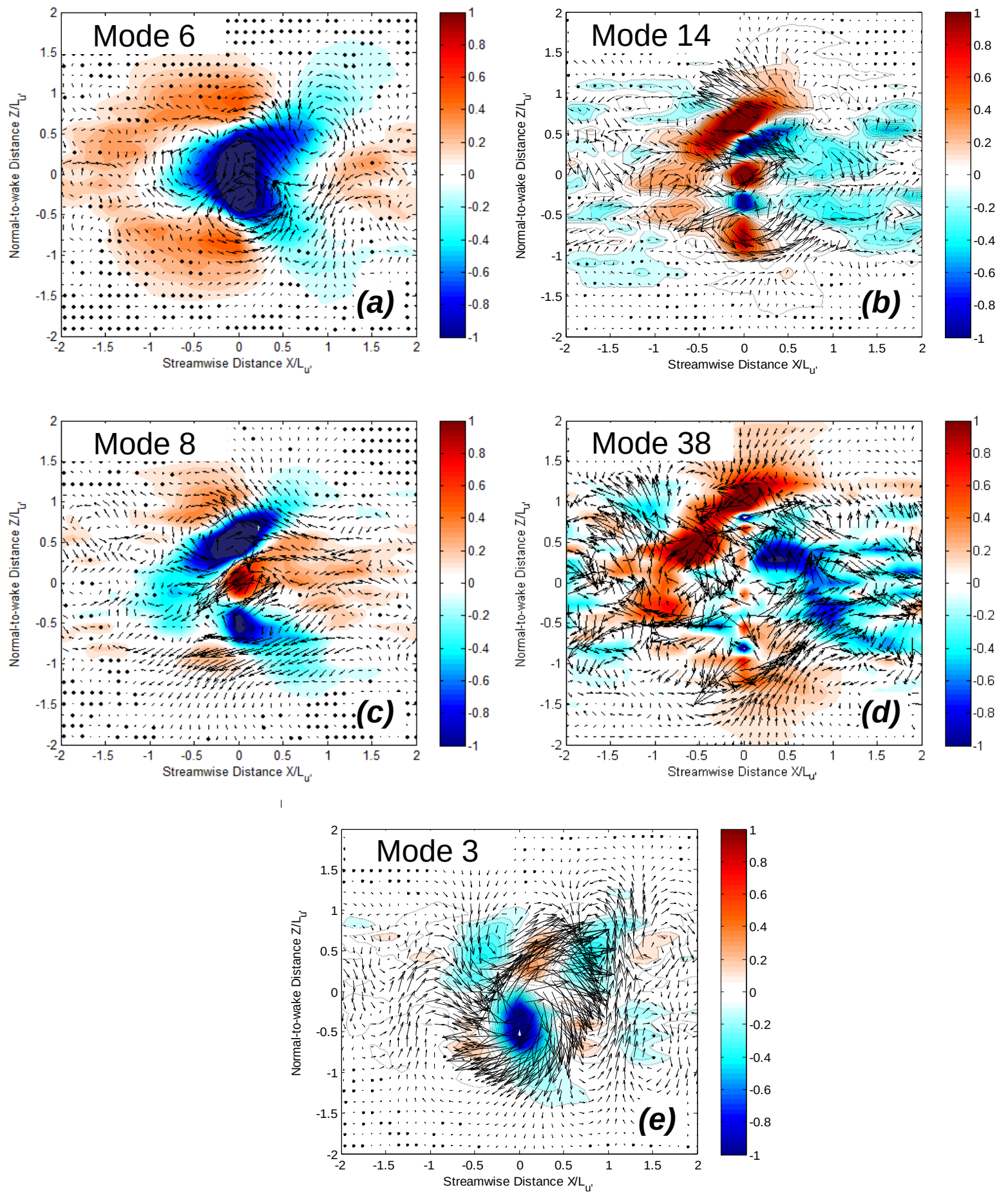


Figure 7.4 Compact Eddy Structures associated with the 5 driving modes - Baseline Blades. Contours indicate spanwise velocity component.

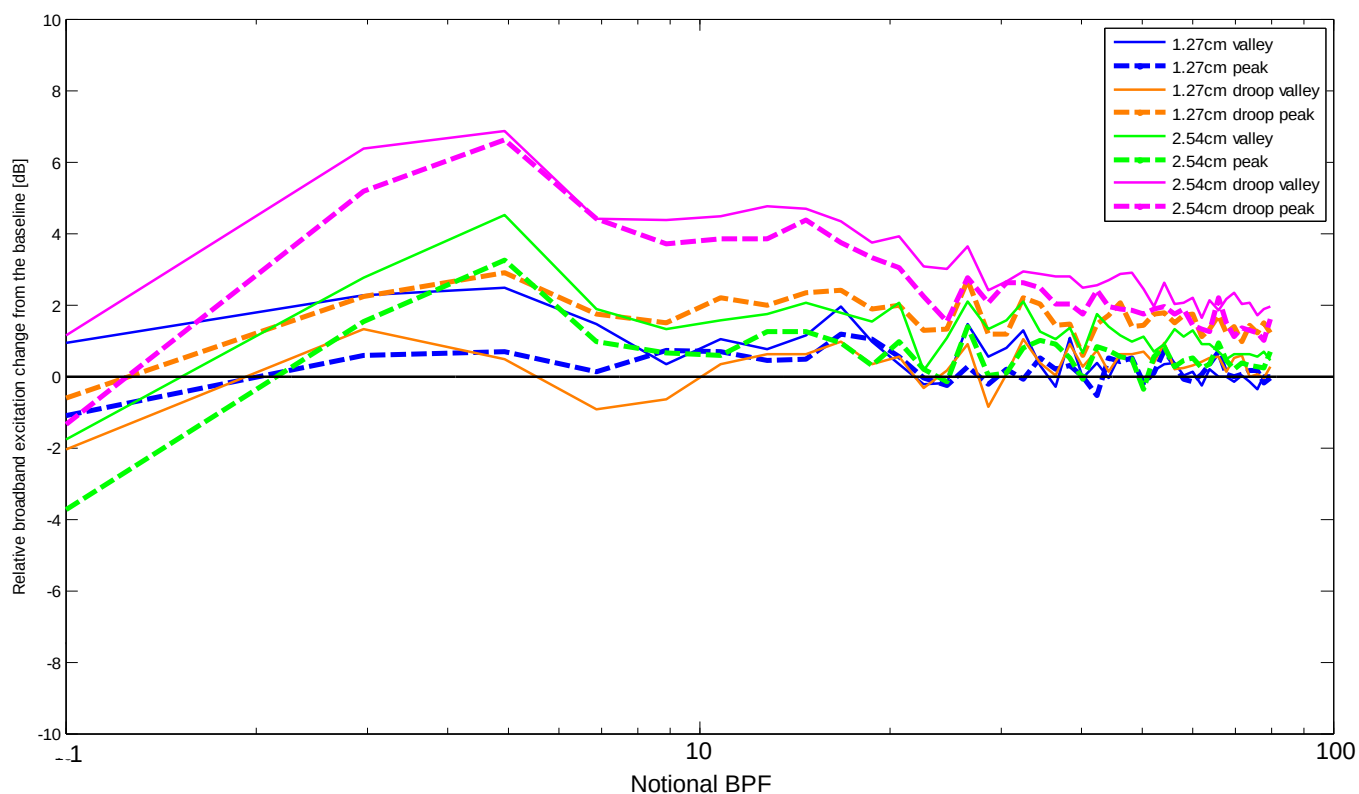


Figure 7.5 Impact of the trailing edge serrations on the broadband excitation for a perpendicular blade-wake interaction. Changes (in dB) are expressed relative to the baseline excitation.

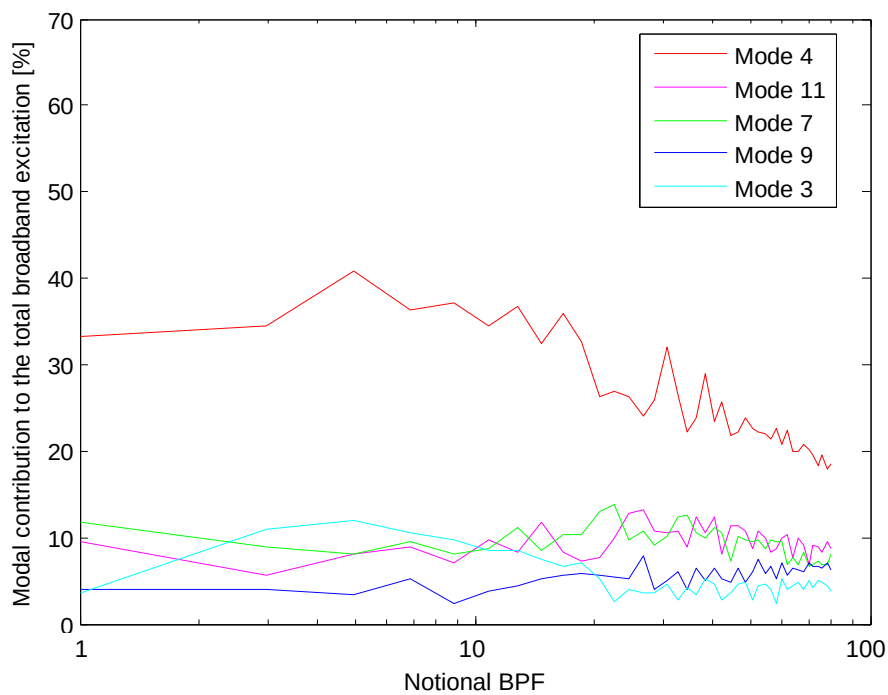


Figure 7.6 Relative contributions of the 5 driving modes to the total broadband excitation – 1.27cm serration blades - serration valley.

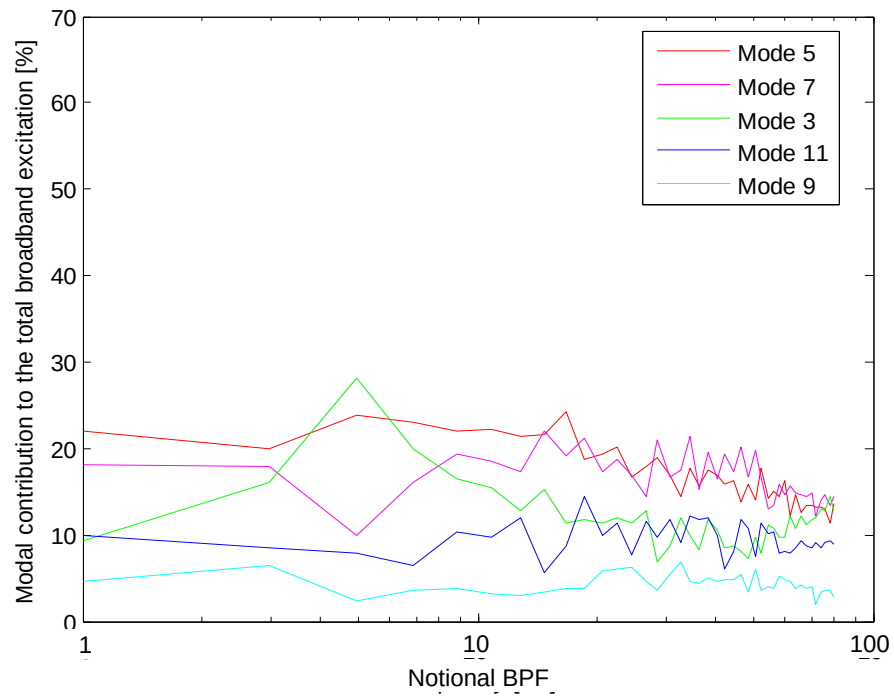


Figure 7.7 Relative contributions of the 5 driving modes to the total broadband excitation – 1.27cm serration blades - serration peak.

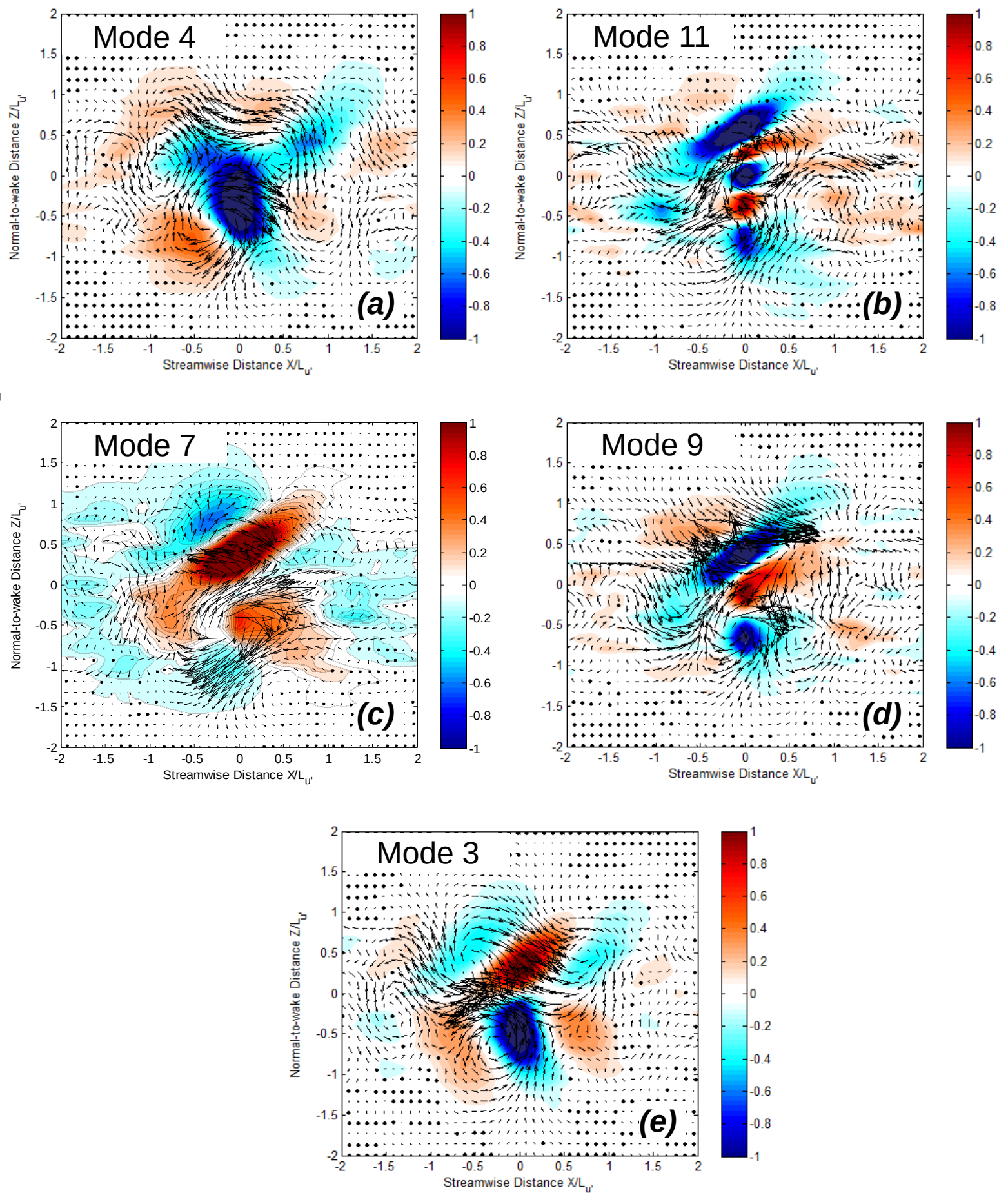


Figure 7.8 Compact Eddy Structures associated with the 5 driving modes – 1.27cm serration blades – serration valley. Contours indicate spanwise velocity component.

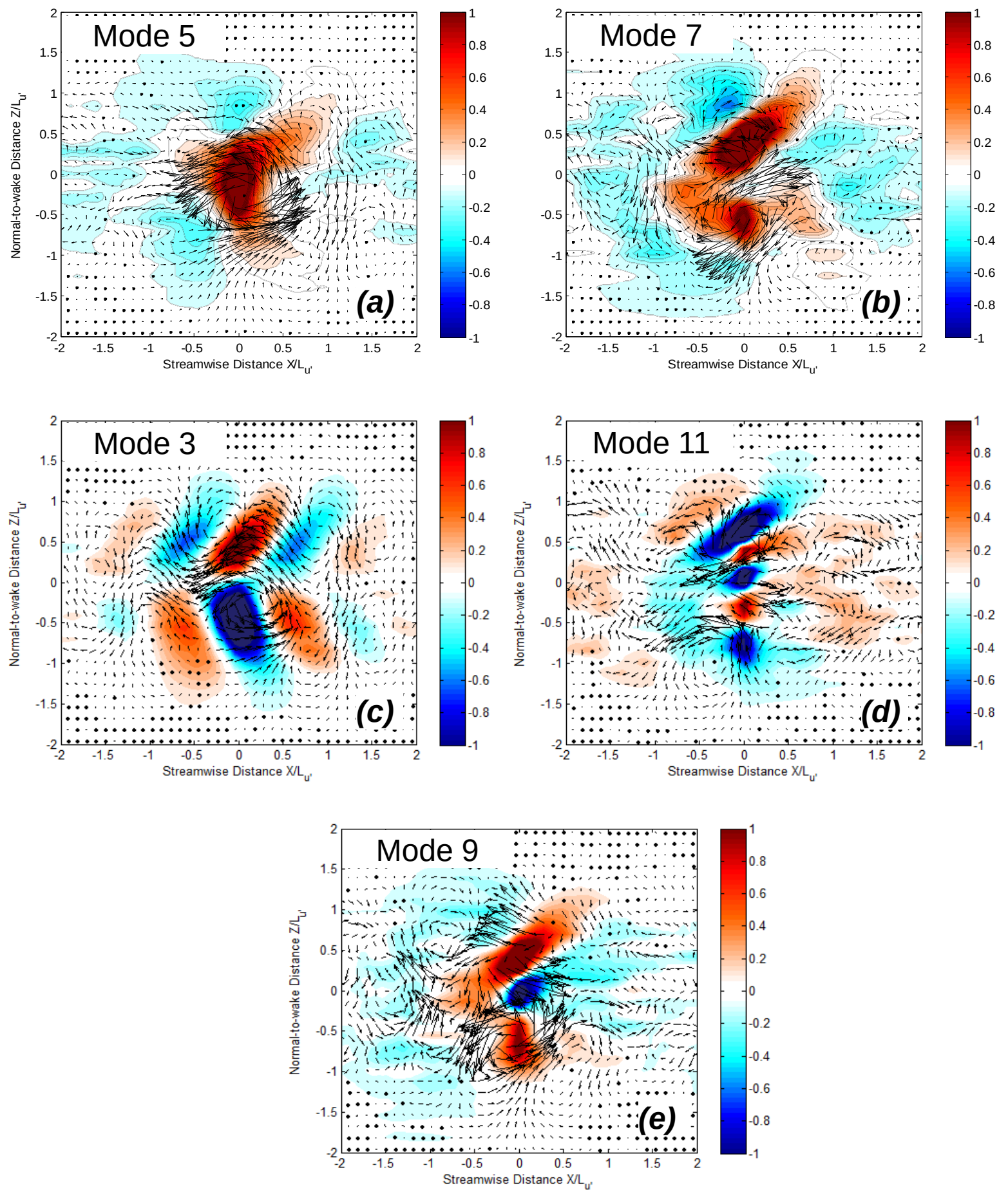


Figure 7.9 Compact Eddy Structures associated with the 5 driving modes – 1.27cm serration blades – serration peak. Contours indicate spanwise velocity component.

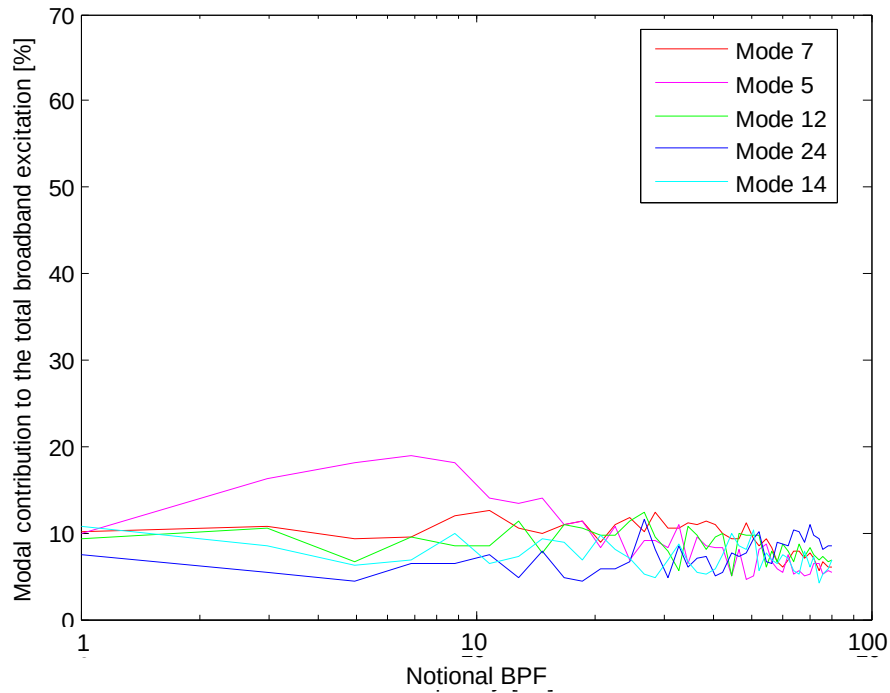


Figure 7.10 Relative contributions of the 5 driving modes to the total broadband excitation – 1.27cm drooped serration blades - serration valley.

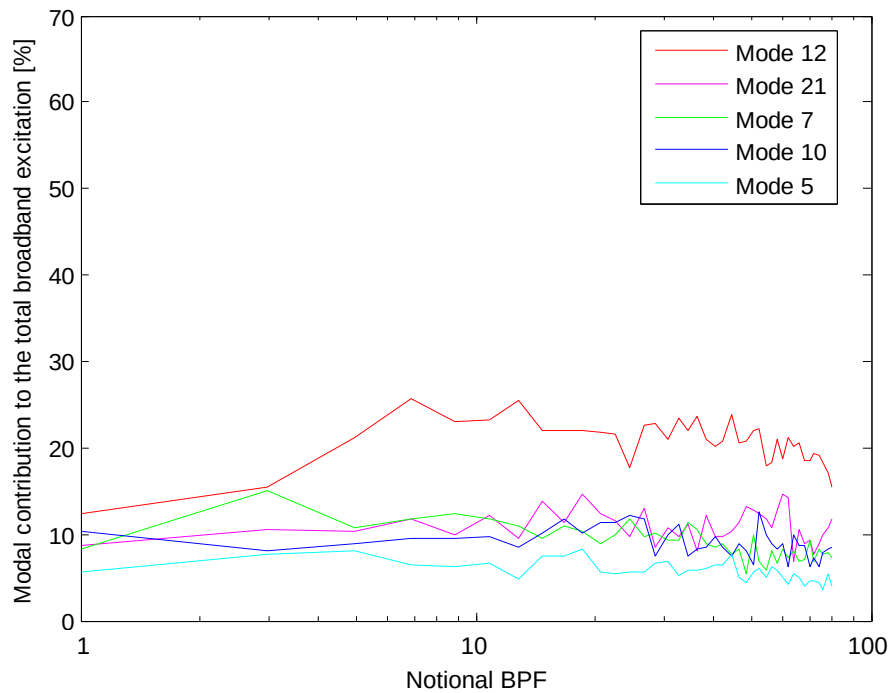


Figure 7.11 Relative contributions of the 5 driving modes to the total broadband excitation – 1.27cm drooped serration blades - serration peak.

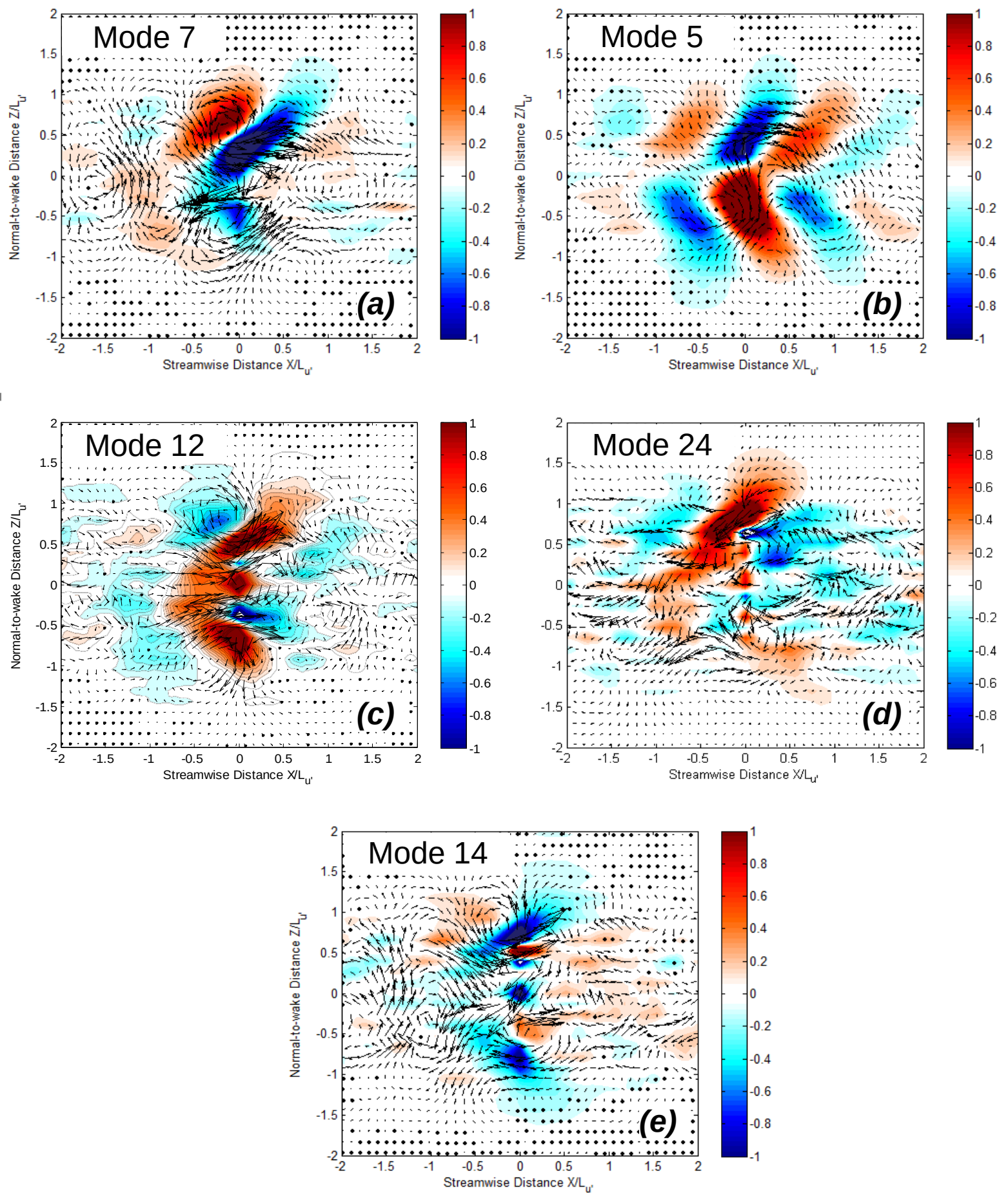


Figure 7.12 Compact Eddy Structures associated with the 5 driving modes – 1.27cm drooped serration blades – serration valley. Contours indicate spanwise velocity component.

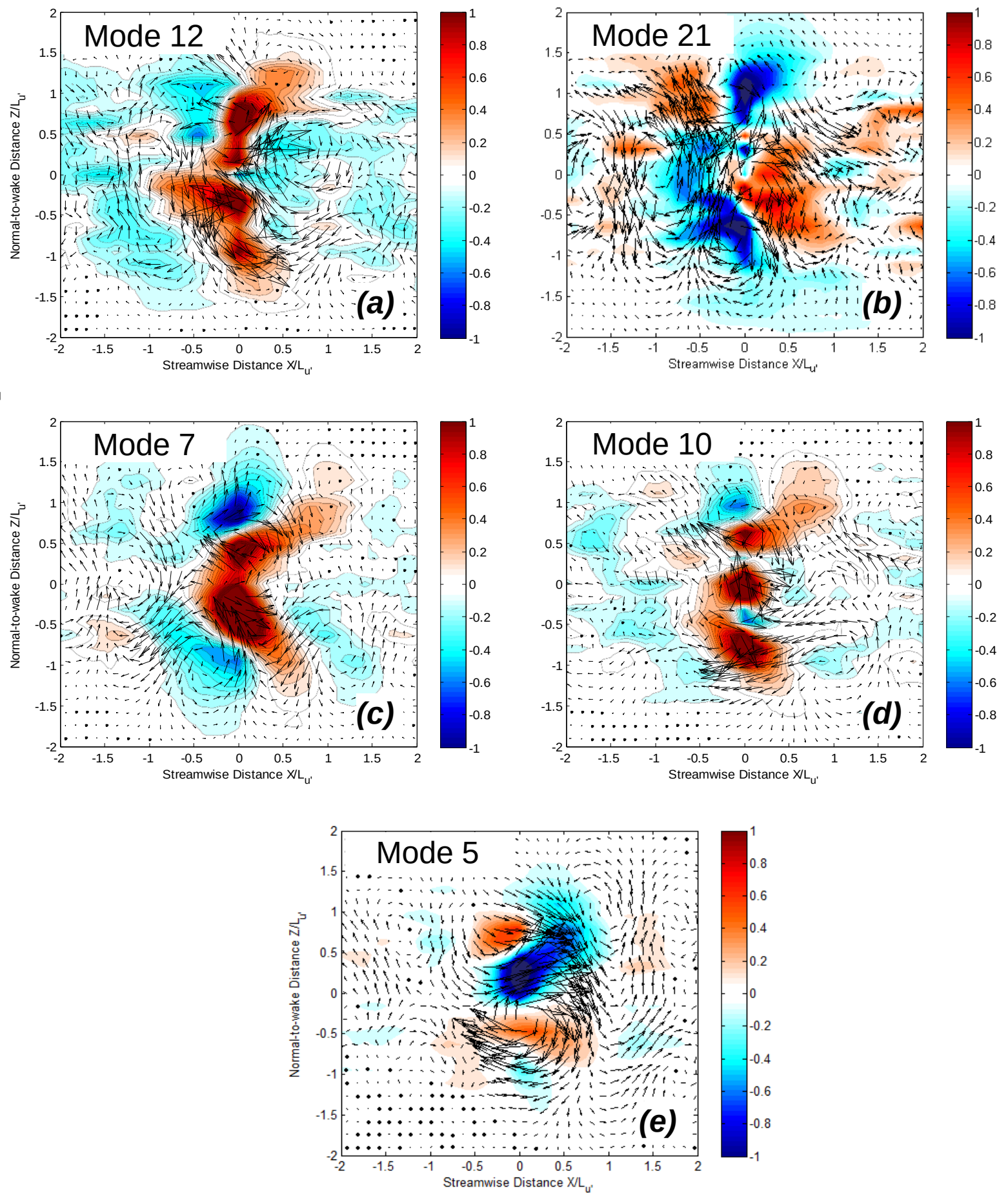


Figure 7.13 Compact Eddy Structures associated with the 5 driving modes – 1.27cm drooped serration blades – serration peak. Contours indicate spanwise velocity component.

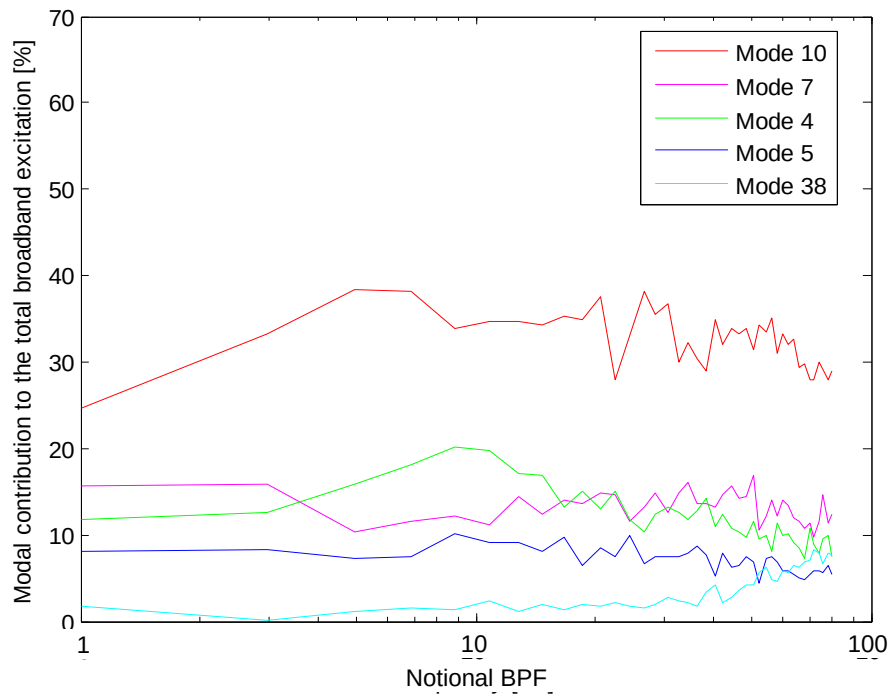


Figure 7.14 Relative contributions of the 5 driving modes to the total broadband excitation – 2.54cm serration blades - serration valley.

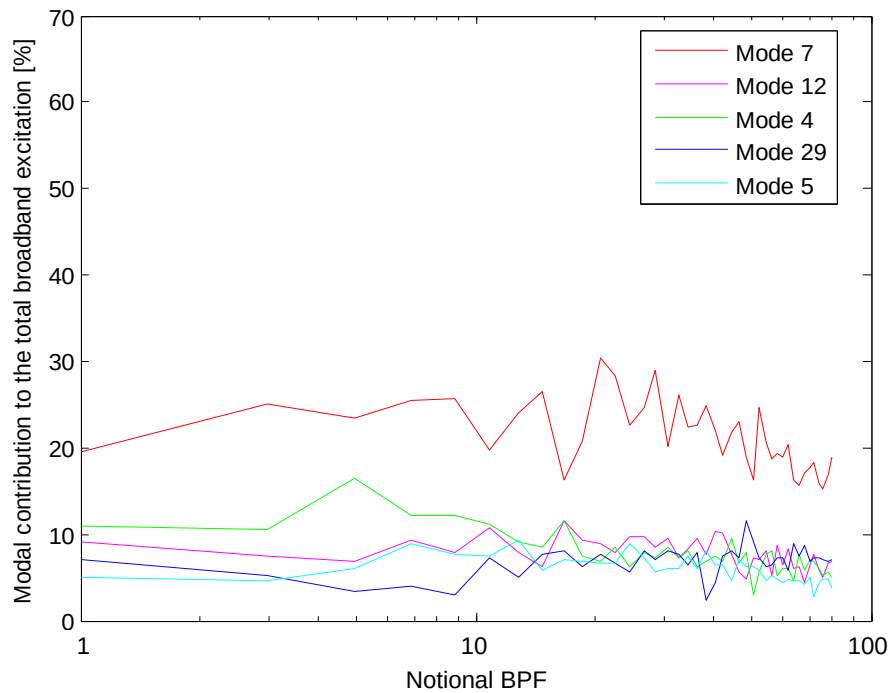


Figure 7.15 Relative contributions of the 5 driving modes to the total broadband excitation – 2.54cm serration blades - serration peak.

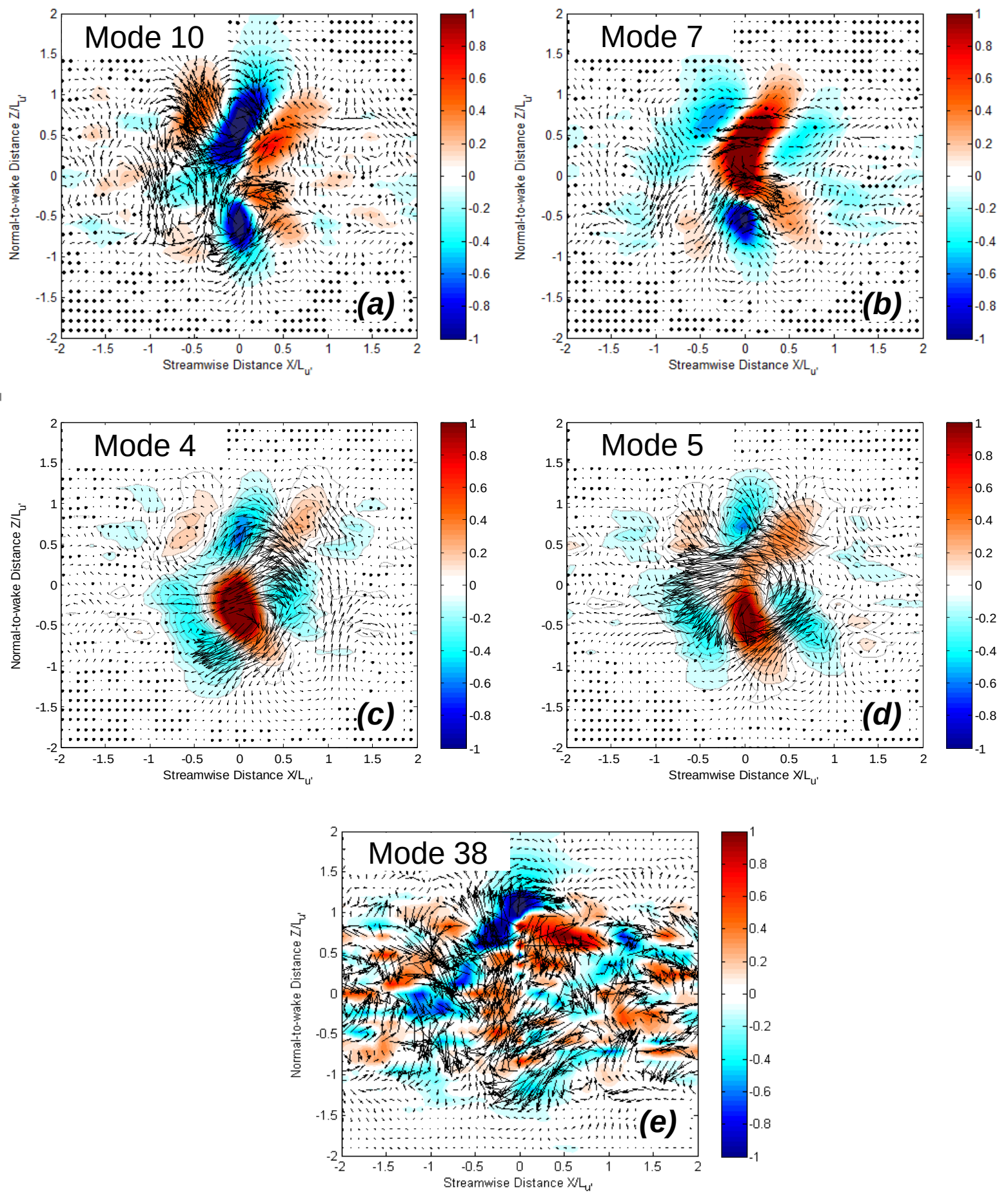


Figure 7.16 Compact Eddy Structures associated with the 5 driving modes – 2.54cm serration blades – serration valley. Contours indicate spanwise velocity component.

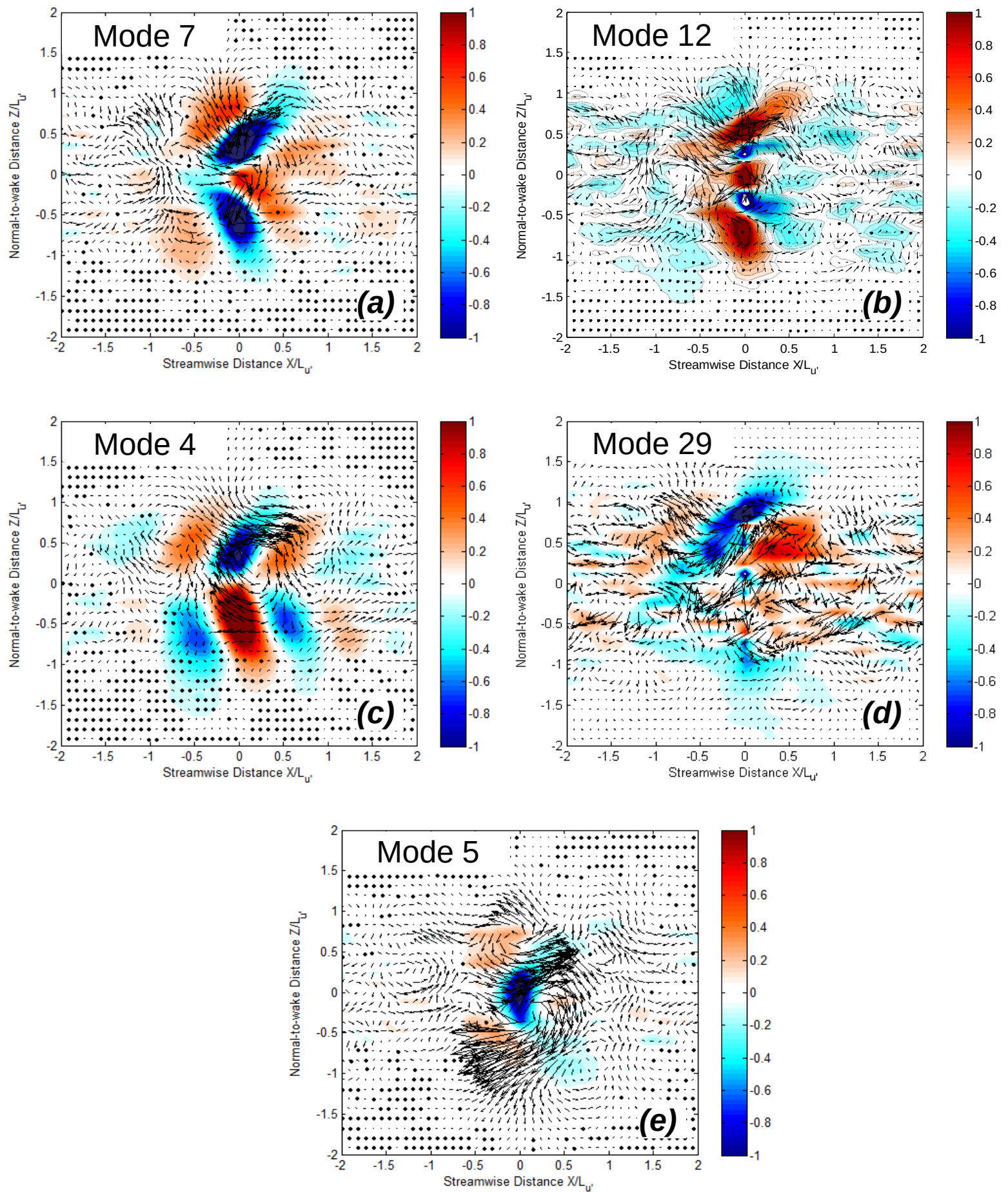


Figure 7.17 Compact Eddy Structures associated with the 5 driving modes – 2.54cm serration blades – serration peak. Contours indicate spanwise velocity component.

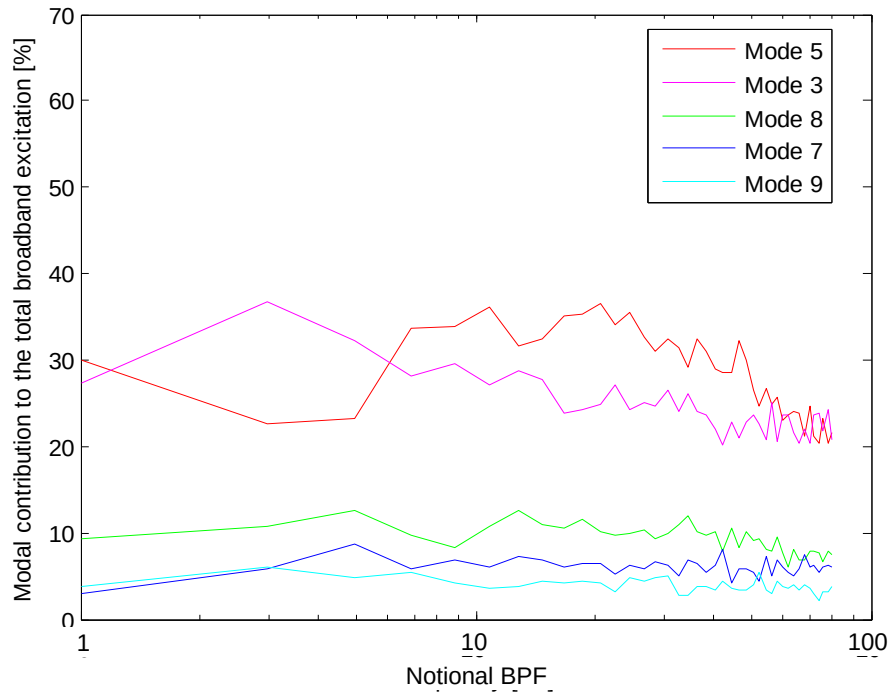


Figure 7.18 Relative contributions of the 5 driving modes to the total broadband excitation – 2.54cm drooped serration blades - serration valley.

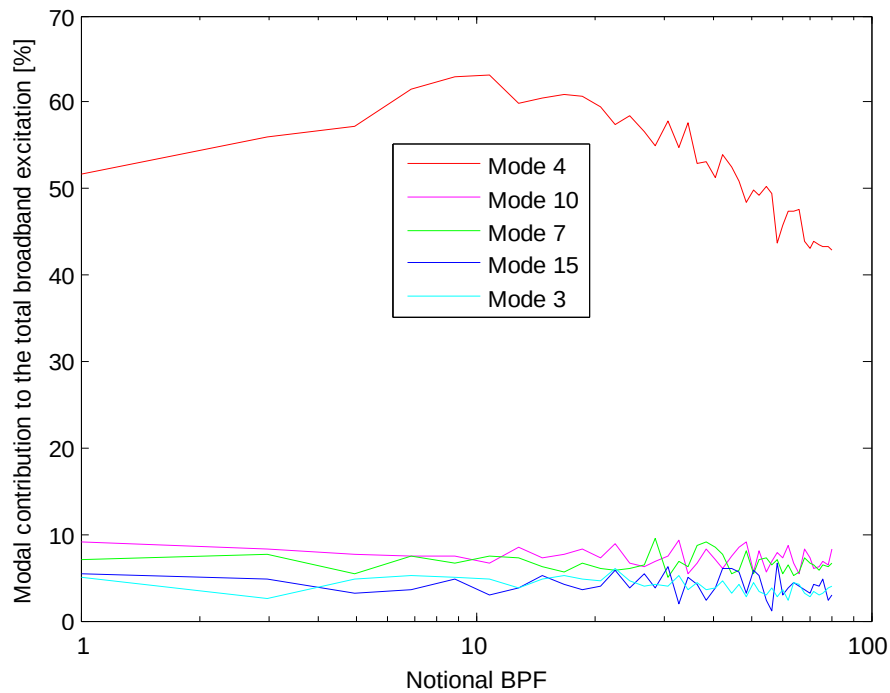


Figure 7.19 Relative contributions of the 5 driving modes to the total broadband excitation – 2.54cm drooped serration blades - serration peak.

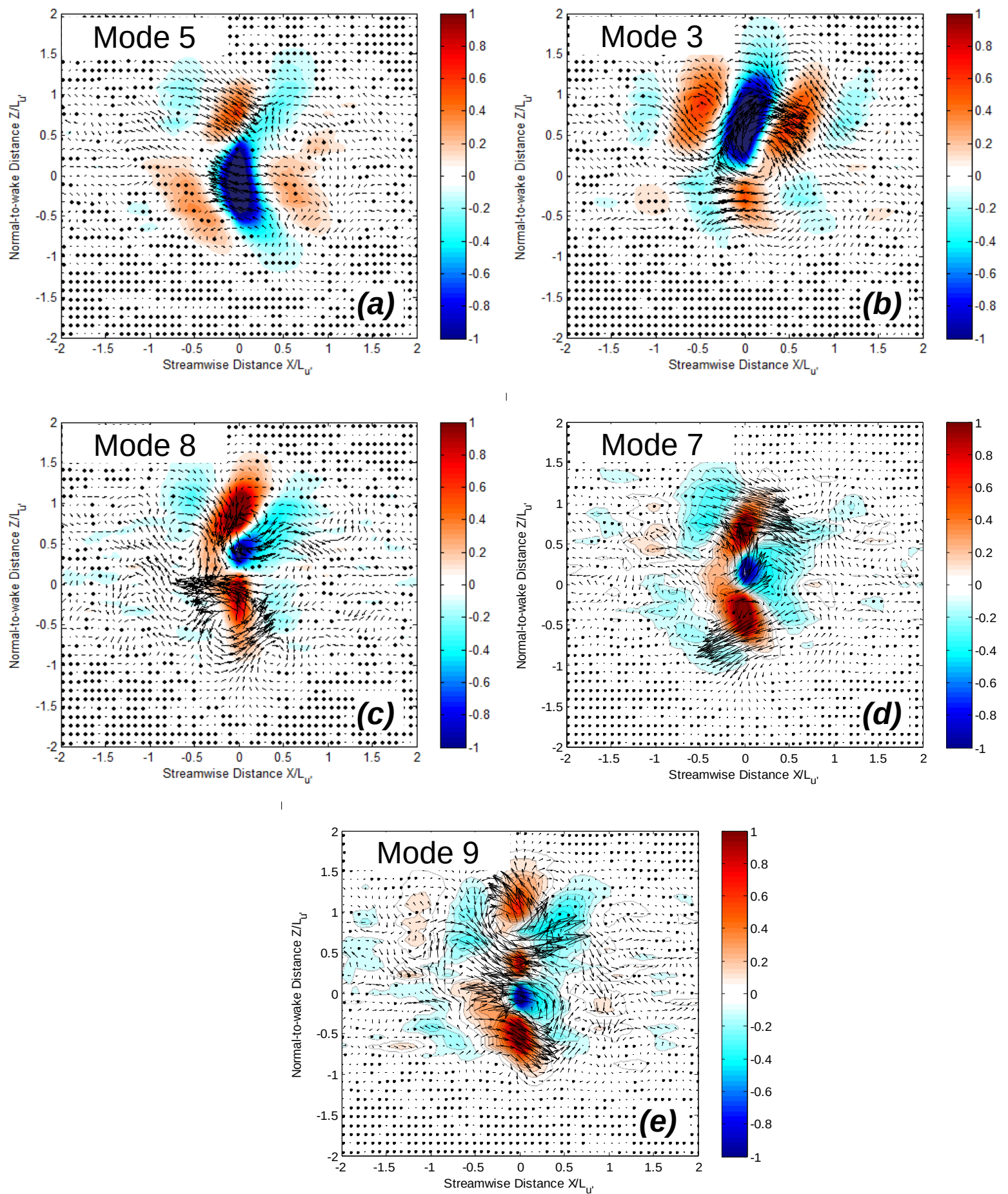


Figure 7.20 Compact Eddy Structures associated with the 5 driving modes – 2.54cm drooped serration blades – serration valley. Contours indicate spanwise velocity component.

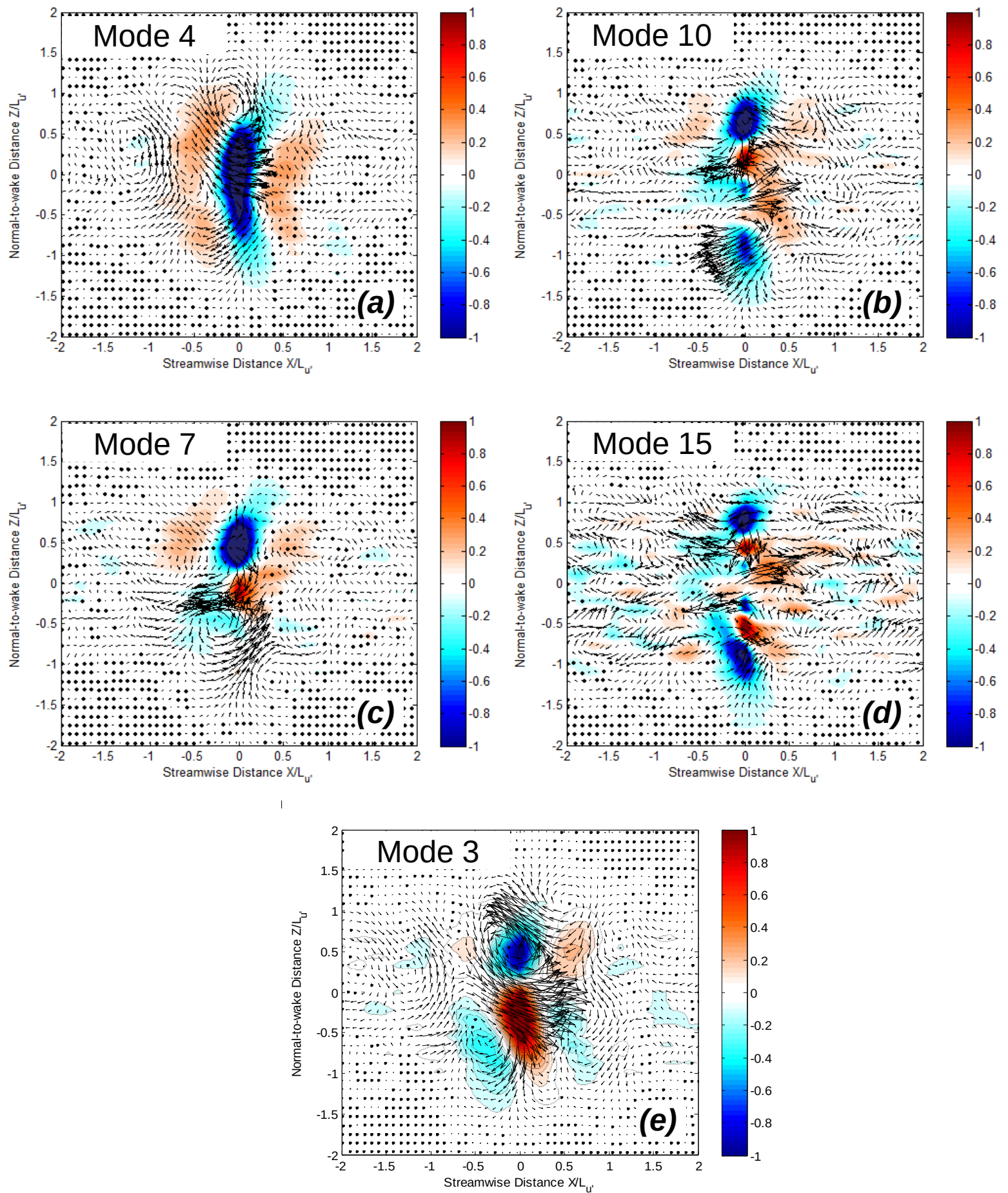


Figure 7.21 Compact Eddy Structures associated with the 5 driving modes – 2.54cm drooped serration blades – serration peak. Contours indicate spanwise velocity component.

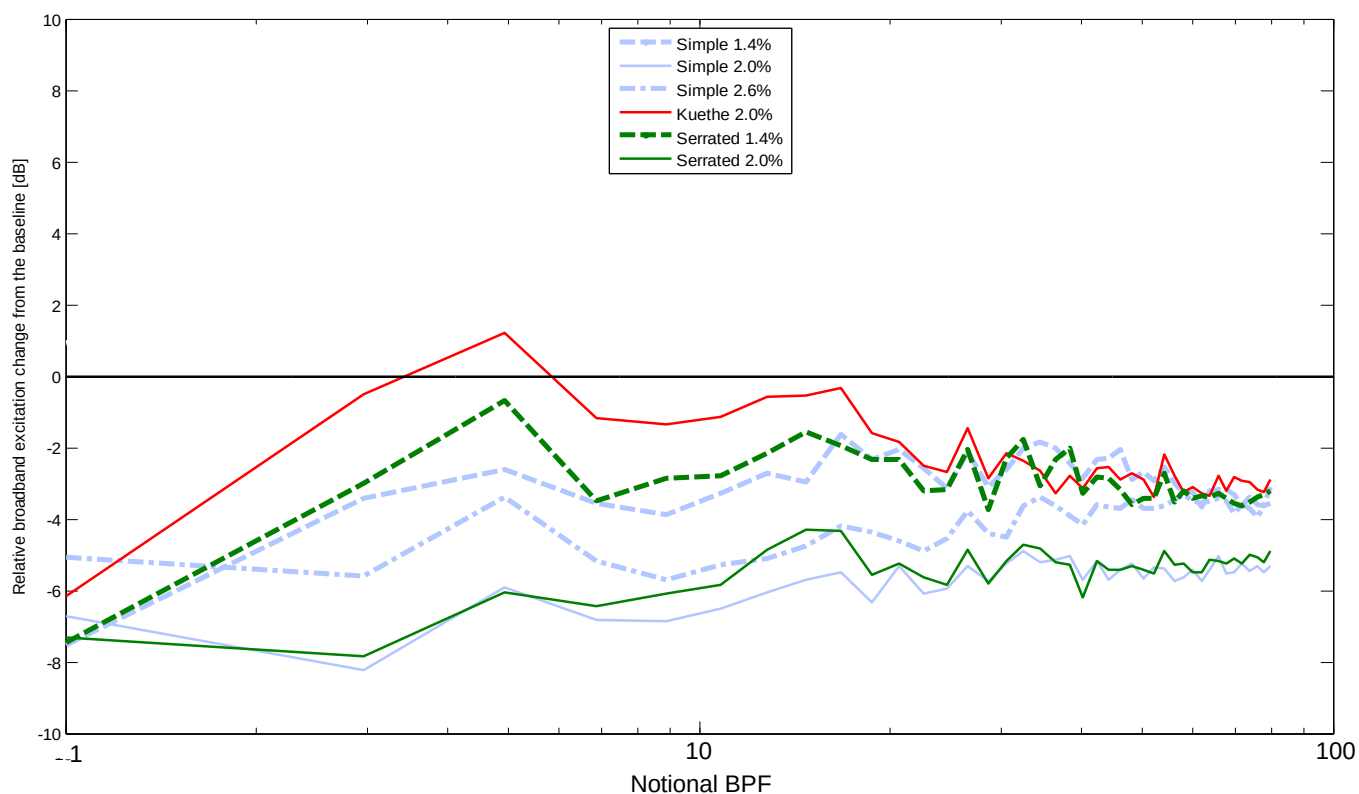


Figure 7.22 Impact of the trailing edge blowing on the broadband excitation for a perpendicular blade-wake interaction. Changes (in dB) are expressed relative to the baseline excitation.

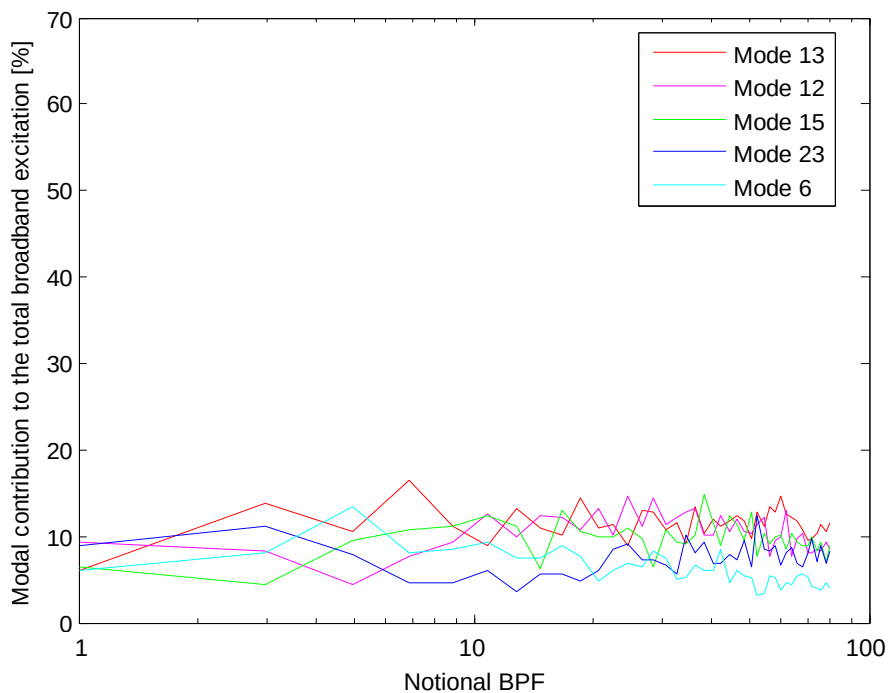


Figure 7.23 Relative contributions of the 5 driving modes to the total broadband excitation – Simple blowing blades at a blowing rate of 1.4%.

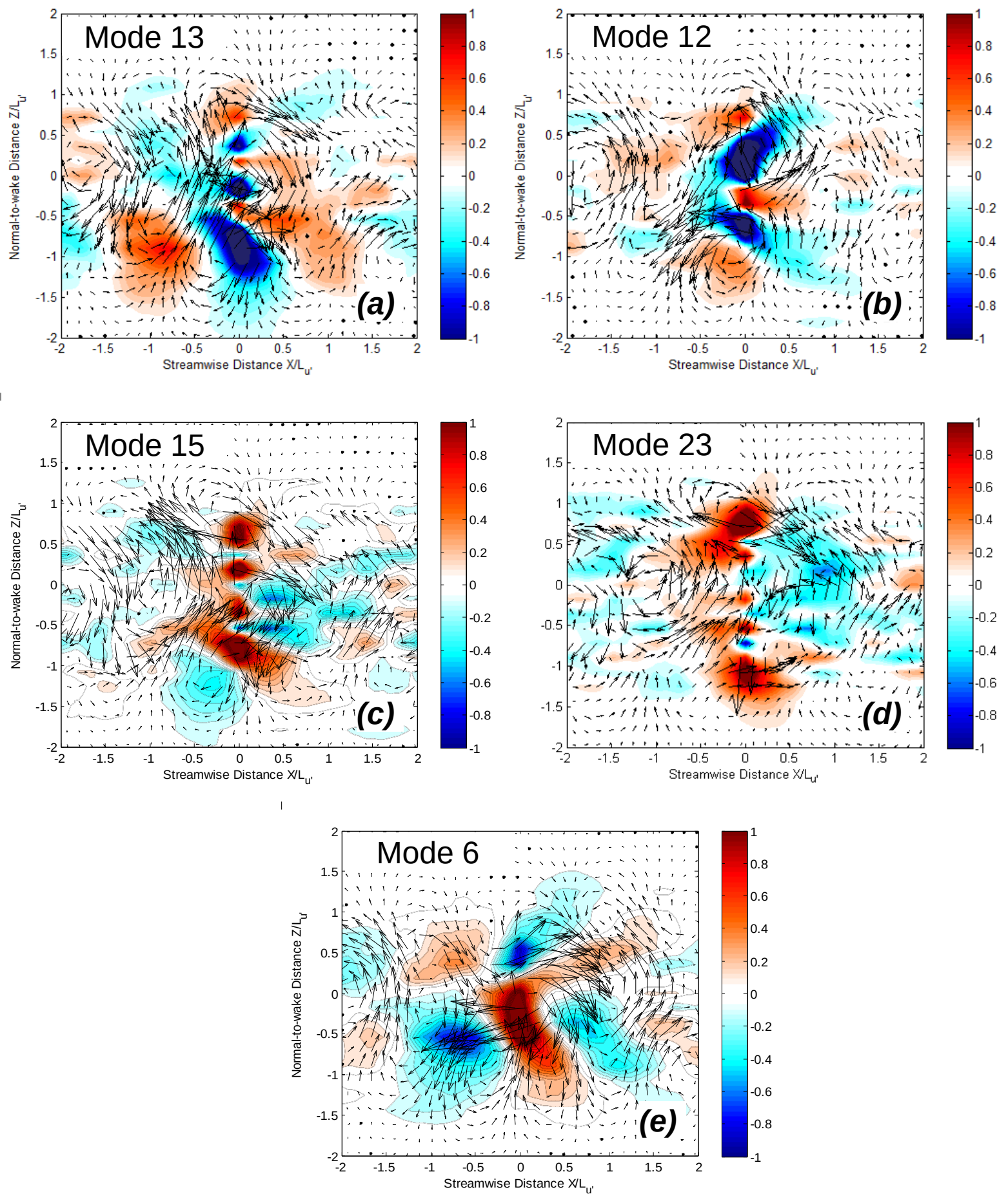


Figure 7.24 Compact Eddy Structures associated with the 5 driving modes – Simple blowing blades at a blowing rate of 1.4%. Contours indicate spanwise velocity component.

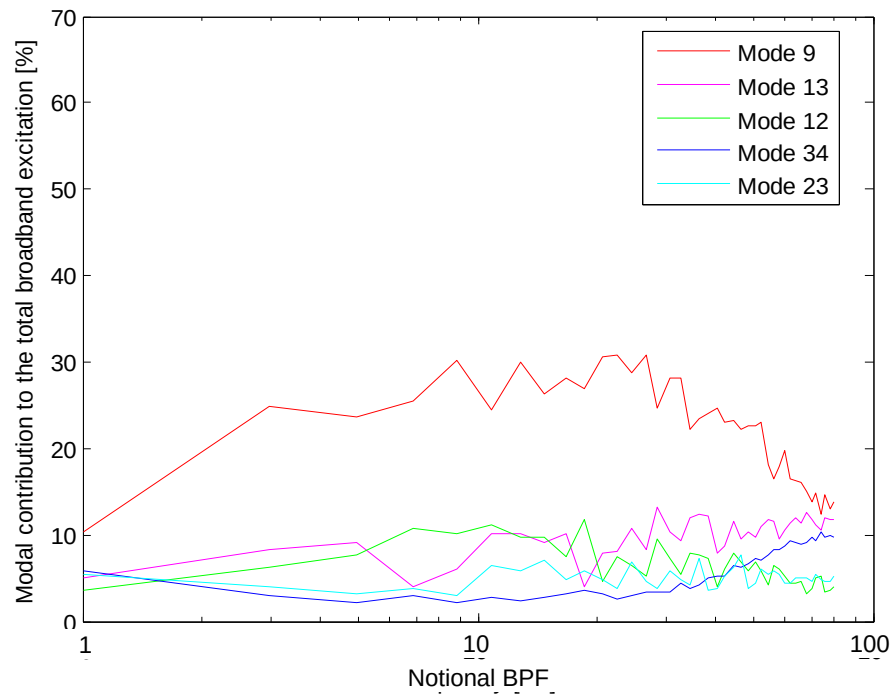


Figure 7.25 Relative contributions of the 5 driving modes to the total broadband excitation – Simple blowing blades at a blowing rate of 2.0%.

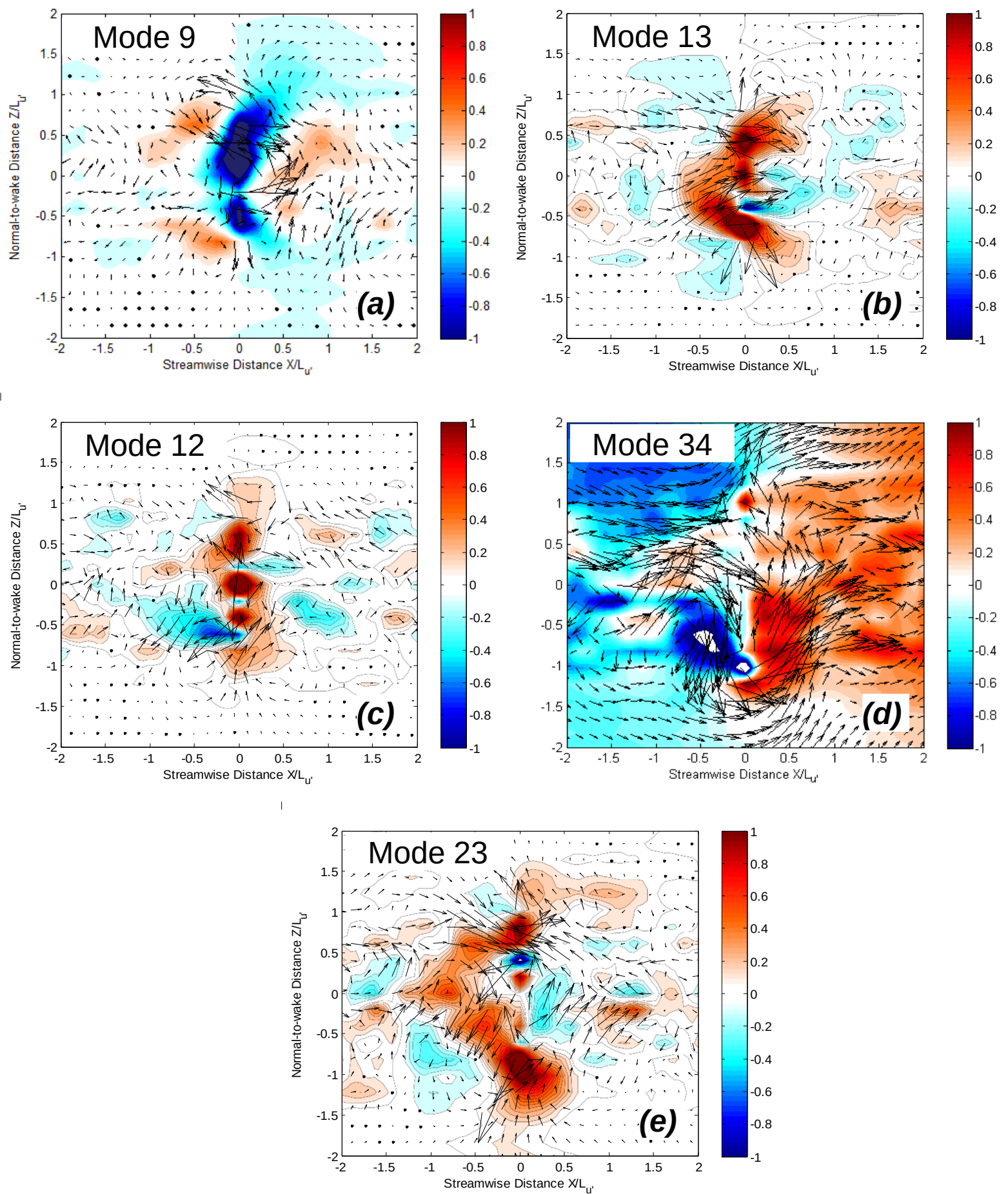


Figure 7.26 Compact Eddy Structures associated with the 5 driving modes – Simple blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component.

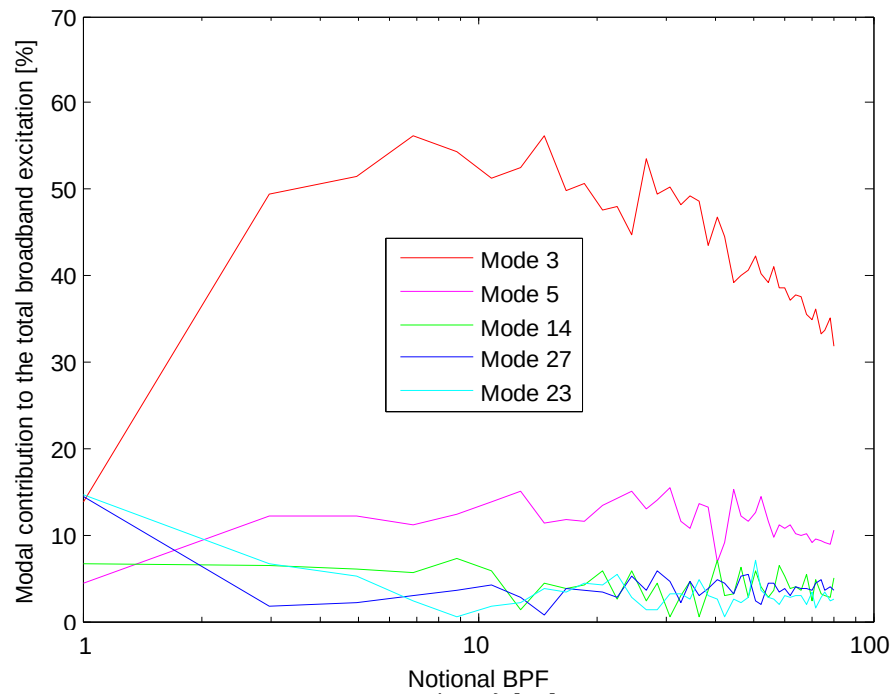


Figure 7.27 Relative contributions of the 5 driving modes to the total broadband excitation – Simple blowing blades at a blowing rate of 2.6%.

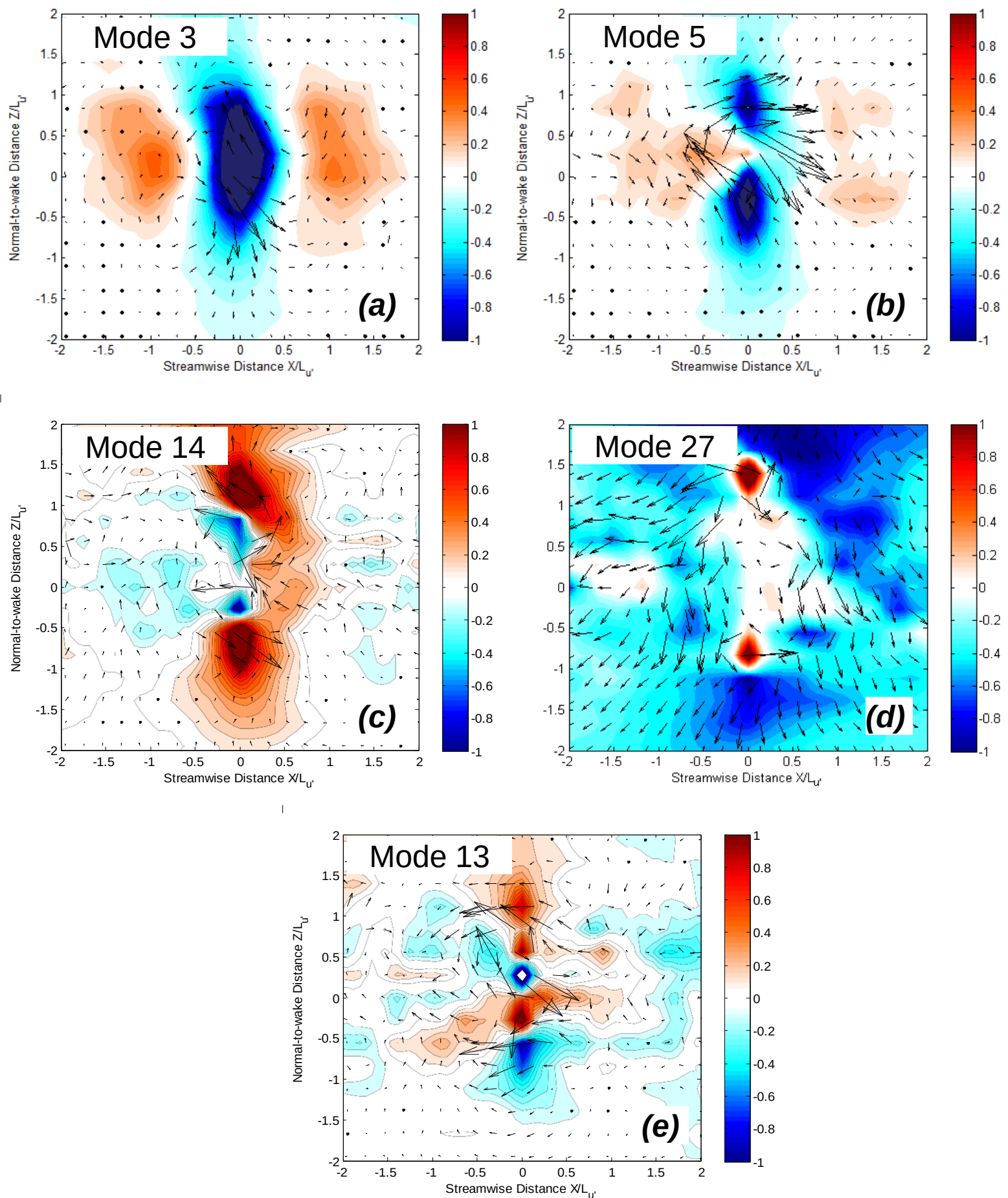


Figure 7.28 Compact Eddy Structures associated with the 5 driving modes – Simple blowing blades at a blowing rate of 2.6%. Contours indicate spanwise velocity component.

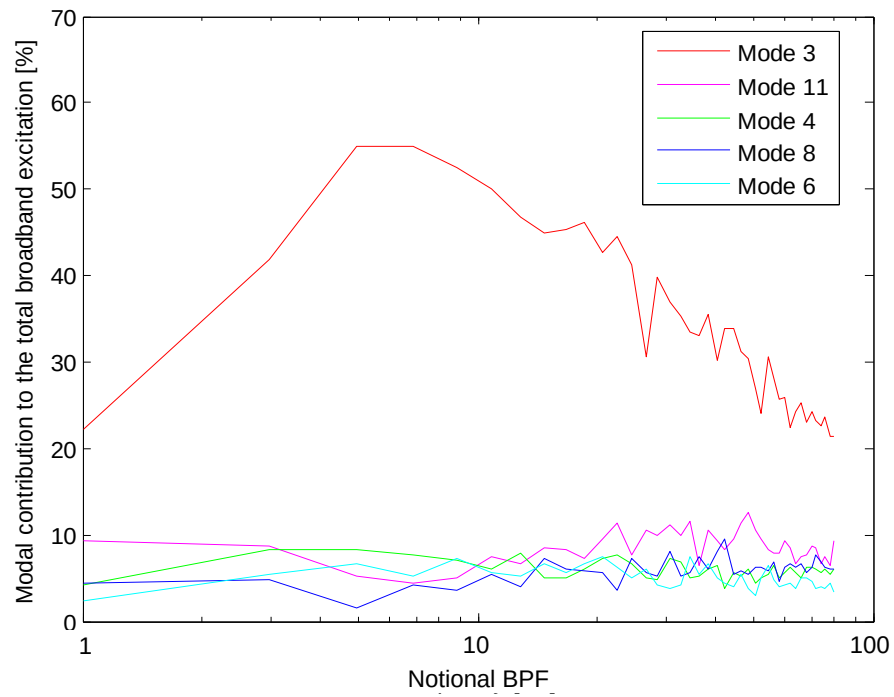


Figure 7.29 Relative contributions of the 5 driving modes to the total broadband excitation – Kuethe blowing blades at a blowing rate of 2.0%.

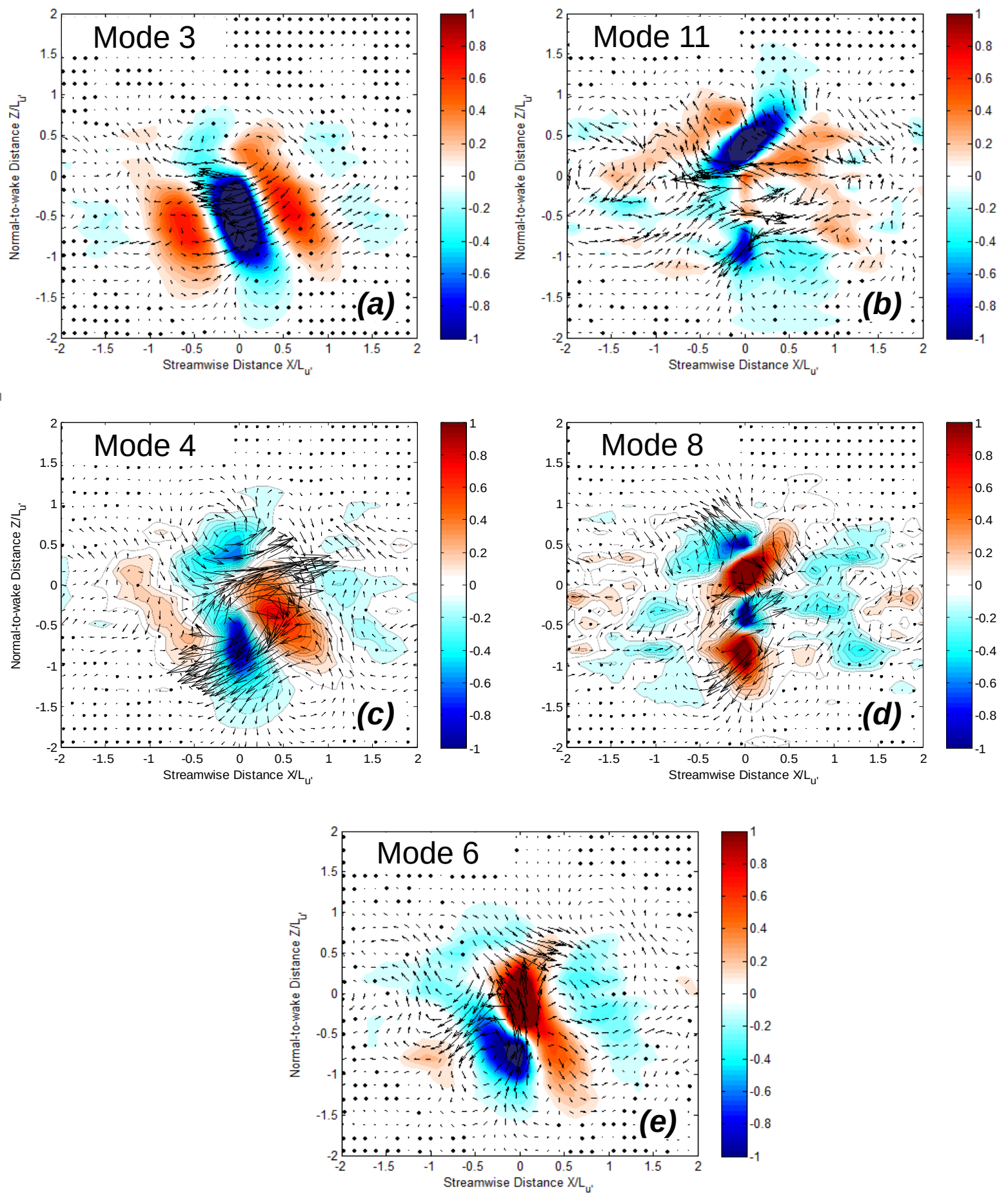


Figure 7.30 Compact Eddy Structures associated with the 5 driving modes – Kuethe blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component.

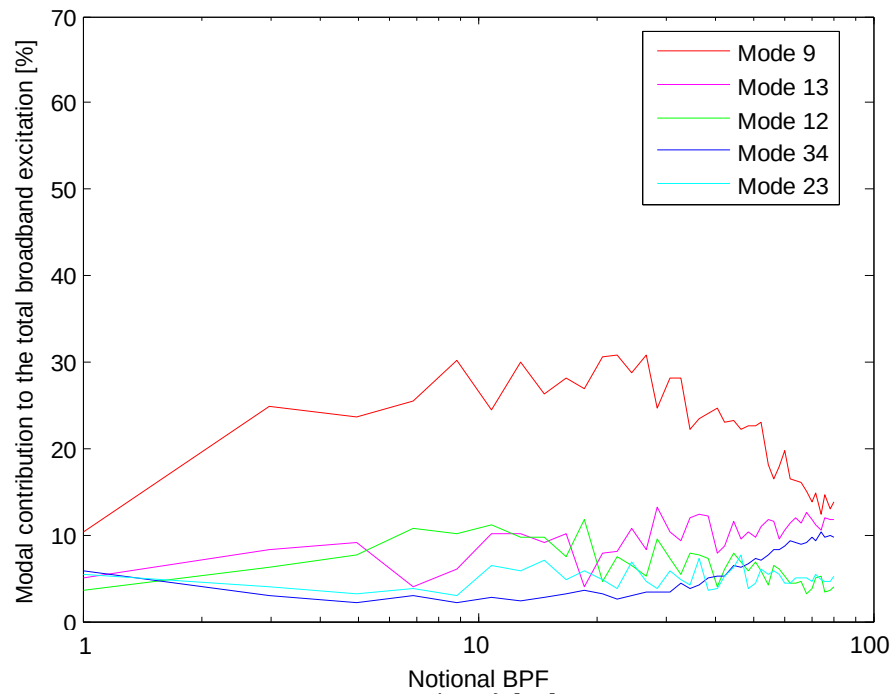


Figure 7.31 Relative contributions of the 5 driving modes to the total broadband excitation – Serrated blowing blades at a blowing rate of 1.4%.

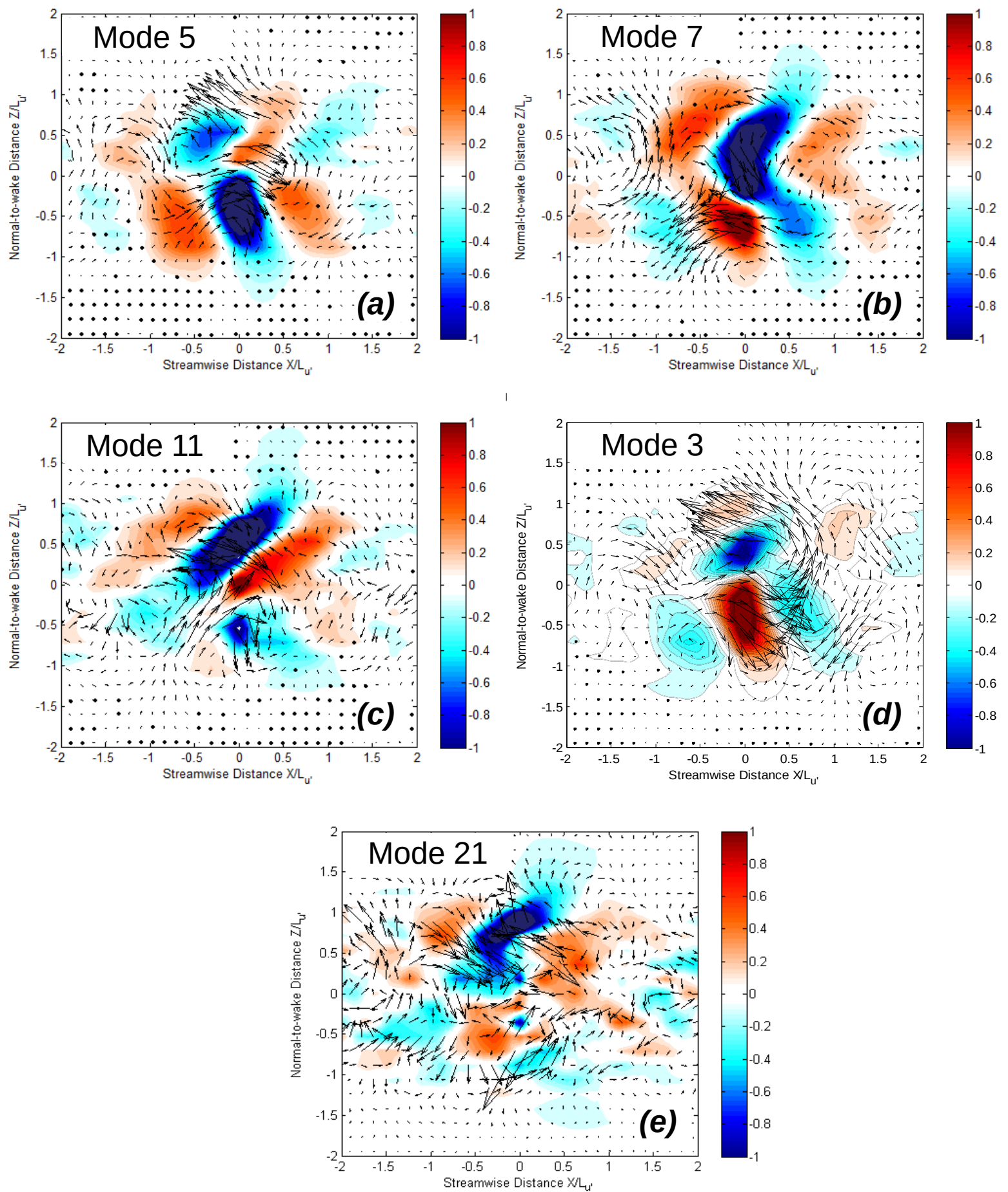


Figure 7.32 Compact Eddy Structures associated with the 5 driving modes – Serrated blowing blades at a blowing rate of 1.4%. Contours indicate spanwise velocity component.

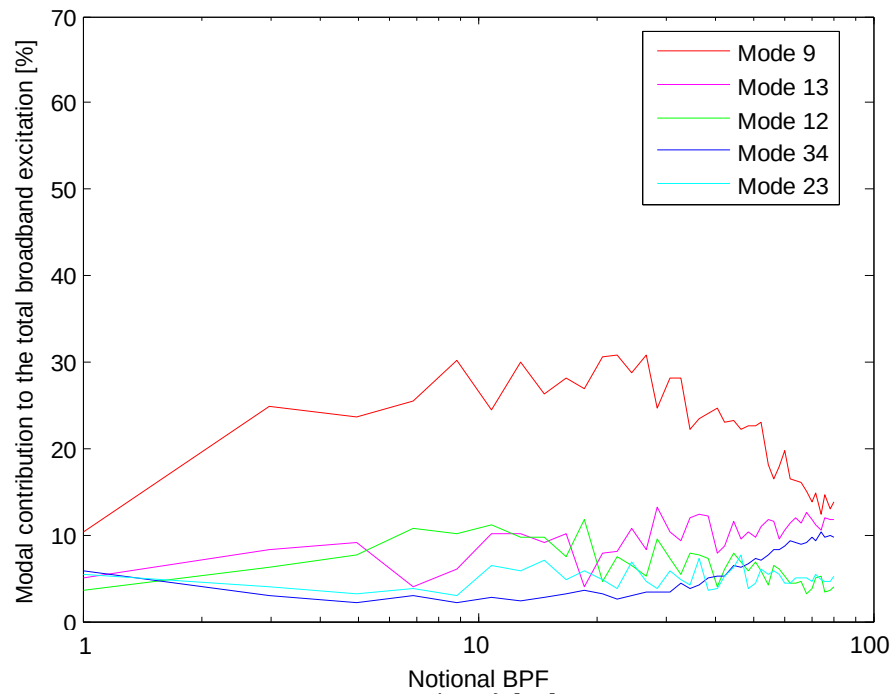


Figure 7.33 Relative contributions of the 5 driving modes to the total broadband excitation – Serrated blowing blades at a blowing rate of 2.0%.

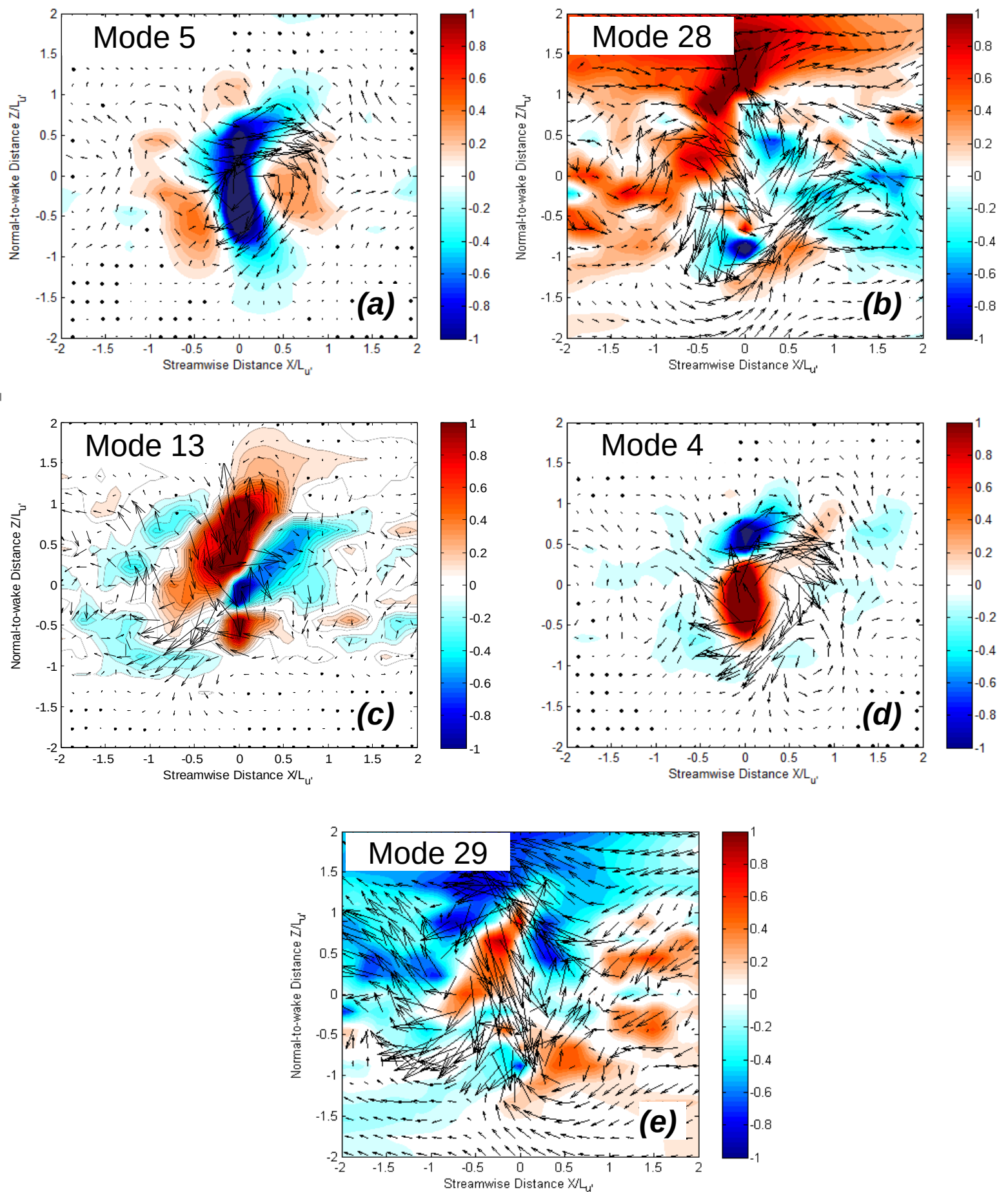


Figure 7.34 Compact Eddy Structures associated with the 5 driving modes – Serrated blowing blades at a blowing rate of 2.0%. Contours indicate spanwise velocity component.

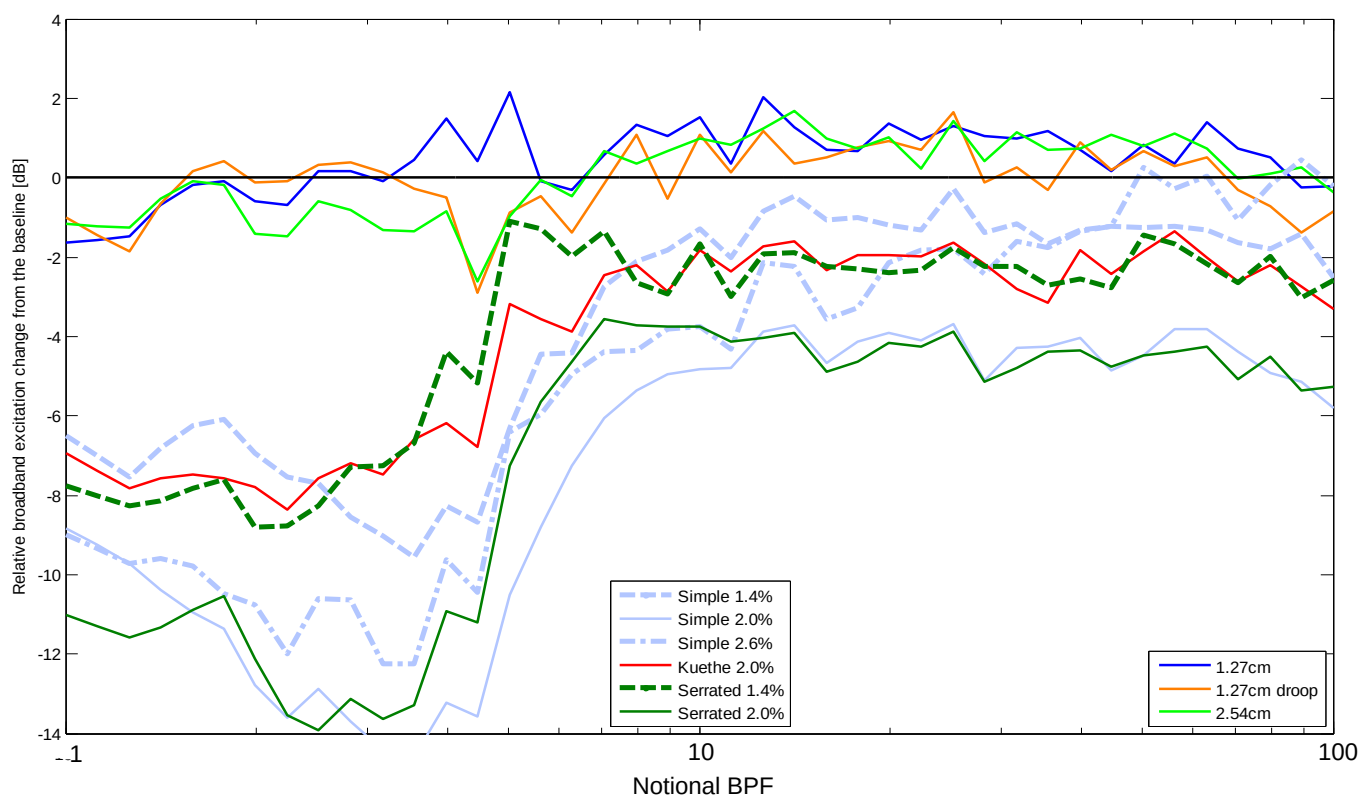


Figure 7.35 Impact of the flow control strategies on the broadband excitation for a parallel blade-wake interaction. Changes (in dB) are expressed relative to the baseline excitation.

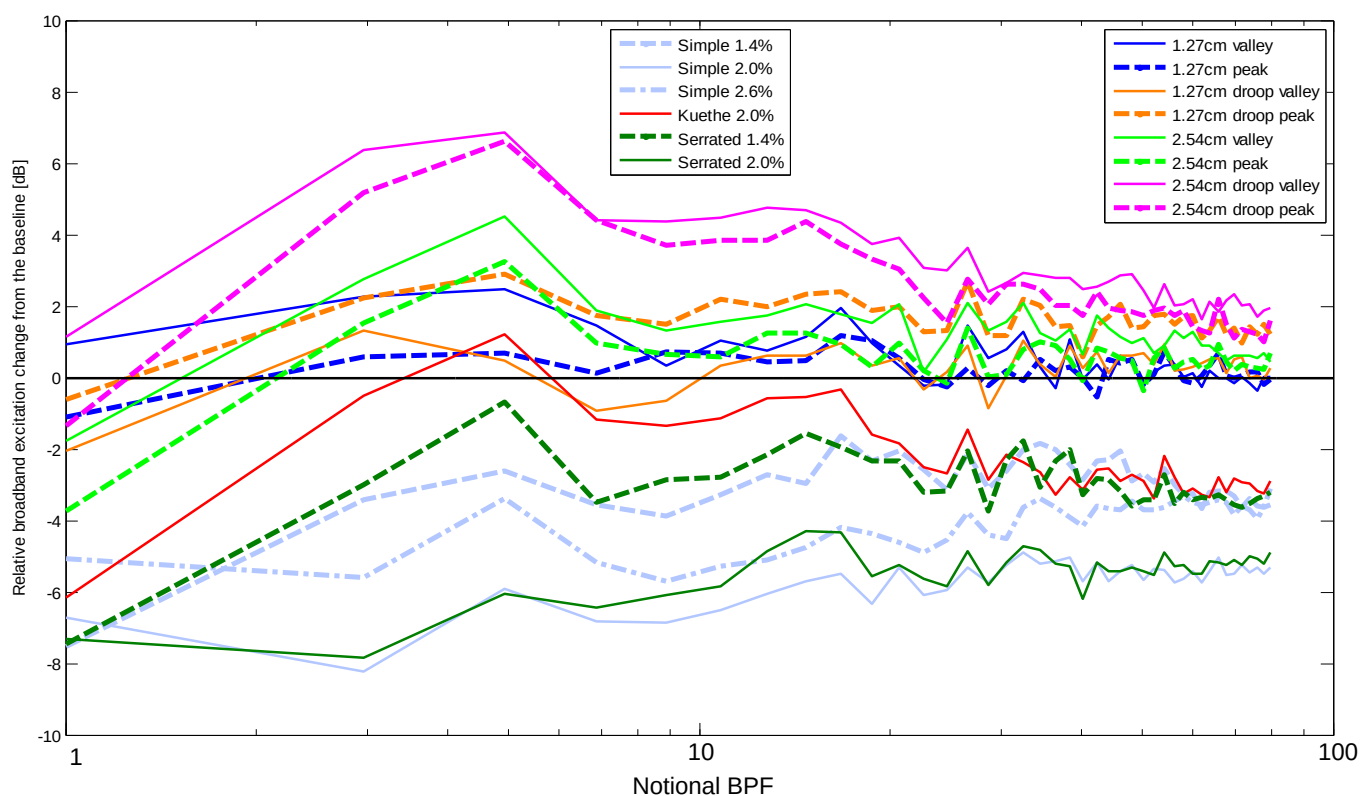


Figure 7.36 Impact of the flow control strategies on the broadband excitation for a perpendicular blade-wake interaction. Changes (in dB) are expressed relative to the baseline excitation.

Chapter 8 - Conclusions

The effects of trailing edge flow control on the wakes of a linear cascade of idealized fan blades was investigated experiments with a view to the likely effects on broadband aircraft engine interaction noise. Three-component hotwire velocity measurements of the two-point velocity correlation were performed in the Virginia Tech Low Speed Linear Cascade wind tunnel to evaluate the impact of various flow control strategies on the organization of the coherent structures of the idealized fan blade wakes and their potential to generate broadband noise. The cascade row consisted of 8 blades (with adjustable tip-gap) and 7-passages at an inlet angle of 65.1° and a stagger angle of 56.9° . The cascade produces a turning angle of 11.8° for a chord Reynolds number of 390,000 and a Mach number of 0.07.

The baseline flow was established by measuring the wake downstream of GE-Rotor-B blades. The seven strategies investigated here consisted in four sets of blades with serrated trailing edges and three sets of trailing edge blowing blades, all based on the baseline blade geometry. The four serrated sets were made of two different serration sizes (1.27cm and 2.54cm), each with two trailing edge cambers (one identical to the baseline blades, one with a 5° increased camber or droop). The three sets of trailing edge blowing blades consisted of a simple blowing configuration (that externally matches the GE-Rotor-B profile with the exception of a blowing slot positioned 3.7% chord upstream of the trailing edge, on the suction side), a Kuethe blowing configuration (identical to the simple blowing blades with the addition of Kuethe vanes (vortex generators) located 6% chord upstream of the blowing slot on the suction side), and a serrated blowing configuration (where 0.55cm serrations were added on both sides of the blowing slot, now moved to the actual trailing edge of the blade).

The trailing edge serration was found to generate corrugated wakes with spanwise variations closely correlated to the serration spacing. The serrations decrease the wake deficit and width (with greatest reductions obtained with the large serrations). The wake decay and growth is increased downstream of the serration peak and decreased at the valley. The turbulence levels are larger downstream of the serration peak. Large

serrations slightly increase the turbulence compared to the baseline. The addition of droop further amplifies the velocity fluctuations.

The analysis of the mean velocity and turbulence stress downstream of the trailing edge blowing blades revealed that the wake deficit and width are significantly reduced. At low blowing rates, the simple blowing configuration was found to actually increase the wake deficit. The addition of Kuethé vanes on the suction side of the blowing blade resulted in a magnification of the region of low momentum near the trailing edge suggesting some possible separation there. This was confirmed by the increased spanwise Reynolds stress measured for this configuration. The serrated blowing was found to be the most efficient at reducing the wake deficit and width at low blowing rates. Turbulence levels are also decreased. At larger blowing rates (beyond 1.7% of the passage through flow), the simple blowing configuration results in greater reductions. Interestingly, the turbulence levels downstream of the serrated blowing blades appear to become independent of the blowing rate between 2.4 and 2.6% of the passage through flow.

8.1. Impact of Flow Control Strategies on the Turbulence

Structure

Measurements of the two-point velocity correlation were taken in the direction normal to the wakes, as well as along its span. The normal-to-wake measurements revealed that the trailing edge serrations have little effect on the streamwise velocity fluctuations inside the wake. The scale of the spanwise and normal-to-wake fluctuations were found to be equivalent to or larger than the baseline possibly due to the injection of streamwise vorticity by the serrations coupled with the blunt trailing edge created at the serration valley. Spanwise measurements showed that the small serrations (with and without droop) reduce the spanwise scales associated with the streamwise and spanwise fluctuations but increased those associated with the normal-to-wake fluctuations. The larger serrations were found to reduce all the scales along the spanwise direction especially those associated with the normal-to-wake fluctuations. The impact of the serration on the streamwise scales, deduced from the auto-correlation, was found to be

much simpler as they were all decreased by increasing the serration size and adding droop. Additionally, analysis of the auto-correlation of the normal-to-wake fluctuations revealed the presence of low frequency quasi-periodic structures (less than 500Hz) that were little affected by the serration. These larger scales (especially for the larger serrations) are associated with increased turbulence levels (compared to the baseline), therefore limiting the potential of the serrated trailing edge blade wakes to reduce broadband noise (if they were to interact with a hypothetical downstream blade representing the stator vane).

Proper orthogonal decomposition of the serrated blade wakes was combined with linear stochastic estimation to provide a representation of the characteristic eddies implied by the measured correlation function. The analysis of the characteristic eddies revealed that the serrations do not change the overall turbulence structure. The introduction of streamwise vorticity at the trailing edge of these blades seems to enhance the spanwise velocity fluctuations (especially at the peak of the drooped configurations) and could therefore increase the potential of these wakes to generate broadband noise (in the eventuality of an interaction with a downstream blade).

Trailing edge blowing was found to have a much larger impact on the coherent structures. The simple blowing was shown to significantly affect the size, the organization and the strength of the coherent structures. These changes were also found to be rather complicated as they do not happen monotonically with blowing rate. The addition of Kuethe vanes on the suction side of the blowing blade results in a very complex flow with signs of potential separation. These two blowing configurations are actually believed to enhance the shedding of strong spanwise eddies near the trailing edge (especially at low blowing rates). The serrated blowing blades show the greatest potential to reduce broadband noise as they reduce the turbulence levels and scales without creating potentially detrimental structures. The blowing rates required for these reductions (on the order of 2% of the mass flow through one passage) make it difficult to envision a full-scale implementation of such technology. The characteristic eddies associated with the trailing edge blowing correlation functions revealed that such a strategy primarily reduces the streamwise velocity fluctuations of the average eddies

while producing small spanwise fluctuations. Such findings suggest trailing edge blowing could significantly reduce the wake broadband potential.

8.2. Impact of Flow Control Strategies on the Broadband Excitation

To quantify the impact of the various flow control strategies on the potential of the wakes to generate broadband noise, the blade-wake interaction was modeled as a linear system subjected to an excitation force (the rotor wake turbulence). It is impossible for this study to calculate the output of such system (the radiated pressure field) since it requires the cutting blade response function. It is, however, possible to evaluate the impact of the various strategies by comparing their effects on the excitation of such system (named here “broadband excitation”). While further acoustic measurements of these configurations would be needed to confirm the actual radiation reductions, these results can be treated as a preliminary diagnostic tool to predict the potential of a particular configuration to reduce broadband noise.

The broadband excitation of a perpendicular cut (where the cutting blade is perpendicular to the wake spanwise axis) was obtained by analyzing the frequency content of the characteristic eddies (extracted from the correlation function). Such analysis showed that the serrated trailing edge blades increased the broadband excitation and, therefore, the potential of these wakes to generate noise. This is especially true for the larger serrations that resulted in a 1.2dB maximum increase. The addition of droop increased the excitation for both small and large serrations leading to a maximum increase of up to 3dB downstream of the large serrations. In contrast, every trailing edge blowing configuration was found to produce large reductions in the broadband excitation. The simple blowing configuration produces reductions of 3, 6, and 4dB at 1.4, 2.0, and 2.6% of the through flow. It seems therefore that an optimal blowing rate between 2.0 and 2.6% could result in reductions of at least 6dB. The lower efficiency of the simple blowing at the higher blowing rate is believed to be the result of the increased spanwise velocity fluctuations. The addition of Kuethé vanes on the suction side of the blowing blades significantly decreased the reduction to 2.4dB at a blowing rate of 2.0% (possibly

due to some late flow separation downstream of the vortex generators). The serrated blowing configuration was found to yield reductions similar to the simple blowing configuration.

Most importantly, a specific spanwise velocity fluctuation distribution was found to consistently appear among the driving modes of the broadband excitation. In such a distribution, the spanwise fluctuations appear along nested V-shaped regions of alternating signs of the velocity. Consequently, if a method could be devised to minimize this type of spanwise fluctuations, sizeable reductions of the broadband excitation could follow. At the very least, it would become particularly interesting to obtain a model of the two-point correlation function that would allow one to alter the blade geometry to eliminate the lower modes associated with this type of fluctuations.

The broadband excitation of an idealized parallel interaction (where the cutting blade is parallel to the wake spanwise axis) was obtained by analyzing the change in the spanwise cross-spectrum of the upwash seen by the cutting blade (where homogeneity in the wake spanwise direction was assumed). The trailing edge serration was found to have no positive effects on the broadband excitation of a parallel cut and could actually be increasing it by 1dB at high frequencies (independently of the serration configuration). This behavior is believed to be resulting from the increased spanwise scales (especially for the smaller serrations) coupled with greater turbulence intensities. The increased coherency along the blade span arises from the periodic streamwise vorticity injection by the serrations. While the excitation reductions of a perpendicular interaction were found to be relatively constant over the frequency range, the broadband excitation of a parallel interaction was shown to be dependent on the frequency. The serrated blowing configuration was found to be the most efficient configuration, with high frequency reductions of almost 3dB at 1.4% blowing. The analysis of the simple blowing configuration showed that an optimum blowing rate between 2 and 2.6% could lead to broadband excitation reductions of at least 4dB. The addition of Kuethe vanes on the suction side was found to decrease the efficiency of the simple blowing configuration for a parallel interaction as it promotes coherency along the blade span. Similarly to the serrated trailing edge blades, this coherency is believed to be associated with the periodic injection of streamwise vorticity along the blade span by the Kuethe vanes. In this case

however, such coherency is associated with significant reductions in turbulence intensity thus producing broadband excitation reductions.

The analysis of an idealized parallel interaction (where the cutting blade is parallel to the wake spanwise axis) revealed that the resulting broadband excitations follow the same trends (for almost all the configurations tested) that appear in a perpendicular interaction. While the parallel interaction analysis is highly idealized (mainly by assuming homogeneity in the spanwise direction) it proved to produce similar results. One could, therefore, argue that the excitations resulting from intermediate interactions (such as those occurring in a real aircraft engine in which the stator blade leading edge is at an angle between 0 and 90° to the rotor wake local spanwise axis) should follow the trends described by the perpendicular and parallel interactions. Consequently, it appears that a model assuming a perpendicular interaction could be used as a reference to diagnose the rotor-stator interaction.

8.3. Future Work

The present study showed that two-point velocity measurements could be used to extract a substantial amount of information about the turbulence structure and the potential of this turbulence to generate broadband noise when interacting with an hypothetical stator blade. While these measurements were performed in a relatively simple environment (i.e. a linear cascade), they do require significant amounts of time and attention. It would therefore become particularly attractive to be able to model the two-point correlation from simpler measurements. One such model, described by Devenport *et al.* (2001), allows to estimate the correlation function from Reynolds stress information and one turbulence lengthscale, quantity that can be easily obtained from single-point measurements. Adapting such model to the particular flow conditions discussed here could then create a rapid and powerful diagnostic tools for broadband interaction noise.

The analysis of the broadband excitation suggests that a perpendicular cut could be used as a representative model of the blade-wake interaction. Measurements of the two-point velocity measurements (similar to the normal-to-wake measurements reported

here) could be performed at various angles to the wake spanwise axis to obtain the actual angular dependency of the broadband excitation.

It was shown that the broadband excitation could be used as a diagnostic tool to predict the potential of a particular configuration to reduce broadband noise. The validity of such a tool could be further strengthened by performing acoustic measurement on some of the configurations tested in the present study and comparing them with the broadband excitation results. If they were to agree, the fan blade design process could be significantly reduced.

Bibliography

- Barlow J., 1999, "*Low-Speed Wind Tunnel Testing*", Wiley-Interscience, New York.
- Bearman, P., 1971, "*Corrections for the effect of ambient temperature drift on hot-wire measurements in incompressible flow*", DISA Information, Vol. 11, pp.25-30.
- Berkooz, G., Holmes, P., and Lumley, J., 1993, "*The Proper Orthogonal Decomposition in the Analysis of Turbulent Flows*", Annual Review of Fluid Mechanics, Vol. 25, pp. 539-575.
- Borgoltz A., Craig M. and Devenport W., 2005, "*Trailing Edge Blowing of Fan Blades*", AIAA-2005-3031, 11th AIAA/CEAS Aeroacoustics Conference, May 23-25, Monterey, California.
- Borgoltz A., Devenport W., and Craig M., 2006, "*Space-Time Correlations and Trailing Edge Flow Structure in Fan-Blade Wakes with Trailing Edge Blowing*", AIAA-2006-2480, 12th AIAA/CEAS Aeroacoustics Conference, May 10-12, Boston, Massachusetts.
- Borgoltz A., Geiger D. and Devenport W., 2004, "*Analysis of wakes shed by Idealized Aircraft Engine Fan Blades For Noise Reduction*", AIAA-2004-2912, 10th AIAA/CEAS Aeroacoustics Conference, May 8-10, Manchester, United Kingdom.
- Brookfield J., 1998, "*Turbofan Stator/Rotor Interaction Noise Reduction Through Trailing Edge Blowing*", PhD dissertation, Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology.
- Brookfield J. and Waitz, I., 2000, "*Trailing-Edge Blowing for Reduction of Turbomachinery Fan Noise*", Journal of Propulsion and Power, Vol. 16, No. 1, 2000, pp. 57-64.
- Cimbala J. and Park W., 1990, "*An Experimental Investigation of the Turbulent Structure in a 2-D Momentumless Wake*", Journal of Fluid Mechanics, Vol. 213, 1990, pp. 479-509.
- Craig M., 2006, "*Trailing-Edge Blowing of Model Fan Blades for Wake Management*", M.S. Thesis, Department of Aerospace and Ocean Engineering, Virginia Tech, Avail: <http://scholar.lib.vt.edu/theses/available/etd-01102006-150701/>

- Devenport W., Muthanna C., Ma R. and Glegg S., 2001, “*Two-Point Descriptions of Wake Turbulence with Application to Noise Prediction*”, AIAA Journal, vol. 39, No. 12, December 2001.
- Envia E., 2001, “*Fan Noise Reduction: An Overview*”, AIAA 2001-0661, 39th AIAA Aerospace Sciences Meeting and Exhibit, 8-11 January 2001, Reno, Nevada.
- Fite E., 2006, “*Effect of Trailing Edge Flow Injection on Fan Noise and Aerodynamic Performance*”, AIAA-2006-2844, 3rd AIAA Flow Control Conference, June 5-8, San Francisco, California.
- Geiger D., 2005, “*Comparative Analysis of Serrated Trailing Edge Designs on Idealized Aircraft Engine Fan Blades for Noise Reduction*”, Aerospace and Ocean Engineering Dept., Virginia Polytechnic Institute and State University.
 Avail: <http://scholar.lib.vt.edu/theses/available/etd-01102005-202530/>
- Glegg S. and Devenport W., 2001, “*Proper Orthogonal Decomposition of turbulent flows for aeroacoustic and hydroacoustic applications*”, Journal of Sound and Vibration, vol 239, no. 4, pp. 767-784.
- Guidati G., Ostertag S., and Wagner S., 2000, “*Prediction and Reduction of Wind Turbine Noise: An Overview of Research Activities in Europe*”, ASME Wind Energy Symposium, 19th, Aerospace Sciences Meeting and Exhibit, 38th, Reno, Nevada, January 10 – 13, 2000, pp 219 – 229.
- Halasz C., Arntz D., Burdisso R. and Ng W., 2005, “*Fan Flow Control for Noise Reduction Part 1: Advanced Trailing Edge Blowing Concepts*”, AIAA-2005-3025, 11th AIAA/CEAS Aeroacoustics Conference, May 23-25, Monterey, California.
- Howe M., 1991, “*Noise Produced by a Sawtooth Trailing Edge*”, Journal of Acoustical Society of America, Vol. 90, No. 1, 1991, pp. 482 – 487.
- IATA, 2007, “*What we do for the environment: Fuel Efficiency*”, IATA Website,
 Avail: http://www.iata.org/whatwedo/environment/fuel_efficiency.htm, Last update: 2007,
 Accessed: October 2007.
- Intaratep N., 2006, “*Formation and Development of the Tip Leakage Vortex in a Simulated Axial Compressor with Unsteady Inflow*”, PhD dissertation, Aerospace and Ocean Engineering Dept., Virginia Polytechnic Institute and State University.
 Avail: <http://scholar.lib.vt.edu/theses/available/etd-04112006-165724/>
- Krammer P., Rued K. and Truebenbach J., 2003, “*Technology Preparation for Green Aero Engines*”, AIAA 2003-2790, AIAA/ICAS International Air and Space Symposium and Exhibition: The Next 100 Years, 14-17 July 2003, Dayton, Ohio.

- Kline S. and McClintock F., 1953, “*Describing uncertainties in single sample experiments*”, Mechanical Engineering, vol. 75, 1953, pp 3.
- Kuethe A., 1972, “*Effect of Streamwise Vortices on Wake Properties Associated with Sound Generation*”, Journal of Aircraft, Vol. 9, No. 10, 1972, pp. 715-718.
- Langford M., Minton C., Ng W., Estevadeordal J., and Burdisso R., 2005a, “*Fan Flow Control for Noise Reduction Part 2: Investigation of Wake-Filling Techniques*”, AIAA-2005-3026, 11th AIAA/CEAS Aeroacoustics Conference, Monterey CA, 23 - 25 May.
- Langford M., Minton C., Ng W., Burdisso R., and Halasz C., 2005b, “*Fan Flow Control for Noise Reduction Part 3: Rig Testing of Optimal Design*”, AIAA-2005-3027, 11th AIAA/CEAS Aeroacoustics Conference, May 23-25, Monterey, California.
- Leitch T., Sanders C., and Ng W., 2000, “*Reduction of Unsteady Stator-Rotor Interaction Using Trailing Edge Blowing*”, Journal of Sound and Vibration, Vol. 235, No. 2, 2000, pp. 235-245.
- Lumley J., 1967, “*The Structure of Inhomogeneous Turbulent Flows*”, Atmospheric Turbulence and radio Wave Propagation, Eds. A.M. Yaglom and V.I. Tatarsky, pp 166-176, Nauka, Moscow.
- Ma R., 2003, “*Unsteady Turbulence Interaction in a Tip Leakage Flow Downstream of a Simulated Axial Compressor Rotor*”, PhD dissertation, Aerospace and Ocean Engineering Dept., Virginia Polytechnic Institute and State University.
 Avail: <http://scholar.lib.vt.edu/theses/available/etd-06172003-122153/>
- Muthanna C., 1998, “*Flowfield Downstream of a Compressor Cascade with Tip Leakage*”, MS thesis, Aerospace and Ocean Engineering Dept., Virginia Polytechnic Institute and State University.
 Avail: <http://scholar.lib.vt.edu/theses/available/etd-110798-235327/>
- Muthanna C., 2002, “*The Effects of Freestream Turbulence on the Flow Field through a Compressor Cascade*”, PhD dissertation, Aerospace and Ocean Engineering Dept., Virginia Polytechnic Institute and State University.
 Avail: <http://scholar.lib.vt.edu/theses/available/etd-08222002-194441/>
- Muthanna C., and Devenport W., 2004, “*Wake of a Compressor Cascade with Tip Gap, Part 1: Mean Flow and Turbulence Structure*”, AIAA Journal, Vol. 42, No. 11, pp. 2320-2331, November 2004.
- NASA Facts, 1997, “*Making Future Commercial Aircraft Quieter*”, FS-1997-07-003-LeRC, NASA Lewis Research Center, July, 1997.

- Park W., and Cimbala J., 1991, “*The Effect of Jet Injection Geometry on 2-D Momentumless Wakes*”, Journal of Fluid Mechanics, Vol. 224, pp. 29-47.
- Pope S., 2001, “*Turbulent Flows*”, Cambridge University Press, New York.
- Rao N., Feng J., Burdisso R. and Ng, W., 2001, “*Experimental Demonstration of Active Flow Control to Reduce Stator-Rotor Interaction*”, AIAA Journal, Vol. 39, No. 3, 2001, pp. 458-464.
- Sell J., 1997, “*Cascade Testing to Assess the Effectiveness of Mass Addition/Removal Wake Management Strategies for Reduction of Rotor-Stator Interaction Noise*”, MS thesis, Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology.
- Spitz N., 2005, “*Prediction of Trailing Edge Noise from Two-Point Velocity Correlations*”, Master thesis, Aerospace and Ocean Engineering Dept., Virginia Polytechnic Institute and State University.
 Avail: <http://scholar.lib.vt.edu/theses/available/etd-05122005-135518/>
- Sutliff D., Tweedt D., Fite E. and Envia E., 2002, “*Low-Speed Fan Noise Reduction with Trailing-Edge Blowing*”, AIAA 2002-2492, 8th AIAA/CEAS Aeroacoustics Conference and Exhibit, June 17-19, Breckenridge, Colorado.
- Vijgen P., van Dam C., Holmes B., and Howard F., 1989, “*Wind-Tunnel Investigations of Wings with Serrated Sharp Trailing Edges*”, Low Reynolds Number Aerodynamics Conference, June 5-7, Notre Dame, Indiana.
- Wenger C., 1999, “*Analysis of two-point turbulence measurements for aeroacoustics*”, MS thesis, Aerospace and Ocean Engineering Dept., Virginia Polytechnic Institute and State University.
 Avail: <http://scholar.lib.vt.edu/theses/available/etd-010699-132153/>
- Wenger C., Devenport W., Wittmer K. and Muthanna C., 2004, “*Wake of a compressor cascade with tip gap – Part 3: Two-point statistics*”, AIAA Journal, Vol. 42, No. 11, pp. 2341-2346, November 2004.
- Weygandt J. and Mehta R., 1995, “*Effects of Streamwise Vorticity Injection on a Plane Turbulent Wake*”, AIAA Journal, Vol. 33, No. 1, pp.86-93, January 1995.
- Williams J., 2005, “*Oil Price History and Analysis*”,
 Avail: <http://www.wtrg.com/prices.htm>, Last update: 2007, Accessed: August 2007.
- Wittmer K., Devenport W., and Zsoldos J., 1998, “*A four-sensor hot-wire probe system for three-component velocity measurement*”, Experiments in Fluids, Vol. 24, pp. 416-423.

Aurelien Borgoltz was born on December 16th, 1980, in the city of Rognac, France. He spent his childhood in various cities across France until he joined the Euro-American Institute of Technology in Sophia-Antipolis, France after graduating from high school. He transferred to Virginia Tech at the end of his sophomore year in 2000. After joining the Advanced Turbulent Flows Research Group under the guidance of Dr. Devenport as an undergraduate in June 2001, Aurelien graduated with his Bachelor of Science in Aerospace Engineering in May 2002. He joined the Virginia Tech doctoral program in Aerospace Engineering in 2002 to focus on turbulent flows and associated aero-acoustic phenomena. Aurelien completed this work in November 2007 and graduated with a PhD. in December of the same year.