AN EXPERIMENTAL INVESTIGATION OF PRESSURE FLUCTUATIONS IN THREE-DIMENSIONAL TURBULENT BOUNDARY LAYERS

by

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(ABSTRACT)

This dissertation presents experimental measurements and analysis of the surface pressure fluctuations beneath several turbulent boundary layers of practical interest. Pressure fluctuations in turbulent boundary layers are a source of noise and vibration that can accelerate structural fatigue. Pressure fluctuations and their correlation with velocity fluctuations is an important diffusive mechanism of turbulence transport. The approach was to study the statistics of both the surface pressure and the velocity field through new measurements of the fluctuating surface pressure and existing measurements of the velocity field and the covariance of the surface pressure and fluctuating velocity components.

Measurements were made in three types of flows. The first type of flow was a zero pressure gradient, two-dimensional, turbulent boundary layer ($Re_\theta = 7300$ and $Re_\theta = 23400$). The two-dimensional flows serve as a baseline for comparison to the other three-dimensional flows and validate the experimental techniques used in the present study through comparison with existing measurements. The second type of flow was a three-dimensional, pressure-driven, turbulent boundary layer that forms away from a wing-body junction. Two of this type of boundary layer were studied– $Re_\theta = 5940$ and $Re_\theta = 23200$. The third type of flow was the separating flow about the leeside of a 6:1 prolate spheroid at angle of attack. Measurements were made at two angles of attack, $\alpha = 10°$ and $\alpha = 20°$, and two axial locations, $x/L = 0.600$ and $x/L = 0.772$, in this type of flow.

Spectral scaling is discussed and various scaling combinations of the spectral power density of surface pressure fluctuations beneath two-dimensional boundary layers that cover a

wide range of Reynolds number ($1400 < Re_\theta < 23400$) are presented. The spectral power density of surface pressure fluctuations beneath the separating flow on the leeside of a 6:1 prolate spheroid at 10° angle of attack collapse when normalized using viscous scales. However, the spectral power density of surface pressure fluctuations beneath highly three-dimensional flow contain nearly constant spectral levels within a middle to high frequency range. The nearly constant spectral levels are due to a lack of overlapping frequency structure between the large-scale motions and the viscous-dominated motions since each of these types of motion may have different flow histories due to the three-dimensional flow structure. This effect amplifies the importance of the middle frequency range to p' as compared to two-dimensional flows. In terms of instrumentation, accurate p' measurements in a three-dimensional flow require accurate high frequency ($f > 20$ kHz) p measurements.

The lack of similarity in the shape of the spectral power density preclude a direct extension of “universal” generalizations that are true for surface pressure fluctuations beneath two-dimensional boundary layers. The resulting RMS surface pressure fluctuation distributions reflect the importance of the high frequency wall region contributions. Scaling parameters for the p spectra beneath three-dimensional flows must incorporate local flow structure in order to be successful. Analysis based on the Poisson equation shows that variation of the high frequency spectral levels are related to the variation in near-wall mean velocity gradients and $\overline{v^2}$ structure. In the 6:1 prolate spheroid flow, near regions of crossflow separation there is a local minimum in RMS surface pressure fluctuations, whereas around reattachments and under the large shed vortices there is a local maximum in RMS surface pressure fluctuations.

Measurements of the correlation coefficient between surface pressure and velocity fluctuations show that there can be sources of p away from the wall in three-dimensional flows. Sources of p away from the wall are significant in terms of fluid-structure interaction since they contribute low frequency fluctuations. Structures typically have low resonant frequencies. Sources of p away from the wall are also significant in terms of radiated sound since they are likely to interact with the free-stream and be radiated away as sound.

I must acknowledge some of the many people who have contributed to the completion of this work.

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List Of Tables

a	....	The speed of sound
d	....	Pressure transducer sensing diameter
d_{LOCAL}	....	Prolate spheroid model diameter at a given axial position
f	....	Frequency, Hz
k_1 , k_2 , k_3	....	Wavenumber vector components in the *x*, *y*, and *z* direction, respectively
L	....	Prolate spheroid model length, 1.37 m
P	....	Mean pressure at a point within the flow
p	....	Fluctuation of the surface pressure
Q_e	....	Dynamic pressure at the edge of the boundary layer, $\frac{1}{2}\rho U_e^2$
Q_∞	....	Dynamic pressure of flow far upstream of the measurement location, $\frac{1}{2}\rho U_\infty^2$
r	....	Distance from the prolate spheroid model surface along a line perpendicular to the model axis
r_S	....	Distance between a point where the surface pressure fluctuations are measured and the point in the flow that is the source of the surface pressure fluctuations
Re_L	....	Model length Reynolds number, $U_\infty L / \nu$
Re_θ	....	Momentum thickness Reynolds number, $U_\infty \theta / \nu$
Re_δ	....	Boundary layer thickness Reynolds number, $u_\tau \delta / \nu$
R_{pu}	....	Correlation coefficient of wall pressure and the fluctuating *u*-component of velocity

$$R_{pu} = \frac{\overline{p\,u}}{\sqrt{\overline{p^2}}\sqrt{\overline{u^2}}}$$

R_{pv}	....	Correlation coefficient of wall pressure and the fluctuating *v*-component of velocity

$$R_{pv} = \frac{\overline{p\,v}}{\sqrt{\overline{p^2}}\sqrt{\overline{v^2}}}$$

R_{pw}	Correlation coefficient of wall pressure and the fluctuating *w*-component of velocity $$R_{pw} = \frac{\overline{p\,w}}{\sqrt{\overline{p^2}}\sqrt{\overline{w^2}}}$$
TKE	Turbulent kinetic energy, $\frac{1}{2}\rho(\overline{u^2} + \overline{v^2} + \overline{w^2})$
t	Time
t_{max}	Maximum thickness of the wing, 7.17 cm
u_τ	Friction velocity, $(\tau_W/\rho)^{1/2}$
U, V, W	Mean velocity components
U_i	Mean velocity component, tensor notation where i = 1, 2, 3 coresponds to U, V, W, respectively.
u, v, w	Fluctuating velocity components in the directions of U, V, and W, respectively
u_i	Fluctuating velocity component, tensor notation where i = 1, 2, 3 coresponds to u, v, w, respectively.
U_C	Magnitude of the convection velocity of pressure fluctuations
U_{C1},U_{C2},U_{C3} ...	Convection velocity vector components in the x, y, and z direction, respectively
U_∞	Wind-tunnel free-stream velocity
$d\Omega$	Differential volume element
x, y, z	Coordinate system axes
x_i	Spatial coordinate, tensor notation where i = 1, 2, 3 coresponds to x, y, z, respectively.
α	Angle of attack of model relative to the incident flow
β_{FS}	Free-stream mean flow angle measured relative to the wind tunnel centerline
β_W	Near-wall mean flow angle measured relative to the wind tunnel centerline
δ	Boundary layer thickness. Distance from the wall where $(U^2+W^2)^{1/2}/U_e = 0.995$

δ^* .... Boundary layer magnitude displacement thickness

$$\delta^* = \int_0^\delta \left[1 - \frac{\left(U^2 + W^2\right)^{\frac{1}{2}}}{U_e}\right] dr \qquad (\text{Prolate Spheroid})$$

$$\delta^* = \int_0^\delta \left[1 - \frac{\left(U^2 + W^2\right)^{\frac{1}{2}}}{U_e}\right] dy \qquad (\text{Wing - Body Junction})$$

Δ .... Boundary layer thickness based on the velocity defect law (from Rotta, 1962)

$$\Delta = \frac{\delta^* U_e}{u_\tau} = \int_0^\infty \left(\frac{U_e - U}{u_\tau}\right) dy$$

ν .... Kinematic viscosity of air

ρ .... Mass density of air

θ .... Boundary layer momentum thickness

$$\theta = \int_0^\delta \left[1 - \frac{\left(U^2 + W^2\right)^{\frac{1}{2}}}{U_e}\right]\left[\frac{\left(U^2 + W^2\right)^{\frac{1}{2}}}{U_e}\right] dr \qquad (\text{Prolate Spheroid})$$

$$\theta = \int_0^\delta \left[1 - \frac{U}{U_e}\right]\left[\frac{U}{U_e}\right] dy \qquad (\text{Wing - Body Junction})$$

τ_W .... Shear-stress magnitude at the wall

τ .... Reynolds shear stress, $\rho\left[(\overline{uv})^2 + (\overline{vw})^2\right]^{½}$

ϕ .... Circumferential angle coordinate, measured from windward side of prolate spheroid model

Φ .... Spectral power density of surface pressure fluctuations such that

$$\overline{p^2} = \int_0^\infty \Phi(\omega)\, d\omega$$

Φ_{O1} .... Non-dimensional spectral power density, $\Phi U_e / \tau_W^2 \delta^*$

Φ_{O2} .... Non-dimensional spectral power density, $\Phi U_e / Q_e^2 \delta^*$

Φ_{O3} .... Non-dimensional spectral power density, $\Phi u_\tau / \tau_W^2 \delta^*$

Φ_{O4} .... Non-dimensional spectral power density, $\Phi u_\tau / Q_e^2 \delta^*$

Φ_{O5} .... Non-dimensional spectral power density, $\Phi u_\tau / \tau_W^2 \delta$

Φ_{O6} .... Non-dimensional spectral power density, $\Phi u_\tau / Q_e^2 \delta$

Φ_{O7} .... Non-dimensional spectral power density, $\Phi U_e / \tau_W^2 \delta$

Φ_{O8} .... Non-dimensional spectral power density, $\Phi U_e / Q_e^2 \delta$

Φ_{O9} .... Non-dimensional spectral power density, $\Phi u_\tau / \tau_W^2 \Delta$

Φ_{O10} .... Non-dimensional spectral power density, $\Phi u_\tau / Q_e^2 \Delta$

Φ_{O11} .... Non-dimensional spectral power density, $\Phi U_e / \tau_W^2 \Delta$

Φ_{O12} .... Non-dimensional spectral power density, $\Phi U_e / Q_e^2 \Delta$

Φ_{O13} .... Non-dimensional spectral power density,

$$\frac{\Phi(\omega)\left[U^2+W^2\right]_{\tau_{max}}^{\frac{1}{2}}}{\tau_{max}^2\; y_{\tau_{max}}}$$

Φ_{O14} .... Non-dimensional spectral power density,

$$\frac{\Phi(\omega)\left[U^2+W^2\right]_{W_{max}}^{\frac{1}{2}}}{\left(\frac{1}{2}\rho W_{max}^2\right)^2\; y_{W_{max}}}$$

ω .... Circular frequency, $(2\pi f)$, rad/s

ω_{O1} .... Non-dimensional frequency, $\omega\delta^* / U_e$

ω_{O2} .... Non-dimensional frequency, $\omega\delta^* / u_\tau$

ω_{O3} .... Non-dimensional frequency, $\omega\delta / u_\tau$

ω_{O4} .... Non-dimensional frequency, $\omega\delta / U_e$

ω_{O5} .... Non-dimensional frequency, $\omega\Delta / u_\tau$

ω_{O6} .... Non-dimensional frequency, $\omega\Delta / U_e$

ω_{O7} .... Non-dimensional frequency,

$$\frac{\omega\; y_{\tau_{max}}}{\left[U^2+W^2\right]_{\tau_{max}}^{\frac{1}{2}}}$$

ω_{O8} .... Non-dimensional frequency,

$$\frac{\omega \; y_{W_{max}}}{\left[U^2 + W^2\right]^{\frac{1}{2}}_{W_{max}}}$$

superscript:

( )' .... The root mean square value of a fluctuating quantity

$(\ )^+$ .... Indicates that the variable is made non-dimensional using the viscous scales: τ_W for pressure, u_τ for velocity, and ν / u_τ for length

$(\overline{\ \ })$ .... Denotes a long-time averaged quantity

subscript:

$(\ )_{max}$ .... The maximum of ( ).

When one variable is the subscript to another variable, the latter variable is evaluated at the condition of the former variable. For example, $y_{\tau_{max}}$ is the y location of τ_{max} (maximum Reynolds shear stress)

Note : This document follows the usual tensor convention that a repeated index (i) within a term indicates summation with respect to the repeated index over the range 1, 2, 3.