Boundary Layer Characteristics on a Tiltrotor Blade Model

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(ABSTRACT)

Boundary layer characteristics at the trailing edge of a tiltrotor blade model were measured using a flattened pitot probe and a single hot wire. The blade was mounted in Virginia Tech Stability Wind tunnel stationary on a turntable on the wind tunnel's upper wall with the tip pointing down. The measurement point was located at 1 mm behind the trailing edge to make it possible to measure the flow near the blade surface and measure the boundary layer on both sides of the trailing edge in a same run. Mean velocity profiles were measured for a variety of Reynolds numbers and angles of attack. Turbulence intensity and spectral measurements were performed using a single hot wire at the highest Reynolds number. Conclusion was reached that both of the flattened pitot probe and single hot wire are good for boundary layer thickness measurements. Displacement thickness, which is important in trailing edge noise prediction, was calculated from the profile data and fit using an algebra expression against the tip angle of attack. Once the relationship between tip angle of attack and local effective angle of attack is obtained by lifting line theory, the results can be used in the trailing edge noise prediction code.

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Chapter 1. Introduction

Noise is associated with rapid small-scale pressure fluctuations. These fluctuations are emitted from a source and travel as waves through a medium. A fundamental understanding of the detailed aerodynamics of lifting surfaces is a prerequisite of accurate noise prediction methods. For this reason helicopter rotor blades have long been a subject of aerodynamic interest.

Figure 1-1 (Wagner *et al*, 1996) shows the typical flow around the outer part of a rotor blade. The rotor blades impact with the incoming natural turbulence and generate inflow turbulence noise (Amiet *et* al, 1976), they generate impulsive (BVI) noise when they pass through the tip vortices shed by previous blades (e.g. Preisser *et al.*, 1994), they generate broadband (BWI) noise through their interactions with the turbulent wakes shed by other blades (e.g. Brooks *et al.*, 1989), and they generate broadband self noise as a consequence of the turbulent boundary layers and separated flow regions interact with trailing edge, and tip vortices that develop over their surfaces (e.g. Brooks *et al.*, 1989). Typical rotor frequencies for helicopters are given in figure 1-2 (van Ditshuizen, J. C.A, 1987). Normally only the hearing capability of human being is considered, i.e. higher than 16 Hz. BVI noise dominates the medium frequency region, while the turbulent boundary layer trailing edge noise dominate high frequency region. Laminar boundary layer generate vortex shedding noise which dominates the high-frequency region.

1.1 Airfoil Self Noise

Even a single airfoil in a turbulence-free inflow will generate noise due to the instability in the boundary layer or interaction of eddies in the boundary layer with the airfoil surface. This kind of noise is called airfoil self noise. Depending on the mechanism of its generation, it may be identified as trailing edge noise, laminar boundary layer vortex shedding noise, tip noise, separated/stalled flow noise or blunt trailing edge noise.

If a rotor blade operates at Reynolds numbers less than 10^6, laminar flow regions on either airfoil side may extend to the trailing edge. A resonant interaction of the trailing edge noise with the unstable laminar turbulent transition can occur. An upstream traveling acoustic wave from the trailing edge couples to theTollmiem-Schliching instabilities, resulting in tonal noise, see figure 1-3 (Wagner *et al*, 1996). High levels of noise may occur when the development of instabilities is reinforced by the acoustic field. This kind of noise can be prevented by tripping the boundary layer relatively far upstream of the trailing edge.

At the tip, the pressure difference between suction and pressure side results in a cross flow over the tip which is responsible for the formation of a tip vortex. The flow interacts with the edge of the tip and generates noise. Tip vortex noise is of broadband character and mainly influenced by the convection speed of the vortex and its spanwise extent (Brooks *et al*, 1989). One expects that the location of the vortex core, the strength of the vortex, which depends on the angle of attack, the Reynolds number, and blade loading distribution have influence as well (Figure 1-4) (Wagner *et al*, 1996).

As the angle of attack increases, the boundary layer may separate at a certain point, and stall may occur for high angle of attack (Figure 1-5). Fink and Bailey (1980) found an increase of more than 10 dB in trailing edge noise for stalled flow, relative to for low angles of attack. Paterson *et al* (1974) found the mildly separated flow causes sound radiation from the trailing edge, whereas deep stall causes radiation from the chord as a whole. Noise caused by stalled flow is a broadband in nature and is the only major contributing noise mechanism beyond limiting angles of attack (Brooks *et al*, 1989). It can only be reduced by avoiding stall condition.

Blake (1986) describes the basic mechanisms of blunt trailing edge noise. Depending on the bluntness and shape of the trailing edge and Reynolds number, vortex shedding can occur, resulting in a von Karman type vortex street. The alternating vortices in the near wake produce higher surface pressure fluctuations close to the trailing edge (Figure 1-6). If the thickness of the trailing edge is large enough, fluctuating forces will occur resulting in dipole noise of tonal character.

1.2 Trailing Edge Noise

In most cases, transition from laminar to turbulent flow occurs in the boundary layer on a rotor's blade surface. Important parameters describing the boundary layer turbulence are the length-scale of the energy bearing turbulent eddies, the turbulence kinetic energy, its spectral decomposition, and the eddy convection velocity. Beneath the boundary layer, the turbulence induces a fluctuating pressure field. Its temporal and spatial transform the wavevector-frequency spectrum can be used to compute trailing-edge noise (Howe, 1978).

At low Mach number, turbulence eddies are not good sound sources. If there is a sharp edge close to the eddies, however, they become more efficient as sound sources. Therefore, trailing edge of a blade increases the level of noise radiation from the turbulence eddies in the boundary layer. A simplification model for trailing edge noise was obtained by Howe (1978) by assuming an infinitely extended plane with a vanishing thickness which results in a rather simple directivity distribution with maximium radiation in the direction of the plane. Figure 1-7 shows the influence of finite chord and airfoil shape for a turbulent eddy (point quadrupole) in the vicinity of the trailing edge of a NACA 4412 profile. This is the principal mechanism of turbulence boundary layer trailing edge noise which is called trailing edge noise (Figure 1-8). The important factors which influence trailing edge noise are the convection speed and the length scale of the turbulence eddies. Eddy convection speed relate to the free stream speed, while the length scale relate to the structure of the boundary layer.

Brooks *et al.* (1989) performed a number of aerodynamic and acoustic measurements for a set of seven 2-dimensional NACA 0012 profile sections and 3-dimensional blade tip at Reynolds number between 400,000 and 1,500,000. Boundary layer thickness, displacement thickness, momentum thickness, and sound pressure levels were determined for tripped (at 20% chord) and untripped conditions at free-stream velocities up to 71.3 m/s and angles of attack in the range of 0° ~ 25°. The models were tested in the low turbulence potential core of a jet located in an anechoic chamber. The extensive measurement program resulted in a set of spectral scaling formulas for the sound pressure levels in the vicinity of a profile section which were implemented into FORTRAN code. The noise is described as a function of local Mach number M, which relate to the convection speed, displacement thickness δ^*, which relate to the length scale, length of the blade segment s, angle of attack α and the distance of the source to the observer position r.

1.3 Tiltrotor Blade

Tiltrotor aircraft is a kind of aircraft that can take off and land vertically like a helicopter and also fly like an airplane during cruise (Figure 1-9). The tiltrotor aircraft was designed for military use initially, it can, however, provide a potential alternative means of civilian transportation that would link large cities while consuming a minimum of land area. Experimental research on tiltrotor aircraft was conducted for many years with aircraft like the XV-3 and the XV-15, among others. V-22 Osprey is the most recent tiltrotor aircraft which was developed by navy for military missions. Noise is a major concern for large tiltrotors especially for civil applications.

Tiltrotor blades were designed with shapes that are between helicopter's blades and airplane's propeller to fulfill its unique missions. They produce noise via all the same mechanisms as helicopters. Because it is highly twisted and small aspect ratio and relatively thick, however, the empirical correlations developed from helicopter rotors are not accurate for the tiltrotor problem.

The primary tiltrotor research aircraft of the 1970's and 1980's was XV-15, which was a joint NASA, Army and Bell venture. A joint NASA/Army/Bell Helicopter Textron test of a 15%-scale model V-22 blade was conducted (Marcolini *et al*, 1995). Detailed maps of isolated tiltrotor noise directivity at a number of well-controlled operating conditions were obtained in this test. The most important recent studies of tiltrotor flows are a test of a ¼-scale V-22 rotor in the DNW wind tunnel (Young *et al*, 1999). Prediction and analysis efforts related to these tests have been completed and are underway (Lyle *et al*, 1997, Booth *et al*, 1999, Burley *et al*, 1999). Predictions were centered on developing a generalized Tiltrotor Aeroacoustics Code (TRAC), which will combines CFD flow simulations, wake tracking methods, and BVI, BWI and self-noise acoustic prediction. Boundary layer characteristic on tiltrotor blades is the information that needs to obtain since it is the key to accurate self-noise prediction. Brooks *et al.* (1989) established the correlation of boundary layer parameters with Reynolds number and angle of attack for helicopter-type blades, but it is not comparable to the more twisted, thicker, tiltrotor type blades.

The purpose of the research proposed here is to provide some of the experimental data and understanding needed in the tiltrotor noise prediction code. By mounting the tiltrotor blade model stationary in a conventional wind tunnel, we intend to document the structure of the boundary layers it produces and correlate that with Reynolds number and angle of attack. The boundary layer properties were correlated with the blade tip geometric angle of attack. Using lifting line theory, the relationship between the geometric angle of attack and the effective angle of attack can be established. The experimental data from the linear wind tunnel measurement results can therefore be used in the rotating system noise prediction.

Chapter 2 Apparatus and Instrumentation

2.1 Virginia Tech Stability Wind Tunnel

All measurements were performed in the Virginia Tech Stability Wind Tunnel. The tunnel is a continuous, closed jet, single return, subsonic wind tunnel with a 6'x6' test section 24 feet in length (Figure 2-1). An air-exchange tower provides temperature stabilization. The tunnel is powered by a 600hp DC motor driving a 14.1-foot diameter propeller that has 8 constant pitch blades. This system providing to a maximum speed of about 70m/s. Tunnel speed is regulated by a custom designed Emerson VIP ES-6600 SCR Drive.

Seven stainless steel wire turbulence screens are installed in the 18'x18' settling chamber. Small-scale eddies dissipate before the test section when passing the screens. The contraction ratio between the settling section and test section is 9:1. These ensure that the turbulence levels in the test section are extremely low, on the order of .05% or less (Table 2-1), and flow in the empty test section is closely uniform (Choi and Simpson, 1987).

Freestream Velocity	Streamwise Fluctuations
V [m/s]	u'/V
5	0.018%
12	0.018%
15	0.022%
20	0.028%
30	0.045%

Table 2-1 Stability Wind Tunnel Turbulence Level

2.2 Tiltrotor Blade Model, Blade Holder, and Bracing

Boundary layer and wake velocity measurements were made on a highly twisted model tiltrotor blade. The quarter scale V-22 like blade is called the JVX (Figure 2-2). It is designed for a rotor radius of 2.85 feet, has a tip chord of 3.6 inches and a twist that increases from about -6 degrees at the tip to 30 degrees close to the hub (Figure 2-3 and figure 2-4). Figure 2-5 shows a perspective drawing of the blade from the tip up to 62%

radius of the rotor. The blade has a trailing edge thickness of 0.03 inches for the entire span. To avoid difficulty with traversing to the blade surface, boundary layer properties were obtained from the measurements made at a small distance downstream of the trailing edge, This distance, which should be small to make the boundary layer properties close to those right at the trailing edge, was chosen to be 1 mm to ensure the safety of the single hot wire. Another reason to measure the wake instead of the real boundary layer is that by measuring spectra in the wake, vortex shedding might be identified and therefore obtain the information for vortex shedding noise.

2.2.1 Blade Holder

The JVX blade was mounted cantilever style on a turntable with its tip pointing down toward the wind tunnel floor. Figure 2-6 shows the blade in the wind tunnel. The suction side of the blade is visible. The turntable was designed to hold the blade root firmly and can be turned when the wind tunnel is running to set the angle of attack accurately. Figure 2-7 shows the configuration and dimension of the turntable. The blade was mounted at the center of the turntable with a shaft that hold the blade by fitting it tightly into the blade's axis hole and fixed at the end by a large screw nut. The whole blade's trailing edge can be seen through a plastic glass window in the turntable. The turntable was mounted on the top of the test section, tightened by four clamps after setting the blade's angle of attack each time. Two aluminum beams were used to fasten the turntable to eliminate any vibration (Figure 2-8). When installed, the axis of the blade shaft was perpendicular to the ceiling of the wind tunnel.

The blade's root is in the boundary layer of the wind tunnel test-section ceiling when measuring. Figure 2-9 shows the boundary layer profile on the wind tunnel's ceiling. The stagnation pressure was measured using a Pitot probe with out the blade present. The boundary layer thickness is about 1.6 inch. The shape and dimension of the JVX blade's root can be seen from figure 2-2 and figure 2-10. The nearest measurement station (62% radius from tip) to the root is 9.9 inch from the root.

2.2.2 Bracing the Blade

The JVX blade was made by glass-fiber plastic material that is flexible. Vortex shedding from it can induce vibration. This problem was investigated in a preliminary study. In this study, the blade was set up as in the final measurements. A cathetometer was mounted on the top of the wind tunnel and used to measure the lateral displacement and vibration of the blade tip through the window on the turntable. The cathetometer was made by PTI and can measure distance with an accuracy of 0.01 mm. The actual measurement accuracy was approximately between 0.1 mm to 0.2 mm however due to the vibrations in the cathetometer set up by the wind tunnel.

Results from the preliminary study are shown in table 2-2, where angle of attack means the angle of attack at the blade tip, displacement refers to the displacement of the tip when the tunnel is running compare to the no-flow position (negative for a movement to the pressure side), amplitude of vibration means the distance from the leftmost to the rightmost position of the blade tip.

Angle of Attack (degrees)	Flow Speed (m/s)	Amplitude of Vibration (mm)	Displacement (mm)
0	12	0	1
0	40	0	8
8	12	0	1
8	40	1	9
-20	12	0	0
-20	40	0.5	-3

Table 2-2 Vibration & Displacement when the JVX Blade is in the Wind Tunnel Without Bracing

Due to the high twist of the JVX blade (Figure 2-3), the spanwise locations near the root experience high angles of attack that result in separation even when the tip is at zero angle of attack. The blade does not have visible vibration in this case because the blade is thicker at the root and thinner at the tip and only separation at the tip can produce large vibration. At 8 degrees tip angle of attack, the flow is separated at most locations along the span and therefore the blade has a visible vibration and move to the suction side because of the lift acting on the blade tip region. At -20 degree, the flow separates near the tip at pressure side and the lift is negative at most spanwise locations, thus the blade bends to its pressure side.

From table 2-2, we see that the amplitude of vibration of the blade is as high as 1 mm. Such vibrations would definitely influence measurements of the boundary layer characteristics and the precision with located which a probe could be in the boundary layer. Also, the displacement of the tip would also influence measurements. Bracing was used to eliminate these problems.

A bracing wire was used on the tip of the blade. The bracing was made by attaching an airfoil shaped steel plate on to the tip with a small anchor screw mounted on it. The plate has a thickness of 0.12 inch, which is small compare to the blade scale, so it would influence the flow on the blade. The anchor screw was located on the axis of blade to ensure that it would not translate when the angles of attack was changing by turning the turntable. Figure 2-11 shows the plate with the anchor screw. The intersection of the anchor screw's axis and the surface of the blade tip on the tip chord line and is 0.9 inch from the leading edge. A steel wire with diameter of 0.5 mm was looped around the screw and fastened on each side onto a frame that was screwed onto the wall of the wind tunnel (Figure 2-12 and figure 2-13). The vibration and displacement were measured again after adding the bracing wire, at all prospect angles of attack, no visible vibration was found. A 0.5 mm displacement at the tip was found at 8 degrees angle of attack, which was not considered a problem since this only change the blade's configuration very little. The nearest measurement location was the 5% station, which is 1.71 inch from the tip. This was assumed to be far enough away to avoid the influence of the bracing wire.

2.3 Traverse and Coordinate System

The 2-axis stability wind tunnel traverse, as shown in figure 2-14, was used to position both pressure and single hot-wire probes in the test section. A third axis was added to it to move the probe in streamwise direction. Figure 2-15 shows the picture of the third axis traverse. It can move probes over a range of 5 inches. A separate traverse controller was used to control the third axis traverse.

The accuracy of this combined traverse was studied and a maximum error of 0.1 mm was found. Probes were mounted onto the carriage on the third axis of the traverse.

Two coordinate systems were selected to describe the positions of blade and probes and boundary layer characteristics. One fixed coordinate is fixed relative to the wind tunnel and one relative coordinate is used to describe boundary layer characteristics for different spanwise location and angles of attack.

As described in section 2.2.2, the axis of the blade is fixed relative to the wind tunnel at any angle of attack. It is convenient to select the intersection of the tip's surface and the extension of the axis of the blade shaft to be the origin of the fixed coordinate. The three axis of the fixed coordinate are: x_o point downstream, that is, parallel to the axis of the wind tunnel. y_o points to the suction side of the blade and perpendicular to the side wall of the wind tunnel. z_o points upward and perpendicular to the ceiling of the wind tunnel. With this coordinate defined, when the blade is at zero degree angle of attack at the tip, the leading edge of the tip is at (-0.9, 0, 0) in inches, the trailing edge of the tip is at (2.7, 0, 0) in inches, and the center of the flattened Pitot probe and the single hot wire probe would be at (2.74, 0, 0) in mm if they were used to measure the flow at the tip and were placed at the center of the wake. The blade's axis is parallel to z direction so the angles of attack were defined in x_o-y_o plane with a positive value from y_o to x_o.

Boundary layer properties were measured at a variety of spanwise locations and angles of attacks. A relative coordinate is therefore necessary to describe the local boundary layer characteristics. At any spanwise location and angle of attack, the coordinate system has an origin 1 mm downstream of the trailing edge, with x, y, and z in the same direction of the corresponding axis of the fixed coordinate. In order to have a positive y on both sides of the blade when presenting the boundary layer profiles, the two sides were separated in the data reduction and y was plotted as increasing from the origin on both sides. Fixed and relative coordinate have parrellel axises as shown in figure 2-16.

2.4 Pitot Probe and Static Probe

Preliminary boundary layer calculations suggested that the boundary layers at the JVX blade trailing edge would be on the order of a few millimeters thick. Accurate multi-component velocity measurements are not possible in such a thin region and so boundary layer velocity profiles were measured using single hot-wire anemometry and flattened Pitot probes.

A small-scale flattened Pitot probe was made to document the mean characteristics of the boundary layer. The dimensions of the Pitot probe mouth are 1.32 x 0.50 mm externally and 1.07 x 0.25 mm internally (Figure 2-17).

To get velocity profiles from the measurements the static pressure was measured as well. A commercial static pressure probe was used to do this. The diameter of the static probe is 1.27 mm. The pressure holes are 5.6 mm behind the head. Since the static pressure would not change cross the boundary layer, only one point is needed for measurement, the point at the center of the wake was selected for convenience. Figure 2-18 shows the photo of the flattened Pitot probe and the static probe.

The pressure signal was measured using a set of pressure transducers with ranges from 5 to 20 inches of water. A 0~5 inch transducer was used to document the pressure from Pitot probe for low speed flow, a 0~20 inch transducer was used for high speed. The transducers were made by Honeywell (DRAL5 Series) with error smaller than 0.25% of output voltage. The zero offset value was checked every hour to ensure the pressure measurement accuracy. The plastic tube between the pressure probe and the transducer was approximately 5 meters long with an inner diameter of 6.35 mm. Wind tunnel free stream static and dynamic reference pressures were measured using a large reference Pitot-static probe located in (-14.5, -32,18) in inches in the fixed coordinate system and mounted in the sidewall of the wind tunnel. The same size of plastic tube with a length of 7 meters approximately connected the Pitot-static probe and transducer. A settling time of 3 seconds was used for all pressure measurements.

Stagnation pressure coefficient was obtained by the computer from these three signals as shown in equation 2-1.

$$C_{po} = \frac{P_o - P_\infty}{P_{\infty o} - P_\infty} \qquad 2\text{-}1$$

Where P_o is the pressure from the flattened Pitot probe, $P_{\infty o}$ and P_∞ are the pressure from the wind tunnel's Pitot-static probe.

Static pressure was taken after the Pitot measurement was done for every profile. Static pressure coefficient is defined in equation 2-2.

$$C_p = \frac{P - P_\infty}{P_{\infty o} - P_\infty} \qquad 2\text{-}2$$

Where P is the pressure from the static probe.

Since the transducers only measure positive pressure difference, the measurements were actually made by connecting the stagnation pressure of the free stream to the high port of the measurement transducer and the static pressure to the low port. The pressure coefficient actually measured is thus

$$C_p' = \frac{P_{\infty o} - P}{P_{\infty o} - P_\infty} \qquad 2\text{-}3$$

The relationship between C_p and C_p' is $C_p = 1 - C_p'$.

2.5 Hot-wire Anemometry

Velocity measurements were made using TSI 1210-T1.5 hot-wire probe, as shown in figure 2-19. This is a single hot-wire. The sensor wire is made of etched tungsten wire of 5 µm diameter and approximately 1.5 mm in length with length to diameter ratio of 300. The wire is at a right angle to the probe axis.

The sensor wire was operated using a Dantec 56C17 bridge and Dantec 56C01 constant temperature anemometer unit. The bridges were optimized to give a frequency response greater than 25 kHz. Output voltage from the anemometer bridge was amplified by a x10 buck-and-gain amplifier with a calibrated RC-filter to limit its frequency response to 50 kHz. The amplified signal was then recorded by a Hewlett Packard (HP) E1432A data acquisition system. The HP system also sampled output voltages from the pressure transducer reading the reference dynamic pressure and a digital thermometer reading flow temperature. All the signals were input into an NT workstation from the HP system. HP Vee programs running on the workstation were used to automatically control and coordinate traversing, data acquisition and the logging of reference conditions. The E1432A provides per channel sample rates up to 51.6kHz (with anti-aliasing filters) - more than adequate for the measurement of boundary layer turbulence and spectra.

Probes were calibrated for velocity every half an hour in the tunnel’s free stream by fitting the measured relationship between sensor voltage and cooling velocity to

King's law. The free stream of the tunnel was maintained at 60m/s for all the hot-wire measurements.

Mean velocity and turbulence intensity were obtained by the HP Vee program automatically from the single hot-wire. Spectral measurements need more data records to eliminate the influence of noise. It is impractical to have all the spectral measurements performed with mean velocity measurements. Therefore, spectral measurements were performed separately at less angles of attack. The sampling rate for hot wire measurements was set to be 51200 Hz, record length was set to be 4096, and number of records was set to be 10 for mean and fluctuating velocity measurements and 100 for spectral measurements. Relative uncertainties for velocity measurements for 5% spanwise location and 0 angle of attack on the suction side were computed for some typical cases and listed in table 2-3.

Quantities	Positions in boundary layer (y/δ)	Uncertainties
U/U_e	0.1	1.5%
	0.5	1.4%
	0.8	1.3%
u'/U	0.1	4%
	0.5	4%
	0.8	4%
G_{uu0}	0.1	8%
	0.5	8%
	0.8	8%

Table 2-3 Uncertainties for hot wire measurements

(5% spanwise location, 0 angle of attack, suction side)

2.6 Probe holder and other instruments

For the pressure measurements, the flattened Pitot probe and the static probe were mounted parallel each other with a distance of 1.97 inch in *y* direction and a distance of 0.24 inch in *z* direction between their tips. The wind tunnel traverse was used to move the probe in spanwise direction (*z* direction) and across the boundary layer (*y* direction). The third traverse was used to move the probe in streamwise direction (*x* direction) in order to keep the probe to be at exactly 1mm downstream of the blade trailing edge for all the measurements. Because of the twist of the JVX blade, the direction of the trailing edge changes with spanwise position and angle of attack. The flattened Pitot probe and the single hot wire had to be reoriented in each case by rotate them with respect to their axis to make the wire or the mouth parallel to the blade trailing edge to get the right velocity component. The trailing edge has a sweep angle smaller than 2 degrees which varies with the span. Since the axis of the probes were set to be parallel to *x* axis and could not be changed, The hot wire was actually set to be parallel to the projection of the trailing edge in a plane perpendicular to the *x* axis. This projection is a curve in *y-z* plane. Figure 2-10 shows the angle φ (angle between the projection and *z*-axis) and its variation with *z*.

A magnifying glass was used to compare the probe tip or hot wire with the trailing edge to set the hot wire to be parallel to the trailing edge. The error was smaller than 2 degrees.

A laser beam system was use to determine the blade zero degree angle of attack. The laser beam generator was made by CST Corporation and capable of generating three orthogonal beams with diameters of 1.5 mm. The laser beam generator was installed on a tripod that was placed in the middle of the wind tunnel 3 meters downstream of the blade with a laser beam pointing upstream. The blade tip was in the middle of the wind tunnel, two cotton threads were hung from the leading edge and trailing edge of the blade. When the laser beam was cut evenly by the two threads, the blade tip was taken to be at zero angle of attack. The laser beam generator could be off the center 2 mm at most, which introduced an error of 0.03 degree for the angle of attack. The distance between the two threads is 91 mm, and the laser beam could be off the center of the thread 0.3 mm at most, which introduced an error of 0.19 degree for the angle of attack. The uncertainty of the blade's angle of attack, therefore, is about 0.2 degree.

To locate the probe precisely 1 mm downstream of the trailing edge after every change in angle of attack, a cathetometer was used addition to the streamwise traverse. The cathetometer was mounted at the outside of the tunnel (Figure 2-21). Both the probe and the blade trailing edge can be seen though the Plexiglas wind tunnel window using the cathetometer. The process to position the probe was made in two steps: First, the probe was moved in y direction to make it slightly to the side of the trailing edge. This movement could be judged from the window in the turntable on the top of the wind tunnel. The streamwise traverse then was used to move the probe back and forth until the head of the probe was at the same *x*-location as the blade trailing edge. This was judged by aligning the probe tip and the trailing edge through the cathetometer. Second, the probe was moved downstream of the current position 1 mm using the streamwise traverse. The accuracy of the distance between the probe head and the trailing edge set by this method was investigated in a preliminary entry and the error was found to be smaller than 0.05 mm.

To find the center of the blade wake (The point immediately behind the blade trailing edge), a HP Vee program to find the lowest flow speed point automatically was used. The program would move a probe that was in an arbitrary initial point in the boundary layer to a point where the flow velocity is the lowest by reading the output from the Pitot probe or the single hot wire. The error of the center offset by this method is smaller than 0.13 mm. This method only worked for unstalled flow. For the stalled flow, the center was found manually by observing the position of the probe head and trailing edge through the window in the turntable using the cathetometer. The accuracy achieved by this method was only 0.25 mm.

Chapter 3 Results and Discussion

The flattened Pitot probe and static probe measurements were used to obtain the mean velocity profile at the trailing edge at different Reynolds numbers. Single hot-wire measurements were used to document the mean velocity profile as well as turbulence intensity and spectra at the highest Reynolds number.

Since the JVX blade is a highly twisted blade, the flow characteristics in a linear wind tunnel are different compared to the status when the blade is rotating. There is no universal angle of attack along the span. Angles of attack at the tip were therefore used as reference angles of attack. Local geometric angles of attack can be obtained from the JVX blade twist distribution. Effective angles of attack associated with the boundary layer can be obtained from these by for example lifting line theory approximately. Figure 3-1 is the result from lifting line theory, which shows the effective angle of attack changing with tip angle of attack as a function of spanwise location.

3.1 Measurement locations and Reynolds number

Measurements were made at 6 spanwise locations to get the boundary layer characteristics as a function of spanwise position. Locations were defined by distance from the tip in terms of percent of rotor radius. The whole blade length is 90.6% of the radius, the measurement locations are 5%, 15%, 25%, 38%, 48%, and 62% of the radius from the tip. According to the blade twist distribution as shown in figure 2-3, the angle of attack changes gently from the tip to the 40% location with a linear increase, then change begins to more dramatically towards the root. The 62% spanwise location was a geometric angle of attack of 21 degrees when the tip was at 0 degree angle of attack. Twist angles relative to the tip at the measurement stations are shown in table 3-1. Blade sections at the 6 stations are shown in figure 3-2.

Wind tunnel reference flow speed was set at 20, 40, 50 and 60 m/s to investigate the boundary layer properties as a function of Reynolds number. The flow speed has a variation of ± 0.8 m/s during the measurements. Atmosphere pressure was 944 ± 3 mmHg. Flow temperature was $285 \pm 5\,^{\circ}\mathrm{C}$ during the measurements. The viscosity coefficient changes very little over such temperatures range. We therefore used a Reynolds number for all the measurements based on the tip chord, reference flow speed, and mean temperature. The Reynolds number is shown as table 3-2.

3.2 Tuft Flow Visualization

Since trailing edge noise is generated from the boundary layer in attached flow, our interest is mostly in the attached flow boundary layer properties. To decide which angles of attack should be measured, tuft flow visualization was performed to examine the variation of stall angle with angle of attack and spanwise location. Three rows of cotton thread dyed in fluorescence with a diameter of approximately 0.8 mm and a length of 50 mm were used. The locations of the three rows are at 1, 2, and 3 quarters of the chord from the leading edge. An ultraviolet light was used to illuminate the thread. Figure 3-3 shows an example for the suction side of the blade at -20 degree angle of attack and flow speed was at 30m/s. Flow visualization were performed at intervals of 4 degrees of angle of attack relative to the 6 prospective spanwise locations recorded for reference flow speeds of 20, 30, 40, and 50 m/s. Results are shown at table 3-3 to table 3-6. In these tables, O indicates flow attached, P indicates stalled flow on the pressure side, S indicates stalled flow on the suction side.

3.3 Wake of the JVX Blade

A cross section of the velocity distribution downstream of the blade was taken by single hot wire at a tip angle of attack of -12 degree for a mean flow speed of 60 m/s. The cross section was located at 3 inches downstream of the trailing edge at the tip, which is approximately one tip chord length. With the origin at the trailing edge of 38% spanwise location, measurements were made over an area extending from -3 inch to 3 inch in y direction and -18 inch to 9 inch in z direction. The step size was 0.25 inch in the y direction and 1 inch in the z direction. The single hot wire sensor was aligned with z axis. The measurement was done with no bracing at the tip to eliminate the influence of the bracing wire. Figure 3-4 is the mean velocity distribution and figure 3-5 is the turbulence intensity distribution. The tip is located at $y = -0.715$ inch, and $z = -13$ inch in this coordinate system. An important discovery is that the flow speed at the top is higher than the bottom. The difference is approximately 5% in mean flow speed. This appear to be an effect of the traverse. There is a beam on the traverse that located near the root of the blade (Figure 2-6). The position of the beam is 5 inch downstream of the trailing edge at 82% spanwise location. It is covered with an airfoil shape steel tube with chord length of 4 inch. The flow will accelerate when approaching the leading edge of the tube. It is assumed that this did not affect the boundary layer measurements very much, since all velocities in the final result were normalized by the local edge velocity U_e and such an error in Reynolds number is small enough to avoid influence the properties of the boundary layer.

Boundary layer properties were measured at 1 mm downstream of the trailing edge, actually in the wake region. Measurement locations were read from text files by the HP Vee programs running on the computer to control the traverse's movement. The text files contained 15~20 logarithmically scaled data points for each side of the blade (30~40 points for one scheme) base on the estimation of the boundary layer thickness. After the center was found, the position was set to be $y = 0$, the schemes then were used to move the probe to a positive y position (pressure side) and begin the measurements from there to the negative position (suction side). Table 3-7 shows some typical data point schemes used in both the Pitot probe and hot wire measurements. Mean velocity profiles covering the whole wake that correspond to these data point schemes were shown in Figure 3-6 through 3-13. These figures contain normal conditions and separation/stall conditions, and can be used to compare between the pressure side and the suction side for a variety of spanwise locations and angles of attack. For normal condition, such as 0 degree angle of attack at 5% spanwise location, the boundary layer at both sides has similar shape and thickness since the cross section has a similar shape to symmetric airfoil and at a angle of attack of 1.3 degree. For some extreme conditions, such as 0 degree angle of attack and at 62% spanwise location, the boundary layer is very thin at pressure side and completely stalled at suction side This is because the local geometric angle of attack here is approximately 21 degrees. For normal condition, the point with lowest velocity is easily identified as the center of the wake and was used to be the $y/\delta = 0$ location for boundary layer velocity profiles on both sides of the blade. At large angle of attack, the flow separates and contains reverse flow region. Neither flattened Pitot probe nor single hot wire can measure reverse flow. The results show that the lowest velocity point occurs somewhere in the separation region (Figure 3-13). In these cases the *y*-origin for the boundary layer profiles was chosen by aligning the probe and the trailing edge through the window in the turntable using the cathetometer.

Boundary layer thickness was defined as $\delta_{0.99}$ i.e. the location where mean velocity equal to 0.99 edge flow velocity U_e. Displacement thickness and momentum thickness were defined as follow:

$$\delta^* \equiv \int_0^{\delta}\left(1-\frac{U}{U_e}\right)dy \tag{3-5}$$

$$\theta \equiv \int_0^{\delta}\left(1-\frac{U}{U_e}\right)\frac{U}{U_e}dy \tag{3-6}$$

Where U is the mean velocity measured by Pitot probe or single hot wire.

Shape factor is defined as

$$H \equiv \frac{\delta^*}{\theta} \tag{3-7}$$

Where H is the shape factor.

3.4 Tripping the Blade Boundary Layer

To simulate the much higher Reynolds number of a full scale tiltrotor blade, boundary layer trips were used in measurements. To decide where to place the trips and the best choice of trip material, preliminary measurements were performed. Two materials were used and two locations were measured. The two materials were randomly placed 0.025”glass beads and non-skid tape with a base 0.015”in thickness and roughness height of 0.03”. The width of the trips in both cases were one quarter inch with the trailing edge at 15% and 25% chord length from leading edge of the blade. The trips were placed along the blade span on both sides. Boundary layer properties were measured at 25% and 35% spanwise locations and 0 angle of attack at blade tip with and without the trips.

Figure 3-14 shows the profiles with and without trip at 25% spanwise location, 0 degree angle of attack at tip, and 50m/s reference flow speed. The profiles show that the trip makes the boundary layer thicker at the suction side. They also show that there is no much difference between the two trip materials. Since the non-skid trip is more reliable for span uniform and easy to install and uninstall, it was choose to be the trip material.

Figure 3-15 and figure 3-16 show pressure coefficient profiles with non-skid tape trip placed at different chordwise location for 0 degree angle of attack and 50 m/s reference flow speed. We can see that when the flow is attached (Figure 3-15), tripping the blade boundary layer at the 15% chord location makes the boundary layer thicker than with the trip at 25% chord location. In figure 3-16, it can be seen that tripping the blade at 25% chord length location can promote stall. Therefore, the 15% chord location is a better choice. All the measurements were performed with trip at this location.

To investigate the overall influence of the trip on the boundary layer, measurements were performed using the single hot wire with and without the trip. The data were taken at angle of attack of -12 degree, mean flow speed of 60 m/s, and for 5 spanwise locations at 5%, 15%, 25%, 38%, and 48%. Results are shown in figures 3-17 through 3-42. Look at figure 3-19, the profile measured with no trip seems to indicate separated flow, while the profile measured with the trip appears show no stall. Indicating that the trip delays the separation. From the turbulence intensity plot, we can see that when the boundary layer has a negative pressure gradient, the turbulence intensity is intensified, when the boundary layer has a positive pressure gradient, the turbulence intensity was weakened. (Due to the twist on the blade, the spanwise locations of 5%, 15%, and 25% have negative angles of attack, 38% spanwise location is near the location that local angle of attack is zero, and 48% spanwise location has a positive angle of attack). In figure 3-37 through 3-42, it is seen that the boundary layer thickness was amplified by the trip at all cases. This indicated that tripping the boundary layer makes the boundary layer transition to turbulence earlier and therefore ensures the boundary layer at the trailing edge to be turbulence and easy to measure.

3.5 Pitot Probe and Single Hot Wire measurements

In order to be able to compare the boundary layer characteristics along the span, measurements were made along the entire span at a single angle of attack. Negative 12 degree was selected to be this angle of attack because the flow is attached at most measurement spanwise location. Boundary layer measurements at all spanwise locations were also made at 0 angle of attack. With these considerations, the Pitot probe measurement matrix is shown in table 3-8, in which the symbol ‘O’ means that a measurement was performed at that case. All Pitot probe measurements were performed in these angle of attacks at four reference flow speeds: 20 m/s, 40 m/s, 50 m/s, 60 m/s except for 62% spanwise location which was not measured at 60 m/s.

Single hot-wire measurements were performed to document the mean velocity profile, turbulence intensity and turbulence spectral of the boundary layer at the blade’s trailing edge. Due to the small size of the sensor, single hot-wire can provide mean velocity profile with better resolution than flattened Pitot probe. All measurements were done at the top speed of 60m/s. More data points were taken at each spanwise station with profile for every 2 degrees of angle of attack. Some cases were repetitions of Pitot probe measurements in order to compare the data with Pitot probe measurements. The test matrix for velocity profile measurements for the single hot-wire is shown in table 3-9. Table 3-10 is test matrix for spectral measurements. The spectral measurements were taken at y-locations roughly equal to $y/\delta = 0.1$, 0.5, and 0.8 in both trailing edge boundary layers.

Figure 3-43 through 3-62 compares measurements at the same conditions with the Pitot probe and single hot wire probe. The obvious difference is that the velocities near the wake center have values of $U/U_e = 0.3 \sim 0.4$ for Pitot data and $U/U_e = 0.15 \sim 0.2$ for single hot wire data. Recall the size of the Pitot probe and single hot wire. Pitot probe has a dimension of 0.5 mm in y direction while single hot wire has a diameter of 5 μm. so the single hot wire has a better space resolution than the Pitot probe. Therefore single hot wire can catch lower flow speed. The Pitot probe data agrees with the hot wire data very well except the region near the wall. Figures 3-53 through 3-62 show the boundary layer thickness measurements. The agreement between the Pitot probe measurement and the single hot wire measurement is very good.

3.6 Mean Velocity Profiles

When the data were reduced, the centers of the wake were checked and corrected by defining the lowest velocity point to be the center. The two sides were then separated by making the center to be $y = 0$, and define this to be the wall. Several points need to be mentioned here. First, the measurements were done 1 mm behind the trailing edge, and the flow tends to recover after leave the blade, so the points measured near the wake center will have a larger velocity than the 'real' trailing edge boundary layer value. Second, the trailing edge has a thickness of 0.03 inch, while the smallest step size in the profiles was 0.003 ~ 0.01 inch, which suggest that the first few point from the wake center did not represent points within the 'real' trailing edge boundary layer. Third, due to the dimension of the flattened Pitot probe, the data point near the wake center where the stagnation pressure change dramatically with y may not be captured by the flattened Pitot probe. Bearing these points, we can see a detailed inner region of the turbulence boundary layer cannot be obtained from the current data. The profiles were, therefore, presented by plotting U/U_e against y/δ linearly. Here δ is the boundary layer thickness, U_e is the mean flow velocity at the edge of the boundary layer, U is the local mean velocity.

Figure 3-63 and figure 3-64 show the mean velocity profiles measured at different spanwise stations with the angle of attack is set at -12 degree at the tip. It clearly shows the profile and boundary layer thickness variation along the span. Also stall location can be decided approximately from the profiles. Figures 3-65 through 3-110 show the normalized velocity profiles from Pitot probe measurements. In these figures, profiles with four different Reynolds number are compared to each other. The U denotes mean velocity in streamwise direction. In most cases, the profiles for different Reynolds number are almost identical. This suggests that the mean velocity profiles do not change much with Reynolds number at least for such a Reynolds number variation.

Figures 3-111 through 3-134 show the normalized velocity profiles from single hot-wire measurements. Data for different angles of attack were separated in two figures to make each case easy to identify. Because the hot wire was placed parallel to the trailing edge's projection to a plane that is perpendicular to x direction, and the hot wire measures the velocity magnitude in the plane perpendicular to the wire, according to the single hot wire theory, i.e. the single hot wire measures the mean and fluctuating velocity in the mean flow direction parallel to the surface of the blade. This direction may have a maximum angle of attack of 30 degree to the x-axis. For most conditions, this angle was smaller than 10 degrees. For a normal Pitot probe, an incoming angle of 10 degrees introduces a neglectable error for total pressure measurements. Therefore, the hot wire measures essentially the same velocity as the Pitot probe. For extremely large angles of attack, there will be some difference between the Pitot probe measurements and single hot wire measurements. But these cases involve separated/stalled flow and are less relevant to the most important application of this work.

It is obvious from the figures that the velocity profiles on the suction side change to be less full as the angle of attack is increased and reverse on the pressure side. Considering the flow on the pressure side, separation occurs at large negative angles of attack because of strong adverse pressure gradient. The best way of judging when seperation occurs is to look at the boundary layer thickness variation with angles of attack. When the flow separates, the thickness increases dramatically. This will be discussed in later section. Only deep stall can be easily determined here by looking at the mean velocity profiles. When the mean velocity profiles contain a large inflection region, the flow appears to be stalled. Some angles of attack that seem to be separation/stall on the pressure side are $\alpha = -16^\circ$ at the 5% spanwise location (figure 3-111), $\alpha = -16^\circ$ at the 15% spanwise location (figure 3-115), $\alpha = -22^\circ$ at the 38% spanwise location (figure 3-123), $\alpha = -22^\circ$ and $\alpha = -24^\circ$ at the 48% spanwise location (figure 3-127), and $\alpha = -34^\circ$, $\alpha = -32^\circ$ and $\alpha = -30^\circ$ at the 62% spanwise location (figure 3-131). For the suction side, the flow separates at large positive angles of attack. Obvious stall angles of attack obtain from the mean velocity profiles are $\alpha = 20^\circ$ at the 5% spanwise location (figure 3-114), $\alpha = 6^\circ$ at the 38% spanwise location (figure 3-126), $\alpha = 0^\circ$ at the 48% spanwise location (figure 3-130), and $\alpha = -14^\circ$, $\alpha = -12^\circ$ and $\alpha = -10^\circ$ at the 62% spanwise location (figure 3-134).

3.7 Turbulence Intensity in The Boundary Layer

Figures 3-135 through figure 3-158 show the normalized turbulence intensity from single hot wire. Turbulence intensity data were taken simultaneously with the mean velocity profiles and separated by the HP Vee program automatically. Like mean velocity profiles, data for different angle of attack were plotted separately in two figures to make each case easy to identify. In these figures, u denotes $\sqrt{\overline{u'^2}}$, magnitude of fluctuating velocity in the same direction as mean velocity.

A most in evidence phenomenon in these figures is that for all spanwise locations, turbulence intensity has smallest value when the location angle of attack close to zero, and increase no matter the angle of attack increases or decreases from zero. The maximum turbulence intensity point moves to the boundary layer edge from the wall when angle of attack was increased. When blade has a large angle of attack, the flow becomes separated or stalled, and the turbulence intensity was amplified dramatically at both pressure side and suction side. Further more, Turbulence intensity tends to have similar maximum value at pressure side and suction side. This value can reach to as high as 0.25 in the stall region.

3.8 Turbulence Spectra

Figures 3-159 through 3-232 show the normalized spectral results from the single hot-wire measurements. In these figures:

$$f = \frac{f_0 \delta}{U_e} \tag{3-3}$$

$$Guu = \frac{Guu_0}{U_e \delta} \tag{3-4}$$

Where f_0 denote the frequency in Hertz, G_{uu0} denotes u'^2 per Hertz, they are directly obtained by the HP Vee program. The f and G_{uu} are normalized by boundary layer thickness and boundary layer edge velocity.

After eliminating the electronic interference that induced a high spike of on the spectral plots with a constant frequency of 450 Hz, spectra from different position in the boundary layer were plotted on the same figure. These locations were intended to be at y/δ = 0.1, 0.5, and 0.8. Measurement was done separately with profile measurement to save time. Approximate boundary layer thickness was used in the spectral measurements. Accurate boundary layer thickness was used to correct these locations afterward, therefore, some of the spectral were not measured right at those locations we planned. These actual locations were labeled on each figure. Spectral intensity decrease with the distance from the wall. A -5/3 slope region can be seen on the most of the spectral plot, indicating there are inertial regions present and therefore the flow is turbulent.

A spike of f = 3.0e-3 ~ 1.0e-2 can be seen on most cases. This frequency is in an approximate range of 70 ~ 90Hz. It happens at the pressure side when there is a large angle of attack and on the suction side when there is a large negative angle of attack. The boundary layer in these cases will be more likely to be laminar, but it is apparently too small to be the vortex shedding frequency. The Strouhal number for this frequency is:

$$St = \frac{f_0 c}{U_{ref}} \tag{3-8}$$

Where *c* is the local chord length. For a frequency of 80 Hz and a chord length of 3.6 inches and reference flow speed of 60 m/s, the $St = 0.146$, close to the vortex shedding Strouhal number from a cylinder, so this frequency spike should be the vortex shedding from the whole blade when the blade is at a large angle of attack.

3.9 Boundary Layer Thickness

The object of this project is to provide data for trailing edge noise prediction. The most important property of the flow in this respect is the boundary layer thickness at the trailing edge. (Brooks *et al.*, 1989). Mean velocity profiles (U/U_e vs. y/δ) and turbulence intensity profiles (u/U_e vs. y/δ) can both be used to get the thickness of the boundary layer. For Pitot probe data, the edge of the boundary layer was defined as the location where U/U_e was equal to 0.99. For single hot-wire data, the location where u/U_e equal to 1E-4 was used to be the edge of the boundary layer. When the flow in the boundary layer is stalled near stalled, the method using u/U_e equal to 1e-4 is not valid, so U/U_e equal to 0.99 was used in those cases. Use the u/U_e equal to 1e-4 method, the estimated accuracy of δ is within ± 5%. Use the U/U_e equal to 0.99 method, the estimated accuracy of the boundary layer thickness is within ± 6%. The error range for the integral thickness δ^* and θ is less (Brooks *et al.* 1986).

Boundary layer thickness at the trailing edge of JVX blade from Pitot probe measurements data are shown in table 3-11 and table 3-12. Boundary layer thickness at the trailing edge of JVX blade from single hot-wire measurements data are shown in table 3-13 and table 3-14.

3.9.1 Boundary Layer Thickness as a Function of Reynolds Number

Measurement data for different Reynolds numbers were taken using the flattened Pitot probe and static probe. A crude approximation for the relationship between turbulence boundary layer thickness and Reynolds number was given as (Schetz, 1993)

$$\frac{\delta(x)}{x}=\frac{0.375}{\mathrm{Re}_x^{0.2}} \tag{3-9}$$

Where x is the local chord length, $\delta(x)$ is the boundary layer thickness at x, Re_x is the Reynolds number based on x. At any location, boundary layer thickness will have a slight decrease with the increasing of flow speed. Figure 3-233 and figure 3-234 show the comparison between measurements and theory. Since the theory is coarse and only good for flat plate with 0 angle of attack. The magnitude of the boundary layer thickness from experiment does not agree with the theory at most angle of attack. At a negative angle of attack, however, the experiment data agree with the theory very well. This is easy to understand, for any real airfoil, the boundary layer thickness will have a larger value than flat plate on the suction side due to the pressure increase near the trailing edge. A negative angle of attack can decrease the boundary layer thickness and therefore shows a close value to the flat plate. Furthermore, if we look at the tendency the boundary layer thickness vary with Reynolds number, the experiment data have a good consistent with the theory. The actual relation should be $\delta \sim \mathrm{Re}^{-m}$ with m less than 0.2.

Figures 3-235 through 3-278 is shows the boundary layer thickness result from Pitot probe measurements. At each spanwise and angle of attack, boundary layer thickness was plotted against flow speed i.e. Reynolds number. Result from equation 3.8 was plotted on the graph to compare with the experiment data. The experiment has a very good agreement with the theory. The boundary layer thickness does not change much within such a small change in Reynolds number. Actually the change is hardly distinguished from the measurement error.

3.9.2 Boundary Layer Thickness as a Function of Angle of Attack

Figure 3-279 through figure 3-290 shows the boundary layer thickness versus angle of attack from single hot wire measurement. It is very clear that the boundary layer thickness on the pressure side decreases with the increasing of the angle of attack, while the boundary layer thickness on the suction side increases. When the flow becomes separated, the boundary layer thickness increases dramatically. When the flow stalled at high angles of attack, boundary layer thickness on the suction side becomes very large. In figure 3-277, the boundary layer thickness reaches a peak of 1.5 inches, compare to the chord of 3.65 inches, it is clear that the flow is stalled. By looking at the boundary layer thickness variation with angles of attack, Angles of attack that the flow appears to be separated is as table 3-16.

Figures 3-291 through 3-298 are the contours of boundary layer thickness and shape factor. The unit for the thickness is inches. It clear that the flow separates on suction side for large positive angle of attack and separates on the pressure side for large negative angle of attack. The boundary layer thickness varies with angles of attack and spanwise locations quite smoothly. Stall lines were labeled on the boundary layer thickness contours.

3.9.3 Fitting the Boundary Thickness to an algebraic expression

To fit the boundary layer thickness results into a trailing edge noise prediction code, the thickness variation with Reynolds number, angle of attack and spanwise location needs to be fitted to an algebraic expression. The results show the boundary layer thickness at trailing edge do not change much with Reynolds number and therfore an algebraic expression can not be obtained from the data. Therefore, the data were fitted into expression by the involving of angle of attack and spanwise location.

By comparing the various curve fit, Boltzman function was chosen to be the fit the data because it is simple and agreed with the experimental data very well. The Boltzman function can be written as follow:

$$y = \frac{A_1 - A_2}{1 + e^{\frac{x - x_0}{A_3}}} + A_2 \qquad (3\text{-}10)$$

Where x and y are the independent and dependent variables and A_1, A_2, x_0, A_3 are parameters. For our case, x denotes angle of attack and y denotes boundary layer thickness.

$$\delta = \frac{A_1 - A_2}{1 + e^{\frac{\alpha - x_0}{A_3}}} + A_2 \qquad (3\text{-}11)$$

Where δ can be δ, δ^* or θ, α denote angle of attack at the tip. The unit for thickness is inches, while unit for angle of attack is degrees.

Figures 3-299 through 2-334 shows the comparison between experimental data and curve fit. Parameters for the fitting function were listed in tables 3-16 through 3-21. Once a relationship between the local geometric angle of attack and the effective angle of attack was set up, these fitting curve can be used in the trailing edge noise prediction code.

Brooks *et al* (1989) obtain a series of correlation for the three thickness with Reynolds number in his report from the measurement data on NACA 0012 airfoil at 0 angle of attack. Here we did not correlate the thickness with Reynolds number because the Reynolds number variation is too small in out test and the relation between the thickness and Reynolds number cannot be obtained.

Spanwise locations	5%	15%	25%	38%	48%	62%
Angle of attack (degree)	1.3	3.8	6.4	9.7	12.8	21.2

Table 3-1 Twist angle vs. spanwise locations (Tip angle of attack is at zero)

Flow Speed (m/s)	20	40	50	60
Reynolds Number	119450	238900	298625	358350

Table 3-2 Reynolds number vs. Flow speed

		Angles of attack (degree)										
		-24	-20	-16	-12	-8	-4	0	4	8	12	16
Spanwise locations	5%	P	P	P	O	O	O	O	O	O	O	S
	15%	P	P	P	O	O	O	O	O	S	S	S
	25%	P	P	O	O	O	O	O	S	S	S	S
	38%	P	O	O	O	O	O	S	S	S	S	S
	48%	P	O	O	O	O	S	S	S	S	S	S
	62%	O	O	O	O	S	S	S	S	S	S	S

Table 3-3 tuft flow visualization result at 20m/s (P indicate flow stalled on the pressureside, S indicate the flow stalled on the suction side)

		Angles of attack (degree)										
		-24	-20	-16	-12	-8	-4	0	4	8	12	16
Spanwise locations	5%	P	P	P	O	O	O	O	O	O	S	S
	15%	P	P	P	O	O	O	O	O	S	S	S
	25%	P	P	O	O	O	O	O	S	S	S	S
	38%	P	O	O	O	O	O	S	S	S	S	S
	48%	P	O	O	O	O	S	S	S	S	S	S
	62%	O	O	O	O	S	S	S	S	S	S	S

Table 3-4 tuft flow visualization result at 30m/s (P indicate flow stalled on the pressureside, S indicate the flow stalled on the suction side)

		Angles of attack (degree)										
		-24	-20	-16	-12	-8	-4	0	4	8	12	16
Spanwise locations	5%	P	P	P	O	O	O	O	O	O	S	S
	15%	P	P	P	O	O	O	O	O	S	S	S
	25%	P	P	O	O	O	O	O	S	S	S	S
	38%	P	P	O	O	O	O	S	S	S	S	S
	48%	P	O	O	O	S	S	S	S	S	S	S
	62%	P	O	O	S	S	S	S	S	S	S	S

Table 3-5 tuft flow visualization result at 40m/s (P indicate flow stalled on the pressureside, S indicate the flow stalled on the suction side)

		Angles of attack (degree)										
		-24	-20	-16	-12	-8	-4	0	4	8	12	16
Spanwise locations	5%	P	P	P	P	O	O	O	O	O	S	S
	15%	P	P	P	O	O	O	O	O	S	S	S
	25%	P	P	O	O	O	O	O	S	S	S	S
	38%	P	P	O	O	O	O	S	S	S	S	S
	48%	P	O	O	O	S	S	S	S	S	S	S
	62%	O	O	O	O	S	S	S	S	S	S	S

Table 3-6 Tuft flow visualization result at 50m/s (P indicate flow stalled on the pressureside, S indicate the flow stalled on the suction side)

Spanwise Location	5%		15%	25%	38%	48%		62%
Angles of Attack (Degree)	0	12	-12	-20	0	0	-22	0
Traverse data point in y direction (inch)	0.435	0.261	2	2.9	0.5	0.7	2	0.63
	0.38	0.207	1.5	2.4	0.4	0.55	1.75	0.53
	0.314	0.163	1.2	2	0.33	0.43	1.6	0.43
	0.248	0.129	1	1.7	0.261	0.33	1.5	0.33
	0.196	0.102	0.85	1.5	0.207	0.261	1.47	0.261
	0.155	0.08	0.7	1.47	0.163	0.207	1.4	0.207
	0.122	0.063	0.6	1.4	0.129	0.163	1.33	0.163
	0.096	0.049	0.5	1.33	0.102	0.129	1.26	0.129
	0.076	0.033	0.45	1.26	0.08	0.102	1.19	0.102
	0.059	0.023	0.4	1.19	0.063	0.08	1.12	0.08
	0.046	0.015	0.35	1.12	0.049	0.063	1.05	0.063
	0.034	0.009	0.314	1.05	0.033	0.049	0.98	0.049
	0.022	0.005	0.248	0.98	0.02	0.033	0.91	0.033
	0.012	0.002	0.196	0.91	0.01	0.02	0.84	0.02
	0.004	0	0.155	0.84	0.003	0.01	0.75	0.01
	0	-0.004	0.122	0.77	0	0.003	0.63	0.003
	-0.003	-0.012	0.096	0.7	-0.005	0	0.49	0
	-0.01	-0.023	0.076	0.63	-0.012	-0.07	0.35	-0.1
	-0.02	-0.036	0.059	0.56	-0.023	-0.21	0.21	-0.2
	-0.033	-0.046	0.046	0.49	-0.038	-0.35	0.07	-0.4
	-0.049	-0.059	0.032	0.42	-0.056	-0.49	0	-0.6
	-0.063	-0.076	0.02	0.35	-0.072	-0.63	-0.003	-0.8
	-0.08	-0.096	0.001	0.28	-0.093	-0.7	-0.01	-1
	-0.102	-0.122	0.004	0.16	-0.118	-0.77	-0.02	-1.2
	-0.129	-0.155	0	0.07	-0.152	-0.84	-0.033	-1.4
	-0.163	-0.196	-0.004	0.05	-0.193	-0.91	-0.049	-1.5
	-0.207	-0.248	-0.01	0.03	-0.245	-0.98	-0.063	-1.6
	-0.261	-0.314	-0.02	0.01	-0.31	-1.05	-0.08	-1.7
	-0.33	-0.38	-0.032	0	-0.393	-1.12	-0.102	-1.8
	-0.4	-0.44	-0.046	-0.003	-0.497	-1.19	-0.129	-1.9
	-0.5	-0.52	-0.059	-0.01	-0.627	-1.26	-0.163	-2
	-0.65	-0.75	-0.076	-0.02	-0.8	-1.33	-0.207	-2.1
		-0.95	-0.096	-0.033	-1	-1.4	-0.261	-2.2
		-1	-0.122	-0.049	-2	-1.47	-0.32	-2.3
			-0.155	-0.063		-1.5	-0.4	-2.4
			-0.196	-0.08		-1.6	-0.5	-2.5
			-0.248	-0.102		-1.75	-0.6	-2.6
			-0.314	-0.129			-0.7	-2.7
			-0.38	-0.163			-0.8	-2.8
			-0.435	-0.207			-0.9	-3
			-0.5	-0.261			-1	-3.5
				-0.33			-1.1	-4.2
				-0.4			-1.3	-5
				-0.5			-1.8	
				-0.6			-2.5	

Table 3-7: Data point schemes for mean flow and turbulence intensity measurements (Positive value for pressure side and negative value for suction side)

		Angles of attack (degree)										
		-24	-20	-16	-12	-8	-4	0	4	8	12	16
Spanwise locations	5%				O	O		O		O		O
	15%				O	O		O		O	O	
	25%			O	O	O	O	O				
	38%		O	O	O		O	O				
	48%	O	O		O	O		O				
	62% *	O	O	O	O			O				

Table 3-8 Measurement matrix for Pitot probe (O indicate the mean boundary properties were taken at that spanwise location and angle of attack for all flow speed using flattened and static Pitot probe)
*** 60m/s data were not taken at this spanwise location**

		Spanwise locations					
		5%	15%	25%	38%	48%	62%
Angles of attack (degree)	-34						O
	-32						O
	-30						O
	-28						O
	-26						O
	-24					O	
	-22				O	O	O
	-20			O			
	-18			O	O	O	O
	-16	O	O	O	O	O	
	-14	O	O	O	O	O	O
	-12	O	O	O	O	O	O
	-10	O	O	O	O	O	O
	-8						O
	-6	O	O	O	O	O	O
	-4	O	O		O	O	
	-2	O	O	O	O		
	0	O	O	O	O	O	O
	2	O	O	O	O		
	4	O	O	O	O		
	6	O	O	O	O		
	8	O					
	10	O	O				
	12	O	O				
	14	O					
	16	O					
	18	O					
	20	O					

Table 3-9 Test matrix for mean velocity profile and turbulence intensity measurements for single hot-wire (O indicate measurements were done at that spanwise location and angle of attack)

		Spanwise locations					
		5%	15%	25%	38%	48%	62%
Angles of attack (degree)	-28						O
	-26						
	-24				O	O	O
	-22						
	-20			O			
	-18					O	O
	-16		O	O	O	O	
	-14						
	-12	O	O	O	O	O	O
	-10						
	-8						O
	-6	O	O	O	O	O	O
	-4	O	O		O	O	
	-2						
	0	O	O	O	O	O	O
	2						
	4	O	O	O	O		
	6		O	O	O		
	8	O					
	10						
	12	O	O				

Table 3-10 Test matrix for spectral measurements for single hot -wire (O indicate measurements were done at that spanwise location and angle of attack)

Spanwise location (percent of radius)	Angle of attack (degree)	Referent flow speed (m/s)	δ (inch)	δ^* (inch)	θ(inch)	H
5	-12	20	0.8890	0.2330	0.1320	1.7652
5	-12	40	0.8850	0.2025	0.1236	1.6380
5	-12	50	0.8750	0.2046	0.1254	1.6311
5	-12	60	0.8758	0.2062	0.1279	1.6128
5	-8	20	0.2990	0.0690	0.0460	1.5000
5	-8	40	0.2930	0.0640	0.0420	1.5238
5	-8	50	0.2927	0.0609	0.0404	1.5071
5	-8	60	0.2852	0.0608	0.0408	1.4896
5	0	20	0.1500	0.0328	0.0192	1.7083
5	0	40	0.1470	0.0298	0.0160	1.8667
5	0	50	0.1466	0.0269	0.0186	1.4452
5	0	60	0.1440	0.0237	0.0168	1.4145
5	8	20	0.1057	0.0243	0.0194	1.2526
5	8	40	0.1046	0.0210	0.0148	1.4189
5	8	50	0.1047	0.0198	0.0136	1.4559
5	8	60	0.1030	0.0190	0.0120	1.5832
15	-12	20	0.3860	0.0960	0.0570	1.6842
15	-12	40	0.3890	0.0931	0.0552	1.6851
15	-12	50	0.3820	0.0830	0.0493	1.6820
15	-12	60	0.3877	0.0830	0.0550	1.5095
15	-8	20	0.1990	0.0443	0.0293	1.5096
15	-8	40	0.1960	0.0420	0.0278	1.5093
15	-8	50	0.2007	0.0442	0.0287	1.5406
15	-8	60	0.1959	0.0388	0.0262	1.4851
15	0	20	0.1367	0.0240	0.0147	1.6365
15	0	40	0.1382	0.0233	0.0159	1.4620
15	0	50	0.1366	0.0220	0.0147	1.4946
15	0	60	0.1355	0.0242	0.0167	1.4503
25	-16	20	0.5450	0.1730	0.0910	1.9011
25	-16	50	0.5320	0.1659	0.0851	1.9485
25	-16	60	0.5219	0.1519	0.0830	1.8286
25	-12	20	0.2610	0.0720	0.0449	1.6024
25	-12	40	0.2718	0.0672	0.0406	1.6547
25	-12	50	0.2566	0.0652	0.0397	1.6414
25	-12	60	0.2581	0.0623	0.0383	1.6259
25	-8	20	0.2020	0.0788	0.0400	1.9700
25	-8	40	0.1950	0.0683	0.0263	2.5953
25	-8	50	0.1910	0.0696	0.0249	2.7955
25	-8	60	0.1870	0.0545	0.0261	2.0919
25	-4	20	0.1690	0.0648	0.0310	2.0903
25	-4	40	0.1720	0.0648	0.0300	2.1600
25	-4	50	0.1677	0.0628	0.0291	2.1561
25	-4	60	0.1665	0.0540	0.0222	2.4359
25	0	20	0.1320	0.0390	0.0178	2.1910
25	0	40	0.1320	0.0383	0.0165	2.3212
25	0	50	0.1310	0.0362	0.0169	2.1369
25	0	60	0.1274	0.0344	0.0151	2.2728

Table 3-11 Boundary layer thickness from Pitot probe at pressure side

38	-20	20	0.3950	0.1653	0.0701	2.3586
38	-20	40	0.4024	0.1687	0.0634	2.6616
38	-20	50	0.3969	0.1634	0.0629	2.5993
38	-20	60	0.4073	0.1511	0.0641	2.3562
38	-16	20	0.2860	0.0830	0.0510	1.6275
38	-16	40	0.2850	0.0708	0.0416	1.7042
38	-16	50	0.2850	0.0684	0.0403	1.6959
38	-16	60	0.2818	0.0712	0.0424	1.6791
38	-12	20	0.2060	0.0478	0.0308	1.5525
38	-12	40	0.2041	0.0489	0.0313	1.5624
38	-12	50	0.2043	0.0486	0.0310	1.5660
38	-12	60	0.2064	0.0472	0.0306	1.5425
38	-4	20	0.1778	0.0525	0.0350	1.5000
38	-4	40	0.1771	0.0485	0.0276	1.7572
38	-4	50	0.1739	0.0480	0.0269	1.7844
38	-4	60	0.1691	0.0465	0.0235	1.9811
48	-24	20	0.4880	0.2250	0.0508	4.4310
48	-20	20	0.3960	0.1370	0.0463	2.9614
48	-20	40	0.3920	0.1290	0.0463	2.7870
48	-20	50	0.3870	0.1280	0.0452	2.8294
48	-20	60	0.3801	0.1251	0.0457	2.7357
48	-12	20	0.2030	0.0620	0.0450	1.3778
48	-12	40	0.2060	0.0615	0.0440	1.3977
48	-12	50	0.2068	0.0600	0.0424	1.4151
48	-12	60	0.2033	0.0576	0.0405	1.4209
48	-8	20	0.1695	0.0400	0.0240	1.6667
48	-8	40	0.1686	0.0330	0.0205	1.6131
48	-8	50	0.1629	0.0279	0.0192	1.4501
48	-8	60	0.1665	0.0310	0.0214	1.4502
62	-24	20	0.3000	0.0763	0.0464	1.6452
62	-24	30	0.3052	0.0772	0.0470	1.6418
62	-24	40	0.3039	0.0762	0.0466	1.6345
62	-24	50	0.2991	0.0762	0.0464	1.6434
62	-20	20	0.2360	0.0534	0.0339	1.5762
62	-20	30	0.2368	0.0532	0.0332	1.6031
62	-20	40	0.2380	0.0508	0.0327	1.5547
62	-20	50	0.2280	0.0524	0.0333	1.5728
62	-16	20	0.1970	0.0489	0.0247	1.9839
62	-16	30	0.1950	0.0462	0.0247	1.8709
62	-16	40	0.1975	0.0450	0.0247	1.8246
62	-16	50	0.1944	0.0475	0.0255	1.8631

Table 3-11 Boundary layer thickness from Pitot probe at pressure side (cont.)

Spanwise location (percent of radius)	Angle of attack (degree)	Referent flow speed (m/s)	δ (inch)	δ^* (inch)	θ(inch)	H
5	-12	20	0.1253	0.0280	0.0183	1.5301
5	-12	40	0.1262	0.0239	0.0156	1.5307
5	-12	50	0.1197	0.0217	0.0144	1.5118
5	-12	60	0.1215	0.0252	0.0159	1.5863
5	-8	20	0.1395	0.0370	0.0237	1.5612
5	-8	40	0.1388	0.0309	0.0204	1.5147
5	-8	50	0.1360	0.0273	0.0184	1.4810
5	-8	60	0.1371	0.0268	0.0179	1.4970
5	0	20	0.2100	0.0480	0.0310	1.5484
5	0	40	0.2010	0.0454	0.0301	1.5104
5	0	50	0.2057	0.0392	0.0272	1.4411
5	0	60	0.2022	0.0397	0.0276	1.4417
5	8	20	0.3400	0.0970	0.0530	1.8302
5	8	40	0.3410	0.0960	0.0461	2.0831
5	8	50	0.3388	0.0891	0.0494	1.8030
5	8	60	0.3319	0.0913	0.0509	1.7947
15	-12	20	0.1520	0.0340	0.0229	1.4847
15	-12	40	0.1519	0.0317	0.0202	1.5701
15	-12	50	0.1528	0.0312	0.0204	1.5269
15	-12	60	0.1507	0.0276	0.0178	1.5496
15	-8	20	0.1890	0.0434	0.0306	1.4183
15	-8	40	0.1856	0.0362	0.0243	1.4882
15	-8	50	0.1745	0.0341	0.0230	1.4792
15	-8	60	0.1841	0.0354	0.0240	1.4773
15	0	20	0.2580	0.0790	0.0480	1.6458
15	0	40	0.2550	0.0670	0.0400	1.6725
15	0	50	0.2508	0.0645	0.0396	1.6298
15	0	60	0.2488	0.0575	0.0359	1.6015
25	-16	20	0.1400	0.0338	0.0210	1.6095
25	-16	50	0.1371	0.0306	0.0183	1.6707
25	-16	60	0.1358	0.0330	0.0194	1.7017
25	-12	20	0.1766	0.0388	0.0242	1.6039
25	-12	40	0.1769	0.0383	0.0242	1.5815
25	-12	50	0.1717	0.0375	0.0238	1.5715
25	-12	60	0.1689	0.0358	0.0232	1.5396
25	-8	20	0.2100	0.0646	0.0298	2.1714
25	-8	40	0.2080	0.0683	0.0299	2.2805
25	-8	50	0.2080	0.0648	0.0309	2.0943
25	-8	60	0.1970	0.0609	0.0293	2.0804
25	-4	20	0.2700	0.1040	0.0580	1.7931
25	-4	40	0.2660	0.1040	0.0530	1.9623
25	-4	50	0.2600	0.0930	0.0529	1.7581
25	-4	60	0.2601	0.0830	0.0346	2.4014
25	0	20	0.3290	0.1370	0.0660	2.0758
25	0	40	0.3300	0.1300	0.0560	2.3214
25	0	50	0.3320	0.1290	0.0503	2.5653
25	0	60	0.3165	0.1185	0.0454	2.6121

Table 3-12 Boundary layer thickness from Pitot probe at suction side

38	-20	20	0.1645	0.0395	0.0188	2.1063
38	-20	40	0.1657	0.0453	0.0180	2.5164
38	-20	50	0.1627	0.0470	0.0186	2.5260
38	-20	60	0.1634	0.0428	0.0212	2.0236
38	-16	20	0.1950	0.0456	0.0244	1.8667
38	-16	40	0.1945	0.0413	0.0266	1.5517
38	-16	50	0.1997	0.0426	0.0271	1.5753
38	-16	60	0.1929	0.0404	0.0256	1.5745
38	-12	20	0.2340	0.0567	0.0344	1.6461
38	-12	40	0.2286	0.0549	0.0340	1.6136
38	-12	50	0.2302	0.0545	0.0341	1.5965
38	-12	60	0.2310	0.0522	0.0337	1.5516
38	-4	20	0.3750	0.1530	0.0760	2.0132
38	-4	40	0.3760	0.1228	0.0570	2.1525
38	-4	50	0.3676	0.1235	0.0576	2.1461
38	-4	60	0.3710	0.1046	0.0534	1.9569
48	-24	20	0.1641	0.0440	0.0227	1.9353
48	-20	20	0.1899	0.0396	0.0256	1.5460
48	-20	40	0.1997	0.0396	0.0262	1.5089
48	-20	50	0.2015	0.0387	0.0260	1.4879
48	-20	60	0.1990	0.0427	0.0278	1.5382
48	-12	20	0.2800	0.0690	0.0433	1.5933
48	-12	40	0.2803	0.0695	0.0423	1.6417
48	-12	50	0.2803	0.0682	0.0415	1.6414
48	-12	60	0.2702	0.0634	0.0401	1.5823
48	-8	20	0.3360	0.1040	0.0600	1.7333
48	-8	40	0.3370	0.1070	0.0542	1.9736
48	-8	50	0.3400	0.0970	0.0570	1.7012
48	-8	60	0.3334	0.0873	0.0526	1.6603
62	-24	20	0.2280	0.0654	0.0362	1.8065
62	-24	30	0.2277	0.0615	0.0358	1.7185
62	-24	40	0.2264	0.0562	0.0336	1.6727
62	-24	50	0.2203	0.0545	0.0332	1.6403
62	-20	20	0.2800	0.0974	0.0480	2.0287
62	-20	30	0.2780	0.0913	0.0470	1.9433
62	-20	40	0.2760	0.0858	0.0453	1.8934
62	-20	50	0.2803	0.0785	0.0433	1.8131
62	-16	20	0.3679	0.1493	0.0559	2.6728
62	-16	30	0.3657	0.1381	0.0558	2.4767
62	-16	40	0.3714	0.1368	0.0563	2.4283
62	-16	50	0.3608	0.1292	0.0556	2.3219

Table 3-12 Boundary layer thickness prom Pitot probe at suction side (cont.)

Spanwise location (percent of radius)	Angle of attack (degree)	δ (inch)	δ* (inch)	θ(inch)	H
5	-16	1.5510	0.5489	0.2522	2.1764
5	-14	1.2520	0.3129	0.1765	1.7733
5	-12	1.0450	0.2124	0.1278	1.6617
5	-10	0.7670	0.1276	0.0764	1.6696
5	-6	0.2423	0.0545	0.0324	1.6834
5	-4	0.1959	0.0414	0.0253	1.6369
5	-2	0.1603	0.0344	0.0212	1.6212
5	0	0.1494	0.0303	0.0182	1.6664
5	2	0.1460	0.0284	0.0162	1.7569
5	4	0.1307	0.0260	0.0149	1.7443
5	6	0.1189	0.0230	0.0136	1.6956
5	8	0.1187	0.0240	0.0130	1.8414
5	10	0.1024	0.0216	0.0106	2.0339
5	12	0.0998	0.0241	0.0110	2.1823
5	14	0.1006	0.0224	0.0114	1.9629
5	16	0.0950	0.0186	0.0096	1.9408
5	18	0.0900	0.0219	0.0099	2.2163
5	20	0.0820	0.0220	0.0081	2.7192
15	-16	1.5100	0.5439	0.2193	2.4798
15	-14	0.7600	0.2349	0.1088	2.1594
15	-12	0.4100	0.0986	0.0575	1.7158
15	-10	0.3111	0.0760	0.0419	1.8132
15	-6	0.1996	0.0435	0.0251	1.7350
15	-4	0.1794	0.0387	0.0226	1.7132
15	-2	0.1574	0.0336	0.0191	1.7633
15	0	0.1410	0.0283	0.0162	1.7472
15	2	0.1263	0.0246	0.0137	1.7988
15	4	0.1169	0.0210	0.0115	1.8222
15	6	0.0920	0.0193	0.0096	2.0063
15	10	0.0870	0.0261	0.0093	2.8074
15	12	0.0850	0.0219	0.0096	2.2728
25	-18	0.9509	0.2898	0.1303	2.2251
25	-16	0.7625	0.1689	0.0850	1.9863
25	-14	0.4625	0.1200	0.0704	1.7046
25	-12	0.3108	0.0825	0.0441	1.8688
25	-10	0.2525	0.0591	0.0336	1.7595
25	-6	0.1857	0.0361	0.0220	1.6466
25	-2	0.1531	0.0312	0.0165	1.8924
25	0	0.1497	0.0294	0.0145	2.0270
25	2	0.1176	0.0259	0.0117	2.2211
25	4	0.1162	0.0236	0.0101	2.3337
25	6	0.1644	0.0195	0.0078	2.5124

Table 3-13 Boundary layer thickness from hot wire at pressure side

38	-22	0.9500	0.3580	0.1226	2.9207
38	-18	0.4554	0.1314	0.0601	2.1851
38	-16	0.3406	0.0951	0.0477	1.9924
38	-14	0.2997	0.0743	0.0404	1.8415
38	-12	0.2725	0.0608	0.0351	1.7322
38	-10	0.2422	0.0554	0.0309	1.7937
38	-6	0.2023	0.0383	0.0219	1.7442
38	-4	0.1573	0.0315	0.0173	1.8151
38	-2	0.1508	0.0258	0.0139	1.8644
38	0	0.1400	0.0304	0.0133	2.2857
38	2	0.1300	0.0239	0.0107	2.2231
38	4	0.1300	0.0178	0.0044	4.0824
38	6	0.1300	0.0147	0.0034	4.3066
48	-24	0.6751	0.2085	0.0697	2.9932
48	-22	0.5500	0.1713	0.0639	2.6794
48	-18	0.4012	0.0894	0.0467	1.9137
48	-16	0.3116	0.0764	0.0410	1.8639
48	-14	0.2770	0.0598	0.0342	1.7474
48	-12	0.2480	0.0549	0.0309	1.7786
48	-10	0.2050	0.0431	0.0252	1.7087
48	-6	0.2050	0.0315	0.0168	1.8788
48	-4	0.1747	0.0324	0.0146	2.2145
48	0	0.1150	0.0262	0.0104	2.5086
62	-34	1.0600	0.3630	0.1568	2.3147
62	-32	0.8468	0.2528	0.0892	2.8332
62	-30	0.5947	0.2063	0.0709	2.9098
62	-28	0.5020	0.1689	0.0639	2.6411
62	-27	0.4400	0.1440	0.0587	2.4555
62	-26	0.3810	0.1215	0.0522	2.3298
62	-24	0.3160	0.0817	0.0415	1.9685
62	-22	0.2517	0.0540	0.0289	1.8683
62	-18	0.2219	0.0537	0.0209	2.5676
62	-14	0.1800	0.0409	0.0163	2.5130
62	-12	0.1750	0.0341	0.0148	2.3066
62	-10	0.1600	0.0414	0.0136	3.0349
62	-8	0.1650	0.0315	0.0119	2.6508
62	-6	0.1500	0.0166	0.0147	1.1301
62	0	0.1450	0.0312	0.0166	1.8779

Table 3-13 Boundary layer thickness from hot wire at pressure side (cont.)

Spanwise location (percent of radius from the tip	Angle of attack (degree)	δ (inch)	δ^* (inch)	θ(inch)	H
5	-16	0.1100	0.0180	0.0116	1.5542
5	-14	0.1560	0.0211	0.0132	1.6006
5	-12	0.1630	0.0297	0.0175	1.6976
5	-10	0.1710	0.0357	0.0217	1.6409
5	-6	0.1778	0.0379	0.0223	1.6983
5	-4	0.2001	0.0429	0.0252	1.7045
5	-2	0.2257	0.0545	0.0296	1.8381
5	0	0.2498	0.0637	0.0329	1.9400
5	2	0.2584	0.0680	0.0350	1.9437
5	4	0.2820	0.0710	0.0372	1.9113
5	6	0.3264	0.0864	0.0441	1.9582
5	8	0.3718	0.1003	0.0498	2.0134
5	10	0.4022	0.1181	0.0529	2.2330
5	12	0.4193	0.1197	0.0546	2.1920
5	14	0.6544	0.1096	0.0599	1.8311
5	16	0.9500	0.1846	0.1102	1.6745
5	18	1.2000	0.2680	0.1765	1.5182
5	20	1.4000	0.3705	0.2023	1.8311
15	-16	0.1350	0.0276	0.0162	1.6964
15	-14	0.1550	0.0352	0.0192	1.8341
15	-12	0.1900	0.0406	0.0231	1.7599
15	-10	0.1859	0.0424	0.0247	1.7162
15	-6	0.2321	0.0542	0.0293	1.8516
15	-4	0.2402	0.0577	0.0312	1.8484
15	-2	0.2825	0.0763	0.0366	2.0834
15	0	0.3098	0.0848	0.0421	2.0134
15	2	0.3713	0.1030	0.0473	2.1773
15	4	0.4032	0.1257	0.0535	2.3482
15	6	0.5100	0.1705	0.0650	2.6222
15	10	0.8500	0.3488	0.1461	2.3873
15	12	1.6500	0.6386	0.2435	2.6228
25	-18	0.1480	0.0286	0.0147	1.9506
25	-16	0.1609	0.0384	0.0192	1.9983
25	-14	0.1768	0.0375	0.0204	1.8362
25	-12	0.1968	0.0450	0.0246	1.8313
25	-10	0.2274	0.0555	0.0298	1.8662
25	-6	0.2619	0.0708	0.0370	1.9135
25	-2	0.3445	0.1050	0.0467	2.2505
25	0	0.3931	0.1295	0.0540	2.3959
25	2	0.5022	0.1771	0.0642	2.7607
25	4	0.6048	0.2128	0.0720	2.9562
25	6	0.8537	0.2744	0.0875	3.1353

Table 3-14 Boundary layer thickness from hot wire at suction side

38	-22	0.1700	0.0357	0.0213	1.6795
38	-18	0.2398	0.0421	0.0231	1.8231
38	-16	0.2466	0.0463	0.0266	1.7402
38	-14	0.2406	0.0523	0.0304	1.7235
38	-12	0.2817	0.0655	0.0355	1.8464
38	-10	0.3058	0.0807	0.0417	1.9349
38	-6	0.3930	0.1157	0.0525	2.2042
38	-4	0.4934	0.1444	0.0610	2.3685
38	-2	0.5395	0.1828	0.0696	2.6286
38	0	0.5500	0.2381	0.0811	2.9361
38	2	0.8900	0.3246	0.1137	2.8556
38	4	2.0473	0.4992	0.1708	2.9233
38	6	2.9743	0.7804	0.2982	2.6170
48	-24	0.2409	0.0562	0.0221	2.5489
48	-22	0.2415	0.0478	0.0235	2.0367
48	-18	0.2583	0.0600	0.0314	1.9135
48	-16	0.2574	0.0642	0.0340	1.8914
48	-14	0.3123	0.0789	0.0401	1.9685
48	-12	0.3250	0.0872	0.0423	2.0638
48	-10	0.3400	0.1064	0.0492	2.1620
48	-6	0.4956	0.1650	0.0624	2.6427
48	-4	0.5810	0.1918	0.0680	2.8184
48	0	0.7300	0.3173	0.0915	3.4690
62	-34	0.1350	0.0544	0.0196	2.7770
62	-32	0.1700	0.0568	0.0214	2.6525
62	-30	0.1949	0.0596	0.0247	2.4141
62	-28	0.2073	0.0738	0.0285	2.5902
62	-27	0.2475	0.0862	0.0318	2.7114
62	-26	0.2316	0.0732	0.0337	2.1751
62	-24	0.2961	0.0935	0.0386	2.4253
62	-22	0.3594	0.1307	0.0473	2.7627
62	-18	0.4546	0.1748	0.0583	2.9958
62	-14	0.5000	0.1932	0.0572	3.3795
62	-12	0.5500	0.2066	0.0595	3.4759
62	-10	0.7600	0.2730	0.0981	2.7838
62	-8	0.8450	0.5194	0.1808	2.8725
62	-6	1.3500	0.6799	0.2275	2.9882
62	0	2.3000	1.2801	0.5975	2.1424

Table 3-14 Boundary layer thickness from hot wire at suction side (cont.)

Spanwise locations	Stall angle of attack (degree)			
	Flow visualization results (50m/s)		Hot wire measurements results (60m/s)	
	Pressure side	Suction side	Pressure side	Suction side
5%	-12	12	-10	12
15%	-16	8	-14	10
25%	-20	4	-16	6
38%	-20	0	-18	2
48%	-24	-8	-22	-4
62%	-30	-8	-32	-8

Table 3-15 Comparison for the stall angle obtained by two methods

	A_1	A_2	x_0	A_3
5%	5.774	0.0862	-33.2737	7.5268
15%	13.3271	0.0827	-35.8196	6.4433
25%	17.2757	0.1186	-30.846	4.2994
38%	6.8771	0.1112	-40.892	7.6824
48%	9.5454	0.0868	-47.3998	8.6049
62%	10.9598	0.1523	-45.7621	5.2047

Table 3-16 Fitting parameters for boundary layer thickness on pressure side

	A_1	A_2	x_0	A_3
5%	0.4148	0.0221	-16.3737	4.2469
15%	5.4795	0.0157	-37.2361	6.0442
25%	2.2222	0.0232	-26.4154	4.0268
38%	4.5344	0.0146	-43.4002	6.9264
48%	0.5236	0.027	-26.513	4.7337
62%	3.9865	0.0302	-41.8238	4.199

Table 3-17 Fitting parameters for displacement thickness on pressure side

	A_1	A_2	x_0	A_3
5%	4.8872	0.0087	-45.0166	7.2791
15%	1.6191	0.0084	-33.0075	6.0368
25%	0.9244	0.0105	-25.3184	4.1933
38%	1.0858	-0.0075	-56.2749	13.8822
48%	0.1396	0.0021	-24.1271	8.7498
62%	0.1217	0.0119	-28.3253	4.1325

Table 3-18 Fitting parameters for momentum thickness on pressure side

	A_1	A_2	x_0	A_3
5%	0.1397	0.576	7.783	6.4534
15%	0.1109	6.8453	31.6732	9.1662
25%	0.0992	5.0959	27.8331	10.0976
38%	0.1767	0.7651	-3.4805	5.2626
48%	0.2303	1.4884	0.7525	5.0321
62%	-0.0172	17.9432	37.206	15.0895

Table 3-19 Fitting parameters for boundary layer thickness on suction side

	A_1	A_2	x_0	A_3
5%	0.0007	0.5628	28.7544	13.4113
15%	0.0281	4.219	28.495	6.6601
25%	0.0276	4.885	23.8961	6.3035
38%	0.0307	38.8408	33.0747	6.3561
48%	0.0425	0.344	-3.996	4.7566
62%	0.0098	2.8371	18.6717	12.3513

Table 3-20 Fitting parameters for displacement thickness on suction side

	A_1	A_2	x_0	A_3
5%	0.0024	0.1	9.6831	11.8045
15%	0.0117	0.7487	32.5198	10.2895
25%	-0.0006	0.6638	33.6073	14.0466
38%	0.0198	0.8412	16.9978	7.057
48%	0.0086	0.1586	0.266	10.3702
62%	-0.0021	2.7319	42.7652	15.8833

Table 3-21 Fitting parameters for momentum thickness on suction side

Chapter 4. Conclusion

Boundary layer characteristics at the trailing edge of the tiltrotor blade model were measured with the variation of Reynolds number and angle of attack. The blade was mounted in Virginia Tech Stability Wind Tunnel stationary, with the angle of attack at the tip to be the reference angle of attack. A flattened pitot probe and a single hot wire were used to document the boundary layer at a position 1 mm behind the trailing edge. Comparisons were made between the Pitot probe data and single hot wire data; also trip influence was investigated by comparing the data with and without tripping the blade. A cross section 3 inches behind the trailing edge was measured by single hot wire to document the wake and tip vortex structure.

- Hot wire probe has better spatial resolution than flattened pitot probe, both methods are good for boundary layer thickness measurement.
- Boundary layer mean velocity profiles have a weak relation to Reynolds number variation, small change in Reynolds number does not influence mean velocity profiles.
- At suction side, the mean velocity profiles change from full to less full when angle of attack increases. This tendency makes the flow separate at high angle of attack.
- At suction side, the turbulence intensity in boundary layer increases with angle of attack, and the maximum value point move to boundary layer edge from the wall at the same time. When the flow stalled, turbulence intensity was amplified dramatically at both pressure side and suction side. Also the turbulence intensity tends to have similar maximum value at pressure side and suction side.
- A frequency of 70 ~ 90Hz occurs in the spectra results on one side of the blade when flow separate on the other side. It might be the vortex shedding frequency from the whole blade according to the Strouhal number.
- Boundary layer thickness has a weak relation to Reynolds number, the actual relation should be $\delta \sim \mathrm{Re}^{-m}$ with m less than 0.2.
- Boundary layer thickness on the pressure side decreases with the increasing of the angle of attack, while the boundary layer thickness on the suction side increases. The boundary layer thickness increases dramatically when the flow stalled.

- Displacement thickness can be correlated with tip angle of attack using a Boltzman function.

The present research reveals the structure of the turbulent boundary layer at the trailing edge of the tiltrotor blade. The object of this project is to provide experiment data for using in trailing edge noise prediction code. The experiment data obtained provides the relationship between the boundary layer displacement thickness and the tip angle of attack. In combination with a method, such as lifting line theory, the relationship between the tip angle of attack and the local effective angle of attack can be obtained and therefore the results can be used in the trailing edge noise prediction code.

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