**Hot-Film Measurements of the Steady
and Unsteady Boundary Layer Development
on a Low-Pressure Turbine Airfoil**

By

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M.Eng. (Aerospace Engineering)

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of

Master of Applied Science
in Mechanical Engineering

Department of Mechanical and Aerospace Engineering

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Submitted by Xue Feng Zhang, M.Eng.

in partial fulfillment of the requirements for the degree of
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April 2002

Abstract

The adverse pressure gradients on the suction side of the low pressure (LP) turbine blades increase the possibility of boundary layer separation, particularly under low Reynolds number conditions. Separation bubbles can cause a significant blade loss. Therefore, accurate prediction of boundary layer developments on the blade surface in low Reynolds number conditions is crucial to the improvement of LP turbine design. Recently, the unsteady rotor-stator interaction has received attention. The wakes coming from the previous blade row will impact the boundary layer development on the blade surface.

Boundary layer developments on the suction surface of a linear cascade of LP turbine blades, a set of so-called PAK-B profile blades designed by Pratt & Whitney US, under steady and unsteady conditions at low Reynolds number were investigated by means of surface-mounted hot-films. To achieve a simulation of rotor-stator interactions, a spoked-wheel type wake generator was designed. The Reynolds number based on the cascade inlet velocity and blade axial chord varies from 25000 to 100000 and the free stream turbulence intensity changes between 0.4% and 4.5%. The hot-film data are analyzed in both the time domain and frequency domain. The relationship between the hot-film data and the boundary layer behaviour forms the focus of the present study.

Surface-mounted hot-films can provide information about boundary layer separation, reattachment and transition, even in the case that the hot-film sensors are covered by the separation bubble. Thanks to the fast response of the hot-film sensors, this technique is also suitable for unsteady flow measurement. Under steady flow conditions, boundary layer separation was observed in all examined conditions. At unsteady flow conditions, boundary layer developments are dominated by the incoming wakes.

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Nomenclature

English Symbols

A	=	constant
AVR	=	axial velocity ratio, Equation 4.14
B	=	chord length, constant
C	=	coefficient
$C_{p,l}$	=	blade surface static pressure or blade loading coefficient, Equation 3.19
d	=	bar diameter, three-hole probe diameter
E	=	anemometer output voltage
f	=	frequency
$\bar{f}$	=	reduced frequency, Equation 3.10 and Equation 3.13
FS	=	full scale
FSTI	=	free stream turbulence intensity
h	=	blade span
k	=	constant
K	=	coefficient
l	=	length
LE	=	blade leading edge
m	=	mass
n	=	number
N	=	rotation speed, cycle number

OHR	=	overheat ratio, Equation 3.21
p	=	pressure
P	=	power spectrum
PSD	=	power spectral density
q	=	dynamic pressure
r	=	radius
R	=	resistance
Re	=	Reynolds number, Equation 4.1
RMS	=	root mean square, Equation 4.3 and Equation 4.6
S	=	blade pitch, spacing
t	=	time
T	=	temperature, data length, wake passing period
TE	=	blade trailing edge
Tu	=	turbulence intensity measured in axial direction
u,v, w	=	velocity component in the axial, pitchwise and spanwise directions
U	=	rotating speed
V	=	free stream velocity
WC	=	water column
x, y, z	=	co-ordinates in the axial, pitchwise and spanwise directions
Y	=	total pressure loss coefficient, Equation 5.2

Greek Symbols

α	=	flow angle
β	=	blade metal angle, relative flow angle
γ	=	intermittency factor, blade stagger angle
δ	=	displacement thickness
θ	=	momentum thickness
μ	=	molecular viscosity
ρ	=	density
σ	=	standard deviation
τ	=	quasi-wall-shear stress, Equation 3.25
Φ	=	flow coefficient, Equation 3.8
χ	=	temperature coefficient of resistance
ω	=	angular velocity

Subscripts

0	=	total or stagnation parameter
1	=	inlet measuring plane
2	=	outlet measuring plane
a	=	ambient condition
ax	=	axial direction
b	=	bubble
c	=	contraction section, calibration condition

d	=	drag
in	=	cascade inlet
l	=	loading
m	=	measured
MD	=	maximum displacement
MS	=	mid-span
op	=	operating condition
p	=	pressure
q	=	dynamic pressure
ref	=	reference
R	=	reattachment point
s	=	static pressure
S	=	separation point
t	=	onset of transition
T	=	onset of turbulent or end of transition
w	=	near wall parameter
∞	=	free stream

Superscripts

-	=	time average, Equation 4.2
$\sim$	=	ensemble average, Equation 4.5
$\wedge$	=	mass average, Equation 4.4

Chapter 1

Introduction

The increasing demand for larger thrust and lower weight of aircraft engines has led to the development of highly loaded low-pressure (LP) turbine blades. To achieve the higher blade loading, inevitably blades are subjected to stronger pressure gradients. The adverse pressure gradients on the suction side of these blades increase the possibility of boundary layer separation, particularly under low Reynolds number conditions. Separation bubbles, especially those that fail to reattach, can cause a significant loss in lift, and, consequently, a significant degradation in engine efficiency (Mayle, 1991). A component efficiency drop of the order of 2 percent may occur between takeoff and cruise conditions, due to the lower Reynolds number at high altitude for large commercial transport engines (Volino and Hultgren, 2001).

LP turbine blades are typically of high aspect ratio (e.g., 5:1) and small chord length (Howell *et al*, 2001). As a result, the flow is dominantly two-dimensional and relatively little surface is

covered by secondary flow. Hence, profile losses in the boundary layer are the main loss-generating mechanism. Profile losses include the losses generated in the boundary layers on the blade surface and at the trailing edge. A well-behaved blade pressure side flow contributes little to the total pressure loss (Curtis *et al*, 1997). The magnitude of profile losses strongly depend upon the development of the boundary layer on the blade suction surface. Therefore, accurate prediction of flow separation, reattachment and transition on the suction surface in low Reynolds number conditions is crucial to improving LP turbine design.

The traditional design of turbine airfoils is based on the assumption that the rotor and stator rows are spaced far enough apart such that the flow in each is steady, *i.e.*, that there is no unsteadiness of any sort due to rotor-stator aerodynamic interaction. However, the rows of modern turbines are already very closely spaced. Axial gaps between adjacent rows of approximately $\frac{1}{4}$ to $\frac{1}{2}$ of the blade chord length are common practice (Dring *et al*, 1982). It is clear, therefore, that when rows are closely spaced there can be a strong unsteady interaction, which will impact the aerodynamic, thermal and structural performance of the airfoils. Future designs with higher loading and lower aspect ratios as well as the ever present desire to minimize engine length, will aggravate this condition even further (Dring *et al*, 1982).

The unsteadiness due to the relative motion of the rows of blades will affect the transition processes on the blade surface. Previous researches, such as Addison and Hodson (1990a) have shown that patches of transitional/turbulent flow can be created during the interaction of the upstream wakes with laminar boundary layer. These patches will reduce the blade efficiency.

Fortunately, the so-called calmed region, where the flow relaxes back to the laminar state, following the transitional/turbulent flow can withstand the adverse pressure gradient much better than steady laminar boundary layers. Consequently, attached laminar-like flow can be made to persist downstream of the steady flow laminar separation location, possibly as far back as the blade trailing edge. Most important, the calmed region after the transitional/turbulent flow represents an increase in efficiency as it is essentially laminar in nature and it is attached. Thus, there are two opposing loss-influencing mechanisms at work in the interactions between wakes and the boundary layers. The balance between these two mechanisms is strongly dependent on the free stream conditions and the wake-passing frequency.

The objective of the present project is to investigate the boundary layer behavior on a modern low pressure (LP) turbine blade suction surface and its effect on the blade performance under steady and unsteady conditions. The current work, as the first part of this large project, focuses on the boundary layer development on the blade suction surface under steady and unsteady conditions at low Reynolds number by means of surface-mounted hot-films. The experiment is conducted on a low-speed linear cascade, which is a set of Pratt & Whitney PAK-B LP turbine profile blades. The Reynolds numbers, based on the cascade inlet flow velocity and the blade axial chord, vary between 25000 and 100000. To achieve a simulation of rotor-stator interactions, a spoked-wheel type wake generator was designed. The boundary layer development on the blade suction surface under steady conditions was first investigated, with emphasis on the boundary layer separation, transition and reattachment at low Reynolds numbers. The understanding of the

relationship between the hot-film measurement data and boundary layer behaviours obtained in this condition was then used to interpret the hot-film measurement data under unsteady conditions.

A review of pertinent literature of boundary layer separation and transition on the blade surface and the wake-boundary layer interaction as well as their effects on blade performance is presented in Chapter 2. A summary of the previous studies on the Pratt & Whitney PAK-B LP turbine blades is also discussed in this chapter. Chapter 3 describes in detail the experimental facility setup and measurement techniques used in this study. Data reduction procedures and the preliminary flow quality are presented in Chapter 4. Chapter 5 presents and discusses the experimental results from the surface-mounted hot-film measurements under steady flow conditions, which forms the baseline of future unsteady study. The results for the wake-boundary layer interaction are discussed in Chapter 6. Lastly, conclusions and recommendations for future work are presented in Chapter 7.

Chapter 2

Literature Review

2.1 Introduction

The purpose of this chapter is to review previous research on boundary layer development over airfoil surfaces. The chapter begins with a description of boundary layer separation and transition with a focus on separated flow transition, which is the main topic of the current steady flow study. Following this, a discussion of wake-boundary layer interaction is presented. Unsteady flow in gas turbines caused by wakes from upstream blades have recently received much attention, such as Hodson and Howell (2000) and Solomon and Walker (1995). In this section, the current understanding of the mechanisms of wake-boundary layer interaction and how it affects blade performance is reviewed. The chapter ends with a review of the previous studies on the Pratt & Whitney PAK-B low-pressure (LP) turbine blade, which is the blade profile studied in this project.

2.2 Boundary Layer Separation and Transition

2.2.1 Boundary Layer Separation

Under certain conditions, for example, in strong adverse pressure gradients, low Reynolds number and /or high positive or negative incidence, the boundary layer may separate from the airfoil surface. Within the boundary layer, the viscosity induces surface drag and consequently a streamwise velocity gradient perpendicular to the surface. The retarded flow in the boundary layer may not possess sufficient momentum and energy along the surface to overcome the pressure rise downstream, and finally, the fluid particles near the wall are brought to rest. The main stream, itself decelerating, is unable to energize the fluid in the boundary layer and an almost stagnant fluid region develops near the wall. At the point of separation, the shear layer leaves the surface and the flow direction is at a relatively small angle from the wall.

The major features of the laminar separated flow are shown in Figure 2.1 (modified after Mayle, 1991). Downstream of the separation point, a wedge of recirculating flow develops, which is bounded by the blade surface and the separated shear layer. This fluid wedge makes up the front portion of the separation bubble. The magnitude of the reverse flow velocity in this region is typically very small, on the order of a few percent of that at the edge of the shear layer (Horton, 1969). The displacement effect of this wedge of fluid on the external flow causes a reduction in the adverse pressure gradient compared with that which would exist if the bubble were absent. In most cases, the gradient in surface

pressure and external velocity in this region may be reduced approximately to zero. Once separated transition has occurred, which will be discussed in Section 2.2.2, momentum exchange across this layer by the turbulent mixing process reduces the vertical extent of the reverse flow layer as well as the displacement effect of the bubble. A deceleration of the external flow over the bubble's turbulent portion results in an accompanying adverse pressure gradient. The magnitude of the reverse-flow velocities are much larger in this region, on the order of 20% of the velocity of the free shear layer (Horton, 1969, and Mayle, 1991).

Figure 2.1 Schematic View of the Laminar Separated Boundary Layer Development

In the separation bubble, the flow may be divided into two main regions, which are in general characterized by their corresponding pressure distributions. They are an upstream region of nearly constant pressure and a downstream region with a large pressure recovery. These are shown as regions of constant free-stream velocity and deceleration, respectively. The knee, between these two regions, is assumed as the maximum boundary layer displacement, the location is referenced as X_{MD} in the figure (Mayle, 1991).

Separation bubbles appear in two types, short and long, which have been classified somewhat differently by various researchers. Owen and Klanfer (1953) have classified as short bubbles, those where the bubble length l_b is of the order of one hundred displacement thicknesses at separation, *i.e.* $l_b \sim O(100(\delta_1)_s)$, and long bubbles where $l_b \sim O(10000(\delta_1)_s)$. This is generally known as the Owen-Klanfer criterion. Crabtree (1959) and Mayle (1991) have stated that it is better to differentiate between long and short bubbles by their effect on the pressure distribution rather than by their length. Short bubbles have only a local displacement effect, so that, upstream and downstream of the bubble, the pressure distribution is almost the same as that predicted for the flow over the surface without separation. Long bubbles interact with the exterior flow to such an extent that the pressure distribution over the whole surface is appreciably different from that predicted without them. Since long bubbles produce large total pressure losses and large deviations in exit flow angles for turbomachinery blades, they should be avoided (Mayle, 1991 and Walker, 1993).

Prediction of separation is of considerable practical importance. When significant area of separation exists on the blade surface, the pressure distribution changes and the blade suffers a loss of lift. The prediction of a precise location for the separation point frequently presents difficulty. The extent of a separation bubble can be determined by examining the constant-pressure region of the surface static pressure distribution. For incompressible flow, the surface static pressure can be represented by the pressure coefficient:

$$C_p = \frac{(P_s - P_{ref})}{\frac{1}{2} \rho V_{ref}^2} \quad (2.1)$$

which is related to the velocity variation of the external flow if it is assumed that the surface pressure is the same as the static pressure at the edge of the boundary layer.

Tani (1964) noted that a pressure plateau does not necessarily result when a bubble is formed. Therefore, the zero wall shear stress condition is adopted as a flow separation criterion. Surface-mounted hot-film measurements can be used as a good method for detecting boundary layer separation. The beginning and end of the near-zero mean quasi-wall-shear stress calculated from the hot-film measurement data can be used to clearly determine the flow separation point and reattachment points respectively. The surface-mounted hot-film measurements is the main topic of the current study and will be discussed in detail in the later chapters.

2.2.2 Boundary Layer Transition

In a review of the role of laminar to turbulent transitions in gas turbine engines, Mayle (1991) has adopted the conventional approach of classifying boundary layer transition into natural, bypass and separated-flow modes.

Natural Transition For very low free-stream disturbance where free stream turbulence intensity (FSTI) is less than 1.0 percent, the laminar boundary layer becomes susceptible to small disturbances and develops linear oscillations of well-defined frequency when the momentum thickness Reynolds number, Re_θ , exceeds a critical value. These oscillations, called Tollmien-Schlichting (T-S) waves, are two-dimensional and convect at a typical speed of 0.30-0.35 V_∞ . The instability amplifies within the layer to a point where three-dimensional non-linear unstable waves grow and develop into loop vortices with large fluctuations. Finally, the highly fluctuating portions of the flow develop into turbulent spots, which then grow and convect downstream within the laminar layer to coalesce eventually into a fully developed turbulent boundary layer. Figure 2.2 shows the schematics of the natural transition process (from Schlichting, 1979).

Bypass Transition For transition at high free-stream turbulence levels or high surface roughness, the first and possibly second stages of the natural transition process are completely bypassed such that turbulent spots are directly produced within the boundary layer by the influence of the free-stream disturbances. In this case the formation and amplification process of two-dimensional T-S wave are less evident, if

present at all (Emmons, 1951). This transition process significantly reduces the length of the unstable laminar flow and will promote earlier transition.

Figure 2.2 Schematics of Natural Transition Process (from Schlichting, 1979)

Separated-Flow Transition In a separated flow, a rapid transition may occur in the free shear layer near the surface. Provided the Reynolds number is not too low or the local pressure gradient is not too large, the resulting turbulent free shear layer will force the separated flow to reattach to the blade surface. The bubble length depends on the transition process within the free shear layer and free stream conditions.

The transition to turbulence in separated boundary layers is the result of the superposition of the effects of two different types of instability: Kelvin-Helmholtz (K-H)

instability and Tollmien-Schlichting (T-S) instability. The first type of instability (K-H) can be associated with the separated laminar shear layer and the near-wall low speed flow, which can be regarded as an anti-symmetric mixing layer and is inflectional unstable (Morkovin, 1991). It occurs and develops at a specific location downstream of the separation point. For relatively large Reynolds numbers and mild adverse pressure gradients, the start of transition is likely to precede separation, being induced by the Tollmien-Schlichting instability mechanism. The predominance of one type of instability or another determines the mode of separated flow transition.

The essential features of a laminar separation bubble with transition proposed by Mayle (1991) are illustrated in Figure 2.1. This modified picture of the flow behavior in a separation bubble differs from the simplified model of Horton (1969) and Roberts (1975, 1980) in two important respects: there is a transitional flow region of finite length; and the start of transition occurs in the region of constant pressure. But transition is still assumed complete at the end of the constant-pressure region and the boundary layer is fully turbulent during pressure recovery and reattachment.

Turbulent Spots Bypass transition and the latter stages of the natural transition are characterized by the random production and propagation (in both time and space) of turbulent spots within the boundary layer (Emmons, 1951). Figure 2.3 shows a compilation of various observations of the shape and growth of the turbulent spots after Mayle (1991).

Figure 2.3 Turbulent Spot Geometry, Growth and Propagation (after Mayle, 1991)

Viewed from above, a turbulent spot looks like an arrowhead moving downstream and spreading laterally at a half-angle variously reported from 8° to 12° . The region swept out by the spot is its zone of influence. The convention velocities of the leading and trailing boundaries of the spot are approximately $0.88 V_\infty$ and $0.50 V_\infty$, respectively, as measured in zero pressure gradients by Schubauer and Klebanoff (1956). Their values do not vary with streamwise direction. Thus the spot grows in size but its normalized shape remains the same.

Although shown smooth in the figure, the boundary of the turbulent spot is irregular. Since the spots grow and remain intensely turbulent, they must entrain the surrounding laminar fluid to maintain themselves. Wygnanski *et al.* (1976) reported that the strongest entrainment is at the leading edge and on the upper surface of the trailing edge. Transition to a turbulent boundary layer is completed with a merger of spots.

The degree of transition progression is measured as intermittency (γ) that is defined as the fraction of time which the flow over any point on the surface is turbulent. When $\gamma=0$, the flow is completely laminar. When $\gamma=1$, the flow is fully turbulent. For intermediate values, the flow is part of the time laminar and part of the time turbulent, *i.e.*, transitional.

Various characteristics of a turbulent spot are conveniently described using a space-time (S-T) diagram, shown at the bottom of Figure 2.3. An S-T diagram is a contour plot with time on the y-axis and surface distance on the x-axis. Lines of constant time, parallel to the “Space” axis, provide the instantaneous state of the flow along the surface. Likewise, vertical lines, parallel to the “Time” axis, provide the behavior of the flow as time varies at a given location along the surface. For a constant streamwise velocity, the boundaries are straight lines in S-T plot, otherwise they are curved. The convective velocity of each boundary is the inverse slope of its trajectory. The development of the turbulent spots is shown clearly in the S-T plot.

Calmed Region A calmed region occurs immediately behind a turbulent spot or turbulent strip (Schubauer and Klebanoff, 1956, and Orth, 1993). Its existence is

dependent only on turbulent spots regardless of the transition process. The calmed region is identified as the region of decreasing, but still elevated (compared with laminar level), wall shear stress behind the turbulent spot or strip. The ends of calmed regions that trail turbulent spots are variously reported to travel at approximately 30% of the local free stream velocity, (Gostelow *et al.*, 1996).

The calmed region has a fuller boundary layer profile, which is relaxing from a turbulent to a laminar level. This region is more resistant to flow separation in adverse pressure gradient due to its elevated level of shear stress and low shape factor. The calmed region can therefore be terminated only by the merging of the neighboring turbulent spots or by strong bypass transition events. In the case of turbulent strips, merging occurs only in the streamwise direction. This has the effect of extending significantly the streamwise length of the transition zone (Schubauer and Klebanoff, 1956 and Orth, 1993).

The boundary layer transition from laminar to turbulent flow has been studied both by numerical modeling and experimental investigations. Narasimha (1957) measured the variation of the intermittency through the transition region and showed that it is most accurately represented by a “concentrated breakdown” model, *i.e.*, a model in which all the turbulent spots are initiated at the same streamwise location and the increase in intermittency through transition results purely from the growth in size of these spots. More recently, with the availability of more accurate measurement techniques for intermittency, the validity of this model has been challenged. Johnson and Fasihfar (1994) showed that a concentrated breakdown model did not give a good prediction of

the evolution of spot statistics through transition and that a “distributed breakdown” model, *i.e.*, one where spots are initiated at different streamwise location, resulted in improved prediction.

Johnson (1994) and Mayle and Schultz (1997) have shown that pre-transitional near-wall velocity fluctuations, induced primarily by pressure fluctuations associated with the free-stream turbulence, grow more or less linearly in the streamwise direction. These fluctuations are of long wavelength (greater than 15 to 20 times of the boundary layer thickness), but can be many times greater in amplitude (typical by 20 to 100 boundary layer thicknesses) in the near-wall region than in the free-stream. When these fluctuations reach some critical level (approximately a local turbulence level of 23 percent according to Johnson (1994)) a significant number of turbulent spots are induced and transition begins. Natural transition induced through T-S waves also commences when the waves reach a similar critical amplitude. T-S waves possess a shorter wavelength (typically 2 to 3 δ) and also grow exponentially once the critical boundary layer Reynolds number is exceeded. These observations may form the basis for frequency domain analysis. The structure of turbulent spots has been studied extensively through both experiments and numerical predictions. However, the mechanism leading to the initiation of the spot and turbulence production is not clear.

The surface-mounted hot-film technique has been widely used to investigate boundary layer development. Anderson *et al.* (1991) studied the boundary layer development on wing in the F-14 variable-sweep transition flight experiment by using surface-mounted hot-film sensors. The boundary layer state was indicated by examining

the raw hot-film signals. An example of a typical raw signal is shown in Figure 2.4. Dynamic signals originating in the areas of laminar flow are of lower amplitude or quieter than those originating in areas of turbulent flow. Additional indicators are high amplitude spikes in the output signals: high amplitude spikes in a direction of positive voltage indicates a mainly laminar signal with occasional turbulent bursts, whereas high-amplitude spikes in a negative direction indicates a mostly turbulent signal with occasional periods of laminar flow. These two types of signals were proposed as indicators of the beginning and ending of the transition region. Maximum occurrence of these high-amplitude spikes is at peak transition (*i.e.*, intermittency $\gamma \approx 0.5$).

Figure 2.4 Typical Hot-Film Raw Signals (after Anderson *et al.*, 1990)

Svensdotter and Fransson (1998) measured the boundary layer transition in a cascade at varying Reynolds number and free stream turbulence intensity (FSTI) by means of hot-film and liquid crystal measurements. The state of the boundary layer development was

determined by examining both the raw hot-film signals and the statistical moments including the mean, the standard deviation (RMS) and the skew, which are defined in Section 4.2. The transition indicator from the raw hot-film signals is the same as that used by Anderson *et al* (1990). Figure 2.5 shows the relationship between statistical moments and the intermittency (boundary layer transition state). The RMS is close to zero in laminar flow and increases as the boundary layer starts transition. The maximum RMS occurs at the mid-transition point ($\gamma \approx 0.5$). Then it decreases to the turbulent flow level, which is a little higher than laminar level. The transition position also can be determined from the skew, the third-order statistical moments. The skew is zero during laminar flow, thereafter increasing until it is a positive maximum at an intermittency of 0.25, decreasing through zero at $\gamma \approx 0.5$ to a negative minimum at $\gamma \approx 0.75$ and returns to zero when the intermittency has reached 1.0, *i.e.*, fully turbulent flow.

Figure 2.5 Statistical Moments of Hot-Film Signals v.s. Intermittency (γ)

2.3 Wake-Boundary Layer Interaction

The traditional design of turbine airfoils is based on the assumption that the rotor and stator rows are spaced far enough apart such that the flow in each is steady, *i.e.*, that there is no unsteadiness of any sort due to rotor-stator aerodynamic interaction. However, the rows of modern turbines are in reality very closely spaced. Axial gaps between adjacent rows of approximately $\frac{1}{4}$ to $\frac{1}{2}$ of the blade chord are common practice (Dring *et al*, 1982). It is clear, therefore, that when rows are closely spaced there can be a strong unsteady interaction, which will impact the aerodynamic, thermal and structural performance of the airfoils. Future designs with higher loading and lower aspect ratios and the ever present desire to minimize engine length, will aggravate this condition even further.

The rotor-stator aerodynamic interaction may be divided into two separate effects. The potential or inviscid influence of an airfoil extends both upstream and downstream and typically decay with a length scale equal to the chord of the cascade. The wake, on the other hand, is convected downstream only. The rate of decay of the wake, however, is much less than that of the potential flow. It may still be felt for several chord lengths downstream. Thus, the wake influence from the previous blade row will be the main mechanism in the rotor-stator interaction.

2.3.1 Wake Transport Mechanisms

Casciaro *et al* (2000) define a wake as any velocity deficit in the body-relative frame

of reference occurring in a space much smaller than the one analyzed. This means that, if the instantaneous velocity field is decreased from the undisturbed value, a wake looks like a backward-facing jet, that is the so-called “negative jet”. Meyer (1958) was one of the first to use the idea of the negative jet to explain the unsteady behavior in compressor stages. Figure 2.6 shows a schematic interpretation of his model. The negative jet draws fluid from the pressure surface onto the suction surface and results in different patterns of velocity and pressure fluctuations on the pressure side and suction side.

Figure 2.6 Schematics of Representation of Wake as a Negative Jet (after Meyer, 1958)

Recently, Hodson and Dawes (1998) claimed that the wake transport in the blade passage could be explained through convective mechanisms of a negative jet being chopped by the following row, bowed and sheared by the pressure/velocity field. Figure 2.7 presents a schematic picture of the wake-boundary layer interaction in an LP turbine

after Hodson and Dawes (1998). As wakes convect through the next blade row, they are chopped into segments. The segments of the wakes behave as a negative jet impinging on the airfoil surface as they are transported with the free-stream fluid. Once the wake has been chopped by the next row blade, the newly formed wake segment becomes distorted.

Figure 2.7 Schematics of Wake-Boundary Layer Interaction (from Hodson and Dawes, 1998)

There are three reasons for this distortion (Hodson, 1985a). The first form of distortion is because the negative jet draws wake fluid away from the pressure surface onto the suction surface, which results in a broadening of the wake near the suction surface and a thinning near the pressure surface. The second form of distortion results in a shearing and therefore lengthening of the wake segment. It arises as a result of the different suction and pressure surface convection velocities. A further consequence of

this shearing action is that the requirement for the conservation of mass results in a thinning of the wake as it becomes elongated. The third form of wake distortion begins as the wake first meets the leading edge of the blade. The downstream side of the wake is accelerated over the blade surfaces and away from the upstream side which remains in the vicinity of the stagnation point. As a result of the velocity distribution on the blade this broadening of the wake segment in the vicinity of the blade suction surface is much more pronounced over the leading part of the suction surface. The behavior of the negative jet gives rise to fluctuations in the surface velocity and pressure.

2.3.2 Wake-Induced Transition

Since the flow in a gas turbine is periodically unsteady, so is transition. The largest effect of unsteadiness on boundary layer transition is caused by the periodic passing of the wakes from the upstream airfoils and is called wake-induced transition (Mayle and Dullenkopf, 1989). Transition induced by the wakes appears to bypass the first stage of the natural transition process. In fact, it seems that the wakes are so disruptive to the separated free shear layer that turbulent spots are formed immediately and coalesce into a turbulent strip, which then grows and propagates downstream. Between these turbulent strips, transition by any other process is possible and, indeed, has been detected (Mayle, 1991). Thus, transition can occur in multiple modes (therefore called “multi-mode”) at different locations on the same surface at the same time. In other words, an instantaneous snapshot of the flow over an airfoil may show a laminar boundary layer near the leading edge, followed by a wake-induced transition to turbulent flow and

another laminar flow region with a subsequent transition to turbulent flow by any of the normal transition modes.

A space-time (S-T) diagram can illustrate the unsteady transition process by showing variations of the boundary layer state in both time and space on a single diagram. The y-axis shows the wake passing periods and x-axis shows the normalized surface distance. Figure 2.8 presents the schematic S-T diagram of unsteady boundary layer development after Halstead *et al.* (1995a). The increased turbulence intensity in the convecting wake penetrates into the laminar boundary layer on the blade surface. At some location downstream from the leading edge, these wake disturbances initiate turbulent spots, *i.e.*, initiate or induce boundary layer transition before it would have otherwise occurred in the laminar region. In addition, the periodic unsteadiness of the wake influences boundary layer growth.

Figure 2.8 Schematic S-T Diagram of Unsteady Boundary Layer Development.

(After Halstead *et al.*, 1995a)

As turbulent spots within the wake-induced transitional boundary layer convect along the suction surface, they map out a wake-induced path that can be represented on an S-T diagram. The regions marked B are wake-induced transitional strips. The strips have leading and trailing boundaries defined approximately by the convection velocities of the spots. Transition onset for region B begins at a distance L_B from the leading edge. When transition is completed within B and the boundary layer becomes turbulent, this strip continues to the trailing edge as a wake-induced turbulent strip C.

In the path between wakes, the boundary layer development is influenced by more than just the level of free-stream turbulence and pressure gradient. The path between wakes can also be affected by the calmed region (marked D in the figure). Such calmed regions follow the turbulent spots. The higher shear stress in the calmed region is one of the characteristics thought to be effective in suppressing flow separation and delaying transition in the region between wakes (Halstead *et al*, 1995b and Howell *et al*, 2001). Thus, the transition between wakes occurs at a distance L_E from the blade leading edge, which is slightly downstream of the steady flow transition onset location. The turbulent spots produced in this transition region may also generate a calmed region (region G). Turbulent boundary layers follow the transitional regions between the wakes, marked as regions F in the figure, and extend to the trailing edge. Near the blade trailing edge, the boundary layer varies periodically from region C to region F.

Thus, the unsteady boundary layer on the blades develops along two separate, but coupled paths. The first path, called wake-induced path, lies approximately under the wake trajectory but lags the wake somewhat. The second path lies between wakes.

Along both paths the boundary layer goes from laminar to transitional to turbulent flow, with the location of transition onset in each path strongly dependent upon the turbulence intensity, Reynolds number, pressure gradient and the wake strength as well as wake passing frequency. The two paths are coupled by a calmed region which decays across the region between wakes.

Schulte and Hodson (1998) investigated the effects of wakes from upstream moving bars on the losses generated by an LP turbine cascade at various unsteady conditions with different bar diameters and different wake passing frequencies. As wakes convect over the downstream blade, they disturb the boundary layers. And when the boundary layers become more receptive to disturbances, the wakes eventually cause the formation of turbulent spots through the mechanism of bypass transition. These spots travel downstream in the characteristic manner shown in Figure 2.3. Behind the spot is a calmed region, which has a fuller velocity profile. This profile is very stable and does not separate in adverse pressure gradients as easily as a laminar profile. They claimed that it was this ability to withstand adverse pressure gradients that prevents a flow from separating and was responsible for the loss reductions. They also concluded that there existed an optimum reduced frequency and wake strength, which resulted in a very low profile loss and the loss was almost independent of the Reynolds numbers. Figure 2.9 shows the measurement results of Schulte and Hodson (1998).

Funazaki *et al.* (1997) conducted measurements of stagnation pressure distributions downstream of a linear cascade of turbine blades that was subjected to periodic wakes from upstream moving bars. They identified a slight reduction in the loss associated with

the wakes. Similar to the study of Schulte and Hodson (1998), they concluded from the flow visualization that a separation bubble on the blade suction surface was diminished due to the wake-blade interaction. Recently, by using thermo-chromic liquid crystals Zhong *et al* (1999a and 1999b) have provided the first real evidence that bypass transition due to incoming wakes does indeed proceed via the formation of turbulent spots, which propagate and grow in the same manner as conventional spots.

Figure 2.9 Stagnation Pressure Loss vs. Reduced Frequency (from Schulte and Hodson, 1998)

2.4 Previous Studies on PAK-B LP Turbine Blades

The Pratt & Whitney PAK-B low pressure (LP) turbine blade profile, which was the blade geometry examined in the present study, represents a modern LP turbine blade design. The blade geometry is shown in Figure 3.3. Several experiments by other

researchers have been performed to examine the performance of this blade and to better understand the boundary layer development (especially the boundary layer transition and separation) on the blade surface under various free stream turbulence levels and a range of Reynolds numbers.

Murawski and Vafai (1999 & 2000) studied the steady boundary layer development on the suction side of the PAK-B blade profile by means of surface static pressure measurements under different Reynolds number and free stream turbulent intensity (FSTI) conditions. Reynolds numbers, based on exit velocity and suction surface length, were varied from 50000 to 300000 and the FSTI was varied from 1.1 to 8.1 percent. Separation was observed at all Reynolds numbers and in all flow cases. The size of the separation bubble was reduced as the Reynolds number and/or FSTI increased. They also investigated the effect of flow separation on the wake formed downstream of the trailing edge, as well as the blade pressure losses by means of hot-wire traverses. They concluded that at high levels of FSTI, increasing the Reynolds number reduced the velocity defect in the wakes, but did not reduce the width of the wake, resulting in only a minimal reduction of the profile losses. For cases of low FSTI, as Reynolds number increased, the suction side boundary layer changed dramatically. The separation zone became smaller, reducing the velocity defect and decreasing the wake width, resulting in a substantial reduction in the blade's profile losses.

Qiu and Simon (1997) also investigated the boundary layer separation and transition on the suction surface of the PAK-B airfoil profile. Experiments were conducted using a single passage cascade with FSTI levels of 0.5, 2.5 and 10 percent and Reynolds numbers

(based on nominal exit velocity and suction surface wetted length) ranging from 50000 to 300000. Detailed velocity profiles, measured in the near-wall region with hot-wire traverse techniques, and surface static pressure distributions were presented. Flow transition was documented using measured intermittency distributions in the attached boundary layer and within the separated shear layer. Flow separation, with transition of the free shear layer over the separation bubble, was observed for the lower Reynolds number cases. Elevated FSTI and increased Reynold number promote earlier transition and smaller separation bubbles.

In parallel with the experimental investigations, numerical studies on the PAK-B geometry were also performed. Dorney and Ashpis (1999) studied the low Reynolds number effects on the profile losses. Recently, Dorney *et al.* (2000) numerically investigated the blade losses with boundary layer trips. They concluded that tripping the boundary layer is an effective mechanism for reducing losses at low Reynolds number, but not at higher Reynolds number. The early boundary layer transition, induced by the tripping, causes the separated flow to reattach early and reduces the separation bubble size. Especially for low Reynolds number flow, the tripping-induced transition could force the open bubble to reattach, which results in a significant losses reduction.

Although some work has been conducted on the PAK-B blade profile, as discussed above, the boundary layer behavior under unsteady conditions, *i.e.*, the wake-boundary layer interaction, has not been investigated experimentally. However, the unsteady boundary layer developments are very important for modern LP turbine blade design, especially under low Reynolds number conditions. The experimental study of the wake-

boundary layer interaction on the blade suction surface and its effect on the blade performance is the main objective of the current project. To investigate the boundary layer behavior under unsteady conditions, a fast-response measurement technique was required. Surface-mounted hot-films have been used for this task. As the baseline of the unsteady study, an investigation of the steady boundary layer development on the blade suction surface was first conducted by means of surface-mounted hot-film sensors. The relationship between the hot-film measurement data and the boundary layer transition and separation then was used to interpret the unsteady hot-film measurement data. These two items form the main parts of this thesis.

Chapter 3

Experimental Apparatus

3.1 Low-Speed Wind Tunnel

All experiments were conducted in the low-speed, open-return wind tunnel at Carleton University. A schematic of the wind tunnel is shown in Figure 3.1. The wind tunnel was commissioned by Rodger (1992).

The air is drawn in through a bell-mouth inlet by a centrifugal fan, which is driven by an AC motor. A variable frequency controller allows the fan speed to be varied over a wide range. The fan is capable of delivering a mass flow rate up to 5 kg/s at a total pressure of 0.12 meter of water column (gauge). The fan delivery air first goes through a hexagonal honeycomb consisting of 9-mm-wide and 250-mm-deep cells which remove any swirl in the flow. The air is then diffused through a straight conical diffuser with an area ratio of 7 and an equivalent cone angle of 19° . This

diffuser contains five fine single-layered and evenly spaced stainless steel screens, which are used to reduce mean-flow non-uniformities. The settling chamber contains four stainless steel screens, which are used to reduce the large-scale turbulence. The flow leaves the settling chamber through a contraction prior to entering the test section (shown in Figure 3.2). The contraction section has an inlet-to-exit area ratio of 14, which accelerates the flow to the required velocity. The contraction section inlet static pressure (P_{c1}) and outlet static pressure (P_{c2}) are used to monitor the wind tunnel operating conditions, and P_{c2} is also used as the reference pressure in pressure measurements.

Figure 3.1 Schematic of the Low-Speed Wind Tunnel from Rodger (1992a)

Typically, the maximum running speed of the fan is about 1500 RPM. The maximum tunnel exit velocity is then about 30 m/s, which corresponds to a Mach number of about 0.09. Therefore, the flow through the cascade test section can be treated as essentially incompressible. As mentioned, the speed of the AC motor is controlled by a remote variable frequency controller.

The acceleration and deceleration of the motor, along with other parameters can be programmed into the unit. The control frequency signal sent to the four-pole motor can easily be selected and entered via the remote controller. The rotational speed (RPM) of the fan can be calculated as follows:

$$RPM = \frac{f_{input}}{\frac{N_{poles}}{2}} \times 60 = 30 f_{input} \quad (3.1)$$

The free stream turbulence intensity (FSTI) is a measure of the fluctuations in the flow velocity.

Denoting the time averages for the three components of the velocity fluctuation as $\overline{u'^2}, \overline{v'^2}, \overline{w'^2}$,

FSTI of a flow is defined as:

$$FSTI = \frac{\sqrt{\frac{1}{3}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})}}{\bar{u}} \times 100\% \quad (3.2)$$

where $\bar{u}$ is mean free stream velocity in the wind tunnel.

A study by Schlichting (1979) concluded that the nature of the turbulence in a wind tunnel of conventional type with proper settling chamber, honeycombs, screens and contractions can be expected to be homogeneous and nearly isotropic. Therefore, at a certain distance downstream of the flow screens, the mean square velocity fluctuations in the three directions can be assumed to be equal, *i.e.* $\overline{u'^2} = \overline{v'^2} = \overline{w'^2}$. In this case the longitudinal velocity fluctuation u' alone can be used for the turbulence intensity. Thus FSTI can be measured only in the streamwise direction,

i.e.,

$$FSTI = T_u = \frac{\sqrt{u'^2}}{\bar{u}} \quad (3.3)$$

The basic FSTI in the test section near the test cascade is about 0.4 %. The level of FSTI can be raised by means of a turbulence-generating grid, which will be discussed in Section 4.1, placed upstream of the test cascade.

3.2 Test Section and Cascade Geometry

Figure 3.2 shows a schematic of the linear cascade test section. The cross section is rectangular with 65 cm in height and 20 cm in width. The cascade is mounted on an aluminum turntable and a plexiglass window forms the front wall. The large turntable supported by a steel shaft and two pillow block bearings allows variation in the cascade incidence. The turntable can be rotated through a turning angle of about 60°. For the present study the turntable was set to give the blade design incidence, which corresponds to an inlet velocity which is 35° from the axial direction relative to cascade. The cascade blades are bolted to a 0.5" thick aluminum mounting plate. The plate, which is flush with the backwall of the test section, can be easily removed to give access to the blades. The entire assembly is mounted on a wheeled steel frame that allows it to be moved from the wind tunnel outlet. The plexiglass that forms the front wall of the test section allows visual inspection. It stands on its own wheeled frame and is easily pulled back to allow access to the cascade. During unsteady experiments, the plexiglass front wall was replaced by a

1. TURNTABLE	4. FLOATING WALL
2. TAILBOARDS	5. B.L. BLEED SLOTS
3. SIDE FLAPS	6. INSTRUMENT SLOTS

Figure 3.2 Schematic of the Variable Incidence Cascade Test Section

spoked-wheel type wake generator, which will be discussed in Section 3.3. At the upstream end of the test section, vertical bleed slots are used to remove the boundary layer developed inside the contraction.

The adjustable side flaps and the tailboards are mainly used to control the flow uniformity at the cascade inlet and periodicity at the cascade outlet for each operating condition. Both side flaps and the tailboards are used to adjust the inlet flow uniformity. The two tailboards, flush with the top and bottom blades respectively, are mainly used to trim the outlet flow periodicity. Of course, for the incompressible flow the adjustment of any controlling surface will affect both the upstream and downstream flow. The flow uniformity and periodicity will be discussed in detail in Chapter 4. A floating wall at the bottom of the cascade compensates for changes to test section height when the incidence is varied. The two bypass flaps control the amount of air that passes under the floating wall.

The cascade contains of a set of nine Pratt & Whitney PAK-B low pressure turbine blades. Figure 3.3 shows the three middle blades of the cascade and the inlet and outlet measuring planes. The blades have an axial chord (B_x) of 75.0 mm (2.97 inch) and a blade span (h) of 200.0 mm (7.91 inch). For the present study, the test section is set for the design specifications with an inlet angle of 35° and an exit angle of 60° . The center blade can be replaced with a blade instrumented with static pressure taps or an instrumented surface-mounted hot-film blade as described later.

Number of Blades	9	Axial Chord (B_x)	75.0 mm
True Chord (B)	83.4 mm	Blade Spacing (S)	66.8 mm
Blade Span (h)	200 mm	Stagger Angle (γ)	26°
Inlet Metal Angle (β_1)	35°	Outlet Metal Angle (β_2)	60°
Solidity (B_x/S)	1.13	Aspect Ratio (h/B_x)	2.41

Figure 3.3 Pak-B LP Turbine Cascade Geometry and Measuring Planes

As discussed in Chapter 4, the inlet and outlet conditions were documented from 3-hole probe traverses at $1.2 B_x$ upstream and $0.5 B_x$ downstream of the cascade respectively. The two-dimensionality of flow was inferred from the axial velocity ratio (AVR) calculations.

3.3 Wake Generator

To achieve a simulation of rotor-stator interactions, a spoked-wheel type wake generator was designed, as shown in Figure 3.4, which can generate moving wakes ahead of the cascade blades.

The wake generator consists of a solid disk (wheel) with a radius of 350 mm (13.8 inches), mounted on a pivoting frame, which allows the wheel to be used with cascades at varying incidence angles. The wheel is mechanically connected to a 3 hp, 4-pole, AC motor by a timing belt. A pulley reduction ratio of 1.9 is used on this system. The AC motor is digitally controlled by a Mitsubishi variable frequency controller. The wakes are generated by cylindrical bars that are fastened to the disk. Up to 120 equally-spaced 200 mm long cylindrical bars can be mounted on the wheel. The number of bars mounted on the wheel can be changed easily. The required diameter of the cylindrical bars to achieve similarity can be determined from the assumed upstream blade total pressure loss and bar drag coefficient, which will be discussed later. A photo detector is mounted at the wheel rotating shaft to generate an once-per-revolution signal used as a trigger signal for data acquisition system. This trigger signal ensures the data acquisition system start to sample data at the same wheel rotational location (or phase) for different cycles.

(a)

(b)

Figure 3.4 Schematic of Wake Generator

(a) Front View of the Spoked-Wheel (b) Wake Generator Structure

Early in the study, a problem with vibration of the bars was encountered in the designed operating range. The resulting vibration caused a number of bars to fail. Fortunately, neither the cascade nor the instrumentation was damaged by this failure. To change the natural frequency of the bars, a 3.175 mm O.D., 40 mm long Copper tube was welded at the root of each bar. The rotating plane of the bars was placed at a distance of 60% axial chord upstream of the cascade leading edge (shown in Figure 3.3), which produces flow conditions at the leading edge of the cascade similar to those produced by PAK-B cascade itself. The location of the axis of the wake generator was adjusted such that one of the bars is aligned with the leading edge of the center blade in the cascade when the bar moves just ahead of this target blade.

3.3.1 Spoked-Wheel Control Frequency

The AC motor is controlled by a digital frequency controller. The rotational speed of the motor, N_{motor} , and controller frequency input signal are related by the following expression:

$$N_{motor} = \frac{\text{controller input frequency}}{\text{number of poles in the motor} / 2} \times 60 = 30 f_{control} \quad (3.4)$$

Hence, the wheel rotating speed, N_{wheel} , is

$$N_{wheel} = \frac{N_{motor}}{\text{reduction pulley ratio}} = \frac{30}{1.9} f_{control} \quad (3.5)$$

The wheel angular velocity, ω_{mean} , is calculated as

$$\omega_{wheel} = \frac{2\pi N_{wheel}}{60} = \frac{\pi}{1.9} f_{control} \quad (3.6)$$

The mean radius, r_{mean} , from the center of the wheel to mid-span of the bar, is 450 mm. The velocity of the bar at mid-span is then calculated as:

$$U_{bar} = r_{mean} \omega_{wheel} = \frac{\pi}{1.9} f_{control} r_{mean} \quad (3.7)$$

The flow coefficient, Φ , is defined as:

$$\Phi = \frac{V_{ax}}{U_{bar}} = \frac{V_1 \cos \alpha_1}{U_{bar}} \quad (3.8)$$

where V_1 is cascade inlet velocity, α_1 is the cascade inlet flow angle.

Therefore, the controller input frequency for a given condition is calculated as

$$f_{control} = \frac{1.9 V_1 \cos \alpha_1}{\pi r_{mean} \Phi} \quad (3.9)$$

which is a function of flow coefficient (Φ) and free stream velocity (V_1).

3.3.2 Reduced Frequency

The wake passing frequency is referenced as a non-dimensional unsteadiness parameter, the reduced frequency, $\bar{f}$. There are at least two different definitions used in the literature.

Hodson (1985a, 1989) defines the reduced frequency as:

$$\bar{f}_{Hodson} = \frac{f_{bar} B_x}{V_2} \quad (3.10)$$

where V_2 is blade outlet velocity, B_x is the blade axial chord and f_{bar} is the bar passing frequency defined as:

$$f_{bar} = n_{bar} \frac{N_{wheel}}{60}$$

where n_{bar} is the number of the bars (spokes) on the wheel. For the present configuration, then from Equation 3.5,

$$f_{bar} = n_{bar} \frac{f_{control}}{3.8} \quad (3.11)$$

Substituting Equation 3.9 into Equation 3.11, the reduced frequency may be written as:

$$\bar{f}_{Hodson} = \frac{\left(n_{bar} \frac{f_{control}}{3.8} \right) B_x}{V_2} = \frac{n_{bar} B_x \cos \alpha_1}{2\pi r_{mean} \Phi (V_2 / V_1)} \quad (3.12)$$

Sharma (1988) defines the reduced frequency as a ratio of two time scales: one represents the residence time of wake fluid particles in the blade passage and the second represents the period between the upstream wakes entering the blade passage, *i.e.*,

$$\bar{f}_{Sharma} = \frac{\frac{B_x}{V_{ax}}}{\frac{S_{bar}}{U_{bar}}} = \frac{\frac{B_x}{V_{ax}}}{\frac{1}{f_{bar}}} = \frac{B_x U_{bar}}{V_{ax} S_{bar}} \quad (3.13)$$

which corresponds directly to the number of wakes within a single blade passage at a given instant, making this definition more physically meaningful than that given by Equation 3.12.

The bar spacing S_{bar} is

$$S_{bar} = \frac{2\pi r_{mean}}{n_{bar}} \quad (3.14)$$

Therefore, Sharma's reduced frequency can be written as

$$\bar{f}_{Sharma} = \frac{n_{bar} B_x}{2\pi r_{mean} \Phi} \quad (3.15)$$

The relationship between these two definitions of reduced frequency is

$$\frac{\bar{f}_{Sharma}}{\bar{f}_{Hodson}} = \frac{(V_2 / V_1)}{\cos \alpha_1} \quad (3.16)$$

Figure 3.5 shows the combination of reduced frequency and flow coefficient that can be obtained for different numbers of spokes mounted on the wheel.

3.3.3 Cylindrical Bar Aerodynamic Characteristics

Pfeil and Eifler (1976) (as referred by Schulte and Hodson, 1998) showed that the far wake of an airfoil and that of a cylindrical body of the same drag is almost the same. If the total pressure loss coefficient of the blade is defined by:

$$Y_p = \frac{\Delta P_0}{\frac{1}{2} \rho V_2^2} \quad (3.17)$$

then the loss coefficient is related to the drag coefficient C_d according to the equation:

$$Y_P = \frac{C_d d}{S_{bar} \cos \beta} \quad (3.18)$$

where d is the diameter of the cylindrical bars, β is the flow angle relative to the cascade of moving bars and S_{bar} is the space between bars. With a drag coefficient of approximately unity, the values for S_{bar} and β being given by the reduced frequency and the flow coefficient, one can determine the bar diameter d that is necessary to simulate a turbine blade with a certain wake defect. For current study, the bar diameter was set as 1.56 mm.

Figure 3.5 Available Reduced Frequency vs. Flow Coefficient

3.4 Pressure Measurements

3.4.1 Three-Hole Pressure Probe Measurements

A three-hole pressure probe was used to measure flow velocity magnitude, flow angle and static pressure both upstream and downstream of the cascade (see Figure 3.3) for the steady flow cases. The probe geometry is shown in Figure 3.6. As seen from the figure, the probe head is 1.91 mm wide, which is less than 3% of the blade pitch. The probe dimensions allow flow measurements with small probe interference and high spatial resolution.

Figure 3.6 Three-Hole Pressure Probe Geometry

Prior to the cascade experiments, the three hole probe was calibrated in a flow for which the total pressure, velocity and flow direction are known and at the same probe Reynolds number as that which the probe will encounter in the measurements. The calibration apparatus used here was

modified after that used by Yaras (1990). Calibration data were taken over a range of $\pm 20^\circ$ at half degree intervals. The data was then used to form the coefficients defined in the method for three-hole probe data reduction by Lewis (1966). These coefficients are stored in a look-up table and subsequently used to calculate the flow angle, dynamic pressure, static pressure and total pressure from the experimental measurements. Appendix A describes the detailed procedure of the three-hole pressure probe calibration.

The uncertainty in the flow angle measurements due to calibration errors is estimated to be $\pm 0.5^\circ$ within a $\pm 20^\circ$ range. Another possible source of error in measuring the flow angle may arise due to the shear in the plane of the probe, as will occur in the wake of the blade. In a highly sheared flow, because of the finite width of the probe, there will be a difference in the dynamic pressure across the face of the probe. This could be misinterpreted by the probe as flow angle. However, the total pressure measured by the center hole of the probe would not be affected much. By checking the pitchwise variation in total pressure measured by the probe, we can determine whether the probe is in the blade wake or not, which will be discussed in Section 4.3.2.

During pressure measurements the probe was calibrated once a week. Care must be taken in handling the probe to ensure that the probe tip is not damaged or altered in any way. Occasional cleaning of the probe is also necessary to remove any dirt particles, which could alter the calibration curves.

3.4.2 Blade Surface Static Pressure Measurements

The blade surface static pressure distribution measurements were performed for the steady flow cases using an instrumented blade. The center blade in the cascade can be replaced by the instrumented blade which has 32 static pressure taps. There are 20 taps on the suction side and 12 on the pressure side. Figure 3.7 shows the schematic of the instrumented loading blade. The locations of the static taps are given in Appendix B.

Figure 3.7 Instrumented Loading Blade with Static Tap Locations

The blade surface static pressure coefficient C_{pi} is defined as:

$$C_{pi} = \frac{\bar{P}_{0i} - \bar{P}_s}{\bar{P}_{0i} - \bar{P}_{s1}} \quad (3.19)$$

where $\bar{P}_s$ is the time average of measured surface static pressure. $\bar{P}_{0i}$, $\bar{P}_{s1}$ are the time averages of the cascade inlet total pressure and static pressure respectively. The results of the surface static pressure measurements will be discussed in Section 5.2.

3.5 Thermal Anemometry

3.5.1 Constant-Temperature Anemometry System

A 10-channel A.A. Lab System Model AN-1003 constant-temperature anemometry system was used for hot-wire and hot-film measurements. The connected hot-wire or hot-film sensor is heated to a temperature higher than that of the measured flow. Using electronic circuitry, the anemometer stabilizes and maintains the probe temperature at a constant level throughout the measurement. Since the fluid flowing past the probe has a lower temperature than the probe, the sensor is constantly being cooled by the flow. Since anemometer must maintain the probe temperature at a constant level, it is therefore sensitive to the rate at which it is being cooled. This cooling rate is then translated to a continuously changing voltage. The voltage signal then undergoes signal conditioning (low-pass filter) to filter out noise and improve the signal/noise ratio.

The operating temperature (T_{op}) of the sensor can be calculated from:

$$T_{op} = T_a + \left(\frac{R_{op}}{R_a} - 1 \right) \frac{1}{\chi_{20}} \quad (3.20)$$

where R_{op} is the resistance of the sensor at the overheated temperature (operating temperature), R_a is the resistance of the sensor at the flow temperature (T_a) and χ_{20} is the sensor temperature coefficient of resistance (TCR) at 20 °C.

The overheat ratio (OHR) of the hot-wire or hot-film sensor is defined as

$$OHR = \frac{R_{op}}{R_a} \quad (3.21)$$

The OHR fixes the temperature difference between the sensor and the flow (refer to Equation 3.20). The higher the OHR, the greater the system bandwidth and the higher the sensitivity of the probe. Therefore, to obtain the highest frequency response from the system the highest possible overheat ratio should be used. However, higher operating temperature will increase the sensor oxidation process and furthermore above a certain temperature, the probe will burn out.

The frequency response of the sensor can be determined with a step signal test that is available from the anemometer. The goal is to adjust the system damping factor to an optimum point to allow as fast a response time as possible without producing unstable oscillations.

3.5.2 Measurements Using Hot-Wire

A DANTEC Model 55P01 hot-wire was used to measure the flow velocity for the unsteady cases, as well as the upstream turbulence intensities for all cases. The platinum-plated tungsten wire sensor measures 1.25mm (0.005 in) in length with a diameter of 5-micron (0.0002 in). The sensor resistance at 20 °C (R_{20}) is about 3.3 Ω and the leads resistance is about 1.0 Ω . The temperature coefficient of resistance (TCR, χ_{20}) is given by the manufacturer as 0.36%/°C. From Equation 3.20 the hot-wire sensor operating resistance (R_{op}) is

$$R_{op} = R_{20} + \chi_{20} R_{20} (T_{op} - T_a) \quad (3.22)$$

where T_{op} is the hot-wire operating temperature and T_a is usually about 20 °C.

The hot-wire was calibrated based on King's law, which relates the Nusselt number, Nu, or non-dimensional heat-transfer coefficient, to the Reynolds number, Re, of the flow around the wire. King's law describes the basic response of the hot-wire anemometer. Based on the assumption of Davies and Fisher (1964), the flow properties are evaluated at the wire surface temperature T_{op} . Then King's law has the following form:

$$E^2 = A + BV^n \quad (3.23)$$

where E is the voltage across the sensor, V is the mean flow velocity, and A and B are functions of $(T_{op} - T_a)$ only. In general, the exponent n takes a value of about 0.5.

The hot-wire was calibrated in the same calibration apparatus as that used for the three-hole pressure probe calibration. The overheat ratio (OHR) was set at 1.51, to give in a sensor operating temperature of 200 °C. The system frequency response was about 140 kHz. For the calibrations, the flow velocities were varied in the range of 0 to 40 m/s, with a total of about 30 data points. More data points were taken in the low velocity range. The hot-wire output signal was first low-pass filtered at 10 kHz and then sampled at 30 kHz with the number of samples being 40960. Figure 3.8 shows a typical hot-wire calibration curve.

Figure 3.8 Typical Hot-Wire Calibration Curve

The effects of ambient temperature (T_a) drift during hot-wire measurements were compensated by Bearman's method (1970) (for more detail see Appendix C). The flow temperature was collected on-line by using a T-type thermocouple.

3.5.3 Measurements Using Surface-Mounted Hot-Films

To investigate the boundary layer development on the blade suction surface, the middle cascade blade can be replaced by an instrumented blade with a SenFlex 9109 closely-spaced array of surface-mounted multi hot-film sensors from Tao Systems Integration Inc. As shown in Figure 3.9, the array consists of 40 individual sensors, spaced at intervals of 0.1 inch in the direction of the flow. The array is deposited on a polyimide substrate which was bonded to the surface of the blade, covering about 88.5% of the suction surface length. The uncertainty of the boundary layer characteristic locations detected from hot-film measurements is about 2% of B_x . Table 3.1 lists the cold resistance (zero flow condition) and normalized locations of the sensors (note that sensor.29 is defective).

Table 3.1 Hot-Film Sensor Cold Resistance and Normalized Locations

No.	R_{cold}	x/B_x	No.	R_{cold}	x/B_x	No.	R_{cold}	x/B_x	No.	R_{cold}	x/B_x
1	6.53	0.067	11	6.78	0.373	21	6.81	0.676	31	6.58	0.863
2	6.56	0.091	12	6.75	0.411	22	6.89	0.701	32	6.83	0.879
3	6.94	0.118	13	7.06	0.446	23	7.00	0.723	33	6.82	0.894
4	6.72	0.146	14	6.80	0.481	24	6.77	0.744	34	7.13	0.910
5	6.93	0.175	15	6.94	0.514	25	7.00	0.763	35	7.00	0.925
6	6.72	0.202	16	6.85	0.546	26	6.77	0.781	36	6.54	0.940
7	6.67	0.231	17	6.78	0.573	27	6.84	0.798	37	6.86	0.954
8	6.99	0.264	18	6.94	0.602	28	7.06	0.815	38	6.95	0.970
9	6.82	0.298	19	6.95	0.629	29	X	0.832	39	6.84	0.985
10	6.86	0.335	20	6.87	0.654	30	6.98	0.848	40	7.12	0.998

(a)

(b)

Figure 3.9 SenFlex 9109 Multi Hot-Film Sensors Array and Normalized Location

The hot-film measurement technique appears to have been first introduced by Bellhouse and Schultz (1966), who used hot-film sensors to measure wall shear stress in laminar and turbulent flow. The similarity between the velocity profile adjacent to the wall and the temperature profile of the thermal boundary layer generated by the heated sensor leads to a relationship between the rate of heat transfer to the fluid and the wall shear stress of the form:

$$\tau_w = k \left(\frac{E^2 - A^2}{\Delta T} \right)^3 \quad (3.24)$$

where k is a constant, ΔT is the temperature difference between the flow and the heated sensor, E is the instantaneous output voltage from the anemometer bridge, and A represents the heat lost to the substrate. The constant A and k may be determined by sensor calibration. But the calibration of hot-film array is very difficult in general and essentially impossible in the present case. However, uncalibrated hot-film data still can provide semi-quantitative data about the state of the boundary layer (Hodson, 1985a,b & 1989).

The semi-quantitative data can be obtained because the rate of heat lost to the substrate, which is proportional to A^2 , is approximately proportional to the square of the voltage E_0 measured under zero-flow conditions. If the bulk temperature of the blade is equal to the air temperature, which will normally be the case, then the temperature difference ΔT is proportional to E_0^2 and so the data may be presented in the form (e.g. Hodson, 1985a):

$$\tau_w \propto \left(\frac{E^2 - E_0^2}{E_0^2} \right)^3$$

The quasi-wall-shear stress is then defined as:

$$\tau'_w = \left(\frac{E^2 - E_0^2}{E_0^2} \right)^3 \quad (3.25)$$

For simplification, the symbol τ will be used to represent the quasi-wall-shear stress in the remaining of this thesis. Equation 3.25 reduces the effects of the small differences in the sensor area, sensor and lead resistance, *etc.*, since these differences affect E^2 and E_0^2 in the same way. Thus, the output from different sensors can be compared. It allows us to attach significance to the relative magnitude of the hot-film output signals. Of course, the units associated with the quantity τ are arbitrary. The quantity $(E^2 - E_0^2)$ is of the same order as E_0^2 . Thus, the accuracy of the measurement of τ is very dependent upon the accurate knowledge of the zero-flow voltage at the temperature of the air encountered during the test. The required E_0 must be obtained at the same temperature as the experiment operating condition just after each run.

For hot-film measurements, to reduced the heating effect from the upstream sensors, the overheat ratio was set at 1.5, which was decided upon comparing the signals from the individual active sensors. The system frequency response was about 26 kHz, which is adequate for the purposes of the present investigation.

Due to the limitation of the data acquisition system, only eight channels can be sampled at the same time. So the 40 sensors were arranged into five groups, as see from Table 3.2. To reduce the heat effect from the neighboring sensor, the sensors in the same group were spaced by one

sensor. The signals were first low-pass filtered at 10 kHz. For the steady cases the signals were then sampled at 40 kHz. In the unsteady cases (with wakes), the sample frequencies were varied with the reduced frequency to make sure that there are at least 200 samples in each bar passing period. For the unsteady cases, 256 cycles of data covering six bar passing periods were recorded for each sensor for ensemble averaging.

Table 3.2 Arrangement of Hot-Film Sensor Groups

Group No.	Sensor No.							
# 1	1	3	5	7	9	11	13	15
# 2	17	19	21	23	25	27	X	31
# 3	33	35	37	39	2	4	6	8
# 4	10	12	14	16	18	20	22	24
# 5	26	28	30	32	34	36	38	40

Svensdotter and Fransson(1998) studied the effect of the roughness due to the surface-mounted hot-film sensors on the boundary layer development using hot-film and liquid crystal transition measurements in a cascade at varying Reynolds number and FSTI. They concluded that the larger surface roughness of the hot-film sensors compared to the liquid crystals did not seem to affect the boundary layer transition location on the blade surface significantly.

3.6 Data Acquisition System

Two data acquisition systems were used in the experiments. A Pressure Systems Inc.(PSI) Model 9010 Intelligent Pressure Scanner was used for pressure measurements, including tunnel contraction pressure difference measurements, three-hole pressure probe measurements and blade surface static pressure distribution measurements. A United Electronic Industries Inc. (UEI) PD2-MFS-8-800/14 PowerDAQ II simultaneous sample and hold board was used for hot-wire and hot-film measurements.

A schematic diagram of the PSI 9010 data acquisition system setup is shown in Figure 3.10. The scanner integrates 16 silicon DH200 pressure transducers, 8 of which are differential ± 5 kPa and the other 8 are absolute 310 kPa range. Only the first 8 differential transducers of ± 5 kPa range were used in the current study. The PSI 9010 unit has a 12 bit sequential analog-to-digital converter. Pressure data in engineering units is output through a serial interface. All data communications between the PSI 9010 module and the host computer are established through the RS-232 port with the Optomux serial communication protocol. A communication rate (baud rate) of 9600 bps was found to be most suitable for error free and time efficient transmission of the data. The sample rate is 12 samples/sec per channel.

For each individual transducer, three sets of calibrations were performed for different pressure ranges by using a micro manometer. For the pressure range of ± 1.0 inch WC (± 250 Pa) the calibration pressure step was 0.05 inch WC. For ± 5.0 inch WC (± 1.25 kPa) and ± 20.0 inch WC (± 5 kPa), the steps were 0.25 inch WC and 1.0 inch WC respectively. Based on the

Figure 3.10 Schematic Diagram of PSI 9010 Data Acquisition System Setup

calibration, the calibration coefficient was calculated, which is the ratio of actual pressure to the output pressure of the PSI 9010 unit. A typical PSI 9010 calibration curve is shown in Figure 3.11. The uncertainty of pressure measurements is estimated as about ± 0.25 Pa.

Figure 3.11 A Typical PSI 9010 Pressure Transducer Calibration Curve

During pressure measurements, 300 samples at each measurement point were collected. Zero offset of the pressure transducers was adjusted at the beginning and at each 15 minute intervals during a run.

The UEI PowerDAQ II data acquisition board, PD2-MFS-8-800/14, is a simultaneous sample-and-hold PCI card capable of acquiring data and streaming it to the hard disk at 800K

samples per second. The board has 8 single-ended 14-bit analog inputs, two 12-bit analog outputs, 32 digital I/O lines and three 16-bit counters. The input to the board could be either unipolar or bipolar, with a 5 or 10 volts range. The sample-and-hold amplifier samples all the input channels simultaneously and then holds the acquired input while the analog-to-digital converter converts it channel by channel. An external TTL signal can be used to trigger the analog sub-systems. During the unsteady flow study, the once-per-revolution signal from the photo detector in the wake generator is used to trigger the data acquisition system. The details of this data acquisition system, including the in-house developed software, is discussed by Mahallati (2002).

3.7 Probe Traversing Mechanism

The spanwise and pitchwise movements of the probes are controlled using a traversing mechanism, which is similar to that used by Rodger (1992). The traversing mechanism uses two 4-phase stepping motors, each driving a $1/4$ -20 threaded rod, to provide the transitional motion. The accuracy of the positioning provided by the traversing mechanism is estimated at ± 0.1 mm. The motors are driven by a controller. The communication between the motor controller and the host computer is provided by TTL signals from the computer's parallel port.

Chapter 4

Experimental Technique

4.1 Wind Tunnel Operating Point

The operating point of the low-speed wind tunnel is mainly determined in terms of the flow Reynolds number (Re). For LP turbine blade, the exit flow Mach number is about 0.8 and nowhere in the blade passage is Mach number larger than 1.0. So there is no shock wave in the blade passage, hence there is no sharp drop in the pressure coefficient ($C_{p,l}$) distribution over the blade. Although the flow Mach number distribution can not be matched to the actual engine conditions in the low speed wind tunnel tests, the similar pressure coefficient distribution over the blade can be achieved by changing the blade geometry. Therefore, as long as the flow Reynolds number and free stream turbulence intensity (FSTI) match the actual engine conditions, the boundary layer development on the blade surface is very similar to that under actual engine conditions. So the measurement results from low speed wind tunnel experiments are still valuable.

The Reynolds number used in this study is based on the cascade inlet flow velocity (V_1) and the blade axial chord (B_x).

$$Re = \frac{\rho V_1 B_x}{\mu} \quad (4.1)$$

The flow density (ρ) and viscosity (μ) are calculated from the atmospheric pressure and flow temperature at the tunnel operating conditions, which are collected on line. The inlet flow velocity (V_1) is determined from the contraction dynamic pressure ($P_{c1}-P_{c2}$) and the cascade inlet dynamic pressure ratio, $C_{q,1}$, which is calculated from the cascade inlet flow uniformity measurements (discussed in Section 4.3.1).

Another important operating condition of the wind tunnel is the free stream turbulence intensity (FSTI). It is a measure of the fluctuations in the flow velocity. FSTI, along with Reynolds number, influences the development of the boundary layer, which in turn affects the aerodynamic performance of the blades.

The residual FSTI near the cascade inlet is about 0.4 %, measured by using a single hot-wire. Turbulence intensities between wakes in actual engine operating conditions are approximately 3 - 5% (Halstead, *et al*, 1995a). The level of FSTI in the test section was raised from 0.4% to 4.5% by means of a square-bar turbulence-generating grid, placed 18.5 axial blade chord length upstream of the test cascade center blade leading edge. The turbulence grid consists of 3 vertical and 12 horizontal square bars, each 12.7 mm (0.5 inch) in width. The bars are spaced 50.8 mm

(2 inches) center to center in accordance with guidelines suggested by Roach (1987) for isotropic turbulence. The detailed turbulence-generating grid design procedure and measurement results are discussed by Mahallati (2002).

4.2 Data Analysis

4.2.1 Time Average

For a time series x_n , the time average or mean ($\bar{x}$) is defined as:

$$\bar{x} = \frac{1}{N} \sum_{n=1}^N x_n \quad (4.2)$$

where N is the total sample number.

The root-mean-square (RMS) of the time series x_n is given by

$$RMS = \sqrt{\frac{1}{N} \sum_{n=1}^N (x_n - \bar{x})^2} \quad (4.3)$$

which is the average variation from the mean value.

The RMS of a signal shows the amount of deviation from the mean of that signal. The RMS represents the modulus of the deviation, so it does not distinguish between positive and negative deviation from the mean.

4.2.2 Mass Average

The mass average of a flow property parameter x is defined as:

$$\hat{x} = \frac{\int x dm}{\int dm}$$

The mass flow rate ($\dot{m}$) for an infinitesimally thin strip at midspan, and for one blade passage can be written as $\dot{m} = \int_0^S \rho V_{ax} dy$. Assuming $\rho = \text{constant}$ for incompressible flow,

then the mass average can be written as:

$$\hat{x} = \frac{\int x dm}{\int dm} = \frac{\int_0^S x \rho V_{ax} dy}{\int_0^S \rho V_{ax} dy} = \frac{\int_0^1 x V_{ax} d\left(\frac{y}{S}\right)}{\int_0^1 V_{ax} d\left(\frac{y}{S}\right)} \quad (4.4)$$

where V_{ax} is the axial flow velocity, $\frac{y}{S}$ is the normalized pitchwise distance and S is blade pitch.

4.2.3 Ensemble Average

The use of phase-locked averaging to process the measurement data obtained in rotating machinery is a well-established technique. The ensemble mean of a quantity is found by taking an average of the signal at a fixed time past the trigger pulse (the phase) and over a large number of periods (cycles). The phase (or time) is measured with reference to the trigger

pulse. In the current study, the trigger pulse is obtained once per revolution of the spoked wheel, as described in Section 3.3.

The ensemble mean of a quantity x at a particular phase or time (t) is defined as:

$$\tilde{x}(t) = \frac{1}{N} \sum_{k=1}^N x(t)_k \quad (4.5)$$

where t is the time relative to the trigger signal and x could be velocity, shear stress *etc.*, N is the total number of cycles. In the current study, an once-per-revolution trigger signal is available from the photo detector mounted on the rotating wheel shaft in the wake generator.

The ensemble RMS is defined as:

$$x(t)_{RMS} = \sqrt{\frac{1}{N} \sum_{k=1}^N (x(t)_k - \tilde{x}(t))^2} \quad (4.6)$$

where t is the time from the once-per-revolution trigger signal and $\tilde{x}(t)$ is the ensemble mean at that time, N is the total cycle number.

The ensemble-skew is the third-order statistical moment of a signal, which distinguishes the positive or negative deviation of the signal at a particular time from the mean at the same time.

It is defined as:

$$x(t)_{SKEW} = \frac{\frac{1}{N} \sum_{n=1}^N (x(t)_k - \tilde{x}(t))^3}{x(t)_{RMS}^3} \quad (4.7)$$

The ensemble averaging technique is used to analyze the unsteady data, which will be discussed in Chapter 6.

4.2.4 Power Spectral Density

The power spectral density, PSD, describes how the power of a time series is distributed with frequency (f). Mathematically, it can be defined as the Fourier Transform of the autocorrelation sequence of the time series. The Fourier representation of a time series $x(t)$ is defined as:

$$X(f_k) = \lim \frac{1}{T} \int_{-1/2T}^{1/2T} x(t) \exp(i2\pi f_k t) dt \quad (4.8)$$

where T is the data length. The power spectrum is then defined as:

$$P(f_k) = E\{X(f_k)X^*(f_k)\} \quad (4.9)$$

where $X^*(f_k)$ is the complex conjugate of $X(f_k)$.

The power spectrum represents the contribution to the power (proportional to the mean square) from the frequency components at frequency of f_k over the width of Δf . The power spectral density distribution is one of the analysis methods used here to help identify the

boundary layer transition (Volino and Hultgren, 2001 and Lee and Kang, 2000). In laminar flow, the PSD value is low and mainly in lower frequency range. It increases in magnitude and frequency band as the boundary layer starts transition and reaches the maximum frequency range at mid-transition (intermittency $\gamma \approx 0.5$), then decreases when the boundary layer approaches turbulent. Furthermore, if the boundary layer transition happens in natural mode there are spectral peaks in the T-S wave frequency range that may be visible in the PSD distribution. The detail of frequency domain analysis of the present steady hot-film data will be discussed in Chapter 5.

4.3 Flow Quality

The flow quality in the cascade test section was examined by the inlet flow uniformity, outlet flow periodicity and flow two-dimensionality. The adjustable surfaces in the test section, shown in Figure 3.2, were used to control the flow quality. The measurements were conducted by means of the three-hole pressure probe traverses at 1.2 axial chord length upstream of the blade leading edge measuring plane and at 0.5 axial chord length downstream of the blade trailing edge measuring plane (refer to Figure 3.3).

Three-hole probe measurement data were calculated from the probe calibration curves and then reduced to five parameters: flow angle α , velocity ratio C_v , static pressure ratio C_{ps} , dynamic pressure ratio C_q and total pressure ratio C_{p0} . In the data reduction, the cascade inlet

parameters were normalized by the parameters at wind tunnel contraction outlet and cascade outlet parameters were normalized by the cascade inlet parameters.

The velocity ratio C_v is defined as:

$$C_v = \frac{\bar{V}}{\bar{V}_{ref}} \quad (4.10)$$

For cascade inlet flow $C_{v,1} = \frac{\bar{V}_1}{\bar{V}_c}$, where $\bar{V}_c$ is the mean flow velocity at the wind tunnel contraction outlet. For outlet flow $C_{v,2} = \frac{\bar{V}_2}{\bar{V}_1}$.

The static pressure ratio C_{ps} is defined as:

$$C_{ps} = \frac{\bar{P}_s - \bar{P}_{s,ref}}{\bar{P}_{0,ref} - \bar{P}_{s,ref}} \quad (4.11)$$

For inlet flow $C_{ps,1} = \frac{\bar{P}_{s1} - \bar{P}_{c2}}{\bar{P}_{c1} - \bar{P}_{c2}}$, for outlet flow $C_{ps,2} = \frac{\bar{P}_{s2} - \bar{P}_{s1}}{\bar{P}_{01} - \bar{P}_{s1}}$.

The dynamic pressure ratio C_q is defined as:

$$C_q = \frac{\bar{P}_0 - \bar{P}_s}{\bar{P}_{0,ref} - \bar{P}_{s,ref}} \quad (4.12)$$

For inlet flow $C_{q,1} = \frac{\bar{P}_{01} - \bar{P}_{s1}}{\bar{P}_{c1} - \bar{P}_{c2}}$, for outlet flow $C_{q,2} = \frac{\bar{P}_{02} - \bar{P}_{s2}}{\bar{P}_{01} - \bar{P}_{s1}}$.

The total pressure ratio C_{p0} is defined as:

$$C_{p0} = \frac{\bar{P}_0 - \bar{P}_{0,ref}}{\bar{P}_{0,ref} - \bar{P}_{s,ref}} \quad (4.13)$$

For inlet flow $C_{p0.1} = \frac{\bar{P}_{01} - \bar{P}_{c1}}{\bar{P}_{01} - \bar{P}_{s1}}$, for outlet flow $C_{p0.2} = \frac{\bar{P}_{02} - \bar{P}_{01}}{\bar{P}_{01} - \bar{P}_{s1}}$.

These coefficients are used to examine the cascade inlet flow uniformity and outlet flow periodicity, monitor the wind tunnel operating conditions and calculate the blade profile losses.

4.3.1 Inlet Flow Uniformity

The cascade inlet flow uniformity is very important to ensure constant angularity and velocity across each blade inlet in the cascade. The adjustable side flaps and tailboards in the test section, which are shown in Figure 3.2, are mainly used to control the flow uniformity for each operating condition.

A pitchwise traverse with the three-hole pressure probe was carried out at 1.2 axial chord length upstream of the blade leading edge plane. The measurements were first taken at eight locations near extremes of the measuring length. Since the change in any control surface position will affect the entire flow, the adjustment procedure must be repeated until the parameter differences at the two extremes are small. Then the full pitchwise traverse with evenly spaced measurement points was taken across the three middle blade pitches. The control surfaces were then fine-tuned to give the best possible inlet uniformity. This procedure was repeated for each operating conditions, *i.e.*, for four Reynolds numbers ($Re = 2.5 \times 10^4$,

5.0×10^4 , 1.0×10^5 and 1.5×10^5) and two FSTI levels (FSTI = 0.4% and 4.5%). Since for incompressible flow the adjustment of the control surfaces during the outlet flow periodicity measurement, which are described in Section 4.3.2, would change the inlet flow conditions, the inlet flow uniformity measurements were repeated after the outlet flow periodicity measurements.

The typical inlet flow uniformity plots covering three blade pitches at the middle of the cascade at an inlet Reynolds number of 100000 and FSTI = 0.4% and 4.5% are presented in Figure 4.1 and Figure 4.2 respectively. The flow inlet angle and velocity profile are the main parameters to ensure the flow uniformity. The flow angularity at the inlet to the cascade varies periodically about $\pm 0.5^\circ$ due to the potential effect of the blades. The actual angle seen by the cascade blades, however, may be varying by $\pm 0.5^\circ$ of the measured value due to the uncertainty in the three hole pressure probe measurements. This would show up as a systematic shift of the flow angle curve. The inlet velocity profiles also vary slightly due to the blade potential effect. The cascade inlet dynamic pressure ratio ($C_{q,i}$) is used to calculate the cascade inlet velocity from the contraction dynamic pressure ($P_{c1} - P_{c2}$) and then used to set the wind tunnel operating conditions.

Figure 4.1 Typical Inlet Flow Uniformity for $Re=100000$, $FSTI=0.4\%$

(a) Flow Angle (α_1)

(b) Flow Velocity Ratio ($C_{v,1}$)

(c) Dynamic Pressure Ratio ($C_{q,1}$)

(d) Total Pressure Ratio ($C_{p0,1}$)

Figure 4.2 Typical Inlet Flow Uniformity for $Re=100000$, $FSTI=4.5\%$

(a) Flow Angle (α_1)

(b) Flow Velocity Ratio ($C_{v,1}$)

(c) Dynamic Pressure Ratio ($C_{q,1}$)

(d) Total Pressure Ratio ($C_{p0,1}$)

4.3.2. Outlet Flow Periodicity

The aerodynamic behavior of the blades is influenced by the presence of the adjacent blades. In the real engine, the blades are located around a circumference. In principle, it would require an infinite number of blades to simulate this condition in a linear cascade. However, the required flow Reynolds number, aspect ratio and blade spacing limit the blade numbers in the cascade. To simulate as closely as possible an infinite blade row, the tailboards downstream of the trailing edges of the end blades are used to guide the outlet flow and obtain periodicity in the cascade outlet flow.

A coarse three-hole probe traverse at 0.5 axial chord length downstream of the blade trailing edge was first performed across the full cascade. The two tailboards were the main control surfaces for adjusting outlet flow periodicity. Sometimes the two side flaps also needed to be adjusted by small amounts. The total pressure and the flow angle were the main criteria for this adjustment. Once approximate flow periodicity had been achieved, the traverse was repeated with a smaller step across the wakes. The position of the tailboards was then fine tuned until the periodicity was achieved for the three middle blades

Figure 4.3 and Figure 4.4 show the typical outlet flow periodicity measurement results at a Reynolds number of 100000 with FSTI= 0.4% and 4.5% respectively. The wakes after the blade trailing edges can be detected from the total pressure ratio plots in Figure 4.3 (d) and 4.4 (d). Due to the effect of the shear flow in the wakes, the measured flow angles across the

Figure 4.3 Typical Outlet Flow Periodicity for $Re=100000$, $FSTI=0.4\%$

(a) Flow Angle (α_2)

(b) Flow Velocity Ratio ($C_{v,2}$)

(c) Static Pressure Ratio ($C_{ps,2}$)

(d) Total Pressure Ratio ($C_{p0,2}$)

Figure 4.4 Typical Outlet Flow Periodicity for $Re=100000$, $FSTI=4.5\%$ (a) Flow Angle (α_2)(b) Flow Velocity Ratio ($C_{v,2}$)(c) Static Pressure Ratio ($C_{ps,2}$)(d) Total Pressure Ratio ($C_{p0,2}$)

wakes are not the true flow angles (refer to Section 3.4.1). But as shown in Figure 4.3 (a) and 4.4 (a), the measured flow angles vary periodically across the three blade pitches. Figure 4.3 (b) and 4.4 (b) show that the cascade exit-to-inlet velocity ratio (V_2/V_1 or $C_{V,2}$) is about 1.6. These three-hole probe pressure measurement results are also used to calculate the blade profile measured losses in steady conditions, which will be discussed in Chapter 5.

4.3.3 Two-Dimensionality of the Flow

The flow two-dimensionality is a very important flow quality parameter in linear cascade tests, which are intended to measure the characteristics of just the airfoil profile. The degree of flow two-dimensionality has generally been determined by measuring the axial velocity-density ratio (AVDR) across the blade row. AVDR is the ratio of mass flow rate per unit area at the outlet of the cascade to that at the inlet as measured for the stream-tube at mid-span. A value of unity for AVDR, as evaluated at mid-span, indicates that on average there is no contraction or expansion of the stream-tube passage through the cascade. For incompressible flow such as that in low speed wind tunnel, since the flow density can be assumed to be constant, the axial velocity ratio (AVR) is usually used. The AVR can be defined mathematically as:

$$AVR = \frac{\hat{V}_{ax2,MS}}{\hat{V}_{ax1,MS}} \quad (4.14)$$

where $\hat{V}_{ax1,MS}$ and $\hat{V}_{ax2,MS}$ is mass-averaged inlet and outlet axial flow velocity measured at mid-span respectively.

For the current study, the AVR was calculated from the three-hole pressure probe measurements at the mid-span of the inlet and outlet measuring planes. An AVR equal to 1.0 is a necessary, but not sufficient, condition for ensuring two-dimensional flow through the cascade (Rodger *et al.*, 1992). Here it is used to check the flow two-dimensionality. Figure 4.5 shows the flow AVR at different operating conditions. From the near unity values, it can be concluded that the flow at the mid-span is almost two-dimensional. Rodger *et al.* (1992) has investigated the significance of the variation of mid-span losses and deviation angle with AVR and showed that the small variation of AVR, such as that in current cases, would not change the losses and deviation much.

Figure 4.5 Flow AVR at Different Flow Conditions

Chapter 5

Presentation & Discussion of Steady Results

5.1 Introduction

The steady boundary layer developments on the suction surface of the Pratt & Whitney PAK-B low pressure (LP) turbine blade were studied by means of surface static pressure taps and surface-mounted hot-film sensors. The current study, as the baseline for the future unsteady study, was focused on the boundary layer separation, transition and reattachment under steady flow conditions, *i.e.*, with no wake coming from previous blade rows. The experimental data were collected for eight cases: two free-stream turbulence intensities (FSTI) of 0.4% and 4.5% and four Reynolds numbers of 25000, 50000, 100000 and 150000 based on the cascade inlet velocity (V_1) and blade axial chord (B_x).

In the profile static pressure distribution, the boundary layer separation point is usually assumed to be at the beginning of the constant-pressure plateau. The reattachment point

corresponds to the point of intersection of the measured pressure shape with the potential pressure curve (refer to Section 2.2.1).

Surface-mounted hot-film measurements can provide more information about the boundary layer development. The boundary layer separation point and reattachment point can be determined from the beginning and end of the near zero mean quasi-wall-shear stress (τ) calculated from the hot-film measurement data. The RMS value of the hot-film measurement is used to provide information about the boundary layer state (that is, laminar, transitional or turbulent). The raw hot-film signals can be used to gain further insights into the boundary layer development. Furthermore, the fast response of the hot-film sensors makes this technique suitable for unsteady flow measurements. The relationship between the hot-film measurement data and the boundary layer conditions is examined in this chapter for the steady flow case. The understanding developed here will then form the basis for interpreting later unsteady flow data.

5.2 Surface Static Pressure Measurements

The blade surface static pressure coefficient ($C_{p,l}$) distributions for the range of free stream conditions examined are presented in Figure 5.1. Boundary layer separation is observed on the suction surface in all conditions. For Reynolds numbers of 25000 and 50000, at FSTI = 0.4%, the boundary layer fails to reattach before the trailing edge of the blade. In all other cases a closed separation bubble is present.

Figure 5.1 Surface Static Pressure Coefficient Distributions

(a) FSTI=0.4% (b) FSTI=4.5%

In the conditions of high Reynolds number ($Re=100000$ and 150000) with low and high FSTI and the conditions of low Reynolds number ($Re=25000$ and 50000) with high FSTI, the flows continually accelerate on the front portion of the suction surface and reach the maximum velocity at about $0.62 B_x$ (the blade suction peak). Then the flow undergoes deceleration and consequently separates from the blade surface downstream at around $0.73 B_x$ due to the adverse pressure gradient and a separation bubble forms. The forward portion of the separation bubble is a constant-pressure region. The free shear layer over the separation bubble entrains high momentum fluid from the free-stream flow and forces the flow to reattach before the trailing edge; the pressure is then recovered. The flow separation points do not change much in the different flow conditions. However, the reattachment point strongly depends on the flow conditions. As the Reynolds number or FSTI increases, the reattachment point moves upstream and the separation bubble size is reduced. Since the separation bubbles only locally affect the pressure distribution on the blade surface, the separation bubbles formed in these conditions are usually referred to as short bubbles (refer to Section 2.2.1).

For low Reynolds number flows, *i.e.*, $Re=25000$ and 50000 , at low FSTI ($FSTI=0.4\%$), the suction peak moves to about $0.49 B_x$. The boundary layer separates early (at about $0.62 B_x$) and never reattaches before the trailing edge of the blade. This type of bubble changes the whole surface pressure distribution on the suction side, so they are classified as long bubbles (Section 2.2.1).

The current measured results of the blade surface static pressure distributions are similar to the results by Murawski and Vafai (2000). They measured the surface static pressure

distribution on the same blade geometry and in the similar range of flow conditions.

The locations of the boundary layer separation point and especially the reattachment point are often difficult to determine precisely from surface static pressure distributions. For example, examining the surface static pressure coefficient distribution at the flow condition of $Re = 100000$ and $FSTI = 0.4\%$ in Figure 5.1 (a), the static pressure coefficient begins to level off at about $0.71 B_x$ (marked “A” in the figure) probably due to the effect of the separation bubble on the pressure distribution before the separation point. The pressure coefficient at $0.74 B_x$ (marked “B”) is higher but very close to the constant-pressure plateau value. Therefore it could be assumed that the flow separates between 0.71 and $0.74 B_x$, say $0.73 B_x$. But the reattachment point is very difficult to detect accurately. The commonly used criterion to detect the reattachment point from the static pressure distribution is that the reattachment point corresponds to the intersection point of the measured pressure shape with the potential pressure curve. But it is not easy to determine the potential pressure curve or the intersection point from experimental data only. In current case, the flow may reattach between $0.86 B_x$ and $0.91 B_x$ (marked “C” and “D” respectively in the figure).

Mayle (1991) assumed that the separated flow transition completes at the end of the constant pressure region, *i.e.*, the maximum height of the separation bubble or the knee of the static pressure distribution (refer to Figure 2.1). The knee of the static pressure distribution for Reynolds number of 100000 with low $FSTI$ is marked as “E” in Figure 5.1(a), which occurs at about $0.83 B_x$. But the surface-mounted hot-film measurements discussed later suggest that this is not this case. Moreover, there is not obvious knee in the pressure distribution for $Re = 150000$ at low $FSTI$. The pressure distribution measurement

results will be compared with the hot-film measurement results in Table 5.1.

In any case, such static pressure distributions can not be measured for unsteady flow, at least for the low levels of dynamic pressure present in the current study, due to the low frequency response of the measurement system. Also, the static pressure measurements can not provide boundary layer transition information. The surface-mounted hot-film measurements can be used to detect these points and can provide more information about boundary layer development. The surface-mounted hot-film measurement data for the steady cases are examined next.

5.3 Surface-Mounted Hot-Film Measurements

Surface-mounted hot-film data were collected for all the eight examined flow conditions. For each hot-film sensor, 20480 samples were recorded at a sampling rate of 40 kHz. The quasi-wall-shear stress (τ), calculated from un-calibrated hot-film sensor signals by using Equation 3.25, forms the basis for the present analysis. The boundary layer behaviors are determined by the analysis of the experimental data in both the time domain and the frequency domain. The measurement result will be presented and discussed by means of time average (mean) and RMS of the quasi-wall-shear stress and raw hot-film signals as well as the power spectral density (PSD) distributions. The RMS of the quasi-wall-shear stress is normalized by the mean value at the same chordwise location to alleviate the effect of the mean value variation on the RMS.

5.3.1 High Reynolds Number Cases ($Re=100000$ & 150000)

The distributions of mean and normalized RMS of the quasi-wall-shear stress from the hot-film measurements for $Re=100000$ at low and high FSTI (FSTI=0.4% & 4.5%) are shown in Figure 5.2. In the figures, the measurement data points are arbitrarily connected with straight lines although there is some scatter in the data. The lines are intended simply to guide the eye. The scatter is believed to be mainly due to differences among the uncalibrated hot-film sensors such as differences in resistance of the sensors and/or leads, and is not the result of the flow physics.

The mean quasi-wall-shear stress, shown in Figure 5.2(a), first decreases near the blade leading edge due to the strong favorable pressure gradient. But it starts to increase after about $0.20 B_x$. This trend does not physically match the predicted wall shear stress distribution along an airfoil surface. It may be because that Equation 3.25 was derived from the flow with zero pressure gradient, it may not be valid for the flow with such strong pressure gradient. Since essentially the hot-film sensors measure the heat losses, the quasi-wall-shear stress goes up as the flow accelerates. Then the maximum mean quasi-wall-shear stress is expected at the blade suction peak, which is located at about $0.62 B_x$ for current flow conditions according to the surface static pressure measurements. However, the measured peak values of the mean quasi-wall-shear stress from the hot-film measurements seem to be about $0.02 B_x$ earlier than the suction peak. The uncertainty in the spatial location of both the pressure taps and the hot-film sensors is in the order of $2\% B_x$, which may account for this disagreement.

Figure 5.2 Mean and Normalized RMS of Quasi-Wall-Shear Stress at $Re=100000$

(a) Mean (b) Normalized RMS

The strong favorable pressure gradient keeps the flow essentially laminar up to the suction peak, as evident from the low RMS values in Figure 5.2(b). Due to the disturbances in the free stream at high FSTI, the mean quasi-wall-shear stress and RMS values are higher than those at the low FSTI condition.

After the suction peak, the mean quasi-wall-shear stress suddenly decreases due to the flow deceleration on the aft portion of the blade suction side. Shortly after the suction peak, the boundary layer separates from the blade surface, as indicated by the near-zero values of the mean quasi-wall-shear stress. The change in gradient of the mean quasi-wall-shear stress before separation point is probably the result of the effect of the separation bubble on the upstream flow field. Flow reattachment is indicated by the end of the near-zero mean quasi-wall-shear stress. For low FSTI flow, the boundary layer separates at about $0.72 B_x$ and reattaches at about $0.82 B_x$, while for high FSTI flow, it separates at about $0.74 B_x$ and reattaches at about $0.78 B_x$.

Interestingly, some cases show intermediate levels of mean quasi-wall-shear stress at one or two sensors between the separated region (near-zero mean quasi-wall-shear stress) and the complete reattachment flow levels, such as that marked “A” and “B” in Figure 5.2(a). This is probably because around the boundary layer reattachment point, the velocity profile has to recover from the typical separated profile to attached flow profile, which results in a lower near wall velocity region downstream of the reattachment point (refer to Figure 2.1).

In both low and high FSTI conditions, the normalized RMS values (in Figure 5.2(b))

starts to increase at about $0.60 B_x$. This indicates the development of instabilities in the boundary layer and it is believed that the flow is starting to undergo transition (Svensdotter and Fransson, 1998, also refer to Figure 2.5). The transition onset location also can be detected from the hot-film raw signals discussed later. In both cases, the boundary layer is starting to undergo transition prior to separation.

Svensdotter and Fransson (1998) claimed that for the attached flow, the peak RMS value corresponds to the mid-transition (intermittency $\gamma \approx 0.5$) location. In current study, since the separated flow transition happens in the free shear layer over the separation bubble, the hot-film sensors under the bubble may be thought to provide incomplete information about transition. However, the measurement results from hot-wire boundary layer traverse by Yaras (2002) suggest that the characteristic locations of the boundary layer transition detected from the measurements above the free shear layer and in the separation bubble are not significantly different. In current hot-film measurements, the normalized RMS in Figure 5.2(b) varies continuously both outside and inside of the separation bubble. This suggests that the hot-film measurements can provide useful information about the separated flow transition by using proper normalization. The flow transition develops very quickly after the boundary layer separates, indicated by the sharp increase of the normalized RMS. The maximum RMS occurs at $0.82 B_x$ and $0.76 B_x$ respectively for low and high FSTI flows.

The sharp decrease in RMS values after flow reattachment point shows that the reattached boundary layer is still transitional, which will be discussed in detail in the later raw signal analysis. The decrease in the mean shear stress and RMS becomes more gradual after around $0.91 B_x$ for low FSTI flow and $0.86 B_x$ for high FSTI flow, which indicates the

development of turbulent flow (refer to Figure 2.5). Thus the boundary layer transition is believed to end at $0.91 B_x$ and $0.86B_x$ for low and high FSTI flow respectively. The RMS distribution in Figure 5.2 (b) also shows the boundary layer transition in high FSTI condition occurs earlier than that in the low FSTI condition due to the high disturbance in the free stream flow.

The third order statistical moment of the hot-film measurement data, skew defined in Equation 4.7, also has been used to provide information about the boundary layer transition progression. As shown in Figure 2.5, the skew is zero in laminar flow and increases as the boundary layer starts transition. It reaches the positive maximum when intermittency γ is 0.25 and then go back to zero at mid-transition ($\gamma=0.5$). The negative maximum skew occurs at $\gamma=0.75$ and it return to zero again in fully turbulent flow. Figure 5.3 presents the skew of the quasi-wall-shear stress from the hot-film measurements for $Re=100000$ at low and high FSTI.

In both low and high FSTI cases, the skew starts to take negative value at the location where the peak RMS occurs in Figure 5.2(b) and reaches the negative maximum at $0.88 B_x$ and $0.80 B_x$ respectively. This agrees with the common used rule discussed above. But it does not go back to zero in the fully turbulent flow and also there are large scatters in the data. Moreover, the skew is expected to be positive in the early transition stage (*i.e.*, γ between 0 and 0.5). However, it is not clearly shown in the figure. Furthermore, there is no additional information about the boundary layer transition state provided from the skew than the normalized RMS in current study. Therefore, the skew of the quasi-wall-shear stress will not be presented in the following discussion for other examined conditions.

Figure 5.3 Skew of Quasi-Wall-Shear Stress at $Re=100000$

The time histories of the raw quasi-wall-shear stress for selected hot-film sensors at $Re=100000$ are presented in Figure 5.4. For the low FSTI flow (Figure 5.4(a)), the signals from sensors on the forward part of the suction surface (*i.e.*, before $0.55 B_x$) are relatively quiet, confirming that the boundary layer is laminar. The most interesting signals are from the sensors located at $0.55 B_x$ and $0.57 B_x$ (marked “A” and “B” in the figure respectively). The signal from sensor at B has downward tails, marked “T” in the figure, which has been interpreted as suggesting the start of boundary layer transition (Svensdotter *et al*, 1998 and Anderson *et al*, 1991). Here the transition onset is taken to occur when the instabilities in the boundary layer are amplified and grow into loop vortices with large fluctuation. Turbulent spots may not necessarily occur. It corresponds to the slow increasing of the RMS in Figure 5.2(b). The fluctuation frequency from the sensor at B also appears to be higher than that from the sensor at A. The observation regarding the frequency of the fluctuations is confirmed by the frequency domain analysis discussed later.

Figure 5.4 Time Histories of the Raw Quasi-Wall-Shear Stress at $Re=100000$ (a) $FSTI=0.4\%$ (b) $FSTI=4.5\%$

The signals from the sensors under the separation bubble (between $0.72 B_x$ and $0.82 B_x$) are relatively quiet and with near zero mean values. Once the flow reattaches (at about $x/B_x=0.82$), the signal jumps to a high mean level and the fluctuations are large. The upward tails in the signal from the reattachment point, marked “T” in the figure, indicate the flow is still transitional (Svensdotter *et al*, 1998 and Anderson *et al*, 1991). The increase in the fluctuation magnitude from the next downstream sensor ($x/B_x=0.85$) indicates the transition is still developing. The decrease in mean level and fluctuations from the sensor far downstream of the reattachment point (for example the signal at $x/B_x=0.95$) shows the flow has become completely turbulent before the blade trailing edge.

For the high FSTI flow (Figure 5.4(b)), signals from the forward portion of the blade suction surface (before $0.55 B_x$) contain low frequency fluctuations, which is thought to be due to the disturbance wave in the free stream flow. The instabilities in the boundary layer starts to develop at $x/B_x=0.57$, which is indicated by the increased fluctuation frequency (comparing to the fluctuations of the signals at 0.41 and $0.55 B_x$). The downward tails (marked as “T” in the figure) at this location are not obvious due to the high free stream fluctuation in this flow condition. The signals from the sensors under the separation bubble (*i.e.*, between 0.74 and $0.82 B_x$) are also quiet. The signal from the sensor at the reattachment point ($x/B_x=0.82$) has upward tails, which indicates the reattached flow is also transitional. The fluctuation magnitude of the signal from the sensor downstream of the reattachment point (at $0.85 B_x$) decreases, which indicates the transition is almost complete there. The small fluctuation at the far downstream (*i.e.*, $x/B_x=0.95$) again indicates the completely turbulent flow state.

The frequency-domain plots, Figure 5.5, show the power spectral distribution of the signal from selected hot-film sensors at $Re=100000$ with low and high FSTI. The power spectral density distribution can also be used to determine the boundary layer transition (refer to Section 4.2.4). For the low FSTI case (Figure 5.5(a)), the signals from the sensors before $0.55 B_x$ have spectral peaks at about 1.2 kHz, but the spectral magnitudes have not been amplified, such as the peaks marked “A” and “B” in the figure. It may be open to other interpretation, but this frequency is in the same order of the predicted Tollmien-Schlichting (T-S) wave frequency in this flow condition. The predicted T-S wave frequency is based on the correlation of Warren and Hassan (1998), which relates the T-S wave frequency to the boundary layer momentum thickness (θ), and the numerical simulation on PAK-B profile by Langtry (2002). While at $0.57 B_x$, the magnitude of the spectral peak increases (marked “C”) and there are more peaks at around 2.3 kHz (such as that marked “D”), which suggests the development of the T-S wave (Volino and Hultgren, 2001). Thus, in this flow condition the boundary layer starts transition in the natural mode before separation.

Although the spectral peaks in this region seem to support the argument about the T-S wave development, it is a little unexpected. Based on the correlation of Warren and Hassan (1998), the T-S wave frequency should increase as the boundary layer develops downstream. But from Figure 5.5(a), it can be seen that the spectral peaks occur at almost the same frequency at different streamwise locations between $0.20 B_x$ and $0.60 B_x$. This may be because the strong favorable pressure gradient on the blade suction surface in this region makes the boundary layer develop slowly and the boundary layer thickness does not change much along the streamwise direction, so neither does the T-S wave frequency.

Figure 5.5 Power Spectral Distribution at $Re = 100000$

(a) FSTI=0.4% (b) FSTI=4.5%

Another possible reason is that these spectral peaks came from the environment noise. But it seems not occur in all test cases discussed later. Thus, more further work may be needed to check this observation.

The signal from the sensor located immediately after the flow reattachment point (*i.e.*, at $x/B_x=0.82$) has high spectra at very wide frequency range, which confirms that the reattached flow is transitional (Volino and Hultgren, 2001 and Lee and Kang, 2000). The spectra from the sensor located at $0.85 B_x$ have almost uniform distribution in a wide frequency range, which suggests the transition of the reattached flow still develops (Lee and Kang, 2000). Near the trailing edge the spectral magnitude is low and mainly at low frequency range, which indicates the flow is completely turbulent there.

For high FSTI flow (Figure 5.5(b)), the signals from the sensors on the forward part of the suction surface have high spectral magnitude at low frequency range, which is due to the low frequency disturbance wave in the free stream. The increasing spectral magnitude at the higher frequency range at $x/B_x=0.55$, marked “E” in Figure 5.5(b), indicates the beginning of the boundary layer transition. No spectral peak in T-S wave frequency range is found. Therefore, the boundary layer transition in this high FSTI flow condition starts in bypass mode before separation. The transitional reattachment state is also confirmed by the wide frequency range of the spectral distribution at $0.80 B_x$. The low spectral magnitude at far downstream of the reattachment point (*i.e.*, at $x/B_x=0.95$) shows the completely turbulent boundary layer state. Another phenomenon needed to mention here is the low spectral magnitude at low frequency range in the turbulent flow region (*i.e.*, at $x/B_x=0.95$). This indicates that the inner layer of the turbulent boundary layer is not affected much by the free

stream disturbance.

The distributions of mean and normalized RMS values of quasi-wall-shear stress for $Re=150000$ at low and high FSTI cases, presented in Figure 5.6, show the similar pattern as $Re=100000$ flow. Even in this higher Reynolds number conditions the boundary layer still separates from the blade suction surface. But the separation bubble size is reduced. For the low FSTI flow, the boundary layer separates at about $0.72 B_x$ and reattaches at about $0.80 B_x$. While for the high FSTI flow, it separates at about $0.74 B_x$ and reattaches at about $0.78 B_x$. In both cases, the boundary layer starts to undergo transition prior to separation and reattaches transitional. The detail information about the characteristic locations of the boundary layer development can be found in Table 5.1.

Figure 5.7 and 5.8 present the time histories of the raw quasi-wall-shear stress and power spectral distributions for selected hot-film sensors at $Re=150000$, respectively. For the low FSTI flow, the boundary layer starts laminar from the blade leading edge and begins transition at $0.55 B_x$, which is indicated by the presence of downward tails in the raw signal. The spectral peaks in the power spectral distribution again confirm the natural mode of the boundary layer transition. The raw signals and spectral distributions at and after the reattachment point, which is located at about $x/B_x=0.82$, show that the reattached flow is transitional. The boundary layer transition is almost complete at $0.89 B_x$. For high FSTI flow, the favorable pressure gradient keeps the boundary layer laminar up to $0.41 B_x$, even through there are large low-frequency fluctuations in the flow. The boundary layer starts transition in bypass mode at $0.55 B_x$. The flow separates at about $0.74 B_x$, and then reattaches transitionally at $0.78 B_x$. The boundary layer transition ends at about $0.85 B_x$.

(a)

(b)

Figure 5.6 Mean and Normalized RMS of Quasi-Wall-Shear Stress at $Re=150000$

(a) Mean (b) Normalized RMS

Figure 5.7 Time Histories of the Raw Quasi-Wall-Shear Stress at $Re=150000$ (a) $FSTI=0.4\%$ (b) $FSTI=4.5\%$

Figure 5.8 Power Spectral Distribution at $Re = 150000$

(a) FSTI=0.4% (b) FSTI=4.5%

5.3.2 Low Reynolds Number Cases ($Re=25000$ & 50000)

The mean and normalized RMS values of the quasi-wall-shear stress from the surface hot-film measurements at $Re=25000$ with low and high FSTI are shown in Figure 5.9. For the low FSTI flow, the boundary layer starts laminar, which is indicated by the low and flat normalized RMS values, and separates at $x/B_x=0.60$, which is about 10 percent axial chord earlier than that in the high Reynolds number cases. The separated boundary layer fails to reattach before the blade trailing edge and results in an open separation bubble. The mean quasi-wall-shear stress distribution in this condition does not take the same shape as that in the higher Reynolds number and/or high FSTI conditions, which suggests the separation bubble changes the whole flow field on the blade suction surface and it is a long separation bubble. This agrees with the observation from surface static pressure measurements. The higher mean level at the rear portion of the separation bubble indicates there exist strong reverse flow, which also can be seen in the raw hot-film signals discussed later.

At $Re=25000$ and low FSTI (Figure 5.9(b)), there are sharp increases in RMS between 0.50 and $0.60 B_x$. This seems to suggest that the boundary layer starts transition before separation, but there is no evidence showing the occurrence of transition at this region in the hot-film raw signals and the power spectrum distributions. The similar observation is also noticed at $Re=50000$ and low FSTI. This phenomenon seems to only occur in the flow conditions where long separation bubbles were formed. It may be due to the effect of the long bubble on the pressure distribution, which reduces the mean quasi-wall-shear stress. Since the RMS values presented in the figures are normalized by the mean value, the

(a)

(b)

Figure 5.9 Mean and Normalized RMS of Quasi-Wall-Shear Stress at $Re=25000$

(a) Mean (b) Normalized RMS

rapid increase in normalized RMS appears before the boundary layer separation. It does not suggest the beginning of boundary layer transition. In the current case, the boundary layer may start transition at $0.62 B_x$. The peak RMS occurs at $0.80 B_x$ and the separated flow transition may end at about $0.90 B_x$.

For the high FSTI flow, the boundary layer also starts laminar and separates shortly after the suction peak at about $0.68 B_x$. The flow reattaches before the blade trailing edge (at about $x/B_x=0.86$). The slow decrease in the mean shear stress and RMS after reattachment point suggests the flow reattaches completely turbulent.

The time history traces for selected hot-film sensors at $Re=25000$ are presented in Figure 5.10. For low FSTI flow (Figure 5.10(a)), the signals are relatively quiet and no downward tails appear before the separation point (the signals before $0.60 B_x$). Thus the boundary layer does not appear to undergo transition before separation. In the forward portion of the separation bubble (between 0.60 and $0.76 B_x$), the signals are very quiet and with near zero mean value. However, the signals at the aft portion of the bubble (for example, the signal at $x/B_x=0.82$) contains low frequency fluctuations, which is believed to be the reverse flow in the open separation region.

For the high FSTI flow (Figure 5.10(b)), the time histories of the hot-film signals before the separation point contain only some low frequency fluctuations. There is no evidence suggests the boundary layer starts transition before separation. The separated flow reattaches at about $0.85 B_x$. Compared with the high Reynolds number conditions, the reattachment point moves downstream. After the flow reattaches, the signals do not have

Figure 5.10 Time Histories of the Raw Quasi-Wall-Shear Stress at $Re=25000$ (a) $FSTI=0.4\%$ (b) $FSTI=4.5\%$

significant tails, which indicates the flow is fully turbulent. The transition thus appears to be completed in the free shear layer above the separation bubble.

Figure 5.11 presents the power spectrum of the signals from selected hot-film sensors at $Re=25,000$ with low and high FSTI. In the low FSTI case (Figure 5.11(a)), there are no amplified spectral peaks in T-S wave frequency range before separation, which confirms that the boundary layer separation is laminar. The signals from the sensors located at the rear portion of the open separation bubble (after $0.76 B_x$) have high energy contained at relative low frequencies due to the strong reverse flow. In the high FSTI case (Figure 5.11(b)), the signals contain high energy at low frequencies before separation due to the disturbance in the free stream flow. There is no high power spectra at higher frequency range, confirming that transition does not start before boundary layer separation. The signals from the sensors located at and after the reattachment point (at about $x/B_x=0.85$) do not have high energy content at the high frequency range, which suggests that the reattachment flow is completely turbulent.

The mean quasi-wall-shear stress and normalized RMS of the hot-film measurements at $Re=50000$ with low and high FSTI are presented in Figure 5.12. For low FSTI flow, the laminar boundary layer separates at $0.63 B_x$. The separated flow does not reattach before the blade trailing edge, resulting in a long open separation bubble. The higher mean shear stress at the aft region of the open bubble is also because of the strong reverse flow. The separated flow transition starts at $0.65 B_x$ and ends at $0.85 B_x$ as identified by the normalized RMS. The maximum RMS occurs at $0.78 B_x$. For high FSTI flow, the boundary layer separates at $0.72 B_x$, almost the same location as that for high Reynolds number flows, and reattaches

Figure 5.11 Power Spectral Distribution at $Re = 25000$

(a) FSTI=0.4% (b) FSTI=4.5%

Figure 5.12 Mean and Normalized RMS of Quasi-Wall-Shear Stress at $Re=50000$

(a) Mean (b) Normalized RMS

at $0.80 B_x$. The slightly increasing RMS before flow separation suggests the boundary layer may be starting to undergo transition before separation due to the high disturbance in the free stream flow. But the raw signals and the power spectral distributions at these locations, which will be discussed later, show that it is simply due to the development of the instabilities in the boundary layer. The rapid decrease in RMS after the flow reattachment identifies the reattached flow still transitional. The peak RMS occur at $0.82 B_x$.

The time histories of the raw quasi-wall-shear stress and power spectral distributions for selected hot-film sensors for $Re=50000$ are shown in Figure 5.13 and Figure 5.14 respectively. For the low FSTI flow, the quiet signals from the sensors located before the separation point (at about $x/B_x=0.63$) indicate that the boundary layer is laminar before separation and the power spectral distributions at these locations confirm this observation. The signals from the sensors in the forward portion of the open separation bubble (for example the signal at $0.68 B_x$) are very quiet and with near zero mean values. The signals from the sensors located at the rear portion of the separation region have low frequency fluctuations and the mean values are away from the zero level. This indicates there is strong reverse flow at this aft separation region. The spectral distributions in this region also show the existence of the high energy reverse flow.

For high FSTI flow, both the raw signals and the spectral distributions from the hot-film sensors located before the separation point, which occurs at $0.72 B_x$, show the low frequency fluctuation. This is again the disturbance in the free stream flow. The fluctuation frequency in the signal before the flow separation point seems not change much, which suggests that the boundary layer does not start transition before separation. The signals from the sensors

Figure 5.13 Time Histories of the Raw Quasi-Wall-Shear Stress at $Re=50000$

(a) FSTI=0.4% (b) FSTI=4.5%

Figure 5.14 Power Spectral Distribution at $Re = 50000$

(a) FSTI=0.4% (b) FSTI=4.5%

in the short bubble are very quiet. The raw signal at the reattachment point ($x/B_x=0.80$) has upward tails and the spectral distribution shows the high energy contained in a wide frequency range. Thus, the boundary layer reattaches transitional in this flow condition. The decreasing raw signal fluctuation and the reduced high energy containing frequency range at the downstream location indicates the reattached boundary layer is in the late transition stage. The boundary layer becomes fully turbulent shortly after the reattachment point.

5.4 Stagnation Pressure Losses

The effects of flow separation and reattachment or the lack of it on the blade profile losses are very significant (Mayle, 1991 and Walker, 1993). The measured blade profile losses in steady conditions are calculated from the three-hole pressure probe measurements at the inlet and outlet of the cascade. The blade profile measured loss is defined as:

$$Y_p' = \frac{\bar{P}_{01} - \bar{P}_{02}}{\bar{P}_{02} - \bar{P}_{s2}} \quad (5.1)$$

where $\bar{P}_{01}$, $\bar{P}_{02}$ are the time average of the inlet total pressure and the outlet total pressure respectively and $\bar{P}_{02} - \bar{P}_{s2}$ is the time average of the outlet dynamic pressure.

The mass averaged blade measured loss Y_p for one blade pitch is defined as:

$$Y_p = \frac{\int Y_p' d\dot{m}}{\int d\dot{m}} = \frac{\int_0^1 Y_p' V_{ax} d\left(\frac{y}{s}\right)}{\int_0^1 V_{ax} d\left(\frac{y}{s}\right)} \quad (5.2)$$

Figure 5.15 presents a plot of the stagnation pressure loss coefficient versus Reynolds number at two different FSTI levels. For the flow with low FSTI, the stagnation pressure loss is almost constant for Reynolds number greater than 100000. At low Reynolds numbers the loss rises steeply due to the large open separation bubbles. For the flow with high FSTI, the profile loss is weakly dependent on the Reynolds number. The loss rises only slightly as the Reynolds number is reduced but it is still much lower than that with lower FSTI. In another words, the measured profile loss almost keeps constant in the short bubble mode in different conditions. But it increases significantly when the separation bubble changes from the short bubble mode to the long bubble mode.

Figure 5.15 Stagnation Pressure Losses vs. Reynolds Number

5.5 Summary of Steady Measurement Results

Boundary layer separation, transition and reattachment on the suction side of the PAK-B LP turbine blade in different steady flow conditions have been studied by means of surface static pressure measurements and surface-mounted hot-film measurements. Both Reynolds number and free-stream turbulence intensities have a significant effect on the boundary layer development. The stagnation pressure losses show the influence of the boundary layer development on the blade performance.

Table 5.1 summaries the boundary layer behaviors on the blade suction surface under different free-stream conditions based on the results from the surface static pressure measurements and the surface-mounted hot-film measurements. The information from static pressure distribution is relatively rough as discussed in the previous sections.

In a review of the role of laminar to turbulent transitions in gas turbine engines, Mayle (1991) presented a modified model of the separated flow transition (refer to Section 2.2.1). Separated flow transition occurs when a boundary layer separates, and transition proceeds in the free shear layer above the separation bubble constant pressure region. The transition region propagates toward the wall, giving a growing turbulent zone until the flow reattaches as a fully turbulent boundary layer. The transition is assumed complete at the end of the constant pressure region, *i.e.*, the maximum height of the separation bubble. However, compared with Mayle's proposed separated flow transition model, the present measurement results have several different characteristics. There are evidences that the boundary layer transition may occur prior to the flow separation and the reattached boundary layer is not

necessary fully turbulent, for example in the high Reynolds number conditions. These observations were also indicated by the study of Hatman and Wang (1999).

Table5.1 Summary of Boundary Layer Behaviors

	FSTI	0.4 %				4.5 %			
	Re	25,000	50,000	100,000	150,000	25,000	50,000	100,000	150,000
Static Tap	X_s/B_x	0.64	0.64	0.73	0.73	0.74	0.74	0.76	0.76
	X_R/B_x	--	--	0.88	0.86	0.95	0.88	0.85	0.83
	X_{MD}/B_x	0.95	0.84	0.83	0.80	0.86	0.82	0.80	0.78
Hot-Film	X_s/B_x	0.60	0.63	0.72	0.72	0.68	0.72	0.74	0.74
	X_R/B_x	--	--	0.80	0.78	0.85	0.82	0.78	0.78
	X_t/B_x	0.62	0.65	0.57	0.55	0.68	0.68	0.55	0.55
	$X_{0.5}/B_x$	0.80	0.78	0.82	0.80	0.76	0.80	0.76	0.76
	X_T/B_x	0.90	0.85	0.91	0.89	0.90	0.85	0.86	0.85

X_s = Separation Point

X_R = Reattachment Point

X_t = Onset of Transition

X_T = Onset of Fully Turbulent Flow

$X_{0.5}$ = Peak RMS Location

X_{MD} = Maximum Displacement

Under low free-stream turbulence condition (FSTI=0.4%), the low Reynolds number flows ($Re=50000$ & 25000) separate laminar early. The flow has difficulty reattaching itself to the suction surface due to the low momentum transfer associated with the free shear layer. This results in a long open separation bubble and a high profile loss. While the increased Reynolds number causes the flow transition to move towards the blade leading edge. The better turbulent mixing due to the earlier transition allows an earlier reattachment and thus a short bubble forms, resulting in a lower profile loss. Under high free-stream turbulence condition (FSTI=4.5%), the flows separate at almost the same location and all reattach

before the trailing edge. For low Reynolds number flows, the boundary layers separate laminar and reattach turbulent. The transitions happen in the free shear layer on the separation bubble. The reattachment points move upstream as increasing Reynolds number.

At relatively high Reynolds number ($Re = 1000000$ and 150000), the onset of transition happens prior to boundary layer separation either in the natural transition mode (for low FSTI flow) or in the bypass transition mode (for high FSTI flow). But due to the strong adverse pressure gradient at the aft portion of the blade suction surface, the boundary layer, which is in the early transition stage, still separates from the blade surface. Since in this case the free stream flow has high energy, a slightly turbulent mixing may sufficient to ensure the flow reattachment. Thus, in the high Reynolds number conditions the reattachment flow could be transitional.

It has been shown that hot-film measurements can provide more detail and accurate information about the boundary layer state on the blade surface than the surface static pressure measurements. The boundary layer separation and reattachment can be detected from the mean quasi-wall-shear stress. The transition state can be identified from the normalized RMS and the raw signals as well as the frequency domain analysis of the hot-film measurement data. The most important is that the surface-mounted hot-film measurements has been proved can provide separated flow transition information by using proper normalization. Furthermore, the hot-film measurements are suitable for the future unsteady study due to the high frequency response. The understanding between the hot-film data and the boundary layer behaviours forms the basis for the unsteady flow study discussed in next chapter.

Chapter 6

Presentation & Discussion of Unsteady Results

6.1 Introduction

The boundary layer development and its effect on the blade performance on the PAK-B LP turbine blade under unsteady conditions have been studied. The experiments were conducted on a large test matrix with various Reynolds numbers, free stream turbulent intensities, reduced frequencies and flow coefficients. As one part of this large project, the work presented in this chapter is focused on the study of boundary layer development on the suction surface by means of surface-mounted hot-film measurements. A few representative cases are presented to demonstrate how to interpret the hot-film measurement results under unsteady conditions. The relationship between the hot-film measurement results and the boundary layer behaviours will be used to investigate the boundary layer development at different test cases. The measurement results discussed in this chapter were conducted at Reynolds number of 100000 and 25000 with

FSTI=0.4%. The flow coefficient (Φ) was set at 0.70 and the reduced frequency was 1.52 (based on Sharma) or 0.78 (based on Hodson), which are in the expected range of interest for actual engines. In the test case of $Re=100000$, 1024 data points covering six wake passing periods were sampled at 56 kHz for each hot-film sensor. In order to apply the ensemble averaging technique, 256 cycles were recorded by means of the once-per-revolution trigger signal from the photo detector in the wake generator. For $Re=25000$, 256 cycle data were taken at a sample rate of 28 kHz, each containing of 2048 samples, which also occupy six wake passing periods.

The measured hot-film data were first reduced to quasi-wall-shear stress (τ) values based on Equation 3.25. Then the ensemble averaging technique was conducted to obtain the ensemble mean and RMS of the quasi-wall-shear stress data. The measurement results will be presented and discussed by means of raw time history and space-time contour plots (S-T diagrams) of the ensemble mean and RMS of the quasi-wall-shear stress. The raw signal contains information about individual occurrences, both random and phase-locked. The ensemble mean contains the information that is phase-locked to the wake passing, while the ensemble RMS contains the information on how the random content of the signal varies as a function of the wake passing period.

6.2 High Reynolds Number Case ($Re=100000$)

A selection of the unsteady time history traces of raw quasi-wall-shear stress from surface-mounted hot-film measurements at $Re=100000$ and FSTI=0.4% with six wake passings is

presented in Figure 6.1. The steady raw hot-film data at the same free stream conditions are also presented in the figure for comparison. It is clear to see the wakes convecting along the blade suction surface from Figure 6.1(b). The wakes are marked as “w” in the figure. The dashed lines, which represent the average flow convecting velocity in the blade passage, show two of the wakes.

Referring to the unsteady signals, on the front portion of the blade suction surface, *i.e.*, before $0.41 B_x$, only relatively low amplitude, low frequency information is present in the raw data. The effect of wake passing is not very distinct in this essentially laminar region. The characteristic shape of the signal fluctuation along the wake passing strip is similar to that of a negative jet as shown in Figure 2.6. However, as both the boundary layer and the wake develop further downstream, the wake passing appears more clear. Between 0.41 and $0.60 B_x$, the raw signals vary periodically due to the high momentum transfer in the wakes. There is no longer the characteristic shape of negative jet in the raw hot-film signals and the wake affected range gets wider as it moves downstream. This is the result of the wake distortion in the blade passage shown in Figure 2.7.

High frequency fluctuations in the raw signal start to occur at $0.41 B_x$, marked “A” in Figure 6.1(b). This suggests that the instabilities in the boundary layer are starting to develop. However, they grow relatively slowly, referring also to the region marked “B” at $0.60 B_x$. Another interesting feature is that the development of the instabilities seems to lag behind the wake passing strip. Howell (1999) suggested that this was because the instabilities in the boundary layer travel at a slower rate of about 70% of the local freestream velocity. Similar observations were made

Figure 6.1 Time Histories of the Raw Quasi-Wall-Shear Stress at $Re=100000$, $FSTI=0.4\%$

by Walker *et al* (1993) from hot-film measurements. The development of the instabilities along the surface from 0.41 to 0.60 B_x is thought to be relatively slow due to the strong favorable pressure gradient in this region. There are more high frequency fluctuations appearing at 0.60 B_x during other wake passings, like the range marked “C” in Figure 6.1(b). The signals between the wakes, such as the range marked “D”, are still relatively quiet at this location. Comparing with the steady measurement results at the same freestream conditions, the boundary layer starts to undergo transition at this location. This seems to suggest that the wake can delay the boundary layer transition between the wakes. Hodson (1985b) claimed that the natural transition between wakes may not have the chance to develop at high reduced frequency.

The near zero mean level signal at 0.72 B_x between the wake passing strips indicates the flow intermittently separates from the blade surface at this location, which is almost the same location as the boundary layer separation point in the steady flow condition. This observation again confirms that the boundary layer separation point does not change much for different flow conditions. The boundary layer under the wake passing strip also separates at the next downstream sensor location (0.74 B_x) if the development of the instabilities is not advanced before this location, such as the range “E”. But if the development of the instabilities starts early, the flow may never separate from the surface, such as in the range “F”. At 0.76 B_x the separated flow reattaches to the blade surface. Compared with the steady flow condition, where the separated boundary layer reattaches at 0.82 B_x , the boundary layer reattaches early in this unsteady condition, which reduces the separation bubble size.

Wake-induced turbulent spots appear to be present from the records at $0.76 B_x$ and $0.80 B_x$. At these locations, the raw signal contains a rapid periodic increase in shear stress followed by a short period of high frequency fluctuation and then a decay back to the less disturbed state. Such traces are typical of those that are observed in boundary layers starting to undergo bypass transition as a result of the passage of the wakes over the blade surface. The rapid and relatively large increase of shear stress is thought to be due to the occurrence of turbulent spots produced in the wake-induced bypass transition process. The exponential decaying and relatively quiescent areas after the turbulent spots are referred to as calmed regions. The elevated shear stress in the initial part of the calmed regions makes the flow between the wakes more resistant to the adverse pressure gradient, resulting in an early boundary layer reattachment (see Section 2.2.2).

Comparing the behaviors between wake-induced high shear stress regions (the turbulent spot regions), for example the areas marked “G” and “H” in Figure 6.1(b), there is some variability in the signal appearance from one wake passing to the next. This difference may be caused either by the random turbulent spot production rate at different times and/or locations or the different wake behaviors after different cylindrical bars. The effect of randomness in the spot generation can be eliminated by ensemble averaging the measurements from many successive passings of the same bar. The ensemble-averaged results will be discussed later.

As the flow develops further on the suction surface (*e.g.*, at location $x/B_x=0.80$), the wake-induced boundary layer transition progresses, and the regions of higher shear stress are greater in extent. For example, compare regions “H” and “I”. This extended high shear stress region is the

result not only of previously-formed turbulent spots growing but also from newly-formed turbulent spots caused by the turbulence close to the wake centerline. As the boundary layer develops, it becomes more sensitive to the free stream turbulence, so that the lower FSTI (compared with the wake centerline, which has the highest turbulence) away from the wake centerline also can induce boundary layer transition. In the area marked “T”, turbulent spots appear to be produced on both side of the wake centerline.

Figure 6.2 presents the plots of the raw signals from four successive hot-film sensors located around the separation bubble (that is between 0.70 and $0.76 B_x$) at the same condition as shown in Figure 6.1(b). The scales in the plots are arbitrary and chosen mainly to make the variation in the signals more clear. From the signal at $0.72 B_x$, the wake-induced turbulent spots (such as these marked “A” and “B” in the figure) can be seen initiated at the rising edge of the high quasi-wall-shear stress regions, marked “C” and “D”. Since the turbulence at the wake centerline is strongest, the first occurrence of the wake-induced turbulent spot should follow it. This also shows that the development of the instabilities in the laminar boundary layer lags a little behind the wake centerline, as discussed earlier.

The development of the wake-induced turbulent spots can be seen in Figure 6.2. There are more turbulent spots generated at “C” than at “B” as the boundary layer develops downstream. It should also be mentioned that the turbulent spots observed beside the wake centerline further downstream, such as the area marked “D” in the figure, may not only be the spots induced by the turbulence next to the wake centerline but also be growing spots from spanwise neighboring

locations.

Figure 6.2 Time Histories of Raw Quasi-Wall-Shear Stress Around Separation Bubble

Comparing the signals at $0.72 B_x$ and $0.76 B_x$, a phase change of the high quasi-wall-shear stress range can be noticed. The high shear stress range at $0.72 B_x$ is due to the development of the instabilities in the boundary layer, which travel after the wake centerline. By comparison the high shear stress range at $0.74 B_x$ results from the wake induced transition. This phase change also shows in the S-T diagram discussed later.

It is also noted in Figure 6.1 (b) that at $0.80 B_x$ the higher frequency fluctuations not only appear in the high-level shear-stress regions but also appear at the low-level shear-stress regions (like the region marked “J”), which indicate that the boundary layer between wakes also starts to undergo transition at this location. Recalling the early discussion of the instability developments in the laminar boundary layer, it can be seen that the calmed regions after the wake-induced turbulent spots can not only prevent the boundary layer separation but also delay the transition between the

wakes. After $0.80 B_x$, the boundary layer transition, both under the wakes and between the wakes, progresses, with the fluctuation magnitudes in the high shear stress regions and low shear stress regions reaching almost the same level, as seen in the signals at 0.86 and $0.93 B_x$. The calmed regions after the wake-induced turbulent spots have vanished. Nevertheless the wake passing can still be clearly seen. Another interesting feature of the calmed region is that if the wake induces boundary layer transition early or the wake-induced turbulent spots form early, the calmed region following these spots is strong and its effect will last far downstream (see the region marked “K” in Figure 6.1).

By approximately the blade trailing edge, i.e. at $0.98 B_x$, turbulent phase of boundary layer development appears to have begun. The mean shear stress decreases and the passing of wakes is much less pronounced, which suggests that the free-stream turbulence above the surface has a relatively small effect on the innermost parts of a turbulent boundary layer.

Space-time contour plots (S-T diagrams) are very useful to present the state of the unsteady flow (refer to Section 2.3.2 and Figure 2.7). Figure 6.3(a) presents the normalized ensemble-averaged values of the mean quasi-wall-shear stress. The contours denote the ensemble-mean $\bar{\tau}(t)$ normalized by the maximum value τ_{Max} at the same chordwise location. This form of presentation emphasizes the periodic fluctuation at the expense of providing the data on the changes in the mean level. For example, the maximum ensemble mean at $0.60 B_x$ is much higher than the maximum mean value at $0.30 B_x$, but both will show a value of $\bar{\tau} / \tau_{Max}$ of 1.0. Figure 6.3 (b)

(a)

(b)

Figure 6.3 S-T Diagrams of Quasi-Wall-Shear Stress at $Re=100000$, $FSTI=0.4\%$

(a) Normalized Ensemble Mean (b) Normalized Ensemble RMS

shows the ensemble RMS of the quasi-wall-shear stress, also expressed as the fraction of its maximum value at the same sensor location.

Six wake passing intervals are shown in the figures. Over much of the blade surface, there are large periodic variations in both the ensemble mean shear stress and RMS, indicating the effect of the passing wake on the boundary layer. The wake is assumed to travel at the local free stream velocity, which varies in the blade passage. The curved line, W^* , drawn in Figure 6.3(a) schematically shows the path of a fluid particle moving in the blade passage. The convecting velocity is lower near the blade leading edge, increases around the suction peak, and then comes down again near the blade trailing edge. For simplicity, a straight line is drawn in the figure (marked as “W”) indicating the path of a particle moving through the blade passage. The slope of the straight line is 1.52, corresponding to the wake passing periods required for the wake to transit the blade passage, as given by Sharma’s value of reduced frequency.

Near the blade leading edge, the wake passing does not have pronounced effect on the ensemble mean quasi-wall-shear stress but it can be detected from the ensemble RMS since the fluctuations near the wake centerline are larger. After about $0.20B_x$, the wake passing can be seen in the ensemble mean plot. The disturbance in the wake causes higher quasi-wall-shear stress along the wake passing path. At about $0.33B_x$ the instabilities in the boundary layer start to develop due to the high disturbances in the passing wakes. Since the instabilities convect at a lower velocity than the wake, the high quasi-wall-shear stress strip, represented by the dashed line W' in Figure 6.3(a), lags behind the wake centerline. The ensemble RMS between 0.60 and $0.70 B_x$

seems to follow the trend of the dashed line W' well. But the ensemble RMS between 0.40 and 0.60 B_x does not follow the trend of either the line W or W' . The reason for this is not clear.

The most interesting phenomena occur when the flow approaches the boundary layer separation point. In the S-T contour plots of mean quasi-wall-shear stress, there are periodic low shear stress regions between 0.70 and 0.80 B_x , which are the separated flow areas. Compared with the steady flow measurement results, the length of the separation region in the chordwise direction (the size of separation bubble) does not change much but it is only present for about 40 percent of the wake passing period. Thus, for most of the time the boundary layer does not separate from the blade surface. Furthermore, even in the separated regions the mean shear stress is not zero. Since the mean values plotted in the figure are the ensemble average of 256 cycles, the non-zero mean value indicates the flow in these regions is partly separated at different times or cycles.

The wake-induced transition occurs shortly after the boundary layer separation point (at about 0.73 B_x , marked "A" in the figure), which is identified by the high ensemble mean and RMS. Then the high shear stress region grows in a wedge shape, *i.e.*, the region between A-B and A-C marked in the figure. The reason for the wedge-like development of the high shear stress is that at point A only the centerline of the wake can induce boundary layer transition, since there the turbulence is highest. As the free shear layer develops downstream, it becomes more sensitive to the free-stream turbulence so that the lower turbulence that is to be found away from the wake centerline also can induce transition, which results in the higher mean shear stress on both sides of

the wake centerline. However, examining the ensemble RMS at this region suggests some different behaviors before and after the passing of the wake centerline. Before the passing of the wake centerline (marked A-D in the figure), *i.e.*, the region on the A-C side, the RMS is high, so that the higher mean shear stress is caused by the wake-induced transition. While after the passing of the wake centerline, *i.e.*, the region on the A-B side, the RMS is low, which suggests that there is a quiet but higher mean quasi-wall-shear stress region after the wake-induced transition. That is believed to be the calmed region following the turbulent spots.

The contour gradients of the ensemble mean in the increasing-time direction in this region (for example, along E-F in Figure 6.3(a)) clearly show a sharp rise as a wake-induced strip arrives, and a slower fall in the relaxing region following its passage. The sharp rise is caused by the formation of turbulent spots induced by the passing wake and the slower fall is the calmed region following the turbulent spots. This agrees well with the observation from the raw hot-film data.

In the S-T diagram, the reverse of the slope stands for the convecting velocity along the chordwise direction. Thus a smaller slope represents a larger convecting velocity. However, the negative slope of A-C does not indicate very high convecting velocity or reverse convecting velocity. It is due to the boundary layer undergoing transition ahead of the arrival of the wake centerline. Furthermore, the ridge of the high mean quasi-wall-shear stress seems to lag a little back from the passing wake centerline. This is because a turbulent spot travels at a slower rate than the wake itself (see Section 2.2.2).

The boundary layer between the wake passings starts transition at about $0.80 B_x$, which is indicated by the increasing mean quasi-wall-shear stress and RMS. Compared with the wake-induced turbulent spots, the mean value and RMS of these newly formed spots are relatively low. Examining the contour gradient of the ensemble mean along G-H in Figure 6.3 (a), the rise of the mean value slows down. This is because the boundary layer transition between wakes more likely happens just before the wake arrival, where the effect of the calmed region from the previous passing wake has become weak. As the boundary layer transition develops downstream, the levels of the mean and RMS become more close to that of the wake passing path. Around $0.95 B_x$, the turbulent spots in the two paths start to merge together. By the trailing edge the flow becomes more uniform and the wake passing is not obvious, which suggests the boundary layer is almost turbulent there.

Another phenomenon that should be mentioned is the boundary layer behavior as affected by the wake of the fifth bar. The wake after the fifth bar seems stronger than others, perhaps due to a difference in the bar vibration. The instabilities in the boundary layer under this wake passing strip are advanced before the flow separation location and the boundary layer never separates under this wake passing strip (see the region marked “M” in Figure 6.3(a)). This also can be seen in the region marked with an ellipse in the raw data trances in (Figure 6.1(b)). Funazaki *et al.* (1999) studied the effect of the wakes after different diameter bars (2mm, 5mm and 10mm) on the boundary layer and observed the similar effects. This may be another approach to reduce the separation bubble size by increasing the wake strength. But the strength of the wake from previous

stage in actual engine can not be changed much.

Compared with the steady flow measurement results, the location and the size of the boundary layer separation do not change much if it separates from the blade surface. But the boundary layer only separates during a small fraction of the wake passing period. Therefore, on average the separation bubble size is reduced. However, based on the measured stagnation pressure losses presented in Section 5.5, the profile losses should not change much when the separation bubble size is in this order. Furthermore, since the wake induces the boundary layer to undergo bypass transition early, a large portion of the blade surface is covered by the transitional/turbulent flow in the wake passing path, which will increase the blade drag. Even though the calmed regions after the wake-induced turbulent spots can delay the boundary layer transition between wakes, the effect of calmed regions in this Reynolds number flow condition are not strong. So the combining effect of the wake passing on the blade profile loss reduction should not be much if it has any. The blade profile losses in unsteady conditions are discussed in detail by Mahallati (2002).

6.3 Low Reynolds Number Case ($Re=25000$)

The steady measurement results discussed in Chapter 5 show that there exists a long open separation bubble on the blade suction surface at the low Reynolds number and low FSTI conditions. Referring to Figure 5.15, the measured stagnation pressure loss will reduce significantly when the separation bubble changes from a long open mode to a short closed mode. The unsteady results at $Re=100000$ discussed above show the incoming wake can induce transition earlier in

bypass mode. Therefore, it will be of interest to look at the unsteady boundary layer development at low Reynolds number. The earlier wake-induced transition may cause the separated flow to reattach before the blade trailing edge and results in a short close separation bubble, which will reduce the profile loss largely.

The time history traces of the raw quasi-wall-shear stress for selected hot-film sensors at $Re=25000$ with $FSTI=0.4\%$ are presented in Figure 6.4. The wake passing is again not obvious near the blade leading edge. The raw hot-film signals after $0.55 B_x$ clearly show the periodic variations associated with the wake passing. The instabilities in the boundary layer start to develop at this location due to the high disturbance in the wake. Compared with the measurement results at the high Reynolds number condition discussed in last section, the starting location of the instabilities development at this low Reynolds number is about $0.15 B_x$ later due to the low momentum in the free stream flow.

The development of the instabilities is slow and there are no high frequency fluctuations shown in the raw signals before $0.63 B_x$, which suggests that the development of the instabilities in the boundary layer is still at an early stage. At this low Reynolds number, the disturbance in the wake is not strong enough to prevent the boundary layer from separating even under the wake passing paths. The flow separates at $0.65 B_x$ at all time regardless the appearance of wakes. Compared with the steady flow measurements, where the boundary layer separates at $0.62 B_x$, the flow separation point moves just a little downstream. Due to the development of the wake-induced transition, the flow in the wake passing path starts to reattach at $0.80 B_x$, but the boundary

(a) Steady

(b) Unsteady, with Wakes

Figure 6.4 Time Histories of the Raw Quasi-Wall-Shear Stress at $Re=25000$, $FSTI=0.4\%$

layer is still separated for most of the wake passing period. At $0.85 B_x$, the boundary layer reattaches to the blade surface at all times.

The wake-induced transition can be clearly seen after $0.80 B_x$. The turbulent spots form in the wake passing path and are followed by the calmed regions. Compared with the results for the $Re=100000$ case, the turbulent spot production rate seems lower at this low Reynolds number condition. The quasi-wall-shear stress after the turbulent spots decays much faster and results a large flat low mean quasi-wall-shear stress region between wakes. The persistence of the calmed region after the wake-induced turbulent spots seem to be strong in this low Reynolds number condition and can be noticed even towards the blade trailing edge, for example the region marked “A” in the figure. The boundary layer transition between the wake passings occurs at about $0.88 B_x$, which is identified by the higher fluctuation in the lower mean shear stress region, marked “B” in the figure. The development of the transition between wakes seems relatively slow. The transitional boundary layer on both paths continually develops until the blade trailing edge. In one wake passing period the sensors near the blade trailing edge (for example, the sensor located at $0.98 B_x$) sees the boundary layer periodically change between wake-induced turbulent/transitional, calmed after the wake-induced turbulent spots and transitional between wakes.

Figure 6.5 presents the S-T diagram of the normalized ensemble mean and RMS of the quasi-wall-shear stress at $Re=25000$ and $FSTI=0.4\%$. The six wake passing paths can be clearly seen in the figures. The essentially laminar boundary layer covers the first 60 percent of the blade suction surface in both wake passing path and the path between wakes. The development of the

Figure 6.5 S-T Diagrams of Quasi-Wall-Shear Stress at $Re=25000$, $FSTI=0.4\%$

(a) Normalized Ensemble Mean (b) Normalized Ensemble RMS

instabilities in the boundary layer can be seen by following the dashed line W' marked in the figure. In this low Reynolds number case the ensemble mean and RMS seem match the trend of the 70% freestream velocity trajectory very well. The boundary layer separates from the blade surface around $0.65 B_x$ for all of the wake passing periods. The boundary layer separation region extends about $20\% B_x$ in the chordwise direction. The near zero ensemble mean region covers about 80% of the wake passing period. The near zero ensemble mean in the separation region also suggests the boundary layer separates most of the times or cycles.

The wake-induced transition begins to occur at about $0.75 B_x$, marked “A” in the figure. In the high Reynolds number condition, the wake-induced transition begins to occur shortly after boundary layer separation. But in this low Reynolds number case, the wake-induced transition appear to start a little later (about $10\% B_x$ downstream of the separation point). Due to the low energy content of the mean flow in this low Reynolds number condition, the wake-induced transition only happens close to the highly disturbing wake centerline for a long distance along the blade chordwise direction, which is identified by the straight narrow stripe between “A” and “A' ” marked in the figure. The calmed regions after the wake-induced turbulent spots can be clearly seen. The phase change of high mean value and RMS of the quasi-wall-shear stress is also shown in the figure. The lower mean shear stress and RMS regions occurring at about $0.80 B_x$ suggest that the boundary layer between wakes still separates. The wedge-shaped high mean quasi-wall-shear stress region occurs around $0.84 B_x$. The boundary layer between wakes starts transition at about $0.88 B_x$. The transition in both paths continues developing and the RMS becomes almost

uniform by the blade trailing edge, but the wake passing still can be seen in the mean shear stress. The calmed regions in this low Reynolds number case are persistent. They are still pronounced at $0.95 B_x$.

Recalling the boundary layer development in steady conditions (Section 5.3.2), the flow separated very early (at about $0.62 B_x$) and never reattached, resulting a long open bubble on the aft portion of the blade suction surface. In the unsteady flow condition, the passing wakes do not change the boundary layer separation point much. However, the wake-induced transition forces the separated shear layer to reattach early, resulting a shorter closed separation bubble. This change in the boundary layer separation bubble mode will dramatically reduces the blade profile losses (refer to Section 5.5). The effect of the calmed regions after the wake-induced turbulent spots is very strong in the low Reynolds number condition. This is another main source of the advantage of the wake-induced transition. The fuller velocity profile and elevated mean shear stress level (compared with laminar flow) in the calmed region enables the boundary layer to be more resistant to separation. On the other hand, the calmed region delays the boundary layer transition onset between wakes, which will reduces the blade surface length covered by the turbulent flow, consequently reducing the blade profile losses. Thus under the low Reynolds number conditions, the incoming wake should result in a beneficial effect on the blade performance.

Chapter 7

Conclusions & Recommendations

Boundary layer separation, transition and reattachment on a low pressure (LP) turbine blade under steady and unsteady conditions have been studied by means of surface-mounted hot-film measurements. The effects of free stream conditions and incoming wakes on the boundary layer development were investigated.

It was concluded that hot-film measurements can provide not only semi-quantitative information about the boundary layer development on the blade surface but also instantaneous information thanks to the fast response of the hot-film sensors, which make this technique suitable for unsteady studies. The boundary layer separation and reattachment can be detected from the beginning and end of the near zero mean quasi-wall-shear stress calculated from the hot-film measurements. The normalized RMS of the hot-film data can provide transition information, even in the case that the hot-film sensors are covered by separation. The hot-film raw signals can be

used to gain further insights into the boundary layer development at steady and unsteady conditions. Additionally, the space-time contour plots of the normalized ensemble mean and RMS are very useful to present the state of the unsteady flow. The relationship between the hot-film data and the boundary layer conditions as well as the data presentation methods developed here will form the basis for interpreting future results from the on-going study of the steady and unsteady flow around the PAK-B and related turbine airfoils.

Regarding the present PAK-B measurements, in steady flow conditions, boundary layer separation on the aft portion of the blade suction surface was observed at all examined conditions. The boundary layer separation point does not change much in different flow condition provided the Reynolds number and free stream turbulence intensity are not too low. However, the boundary layer reattachment point, and thus the separation bubble size, does depend on the free stream conditions. As the Reynolds number and/or FSTI increase, the reattachment point moves upstream, resulting in a reduced bubble size. However, the measured blade stagnation pressure losses do not change much as long as the separated flow reattaches before the blade trailing edge. Under very low Reynolds number and low FSTI condition, the flow is unable to reattach itself to the suction surface by the blade trailing edge and a long open separation bubble forms on the blade suction surface, resulting in a large blade profile loss. It was also found that at relatively high Reynolds number, boundary layer transition may start prior to the flow separation and the transition did not appear to be complete before the flow reattachment..

In unsteady flow conditions, the incoming wakes impinge on the laminar boundary layer on the

forward portion of the blade suction surface. The wakes appear to induce transition in the bypass mode in the separated shear layer due to the high disturbance in the wakes. Turbulent spots are formed in the wake-induced transition strips and followed by the calmed regions, where the flow relaxes back to the laminar state. In the calmed region, the fuller velocity profile and elevated mean shear stress level enable the boundary layer to resist separation for a period of time. Furthermore, the calmed region delays the boundary layer transition onset between wakes, which will reduce the blade surface length covered by the turbulent flow, consequently reducing the blade profile losses.

In the high Reynolds number case, since the separation bubble is already small in steady conditions, the positive influence of the wake passing on the blade performance is small if present at all. Moreover, the fast wake-induced transition may cause large blade surface length covered by the turbulent flow in the wake passing path and the effect of the calmed regions between wakes is not pronounced in this flow condition (refer to Section 6.2). In low Reynolds number case, the wake-induced transition together with the calmed region after it force the separated flow reattach early. The change in separation mode from long open bubble to short closed bubble should significantly reduce the blade profile losses. The effect of the calmed region in this condition is very persistent and even exists near the blade trailing edge. This large extension of the laminar-in-nature calmed region on the aft portion of the blade suction surface will also improve the blade efficiency. Thus, in low Reynolds number conditions the wake from the previous blade row should produce beneficial effects on the blade performance.

Turning now to recommendations, although the surface-mounted hot-film has been demonstrated to provide information about boundary layer separation and transition, the trend of the quasi-wall-shear stress calculated based on Equation 3.25 does not physically match the expected wall shear stress distribution on the blade surface, perhaps due to the effect of the strong pressure gradient. Thus, it would make surface-mounted hot-film measurement more useful if a new relationship between the wall shear stress and heat transfer under non-zero pressure gradient can be determined.

Regarding the unsteady study, there are two opposing mechanisms at work in the interactions between wakes and the boundary layer. The early wake-induced transition in the wake passing path can cause large extended turbulent strips, which will reduce the blade efficiency. On the other hand, the calmed regions following the wake-induced transition can withstand adverse pressure gradient much better because of the fuller velocity profile, which is beneficial. The balance between these two mechanisms in the process of wake-boundary layer interaction strongly depends on the free stream conditions. Thus it would be of interest to investigate the unsteady boundary layer behavior as well as the blade profile losses at different free stream Reynolds numbers, turbulent intensities, flow coefficients and wake passing frequency, as measured by the reduced frequency. In fact these are the objectives of the on-going larger project of unsteady study on PAK-B LP turbine blade. The measurement results about boundary layer development on the blade suction surface and its effect on the blade performance at different free-stream conditions and different wake passing frequencies will be discussed in detail by Mahallati (2002).

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Appendix A

Three-Hole Pressure Probe Calibration

The three-hole probe was calibrated in a low turbulence calibration box where the flow total pressure, velocity and flow direction were known. And the probe calibration was performed at the same probe Reynolds numbers encountered during the experiments. The probe Reynolds number (Re_d) is based on the mean flow velocity and the probe diameter ($d=0.72\text{mm}$). This calibration was checked regularly during the experiments. Measurements were taken over a range of $\pm 20^\circ$ at half degree intervals and the Reynolds numbers based on the probe diameter were 100, 200, 450, 650 and 1000. The data was then used to form the coefficients listed in Equation A.1, as defined in the method for three hole probe data reduction by Lewis (1966).

These coefficients are formed a look-up table and are subsequently used to calculate the flow angle, dynamic pressure and static pressure. The three hole probe can only be used for measuring the yaw angle in the plane of the probe. During the reduction of probe data, the sign of the flow angle relative to the probe axis is determined by comparing the probe pressure P_2 and P_3 . The magnitude of the angle is obtained from the coefficients $K_{\phi 2}$ and $K_{\phi 3}$. The employment of two

coefficients instead of one provides better accuracy in extracting the flow angle. As seen from Figure A.1, $K_{\phi 2}$ is Reynolds number dependent at large positive flow angle. So it is mostly suitable for flow angle ranges between -20° and 10° . Therefore, for the remaining part of the flow angle range considered, the coefficient $K_{\phi 3}$ is used instead (Figure A.2), which is Reynolds number independent in positive flow angle range.

$$K_1 = \frac{P_1 - P_s}{P_0 - P_s}$$

$$K_{12} = \frac{P_1 - P_2}{P_0 - P_s}$$

$$K_{13} = \frac{P_1 - P_3}{P_0 - P_s}$$

(A.1)

$$K_{23} = \frac{P_2 - P_3}{P_0 - P_s}$$

$$K_{\phi 2} = \frac{P_1 - P_2}{P_1 - P_3}$$

$$K_{\phi 3} = \frac{P_1 - P_3}{P_1 - P_2}$$

where the pressure indices (1, 2 and 3) in the above coefficients correspond to the port numbering shown in Figure 3.6.

Once the flow angle is determined, the local dynamic pressure is extracted from the

coefficients K_{12} , K_{13} or K_{23} . As seen from Figure A.3, K_{12} is Reynolds number dependent in the positive flow angle range. The same is true for negative flow angle for K_{13} (Figure A.4). Therefore, for positive and negative flow angle K_{13} and K_{12} are used respectively. There is an exception to this whereby these two coefficients approach zero. Since in the calculation of the dynamic pressure the coefficient appears as the denominator, if it is close to zero, a small change in its value will result in large changes in the dynamic pressure. Therefore, for regions where the coefficients K_{12} and K_{13} are close to zero, which correspond to -20° to -10° and 10° to 20° flow angle range, K_{23} is used instead (Figure A.5). This reduces the possibility of the excessive errors in certain flow angle ranges. The static pressure is extracted from the coefficient K_1 . As seen from Figure A.6, this coefficient does not appear to be dependent on Reynolds number throughout the calibration range.

Piecewise least-square polynomials were fitted to the above described calibration curves. The order of the polynomials were typically 6 to 8. Each data point is therefore unique and independent of all other points which insures good resolution and less possibility of error in the data reduction process.

Figure A.1 Variation of K_{ϕ_2} with Yaw angle Figure A.2 Variation of K_{ϕ_3} with Yaw angle

Figure A.3 Variation of K_{I2} with Yaw angle Figure A.4 Variation of K_{I3} with Yaw angle

Figure A.5 Variation of K_{23} with Yaw angle Figure A.6 Variation of K_1 with Yaw angle

Appendix B

Static Tap Locations of the Instrumented Loading Blade

Table B.1 Static Tap Locations of the Instrumented Loading Blade

Suction Side							
Tap No.	x/Bx	Tap No.	x/Bx	Tap No.	x/Bx	Tap No.	x/Bx
1	0.006	6	0.492	11	0.665	16	0.826
2	0.072	7	0.546	12	0.685	17	0.867
3	0.153	8	0.596	13	0.705	18	0.914
4	0.347	9	0.620	14	0.732	19	0.966
5	0.435	10	0.643	15	0.757	20	0.996
Pressure Side							
Tap No.	x/Bx	Tap No.	x/Bx	Tap No.	x/Bx	Tap No.	x/Bx
21	0.940	24	0.752	27	0.423	30	0.158
22	0.875	25	0.626	28	0.360	31	0.106
23	0.809	26	0.537	29	0.211	32	0.055

Appendix C

Hot-Wire Calibration Temperature Compensation

The output of a hot-wire anemometer is directly related to the convective cooling effect of the flow passing over the sensor and is dependent on the temperature difference between the sensor and the flow. A constant temperature hot-wire anemometer, as its name suggests, is designed to maintain the temperature of the sensor constant under changing flow conditions. The change of the anemometer output can be caused by not only the change of the flow velocity but also the change of the ambient temperature (T_a). Therefore, it is necessary to compensate the effect of the ambient temperature drift on the hot-wire measurements. Bearman's method (1970) was used in current study. For an unlinearized hot-wire anemometer, Equation 3.27 gives

$$E_c^2 = A + BV^n \quad \text{at calibrating temperature } T_{a,c} \quad (C.1)$$

$$E_m^2 = A' + B'V^n \quad \text{at measuring temperature } T_{a,m} \quad (C.2)$$

where $\frac{A}{A'} = \frac{B}{B'} = \frac{T_{op} - T_{a,c}}{T_{op} - T_{a,m}}$ and T_{op} is the hot-wire operating temperature.

Let $\frac{T_{a,c} - T_{a,m}}{T_{a,c}} = \varepsilon$ and the overheat ratio (OHR) $\theta = \frac{T_{op}}{T_{a,c}}$

then

$$\frac{A}{A'} = \frac{B}{B'} = \frac{\theta - 1}{\theta - 1 + \varepsilon} = \frac{\sigma}{\sigma + \varepsilon} \quad (C.3)$$

where $\sigma = \theta - 1$.

Substituting Equation C.3 into Equation C.2 gives

$$E_m^2 = A \frac{(\sigma + \varepsilon)}{\sigma} + B \frac{(\sigma + \varepsilon)}{\sigma} V^n \quad (C.4)$$

$$\text{Now let } E_m = E_c + \sigma E \quad (C.5)$$

Substituting Equation C.5 into Equation C.1

$$(E_m - \sigma E)^2 = A + BV^n$$

and combining Equation C.5 and C.4

$$E_m^2 = \left(1 + \frac{\varepsilon}{\sigma}\right) (E_m - \sigma E)^2$$

thus

$$E_m = \left(1 + \frac{\varepsilon}{\sigma}\right)^{\frac{1}{2}} E_c \quad (C.6)$$

If the changes in free stream temperature are small compared with the difference between wire temperature and free stream temperature, i.e., ε/σ is small, Equation C.6 becomes

$$E_c \cong E_m \left(1 - \frac{\varepsilon}{2\sigma}\right)$$

The correct velocity can now be found by placing E_c in Equation 3.27.

$$\left(E_m \left(1 - \frac{\varepsilon}{2\sigma}\right)\right)^2 = A + BV^n \quad (C.7)$$