1. INTRODUCTION

When fluid moves past a solid surface a *boundary layer* of fluid is formed that is distinct from other parts of the flowfield. The boundary layer is typically a thin region of the flowfield immediately adjacent to the solid surface. Within the boundary layer the velocity of the fluid changes from a *free-stream* value away from the surface to the velocity of the surface. Any interaction between the solid surface and the fluid (e.g. friction) takes place through the boundary layer. Therefore, understanding the flow physics of the boundary layer is important.

Boundary layers are divided into two broad categories, *laminar* and *turbulent*. In laminar boundary layers the acceleration/deceleration occurs in a series of layers or laminates of fluid. Each laminate only interacts with adjacent laminates through molecular viscosity. Most boundary layers of practical concern are turbulent. Turbulent flows are characterized by swirls, or eddies, of fluid that vary in spatial and temporal extent. Flow variables such as pressure and velocity fluctuate in a seemingly random way. These fluctuations enhance the mixing of particles within the flow as well as the mixing of flow properties such as momentum. Rather than having laminates that only interact with their immediate neighbor, large scale fluctuations convect fluid near the free-stream boundary to near the wall. The enhanced mixing can be beneficial. An example is a combustor in which the enhanced mixing of fuel and oxidizer increases combustor efficiency. Enhanced mixing can also be undesirable. Higher momentum fluid close to the solid surface increases the friction between the flow and the surface. This means greater drag force on automobiles, aircraft and marine vehicles and greater pressure drop in pipes. The pressure fluctuations generated within the boundary layer of applications such as helicopters, turbomachinery, aircraft, and marine vehicles can generate significant undesirable noise and induce vibrations that can contribute to accelerated structural fatigue.

Flow-induced pressure fluctuations have proven to be a very complex physical phenomena- difficult to calculate and difficult to measure. They are a *broadband* phenomena which means that they exist over a wide range of frequencies. This is because they are produced

by turbulent eddies that have many sizes. The broadband nature of turbulence limits the calculation of pressure fluctuations using direct numerical simulation (DNS) of the governing equation to low Reynolds number flows. *Reynolds number* (= (velocity scale)(length scale) / (kinematic viscosity)) is a certain ratio of flow parameters that is often used as a measure of turbulence. A higher Reynolds number is indicative of a more turbulent flow. Most flows of engineering interest are at high Reynolds number.

It is not currently possible to directly measure the pressure fluctuations *within* the boundary layer because placing a pressure probe within the boundary layer alters the flowfield too greatly. Therefore, pressure fluctuation measurements can only be made at the solid surface beneath the boundary layer. Initially this seems simple- just cut a hole in the surface, place a pressure transducer in the hole and make measurements. However, the turbulent eddies that produce pressure fluctuations extend to very small sizes. Contributions of sources that are smaller than the transducer sensing area are spatially integrated, and thereby attenuated. In the present study a miniature pressure transducer was used along with a pinhole to reduce spatial averaging (attenuation). Another difficulty arises in isolating the pressure fluctuations due to turbulence from the fluctuations due to other sources. Measured pressure signals are usually contaminated by coherent, facility-related acoustic inputs and external vibration of the transducer. Turbulent pressure fluctuations have a relatively small coherence in time and space. A noise cancellation technique originally developed by other researchers was adapted to the present study and used to isolate surface pressure fluctuations due to turbulence. The broadband nature of turbulent pressure fluctuations also requires accurate calibration of the pressure transducer over a wide frequency range. This issue was also dealt with in the present study.

1.1. Motivation

Pressure fluctuations in turbulent boundary layers are a source of noise, through the wake of a vehicle and through large turbulent motions that can cause disturbances in the free-stream flow which propagate away as sound. Pressure fluctuations are also a source of vibrations that can accelerate structural fatigue. Additionally, pressure fluctuations and their correlation with velocity fluctuations is an important diffusive mechanism in turbulence transport. Most fundamental investigations of surface pressure fluctuations have been confined to zero pressure

gradient, two-dimensional, turbulent boundary layers. This is the simple case of a boundary layer on a flat plate that is aligned with the flow. Some empirical relationships with some theoretical basis have been developed to describe surface pressure fluctuations beneath two-dimensional, turbulent boundary layers. The theoretical basis for these relationships is not disputed in the literature, however, there is some discrepancy in their measured behavior. Though studied extensively, the pressure fluctuations beneath the simple case of a zero-pressure-gradient, two-dimensional, turbulent boundary layer is still the subject of current research. Other studies have been done to investigate the effect of pressure gradient and boundary layer separation on surface pressure fluctuations. However, such studies are typically highly idealized laboratory flows that yield some insight on the behavior of surface pressure fluctuations. Researchers have also made measurements on real-world flows such as gliders and aircraft. However, such measurements are difficult to reproduce and only limited measurements of the velocity field were made. The present research seeks to bridge this gap. Accurate surface pressure measurements were carried out and related to extensive velocity field measurements in complex flows of practical interest.

1.2. Background

1.2.1. Coherent Structures

The concept of *coherent structures*, sometimes called *turbulent eddies* or just *eddies*, play an important role in the understanding of turbulence. Therefore, a brief description of coherent structures is warranted here. Many papers have been written on the subject. Recent reviews are given by Hussain (1986) and Robinson (1991). Robinson defines a coherent structure as "a three-dimensional region of flow over which at least on fundamental flow variable (velocity component, density, temperature, etc.) exhibits significant correlation with itself or with another variable over a range of space and/or time that is significantly larger than the smallest local scales of the flow."

Recent investigations of surface pressure fluctuations in two-dimensional turbulent boundary layers have related them to the coherent structures or *organized motions* known to exist in wall-bounded turbulent flows (Kammeyer, 1995; Russell, 1997). Ha (1993) and Lewis (1996) studied coherent structures in the boundary layer of a wing-body junction and Madden (1997) studied coherent structures in the boundary layer of a 6:1 prolate spheroid.

1.2.2. Pressure Fluctuations

The motion of a fluid is described by the Navier-Stokes and mass continuity equations. For an incompressible fluid with constant density and constant viscosity the governing equations may be expressed as,

$$\frac{\partial \vec{U}}{\partial t} + \left(\vec{U} \cdot \nabla \right) \vec{U} \quad = \quad -\frac{\nabla P}{\rho} + \nu \nabla^2 \vec{U} \tag{1}$$

$$\nabla \cdot \vec{U} \quad = \quad 0 \tag{2}$$

The divergence of equation 1 is

$$\nabla \cdot \frac{\partial \vec{U}}{\partial t} + \nabla \cdot \left(\vec{U} \cdot \nabla \right) \vec{U} \quad = \quad -\frac{\nabla^2 P}{\rho} + \nu \nabla \cdot \nabla^2 \vec{U} \tag{3}$$

which may be written as

$$\frac{\partial \left(\nabla \cdot \vec{U} \right)}{\partial t} + \nabla \cdot \left(\vec{U} \cdot \nabla \right) \vec{U} \quad = \quad -\frac{\nabla^2 P}{\rho} + \nu \nabla \cdot \left(\nabla \left(\nabla \cdot \vec{U} \right) \right) - \nu \nabla \cdot \left(\nabla \times \left(\nabla \times \vec{U} \right) \right) \tag{4}$$

The first and fourth terms of equation 4 are identically zero due to mass conservation (equation 2). The last term of equation 4 is zero since it is the divergence of the curl of a vector. Therefore, equation 4 is equal to

$$\nabla \cdot \left(\vec{U} \cdot \nabla \right) \vec{U} \quad = \quad -\frac{\nabla^2 P}{\rho} \tag{5}$$

which may be expressed as

$$\nabla^2 P \quad = \quad -\rho \frac{\partial^2}{\partial x_i \, \partial x_j} \left(U_i U_j \right) \tag{6}$$

which follows the usual tensor convention that a repeated index in a term indicates summation with respect to the repeated index over the range 1, 2, 3. If the terms on the right-hand side of equation 6 are known then equation 6 is a Poisson equation for the pressure. An equation for the fluctuating pressure may be obtained by expressing P and U_i as the sum of a mean and fluctuating part (Reynolds decomposition),

$$P \quad = \quad \overline{P} + p \tag{7}$$

$$U_i \quad = \quad \overline{U}_i + u_i \tag{8}$$

Note that p is used in this section to represent the fluctuating pressure in general, not just the fluctuating surface pressure. Substituting equations 7 and 8 into equation 6 gives

$$\nabla^2 \overline{P} + \nabla^2 p = -\rho \frac{\partial^2}{\partial x_i \partial x_j} \left(\overline{U}_i \overline{U}_j + \overline{U}_i u_j + u_i \overline{U}_j + u_i u_j \right) \tag{9}$$

Averaging equation 9 over time leaves

$$\nabla^2 \overline{P} = -\rho \frac{\partial^2}{\partial x_i \partial x_j} \left(\overline{U}_i \overline{U}_j + \overline{u_i u_j} \right) \tag{10}$$

Subtracting equation 10 from equation 9 gives

$$\nabla^2 p = -\rho \left[2 \frac{\partial \overline{U}_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_j} \left(u_i u_j - \overline{u_i u_j} \right) \right] \tag{11}$$

which is a Poisson equation for the fluctuating pressure. Note that the p in equation 11 represents the fluctuating pressure in general. Equation 11 is valid for all points within the flow. The first term on the right-hand side of equation 11 represents the turbulence-mean-shear interaction. It is linear with respect to the velocity fluctuations and is sometimes called the *rapid* term because it responds quicker to changes in the mean flow. The second term on the right-hand side of equation 11 represents the turbulence interaction with itself. It is non-linear with respect to the velocity fluctuations and is sometimes called the *slow* term because it responds to changes in the mean flow only after the mean flow alters the turbulence.

In order to obtain an equation for the *surface* pressure fluctuation at a point *on the wall* (point O, figure 1), equation 11 is integrated over the half-space above the wall through the use of the symmetric form of Green's theorem,

$$\oint_\Omega \left(\Psi \nabla^2 \Theta - \Theta \nabla^2 \Psi \right) d\Omega = \oint_\Sigma \left(\Psi \frac{\partial \Theta}{\partial n} - \Theta \frac{\partial \Psi}{\partial n} \right) d\Sigma \tag{12}$$

where $\partial/\partial n$ is the derivative in the direction normal to Σ and pointing away from Ω (figure 1). The integration may be performed by making substitutions $\Theta = p$ and $\Psi = 1/r_S$, using spherical coordinates to describe the position of sources of surface pressure fluctuations $\vec{r}_s = (r_S, \vartheta_S, \varphi_S)$, and dividing the surface, Σ, bounding the half-space, Ω, as shown in figure 1,

$$\oint_\Omega \left[\frac{1}{r_S} \nabla^2 p - p\nabla^2\left(\frac{1}{r_S}\right)\right] d\Omega \;\; = \;\; \oint_{\Sigma_1} \left[\frac{1}{r_S}\frac{\partial p}{\partial n} - p\frac{\partial}{\partial n}\left(\frac{1}{r_S}\right)\right] d\Sigma_1$$

$$+ \lim_{r_S \to 0} \oint_{\Sigma_2} \left[\frac{1}{r_S}\frac{\partial p}{\partial n} - p\frac{\partial}{\partial n}\left(\frac{1}{r_S}\right)\right] d\Sigma_2 \qquad (13)$$

$$+ \lim_{r_S \to \infty} \oint_{\Sigma_3} \left[\frac{1}{r_S}\frac{\partial p}{\partial n} - p\frac{\partial}{\partial n}\left(\frac{1}{r_S}\right)\right] d\Sigma_3$$

The second term of the integrand on the left hand side is zero because

$$\nabla^2\left(\frac{1}{r_S}\right) \;=\; 0 \qquad (14)$$

and the last integral on the right hand side is zero since

$$\lim_{r_S \to \infty}\left(\frac{1}{r_S}\right) \;=\; 0 \qquad (15)$$

$$\lim_{r_S \to \infty}(p) \;=\; 0 \qquad (16)$$

Equation 16 is a boundary condition. The pressure fluctuations are assumed zero far from the boundary layer. Also, the second term of the integrand over Σ_1 is zero because at all points on Σ_1 the position vector, $\vec{r}_s = (r_S,\ \vartheta_S,\ \varphi_S)$, is parallel to Σ_1. Therefore, for all points on Σ_1,

$$\frac{\partial}{\partial n}\left(\frac{1}{r_S}\right) \;=\; 0 \qquad (17)$$

Substituting equations 14 - 17 into equation 13 leaves

$$\oint_\Omega \left[\frac{1}{r_S}\nabla^2 p\right]d\Omega \;\;=\;\; \oint_{\Sigma_1}\left[\frac{1}{r_S}\frac{\partial p}{\partial n}\right]d\Sigma_1 + \lim_{r_S \to 0}\oint_{\Sigma_2}\left[\frac{1}{r_S}\frac{\partial p}{\partial n} - p\frac{\partial}{\partial n}\left(\frac{1}{r_S}\right)\right]d\Sigma_2 \qquad (18)$$

For the integral over Σ_2, r_S is constant. Therefore,

$$\partial n \;=\; -\partial r_S$$

$$d\Sigma_2 \;=\; r_S^2\, \sin\vartheta_S\, d\vartheta_S\, d\varphi_S$$

and the integral over Σ_2 becomes

$$\lim_{r_S \to 0} \oint_{\Sigma_2} \left[\frac{1}{r_S} \frac{\partial p}{\partial n} - p \frac{\partial}{\partial n}\left(\frac{1}{r_S}\right) \right] d\Sigma_2 = \lim_{r_S \to 0} \oint_{\Sigma_2} -\left[\frac{1}{r_S} \frac{\partial p}{\partial r_S} - p \frac{\partial}{\partial r}\left(\frac{1}{r_S}\right) \right] r_S^2 \sin\vartheta_S \, d\vartheta_S \, d\varphi_S$$

$$= \lim_{r_S \to 0} \oint_{\Sigma_2} -\left[r_S \frac{\partial p}{\partial r_S} + p \left(\frac{1}{r_S^2}\right) \right] r_S^2 \, \sin\vartheta_S \, d\vartheta_S \, d\varphi_S \qquad (19)$$

$$= \lim_{r_S \to 0} \oint_{\Sigma_2} -\left[r_S \frac{\partial p}{\partial r_S} + p \right] \sin\vartheta_S \, d\vartheta_S \, d\varphi_S$$

Since $\partial p / \partial r_S$ remains finite as $r_S \to 0$,

$$\lim_{r_S \to 0} \left(r_S \frac{\partial p}{\partial r_S} \right) = 0 \qquad (20)$$

which leaves

$$\lim_{r_S \to 0} \oint_{\Sigma_2} \left[\frac{1}{r_S} \frac{\partial p}{\partial n} - p \frac{\partial}{\partial n}\left(\frac{1}{r_S}\right) \right] d\Sigma_2 = \lim_{r_S \to 0} \oint_{\Sigma_2} -\left[r_S \frac{\partial p}{\partial r_S} + p \right] \sin\vartheta_S \, d\vartheta_S \, d\varphi_S$$

$$= \lim_{r_S \to 0} \oint_{\Sigma_2} (-p) \sin\vartheta_S \, d\vartheta_S \, d\varphi_S$$

$$= \int_0^\pi \int_0^\pi (-p_O) \sin\vartheta_S \, d\vartheta_S \, d\varphi_S \qquad (21)$$

$$= \int_0^\pi \left(p_O \cos\vartheta_S \right)_0^\pi \, d\varphi_S$$

$$= \int_0^\pi (-2 p_O) \, d\varphi_S$$

$$= -2\pi p_O$$

The surface Σ_2 has become point O (figure 1) through the limit $r_S \to 0$. Therefore p_O denotes the fluctuating pressure at point O, on the wall. In fact, p_O is quantity of interest in the present development. Substituting equation 21 into equation 18 yields

$$\oint_\Omega \left[\frac{1}{r_S} \nabla^2 p \right] d\Omega = \oint_{\Sigma_1} \left[\frac{1}{r_S} \frac{\partial p}{\partial n} \right] d\Sigma_1 - 2\pi p_O \qquad (22)$$

Evaluation of the integral over Σ_1 is not straightforward and requires consideration of the physical situation. In the limit as $r \to 0$, the surface Σ_1 consists of all points on the wall except point O (figure 1). Also, on Σ_1 $\partial p / \partial n$ is equivalent to $-\partial p / \partial y$ at $y = 0$ in a Cartesian (x, y, z) coordinate

system (figure 1). The pressure gradient is related to the velocity field through equation 1. Since $\vec{U} = (U, V, W)$, equation 1 consists of three scalar equations for momentum transport. By doing a Reynolds decomposition of the *V*-momentum equation, subtracting the mean *V*-momentum equation, applying the continuity equation (equation 2) and requiring that all velocity components, both mean and fluctuating, are zero at $y = 0$ (the "no-slip" condition) one is left with

$$\frac{\partial p}{\partial y}\bigg|_{y=0} = \upsilon \frac{\partial^2 v}{\partial y^2}\bigg|_{y=0} \tag{23}$$

where υ is the kinematic viscosity. Kim (1989), using a direct numerical simulation database of a channel flow (Kim *et al.*, 1987; $Re_\theta = 283$), kept equation 23 as a boundary condition in his calculation of *p* and referred to the solution of $\partial p / \partial y$ at $y = 0$ as the "Stokes" pressure. In his calculation, the Stokes pressure contributed less than 10% to the total *p'* at the wall, which he concluded was insignificant. In the present development, the integral over Σ_1 is assumed insignificant, and neglected. Therefore, the solution to equation 22 may be written as

$$
\begin{aligned}
p_O &= -\frac{\rho}{2\pi} \oint_\Omega \left[\frac{1}{r_S} \nabla^2 p \right] d\Omega \\
&= \frac{\rho}{2\pi} \oint_\Omega \left[2\frac{\partial \overline{U}_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} + \frac{\partial^2}{\partial x_i \partial x_j}\left(u_i u_j - \overline{u_i u_j} \right) \right] \frac{d\Omega}{r_S}
\end{aligned}
\tag{24}
$$

As with equation 11, equation 24 can be split into a *rapid* pressure that describes the mean shear-turbulence interaction and a *slow* pressure which describes the turbulence-turbulence interaction. Since the remainder of this document deals with surface pressure fluctuations, the subscript "*O*" is dropped with the understanding that *p* is the fluctuating pressure at a point on the wall. Equation 24 is rewritten with these considerations as the *Poisson Integral*,

$$p = \frac{\rho}{\pi} \oint_\Omega \left[\frac{\partial \overline{U}_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} \right] \frac{d\Omega}{r_S} + \frac{\rho}{2\pi} \oint_\Omega \left[\frac{\partial^2}{\partial x_i \partial x_j}\left(u_i u_j - \overline{u_i u_j} \right) \right] \frac{d\Omega}{r_S} \tag{25}$$

1.3. Literature Review

1.3.1. Pressure Fluctuations

Pressure fluctuations generated by turbulent flow has received considerable attention over the past 45 years. A review of knowledge about pressure fluctuations beneath turbulent boundary

layers is given by Willmarth (1975). Blake (1986) gives a comprehensive review of experimental research and theory. The review of Eckelmann (1990) covers the period from 1975 to 1987. It focusses mainly on low Reynolds number direct numerical simulations and experiments that used conditional sampling/averaging techniques to investigate the role of coherent structures in the relationship between velocity fluctuations within the turbulent boundary layer and pressure fluctuations at the surface beneath the turbulent boundary layer. The comprehensive review of Bull (1996) covers theoretical and experimental research from the 1950s up to 1992.

Some of the earliest research on turbulent pressure fluctuations is the theoretical work of Lighthill (1952, 1954). His formulation followed an analogy approach. Rather than solve for a turbulent flow directly, he considered an equivalent system of a uniform acoustic medium at rest that is subjected to an external fluctuating stress. The external fluctuating stress is the difference between the momentum fluctuation of the turbulent flow and the hydrostatic pressure of the uniform acoustic medium. This approach is often referred to as *Lighthill's analogy* and is fundamental to modern aeroacoustic theory.

The theoretical work of Kraichnan (1956) and Phillips (1956) focussed on pressure fluctuations within an incompressible, zero pressure gradient, turbulent boundary layer. Their analyses were based directly on the Navier-Stokes equation and assumed that the turbulence was homogeneous in planes parallel to an infinite plane boundary. This assumption allowed them to calculate the wavenumber-frequency spectrum using a partial Fourier transform. Their analysis showed that the wavenumber-frequency spectrum is zero at zero wavenumber independent of frequency. This result is often referred to as the *Kraichnan-Phillips theorem*. Ffowcs-Williams (1982) later showed that the Kraichnan-Phillips theorem is only true in the limit as Mach number goes to zero.

Willmarth and Wooldridge (1962) measured one of the first high quality data sets of surface pressure fluctuations. Measurements of the mean square and power spectrum of pressure, the space-time correlation of pressure in the streamwise direction, and the spatial correlation of pressure in the lateral direction were carried out beneath a thick boundary layer ($Re_\theta = 29000$, 38000). Their analysis showed that pressure-producing turbulent structures are convected

downstream at a speed that varies with wavelength. Long wavelength disturbances are convected downstream faster than short wavelength disturbances. They also showed that pressure-producing turbulent structures decay and vanish after traveling a distance of approximately six wavelengths. The lateral and streamwise length scales of the fluctuating pressure were found to be the same– on the order of the boundary layer thickness.

Corcos (1963) used the measurements of Willmarth and Wooldridge (1962) to develop a correction for measured power spectra that accounts for the attenuation of high frequency spectral levels due to finite (non-zero) transducer size. Corcos (1963) assumed that the cross-spectrum of surface pressure fluctuations was separable in the streamwise and lateral directions. Using this assumption he was able to numerically integrate the spatial correlation data of Willmarth and Wooldridge (1962). The Corcos (1963) correction and spectral attenuation due to finite transducer size is discussed in more detail in §2.3.2.

Schloemer (1967) measured the power spectrum, and the magnitude of the streamwise and lateral cross-spectrum of surface pressure fluctuations. The measurements were carried out in mild adverse, mild favorable, and zero pressure gradient flows. The adverse pressure gradient increased low frequency spectral levels with little effect on the high frequency spectral levels. Decreased high frequency spectral levels were measured in the favorable pressure gradient flow. The decay of a given turbulent structure in the streamwise direction was more rapid in the adverse pressure gradient flow and slower in the favorable pressure gradient flow. The lateral cross-spectral levels were unaffected by the pressure gradient.

Bradshaw (1967) measured power spectra of surface pressure and surface pressure-velocity correlations in a turbulent boundary layer with equilibrium, adverse pressure gradient. His results were presented in the context of "active" shear stress producing motions and "inactive" irrotational motions that contribute little to the production of shear stresses. The concept that the inner turbulent boundary layer consists of active and inactive motions was attributed to Townsend (1961) and the data of Bradshaw (1967) support this concept. Bradshaw (1967) also used dimensional analysis to show that the contribution of the active motions to the wavenumber spectrum of surface pressure fluctuations decays as τ_W^2/k_1 up to a

wavenumber that is proportional to the thickness of the viscous sublayer. Using arguments

relating the existence of an inner boundary layer variable scaling and an outer boundary layer

variable scaling, he proposed that an overlap region exists in the *p* spectrum beneath two-

dimensional, turbulent boundary layers at high Reynolds number. Both inner and outer variable

scalings should collapse the *p* spectrum within the overlap region and the spectrum should decay

as ω^{-1}.

Blake (1970) measured the pressure fluctuations beneath several high Reynolds number

($8210 < Re_\theta < 29800$) zero-pressure gradient smooth-wall boundary layers and several rough wall

boundary layers in which the height and separation of the rough elements were independently

varied. Power spectra and broadband spatial correlations of *p* in both the streamwise and lateral

directions were presented. The smooth-wall *p* spectra showed the overlap region proposed by

Bradshaw (1967), however, the observed spectral decay was $\omega^{-0.75}$. His smooth-wall spatial

correlation data was in agreement with the earlier measurements of Willmarth and

Wooldridge (1962) and his smooth-wall cross-spectral data exhibited the longitudinal and lateral

similarity proposed by Corcos (1963). The high frequency spectral levels of surface pressure on

the rough walls collapsed when normalized using the roughness height, friction velocity, and wall

shear stress. The roughness separation affected the large-scale turbulent motions and the

roughness height was the main influence on the medium and small-scale turbulence.

Fricke (1971) presented measurements of the power spectrum and spatial correlation of

surface pressure fluctuations in the streamwise direction in the separated flow behind a boundary

layer fence. His results show that root-mean-square of surface pressure fluctuations beneath

subsonic, separated flows are an order of magnitude higher than the value measured beneath an

attached boundary layer. He also formulated a model for the root-mean-square of surface

pressure fluctuations beneath the separated flow behind a boundary layer fence that agreed well

with his data. His model was a modified form of Kraichnan's (1956) analysis.

Panton and Linebarger (1974) calculated the one-dimensional wavenumber spectrum of

surface pressure fluctuations in the streamwise direction beneath an equilibrium boundary layer.

They used the formulation of Kraichnan (1956) and only included the mean shear-wall-normal

fluctuating velocity term of the Poisson integral (equation 25). They assumed functional forms for the mean velocity and wall-normal velocity fluctuations. The form of the spatial correlation of wall-normal velocity fluctuations that they used included a scale-anisotropy factor. They show the contribution of the inner, middle, and outer layer to different parts of the wavenumber spectrum. They also show the variation of different parts of the wavenumber spectrum with equilibrium pressure gradient and their scale-anisotropy parameter.

Schewe (1983) measured the surface pressure fluctuations beneath a zero pressure gradient, turbulent boundary layer with transducers of various size and an array of four small transducers. He showed that the probability distribution measured with a large transducer does not resolve the large amplitude pressure events. As the transducer size increases the probability distribution function, skewness, and flatness factor approach a Gaussian distribution. It was shown that a transducer diameter of $d^+ = 19$ is sufficient to resolve the essential structures of the turbulent boundary layer fluctuations. Schewe used his data and the data of selected previous investigations (with higher d^+) to show a trend of increasing measured values of p'/Q_e as d^+ increases.

Simpson *et al.* (1987) measured the power spectrum and convective wave speed of surface pressure fluctuations at several locations beneath a two-dimensional separating boundary layer. The root-mean-square pressure fluctuations increased monotonically through the adverse pressure gradient attached-flow region and the detached-flow region and was proportional to the ratio of the streamwise length scale to the length scale in other directions. The power spectra at several locations that span the development of boundary layer separation collapsed at high frequencies when normalized using δ^*/U_∞ as the time scale and the maximum shearing stress as the pressure scale. The p spectra showed an ω^{-3} decay at the higher frequencies of the separating flow which is in agreement with the earlier investigations of Bradshaw (1967) and Schloemer (1967) of p beneath two-dimensional, adverse-pressure-gradient, boundary layers. The convective wave speed of surface pressure fluctuations at high frequencies decreased downstream of the onset of the separation process. The decrease was attributed to intermittent backflow.

McGrath and Simpson (1987) measured the power spectrum, coherence, and convective wave speeds of surface pressure fluctuations beneath turbulent boundary layers with zero and favorable pressure gradient that covered a range of Re_θ from 3000 to 18800. The power spectra beneath the zero pressure gradient boundary layer collapsed at low frequencies when normalized using δ^*/U_e as the time scale and τ_W as the pressure scale and collapsed at high frequencies when normalized using v/u_τ^2 as the time scale and τ_W as the pressure scale. An overlap region in which both the high frequency scaling and low frequency scaling collapse the power spectra was observed in the zero pressure gradient boundary layers with $Re_\theta > 5000$. The p spectra within the overlap region decayed as $\omega^{-0.7}$ rather than ω^{-1} as proposed by Bradshaw (1967). The lateral coherence in the zero pressure gradient flow decayed faster than in the favorable pressure gradient flow which is in agreement with the earlier investigation of Schloemer (1967). Also, the convective wave speed normalized by the free-stream velocity was faster in the favorable pressure gradient flow which is in agreement with the earlier investigation of Schloemer (1967).

Kim (1989) calculated the pressure fluctuations in a turbulent channel flow using the direct numerical simulation database of Kim *et al.* (1987). He retained the slow pressure term of the Poisson equation (equation 11). He found that the contribution of the slow pressure term to the pressure fluctuations was larger than the rapid pressure contribution throughout the channel except very near the wall, where they were approximately the same. This contradicts the earlier arguments of Kraichnan (1956) and Panton and Linebarger (1974) that the contribution of the slow pressure term to the Poisson equation (equation 11) is negligible. Probability density distributions, power spectra, and spatial correlations of the pressure fluctuations throughout the flow field were also calculated and discussed.

Farabee and Casarella (1991) measured power spectra and cross-spectra of surface pressure fluctuations beneath several two-dimensional, zero pressure gradient, turbulent boundary layers that covered a range of Re_θ from 3386 to 6025. They present experimentally measured power spectra that extend to among the lowest frequencies ever reported. Though not shown, they report that the low frequency spectral levels collapse when normalized using δ^*/U_e as the time scale and Q_e as the pressure scale and follow an ω^2 frequency dependence. They also use the observed scaling behavior of the power spectrum to develop an equation for the mean-square

surface pressure fluctuations that increases as the natural logarithm of the Reynolds number, Re_δ. Their data does not support the streamwise cross-spectral similarity proposed by Corcos (1963). Their convective wave speed data show that sources within the outer and inner boundary layer produce the low and high wavenumber spectrum, respectively.

Keith *et al.* (1992) present power spectra of surface pressure fluctuations from various experimental and numerical studies normalized using several different scaling laws. The attenuation of high frequency spectral levels caused by inadequate transducer spatial resolution is discussed. Dimensional analysis is used to relate various scaling laws to one another and show the Reynolds number (Re_θ) dependence of each of the scaling laws.

Gravante *et al.* (1998) measured power spectra of surface pressure fluctuations beneath several two-dimensional, zero pressure gradient, turbulent boundary layer that cover a Re_θ from 1577 to 7076. Measurements were carried out using transducers with pinhole masks of various sizes ($2 \leq d^+ \leq 27$) in order to investigate the effect of transducer spatial resolution on measured high frequency spectral levels. They concluded that a transducer sensing diameter in the range $12 \leq d^+ < 18$ was required in order to avoid spectral attenuation for frequencies up to $f^+ \equiv f\nu/u_\tau^2 = 1$. However, the reduction in measured values of the root-mean-square surface pressure was barely noticeable for transducers with a diameter $d^+ < 27$.

1.3.2. Wing-Body Junction Flow

The flowfield around a wing-body junction is well documented for a variety of wing shapes and a wide range of Reynolds number. As a turbulent boundary layer on a flat wall flows around a wing mounted normal to the wall, the lateral mean vorticity generated within the boundary layer is stretched around the wing and, in this way, a significant component of vorticity forms in the streamwise direction. A horseshoe vortex that is wrapped around the wing and has legs that extend downstream of the junction is characteristic of a wing-body junction flow (figure 2). Most previous studies have focussed on the complex, highly unsteady flow just upstream of the nose of the wing. Pierce and Tree (1990) conducted an oil flow visualization, measured the mean surface pressure, and used a LDV to measure the streamwise and wall-normal mean velocity components in the nose region of a symmetric wing. The wing section used in their

study had a circular nose and the approach $Re_\theta = 12500$. The focus of their study was to determine a vortex model for the mean flow. Devenport and Simpson (1990) used oil flow visualization, mean pressure measurements on the test wall and wing surface, single-component (streamwise) hot-wire anemometer measurements, and three-component LDV measurements to document the time-averaged and time-dependent turbulent structure in the plane of symmetry just upstream of a wing-body junction. Their study was conducted using the same wing model as used in the present study (3:2 elliptic nose, NACA 0020 tail). The approach Re_θ was 6700. The measurements of the mean velocity and Reynolds stress tensor were used to compute spatial correlations and the turbulent kinetic energy balance. They were the first to report bimodal probability distribution functions of the streamwise and wall-normal velocity at some measurement locations. The bimodal probability distribution functions cause high levels of turbulence intensity. Further references to research concerning the wing-body junction flow are given by Ha (1993), Simpson (1996), Lewis (1996), and Fleming (1997).

Hasan *et al.* (1985) present the mean and fluctuating streamwise component and correlations between the streamwise and wall-normal velocity fluctuations measured with a hot-wire anemometer and surface pressure power spectra and RMS pressure distributions around a wing-body junction. Their measurements were made on irregularly spaced grid of locations that extended from 6.0 times the wing thickness upstream of the wing nose to 2.5 times the wing thickness downstream and laterally from the plane of symmetry to 1.5 times the wing thickness to the side of the wing. The wing cross-section consisted of a 3:1 elliptic nose, parallel mid-body, and a NACA 0020 tail. The free-stream velocity of the approach flow was 30 m/s. The power spectra of wall-pressure show a consistent trend of low frequency spectral levels at locations near the wing that are high as compared to the low frequency spectra at locations away from the wing. They attribute the elevated spectral levels to low frequency organized motions associated with the wing-body junction vortex.

Previous studies of the fluctuating surface pressure in a wing-body junction flow are confined mainly to the unsteady nose region just upstream of the wing. Rife *et al.* (1992) and Shinpaugh (1994) examined the relationship between the bimodal velocity and surface pressure fluctuations in the nose region. Rife *et al.* (1992) measured the streamwise and wall-normal

velocity components and surface pressure simultaneously in a flow with an approach $Re_{\theta} = 6900$. They presented power spectra and probability distribution functions of the surface pressure along with conditionally averaged correlations between the surface pressure fluctuations and each of the velocity components that they measured. Shinpaugh (1994) measured the streamwise and wall-normal velocity components and surface pressure simultaneously in a flow with an approach $Re_{\theta} = 6700$. He presented probability distribution functions of the surface pressure and conditionally averaged correlations between the surface pressure fluctuations and each of the velocity components that he measured. Ölçmen and Simpson (1994) studied the effect of wing shape on surface pressure fluctuations just upstream of a wing-body junction. They studied six different shapes, including the geometry used in the present investigation. They used oil flow visualizations of the near-wall flow and probability distributions and power spectra of the surface pressure fluctuations in their analysis. They were able to empirically relate a fluctuating pressure force to the momentum rate in the streamwise and wall-normal direction.

The velocity field at the measurement stations used in the present study (figure 3) have been extensively documented by Ölçmen and Simpson (1995a, 1996) and Ölçmen *et al.* (1998). The LDV measurements of the complete velocity vector, Reynolds stress tensor and triple products, mean surface pressure measurements, and oil flow visualizations that were performed in conjunction with the above studies were used directly in the present investigation.

1.3.3. Flow Around a 6:1 Prolate Spheroid

The flow about a 6:1 prolate spheroid exhibits open separation phenomena of three-dimensional flow (figure 4). It is reflected by the convergence of skin friction lines (Wetzel *et al.*, 1998). The flow separating from the lee-side rolls up into a strong vortex on each side of the body. This primary vortex may be accompanied by one or more smaller vortices, each of which is associated with a separation and reattachment line. The complex interactions between vortices result in a highly skewed three-dimensional shear layer. Kreplin *et al.* (1985, 1993) Meier *et al.* (1984, 1985) and Vollmers *et al.* (1983) have documented the surface flow, mean surface pressure, skin friction, and mean velocity at several Reynolds numbers and angles of attack. The leeside flow has proven difficult for turbulence models to calculate (Chesnakas and Simpson, 1996; AGARD, 1991; Gee *et al.*, 1992; Sung *et al.*, 1993).

The current study is part of an ongoing effort to extensively measure this flowfield in order to increase the understanding of the flow physics and to provide an experimental data base for comparison with computations. The effects of Reynolds number and angle of attack on boundary layer transition and separation location were studied by Ahn and Simpson (1992). Barber and Simpson (1991) documented the mean and turbulent velocities in the cross-flow separation region, but the use of five-hole pressure probes and crossed hot wires precluded them from obtaining data within the inner boundary layer. Previous studies of a tripped flow at a length Reynolds number $\mathrm{Re_L} = 4.2\times10^6$ by Chesnakas *et al.* (1993) and Chesnakas and Simpson (1994, 1996, 1997) did not suffer this limitation and have documented the turbulence structure, including all Reynolds stresses and velocity triple products, from y^+ closer than 7. This was possible through the use of the specially designed, miniature fiber-optic LDV probe described in Chesnakas and Simpson (1994). The data of Chesnakas et al (1993) and Chesnakas and Simpson (1994, 1996, 1997) were used directly in the present study. Simpson (1989, 1995, 1996) reviewed three-dimensional turbulent separation in detail. Wetzel, *et al.* (1998) focussed on the measurement and quantitative description of three-dimensional crossflow separation.

Much analysis of surface pressure fluctuations beneath equilibrium, 2-D boundary layers exist in the literature. The present study extends this knowledge to the analysis of a complex, 3-D, separating boundary layer of practical interest. Additionally, the flows of the present study cover a large range of Reynolds number. Surface pressure-velocity spatial correlations and the extensive data on the turbulent velocity field are used to explain features of p and p'.

1.4. Outline of Dissertation

This dissertation presents experimental measurements of the surface pressure fluctuations beneath a two-dimensional boundary layer and two three-dimensional turbulent boundary layers of practical interest. The goals of this research were (1) to characterize the surface pressure fluctuations beneath three-dimensional turbulent boundary layers of practical interest, (2) to gain understanding of the effect of flow three-dimensionality on surface pressure fluctuations, and (3) to investigate the relationship between surface pressure fluctuations and the complex, three-dimensional structure of the turbulent velocity field. The approach was to study the statistics of both the surface pressure and the velocity field through new measurements of the fluctuating

surface pressure and existing measurements of the velocity field and the covariance of the surface pressure and fluctuating velocity components. Chapter 2 describes the experimental method used in the present investigation. Chapter 3 presents the measurements of the fluctuating surface pressure beneath two-dimensional boundary layers that serve as a baseline for comparison to the measurements of the fluctuating surface pressure beneath three-dimensional boundary layers. Chapter 4 presents measurements of the root mean square (RMS) and spectral power density of the fluctuating surface pressure at 10 locations beneath the turbulent boundary layer away from a wing-body junction. Some scaling issues are also discussed. Chapter 5 presents measurements of the root mean square (RMS) and spectral power density of the fluctuating surface pressure and surface pressure-velocity correlations about a 6:1 prolate spheroid. Conclusions drawn from this research and suggestions for further research are the subject of Chapter 6.