2. EXPERIMENTAL APPARATUS AND TECHNIQUES

2.1. Test Facilities

2.1.1. Virginia Tech Boundary Layer Wind Tunnel

The Virginia Tech Boundary Layer Wind Tunnel is an open circuit, subsonic wind tunnel. The tunnel test section is 8 m long with a rectangular cross section that is 0.91 m wide with variable height in order to adjust the streamwise pressure gradient (figure 5). Test flows are generated by a 19 kW centrifugal blower that draws air through an air filter and blows the air through a fixed-setting flow damper that is used to control flow speed. Downstream of the blower, a section of honeycomb, a two-dimensional 4:1 contraction ratio, and seven wire-mesh screens reduce the free-stream turbulence intensity to 0.2% at a nominal flow speed of 27 m/s (Devenport and Simpson, 1990). The maximum nominal flow velocity is 32 m/s. As the flow enters the test section, the boundary layer is tripped by a 6.3 mm high step after which it passes through an additional 1.5:1 contraction and reaches a throat where the test section height is 25.1 cm. The nominal flow velocity and temperature are measured at the throat which is 1.63 m downstream of the test section entrance. An additional roughness plate is secured to the test section floor 1.35 m downstream of the test section entrance in order to thicken the boundary layer and thereby produce higher Reynolds number flows (e.g. $Re_\theta = 23400$). The roughness plate is 61 cm long and consists of 3.2 mm high, 3.2 mm wide, square ribs that extend the width of the test section and are spaced 12.7 mm apart in the streamwise direction (Ölçmen *et al.*, 1998). The roughness plate is not required to produce the lower Re_θ (= 7300) flow. The height of the test section gradually increases downstream of the throat in order to allow for the growth of the boundary layer and maintain a very nearly zero streamwise pressure gradient. Hot-wire traverses show that the potential core is uniform within +3%/-1.5% in the streamwise direction and ±2% in the lateral direction (Ölçmen *et al.*, 1998). The wind tunnel is fully contained within an indoor laboratory and the flow temperature is regulated to within ±1°C by a Carrier brand A/C unit. Further information may be found on the Internet at http://www.aoe.vt.edu/aoe/physical/bllab.html.

2.1.2. Virginia Tech Stability Wind Tunnel

The Virginia Tech Stability Wind Tunnel is a continuous, closed jet, single return, subsonic wind tunnel with a 7.3 m long test section that has a 1.8 m square cross section (figure 6). The tunnel was acquired by Virginia Tech in 1958 from the NACA Langley Aeronautical Laboratory where it was originally constructed in 1940. Test flows are generated by a 4.3 m propeller which is driven by a by a 450 kW d.c. motor. The maximum flow velocity is 84 m/s. Tunnel speed is regulated by a custom designed Emerson VIP ES-6600 SCR Drive and the flow temperature is stabilized through the continuous entrainment of atmospheric air by an air exchange tower. The regulated power supply, turning vanes, a 9:1 contraction, and seven wire-mesh screens provide low free-stream turbulence levels — of the order of 0.03% (Choi and Simpson, 1987). A comprehensive discussion of the Virginia Tech Stability Wind Tunnel is given by Simpson (1997). Further information may be found on the Internet at http://www.aoe.vt.edu/aoe/physical/tunnel_descrip.htm.

2.2. Test Flows

2.2.1. Two-Dimensional Boundary Layer

The measurements of p beneath two zero-pressure-gradient, two-dimensional boundary layers (Re_θ = 7300, 23400) were carried out in the Virginia Tech Boundary Layer Wind Tunnel (§2.1.1). For the Re_θ = 7300 flow, the nominal free-stream air speed was 27.5 m/s and measurements were made 303 cm downstream of the test section entrance. The velocity field has been documented by Ölçmen and Simpson (1996) and is discussed further in chapter 3. For the Re_θ = 23400 flow, the nominal free-stream air speed was 32.0 m/s and measurements were made 696 cm downstream of the test section entrance. The velocity field has been documented by Ölçmen *et al.* (1998) and is discussed further in chapter 3. All measurements were carried out at ambient pressure and the flow temperature was 25°C ± 1°C.

2.2.2. Wing-Body Junction Flow

The measurements of p in two pressure driven, three dimensional turbulent boundary layers that are each produced by a wing-body junction geometry were carried out in the Virginia Tech Boundary Layer Wind Tunnel (§2.1.1: figure 7). For one of the flows, the nominal air speed was 27.5 m/s and Re_θ = 5940 based on the momentum thickness at 0.75 chord lengths upstream of the nose of the wing on the tunnel centerline. For the other flow, the nominal air speed was 32.0 m/s and Re_θ = 23200 based on the momentum thickness in the 2-D flow produced by removing the wing. All measurements were carried out at ambient pressure and the flow temperature was 25°C ± 1°C.

In each flow, measurements of *p* were carried out at 10 *stations* that traverse one side of the wing (figure 3) and are away from the horseshoe vortex that forms about the wing-body junction (figure 2). These flows are referred to as "wing-body junction" flows only to distinguish them from the other pressure-driven, three-dimensional turbulent boundary layer that is produced by the flow about a 6:1 prolate spheroid and is also part of the present investigation. The measurement stations were chosen based on the existence of previously documented mean velocity, Reynolds stress, triple products, and skin friction measurements (Ölçmen *et al.*, 1999b; Re_θ = 5940: Ölçmen and Simpson, 1995a, 1996; Re_θ = 23200: Ölçmen *et al.*, 1998, 1999b). The existing velocity measurements were carried out using a three-orthogonal-velocity-component, fiber-optic laser-Doppler velocimeter (LDV) probe (Ölçmen and Simpson, 1995b).

The same wing model was used for both Re_θ flows. It has a maximum thickness of 7.17 cm, chord length of 30.5 cm, and a height of 22.9 cm. The wing cross-section is a 3:2 elliptical nose, with the major axis aligned with the chord, and a NACA 0020 tail joined at the maximum thickness. The wing was mounted at zero angle of attack with the leading edge 302 cm downstream of the test section entrance in the Re_θ = 5940 flow and 707 cm downstream of the test section entrance in the Re_θ = 23200 flow. A 3.7 mm gap was left between the ceiling of the test section and the top of the wing model in order to prevent the formation of a second horseshoe vortex. The mean surface pressure measurements and oil flow visualizations conducted on the test section floor by Ölçmen and Simpson (1995a: Re_θ = 5940) and Ölçmen *et al.* (1998: Re_θ = 23200) confirmed that the wing was mounted at zero angle of attack and showed that blockage effects, due to the test section side walls, are negligible when the test section is configured in the manner used for the present study.

2.2.3. Flow Around a 6:1 Prolate Spheroid

The measurements of *p* beneath the pressure driven, three dimensional turbulent boundary layer that is produced by flow about a 6:1 prolate spheroid were carried out in the Virginia Tech Stability Wind Tunnel (§2.1.2). Measurements were carried out at α = 10°, 20° and *x/L* = 0.600, 0.772. At each of these four measurement *stations*, p was measured at 5° increments of ϕ in the range $90° \leq \phi \leq 180°$ where $\phi = 0°$ is the most windward ϕ *location* and $\phi = 180°$ is the most leeward ϕ location on the model. All measurements were conducted at a constant Reynolds number, $Re_L = 4.20\times10^6$ (50.73 m/s < U_∞ < 55.25 m/s), and ambient temperature. The velocity field at the present measurement stations has been documented by Chesnakas and Simpson (1994, 1996, 1997) and is discussed further in chapter 5.

The 6:1 prolate spheroid that was used for these measurements is 1.37 m long and was constructed of a machined fiberglass skin bonded to an aluminum frame. A circumferential trip, consisting of posts 1.2 mm in diameter, 0.7 mm high and spaced 2.5 mm apart, was placed around the model circumference at $x/L = 0.2$. This fixed the location of transition. Windows of size 30 mm × 150 mm × 0.75 mm (figure 8) were placed in the skin of the model for optical access to the flow (Chesnakas and Simpson, 1994, 1996, 1997). The windows were molded to the curvature of the model and mounted flush with the model surface in order to alleviate flow disturbances. Wax was used to fill any small gaps in the model surface. The model was supported with a rear-mounted, 0.75 m long sting aligned along the model axis and connected to a vertical post extending through the wind tunnel floor.

2.3. Some Measurement Issues

2.3.1. Low Frequency Spectral Contamination

Measured pressure signals are usually contaminated by coherent, facility-related acoustic pressures and external vibration of the transducer. This contamination takes the form of additional spectral energy that is superimposed upon the spectral energy produced by the turbulence and is generally confined to the low frequency end of the spectrum. Low frequency spectral contamination has long been recognized as a source of error in the measurement of turbulent surface pressure fluctuations. Wills (1970) use spatial correlation measurements of p to calculate the spectral contribution due to extraneous sound and vibration. Then, these spectral levels were removed from his measured spectral levels, leaving only the spectral contribution due to the turbulence. Most present day investigations either use an acoustically quiet wind tunnel and accept the experimental uncertainty due to acoustic sources still present or use some type of noise cancellation technique.

Noise cancellation techniques take advantage of the fact that *p* due to external sound and vibration remain coherent over a larger distance and a longer time as compared to *p* due to turbulence. Lauchle and Daniels (1987), Simpson *et al*. (1987), Agarwal and Simpson (1989), and Helal *et al.* (1989) each give a comprehensive review of noise cancellation techniques.

Lauchle and Daniels (1987) carried out measurement of *p* in a pipe flow of glycerine. The glycerine was used to allow for the resolution of the highest frequency *p* by decreasing the d^+ of their transducer through the high viscosity of glycerine (see §2.3.2). They measured *p* using three transducer assemblies equally spaced along the circumference of the pipe at a given axial location. The pipe acts as a waveguide. Facility-related acoustic waves travel through the pipe as plane waves normal to the center axis of the pipe. In this way, the contribution to *p* from to external sound is circumferentially coherent. Each transducer assembly contained a pressure transducer and an accelerometer. Values of *p* were extracted through a combination of subtracting the measured signal from different pressure transducers, subtracting the measured signal from different accelerometers, and computing cross-spectra.

McGrath and Simpson (1987) used two pressure transducers separated by a lateral distance greater than 4 boundary layer thicknesses to measure *p* beneath a 2-D boundary layer. Their measurements were carried out in the Virginia Tech Boundary Layer Wind Tunnel test section which acts like a waveguide to facility-related acoustic waves. Their analysis shows that subtracting the two transducer signals from one another left only the *p* produced by turbulence. The part of the signal measured by each transducer due to external sound and flow unsteadiness produced by the wind tunnel was correlated laterally across the test section. Due to the large transducer spacing, the part of the signal due to turbulence was uncorrelated, but statistically the same since the mean flow was two dimensional. Contamination of the measured signal by external vibration was accounted for by mechanically isolating the pressure transducers from the wind tunnel such as was done in the present study.

Agarwal and Simpson (1989) used two transducers separated by a lateral distance that is slightly less than one-third of the boundary layer thickness. Their measurements were carried out in the Virginia Tech Stability Wind Tunnel test section which acts as a waveguide to facility-related acoustic waves. Their analysis shows that the method of McGrath and Simpson (1987) removes part of the turbulent *p* in addition to *p* from external sources when the microphone spacing is small. However, they show that by time-delaying one of the transducer signal and then subtracting it from the other transducer signal, the *p* due to turbulence can be recovered, provided that the time delay is longer than δ / U_C. They also show that for the technique to work properly the two transducers must be mechanically coupled. Otherwise the *p* due to external sound and vibration measured by the two transducers will not necessarily be correlated to one another.

Ölçmen and Simpson (1994) applied the technique of Agarwal and Simpson (1989) using only one transducer to measure *p* near the nose of a wing-body junction. The time-delay noise cancellation technique of Ölçmen and Simpson (1994) was used in the present study and is described below. In the present study, vibrational contamination of the measured signal was eliminated by mechanically isolating the transducer from the wind tunnel. The signal from a single transducer was delayed by the period of a given frequency and subtracted from the original signal, canceling the contributions from coherent sources at that frequency and higher harmonics.

Consider the pressure signal (mean zero) at two different parts of the measured record, $p(t)$ and $p(t+\Delta t)$, where Δt is the time delay. Each part of the measured signal may be decomposed into a turbulent contribution, p_T, and a contribution due to coherent external sources p_C. It is assumed here that there is no incoherent contribution from external sources.

$$p(t) = p_T(t) + p_C(t) \tag{26}$$

$$p(t+\Delta t) = p_T(t+\Delta t) + p_C(t+\Delta t) \tag{27}$$

Now consider two sub-records where each sub-record is long enough to be stationary. One sub-record starts at $p(t)$ and the other sub-record starts at $p(t+\Delta t)$. The mean square of the sub-record that starts at $p(t)$ subtracted from the sub-record that starts at $p(t+\Delta t)$ is

$$\begin{aligned}\overline{\left[p(t+\Delta t)-p(t)\right]^2} &= \overline{\left[p_T(t+\Delta t)+p_C(t+\Delta t)-p_T(t)-p_C(t)\right]^2} \\ &= \overline{p_T^2(t+\Delta t)} + \overline{p_T^2(t)} + \overline{p_C^2(t+\Delta t)} + \overline{p_C^2(t)} \\ &\quad + 2\overline{p_T(t+\Delta t)p_C(t+\Delta t)} - 2\overline{p_T(t+\Delta t)p_T(t)} - 2\overline{p_T(t+\Delta t)p_C(t)} \\ &\quad - 2\overline{p_C(t+\Delta t)p_T(t)} - 2\overline{p_C(t+\Delta t)p_C(t)} + 2\overline{p_T(t)p_C(t)}\end{aligned} \tag{28}$$

If Δt is short enough such that $p_C(t)$ and $p_C(t+\Delta t)$ are correlated[†], then

$$\overline{p_C^2(t+\Delta t)} + \overline{p_C^2(t)} = 2\overline{p_C(t+\Delta t)p_C(t)} \tag{29}$$

If Δt is long enough such that $p_T(t)$ and $p_T(t+\Delta t)$ are not correlated, then

$$\overline{p_T(t+\Delta t)p_T(t)} = 0 \tag{30}$$

Since, by definition, p_T and p_C are from independent sources, it follows that

$$\overline{p_T(t+\Delta t)p_C(t+\Delta t)} = 2\overline{p_T(t+\Delta t)p_C(t)} = 2\overline{p_C(t+\Delta t)p_T(t)} = 2\overline{p_T(t)p_C(t)} = 0 \tag{31}$$

Substituting equations 29 - 31 into equation 28 leaves

$$\overline{\left[p(t+\Delta t) - p(t)\right]^2} = \overline{p_T^2(t+\Delta t)} + \overline{p_T^2(t)} \tag{32}$$

But, being that both sub-records are stationary,

$$\overline{p_T^2(t+\Delta t)} = \overline{p_T^2(t)} \tag{33}$$

Therefore,

$$\frac{1}{2}\left(\overline{\left[p(t+\Delta t) - p(t)\right]^2}\right) = \overline{p_T^2(t)} \tag{34}$$

The above analysis, which is done in the time domain, is directly applicable to the spectral power density[‡] through Parseval's theorem. Parseval's theorem states that the mean square may be calculated by integrating the square of the time series (mean zero) over all time or, equivalently, integrating the square of the constituent Fourier components over all frequencies. Therefore, the square of the Fourier components at a particular frequency, which is the spectral power estimate at that frequency, is, in effect, the mean square contribution of fluctuations at that particular frequency. So, through equation 34, the power spectrum of a composite signal that is formed by subtracting a sub-record that starts at $p(t)$ from the sub-record that starts at $p(t+\Delta t)$ will contain only the contribution from the turbulence at the frequency $1/\Delta t$ and higher harmonics.

[†] The sub-record that starts at $p(t)$ and the sub-record that starts at $p(t+\Delta t)$ must be taken from a larger single record of contiguous data in order for equation 29 to be valid.

[‡] Also referred to as the power spectrum in the present document

The choice of time-delay is crucial to the success of this noise cancellation technique. The time-delay must be short enough so that equation 29 is valid and long enough so that equation 30 is valid. In practice, most background spectral energy is confined to $f < 100$ Hz, but the results of Agarwal and Simpson suggest that a more conservative estimate would be $f < 1$ kHz. The longest time-delay used for the present measurements was 246 ms[¶]. Since the period of a 1 kHz signal is 1 ms, the highest frequency background spectral energy would need to be coherent for at least 246 periods in order for the constraint imposed by equation 29 to be satisfied. This was assumed to be true in the present study.

In order to satisfy the constraint imposed by equation 30 a long time delay was used. The selection of the time-delay was also influenced by details of the calculation of the power spectrum and follows the development of Ölçmen and Simpson (1994). In the present study, the Fast Fourier Transform (FFT) algorithm of Press *et al.* (1994) was used. This is an algorithm that is based on the Cooley-Tukey Algorithm (1965) which has been optimized for memory usage. It computes the FFT of a discrete time series of N samples that are sampled at a rate of one sample per s seconds where N must be a power of 2. Multiplying the resulting FFT with its complex conjugate yields $N/2$ estimates of the power spectrum that are equally spaced within the frequency range $0 \leq f < 1/(2s)$. The frequency resolution of each power spectral estimate is given by the bin width, $\Delta f = 1/(Ns)$. So, in the end, the power spectrum is estimated at the discrete frequencies $f_n = n/(Ns)$ where $n = 0,1,2,\ldots, (N/2 - 1)$. By Parseval's theorem, the spectral value at f_n is an estimate of the contribution to the mean square from fluctuations in the frequency range $(n - ½)/(Ns) \leq f_n < (n + ½)/(Ns)$[§]. In the present study, the time-delay $\Delta t = Ns$ was used. The time-delay subtraction removes the contribution from coherent sources at the frequency $1/\Delta t$ and higher harmonics. The calculated power spectrum consists of spectral estimates of the

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¶ This time delay was used for the two-dimensional boundary layer and wing-body junction flow data.

§ Note that the power spectral estimate at f_0 contains energy from the mean of the time series and is usually discarded, as was done in the present study. Each measured time series was made to have zero mean value before computing the FFT in order to insure that any remaining spectral energy from frequencies close to the mean value did not *leak* into (contaminate) adjacent, low frequency spectral estimates (side-lobe leakage is discussed by Bendat and Piersol, 1986, pp. 393-400).

contribution to the mean square from fluctuations at the frequency Δf and higher harmonics. Therefore, by using $\Delta t = 1/\Delta f$, the contributions to from coherent sources were subtracted from each spectral estimate that constitutes the calculated power spectrum.

If the time-delay $\Delta t = 1/\Delta f$ is too short to avoid subtracting some of the turbulent contribution, then the record length, N, is too small and should be increased. Otherwise, the resulting Δf will be too large and will not sufficiently resolve the low frequency power spectrum[††]. In the present study, the shortest sub-record is has a period of 29 ms[‡‡]. Therefore, contributions to p that are at frequencies less than 35 Hz are not resolved. However, the contribution to p' from such sources is negligible in the flows of the present study.

2.3.2. High Frequency Spectral Attenuation

In order to accurately measure the pressure fluctuations at a point one would need an infinitely small transducer. However, commercially available transducers have a finite size. The pressure measured by transducers of finite size is the average pressure applied across the transducer sensing area. Pressure fluctuations smaller than the transducer sensing area are spatially integrated, and thereby attenuated. This causes the measured power spectrum of surface pressure fluctuations to be attenuated at high frequencies.

2.3.2.1. Required Transducer Size

While theoretically an infinitely small transducer is required to accurately measure the full spectrum of wall-pressure fluctuations, experiments have shown that a small, but finite, transducer is sufficient. Schewe (1983) determined that a transducer diameter $d^+ < 19$ is sufficient to resolve all essential wall-pressure fluctuations. Gravante *et al*. (1998) report that the maximum allowable sensing diameter to avoid spectral attenuation at high frequencies is in the range $12 < d^+ < 18$, and for $d^+ < 27$ the reduction in p' was "barely observable". The studies of Schewe (1983) and Gravante *et al*. (1998) show that the required sensing diameter depends on the viscous scales of

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[††] The analysis of Agarwal and Simpson (1989) show that Δt must be greater than δ / U_C in order to avoid subtracting part of the turbulent contribution to p.

[‡‡] This time delay was used for the 6:1 prolate spheroid flow data.

the flow to be measured. For flows of interest, particularly high Reynolds number flows, the viscous scales are typically smaller than the diameter of commercially available transducers with sufficiently high sensitivity. Often a pinhole mask is used to decrease the effective sensing area of the pressure transducer in order to resolve this issue (Blake, 1970; McGrath and Simpson 1987; Farabee and Casarella, 1991; Gravante *et al*., 1998). Bull and Thomas (1976) assert that the discontinuity in the wall due to the presence of a pinhole disturbs the flow and leads to a significant error in the measured wall pressure spectrum at high frequencies. However, their assertion is not supported by the favorable comparison of the data of other researchers. For example, the data of Gravante *et al*. (1998) taken using a pinhole ($d^+ = 12$) and the data of Schewe (1983) taken with a flush-mounted transducer ($d^+ = 19$) show nearly identical spectral levels at high frequencies when normalized using viscous scales. It should be noted that the transducer sensing diameter used by Schewe and Gravante *et al*. was more than 4 times smaller than that used by Bull and Thomas. Additionally, Bull (1996) noted in a recent review of knowledge about wall-pressure fluctuations that the error due to the presence of the pinhole may "tend to zero as pinhole diameter is reduced" (p. 308).

A pinhole mask with a diameter of 0.5 mm was used in the present measurement system to reduce spatial averaging. The pinhole mask and transducer dead volume can be approximated as a Helmholtz resonator. The frequency response of a Helmholtz resonator is governed by (as given by Holman, 1989)

$$\frac{p_{TRUE}}{p_{MEASURED}} = \sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\zeta^2\left(\frac{\omega}{\omega_n}\right)^2} \tag{35}$$

$$\phi_H = tan^{-1}\left(\frac{2\zeta}{\frac{\omega}{\omega_n}-\frac{\omega_n}{\omega}}\right) \tag{36}$$

where

$$\zeta = \frac{16\nu}{d^3 a}\sqrt{\frac{3L_H V_H}{\pi}} \tag{37}$$

and

$$\omega_n = \sqrt{\frac{3\pi\, d^2 a^2}{16\, L_H\, V_H}} \quad (38)$$

Figure 9 shows the notation used in equations 37 and 38.

2.3.2.2. Correction Methods

The effects of transducer size, shape and sensitivity has been investigated both theoretically and experimentally (Blake, 1986). Initial investigations of this issue sought to characterize the effect of finite transducer size. Corcos (1963, 1967) estimated the attenuation due to finite transducer size for square and circular transducer shapes and provided a correction in terms a similarity parameter, $\omega d/2U_C$. Corcos (1963, 1967) developed the correction assuming that the transducer sensitivity was uniform over the transducer sensing area and by asserting that the cross-spectral density of pressure fluctuations is separable in the streamwise and spanwise direction based on measurements by Willmarth and Wooldridge (1962). Others have extended the analysis of Corcos (1963, 1967) to consider transducers of different shape and sensitivity (Gilchrist and Strawderman, 1965; White, 1967; Geib, 1969; Chase, 1969) Willmarth and Roos (1965) questioned the validity of the Corcos (1963, 1967) correction by questioning the separability and similarity of the cross-spectral density for small spatial separation. More recent experiments by Farabee and Casarella (1991) and Abraham and Keith (1998) showed that the streamwise cross-spectral similarity proposed by Corcos (1963, 1967) does not agree with their data at small spatial separation and low frequency. Singer (1997) proposed a different form of Corcos' similarity hypothesis that compares better with large-eddy simulation results (Singer, 1996) at mixed streamwise and spanwise, or off-axis, separations.

Despite questions concerning the underlying assumptions of the Corcos (1963, 1967) correction, direct examination has shown that the Corcos correction recovers the true pressure spectrum within limits. Schewe (1983) experimentally determined the Corcos correction to be adequate for $\omega d/U_C < 4$. More recently, Lueptow (1995) used a direct numerical simulation of channel flow (Kim *et al.*, 1987) to investigate the effect of transducer size, shape, and sensitivity on the resolution of high frequency pressure fluctuations. Lueptow reported that the Corcos correction recovers the true wall pressure spectrum for $\omega d/U_C < 11$ for a circular deflection-type