4. WING-BODY JUNCTION RESULTS

This chapter discusses measurements of *p* beneath the three-dimensional flow *away* from a wing-body junction. All measurement stations are outside the horseshoe vortex that forms about the wing-body junction. The present flow is referred to as a "wing-body junction" flow only to distinguish it from the flow about a 6:1 prolate spheroid that is the subject of chapter 5.

The complexity of the skewed 3-D boundary layer (figure 3) necessitates the use of multiple coordinate systems. The Tunnel coordinate system is right-handed with the *x*-axis parallel to the tunnel centerline pointing downstream and the *y*-axis perpendicular to the tunnel floor pointing up. The Wall-Shear-Stress coordinate system is right-handed with the *x*-axis in the shear-stress direction at the wall as approximated by the measured mean-flow angle closest to the wall (Ölçmen and Simpson, 1995a; Ölçmen *et al*., 1996, 1999b). The *y*-axis is normal to the wall, pointing up.

Relevant boundary layer parameters of the present flow are given in tables 4 and 5. For comparison, data measured in 2-D, zero-pressure gradient boundary layers with a Reynolds number comparable to the present flows are also included in tables 4 and 5. The velocity field measurements of the lower Re_θ (= 5940) boundary layer are reported by Ölçmen and Simpson (1996). The velocity field measurements of the higher Re_θ (= 23200) boundary layer are reported by Ölçmen *et al*. (1998). The u_τ at each measurement station was calculated by fitting the *U* data in Wall-Shear-Stress coordinates to a near-wall approximation of Spalding's (1961) law-of-the-wall (equation 48). Profiles of the mean velocity components are shown in figures 41 - 44 and profiles of the Reynolds normal stresses are shown in figures 45 - 50. Details of the velocity field are given in the following sections as they relate to *p*.

4.1. RMS Surface Pressure Fluctuations and Features of the Velocity Field

Each of the *p* spectra was integrated to obtain the $\overline{p^2}$ values given in table 6. For the lower Re_θ flow (table 6) p'/τ_w and p'/Q_e are higher than beneath a 2-D flow and increase with station number for stations 0-3 due to adverse pressure gradient effects on the lower frequencies (Simpson *et al*., 1987). Also, table 6 indicates that most of the *p*' is due to low frequency (f < 1 kHz) fluctuations which increase in magnitude with station number. The $\overline{p^2}$ from low frequencies at station 3 is double the low frequency $\overline{p^2}$ at station 0. The high frequency (f > 1 kHz) contribution to *p*' at stations 0-3 is nearly constant.

The lateral pressure gradient in wall-shear-stress coordinates (table 4) pushes the flow away from the wing at stations 0-3. Ölçmen and Simpson (1996) report that at stations 0-3 the mean flow angle changes monotonically from near the wall to the free stream by $4.4° < |\beta_{FS} - \beta_W| < 25°$ (figure 3). Examination of table 6 and the dimensional *p* spectra (figure 51) suggest that the monotonic (in *y*) turning of the mean flow at stations 0-3 has little effect on high frequency *p* (which have a lower spectral level than the 2-D at comparable Re_θ), but increase the low frequency *p* substantially.

The lateral pressure gradient in wall-shear-stress coordinates (table 4) changes sign between stations 3 and 4. At stations 4-9 the lateral pressure gradient pushes the mean flow back toward the wing. Ölçmen and Simpson (1996, p. 7) observed that "At station 4 the W/u_τ values are close to zero up to $y^+ \approx 40$. Above this *y* location, values monotonically increase. At stations further downstream the effect of the sign change of the lateral pressure gradient is felt most near the wall. This results in negative W/u_τ values ... The pressure force is most effective on the near-wall flow where the momentum of the flow is lowest." Figures 43 and 44 show the W/u_τ mean velocity profiles in wall-shear-stress coordinates. Note that the location of maximum *W* propagates outward from the wall at successive downstream stations.

For stations 4-8 the mean velocity at the boundary layer edge accelerates (table 4). The magnitude displacement thickness, δ^*, decreases as well as the $\overline{p^2}$ contribution from low frequency fluctuations (f < 1 kHz) (table 6). While the details of the above $\overline{p^2}$ discussion is confined to the $Re_\theta = 5940$ flow, similar trends are present in the $Re_\theta = 23200$ data.

4.2. Features of the Dimensional Power Spectra

The most significant feature of the spectral power density spectrum of surface pressure fluctuations (figures 51 and 52) at stations 4-9 is the constant (or nearly constant) spectral levels in the frequency range 2 kHz < f < 5 kHz. A flat mid-frequency spectral region has also been observed in the 3-D flow on the lee-side of a prolate spheroid at angle of attack (chapter 4). In that flow the flat mid-frequency spectral region is believed to due to the lack of overlapping frequency structure between the large-scale motions of the outer layer and the viscous-dominated near-wall region. A similar situation exists in the present flow. The lateral pressure gradient imposed by the presence of the wing skews the near-wall, low momentum mean flow. The larger near-wall velocity gradients associated with the skewed flow presumably produce high frequency pressure fluctuations as prescribed by the Poisson integral (equation 25).

The effect of the flat spectral region on $\overline{p^2}$ is significant. Table 6 shows the effect on $\overline{p^2}$ of removing the spectral contribution that makes the region flat. Figure 53 shows the p spectrum at station 8, $Re_\theta = 23200$ as an example. At station 8 the flat spectral region accounts for 40% of the $\overline{p^2}$ integral (table 6). The method used to remove the flat spectral region was to first find the frequency at which the p spectrum departs from a constant power law decay. At station 8 this frequency is 889 Hz (figure 53). Then, the power law was determined. At station 8, 20 spectral values (166 Hz < f < 889 Hz) were used to determine that the power law, $\Phi(f) = 2.332\, f^{-0.928}$. Next, the end of the flat spectral region was located. Here, the end of the flat spectral region is defined as the frequency at which the p spectrum is parallel to the power law just determined. At station 8 this frequency is 6456 Hz. Finally, the spectral levels at higher frequencies (f > 6456 Hz) were attenuated by a constant factor in order to match up with the spectral level given by the previously determined power law at the end of the flat spectral region. At station 8, $Re_\theta = 23200$, the three parts of the "non-flat" p spectrum (Φ_{NF}) are,

Φ_{NF} = data	for f < 889 Hz
$\Phi_{NF} = 2.332\, f^{-0.928}$	for 889 Hz $\leq f <$ 6456 Hz
Φ_{NF} = 0.3(data)	for $f \geq$ 6456 Hz

The physical mechanism that produces the flat spectral region appears to be independent of, or at least slowly varying with, Reynolds number. As station number increases from 0-3 the p

spectral level beneath the lower Re_θ flow approaches the *p* spectral level beneath the higher Re_θ flow at middle frequencies. The *p* spectra generally overlap at stations 4-9 for 300 Hz < *f* < 3 kHz. An example of this is station 7 (figure 53) where the overlap extends to 7 kHz. Ölçmen *et al.* (1999b) discuss Reynolds number effects for the flows studied here. They found that while the magnitude of the shear stresses (normalized on u_τ) increase with Reynolds number, below $y^+ = 100$ the stresses tend to overlap. The sources of high frequency *p* are located within the near-wall flow.

4.3. Spectral Scaling of Surface Pressure Fluctuations

The *p* spectra of the present study do not collapse when normalized using boundary layer scales that collapse the *p* spectra in 2-D flows. The *p* spectra were normalized using the candidate boundary layer scales given in table 7. The first nine candidate scaling combinations in table 7 (figures 54 - 71) are all permutations of the boundary layer scales that have been shown to scale the *p* spectra beneath equilibrium flows within various frequency ranges. The motivation for the next four candidate scaling combinations in table 7 (figures 72 - 79), which use Δ as the length scale, was the assertion of Rotta (1962) which is supported by Fernholtz and Finley (1995a) that Δ is the proper length scale for the outer layer. The last two scaling combinations in table 7 (figures 80 - 83) were attempted based on the assumption that the source of unique features in the *p* spectra (i.e. the flat spectral region) are unique features in the velocity field. The only scalings which even remotely collapse the *p* spectra in any frequency range are the time and pressure scale combinations: δ^*/U_e, Q_e at $\omega_{O1} > 25$ (figure 59); δ^*/u_τ, Q_e at $\omega_{O2} > 700$ (figure 63); and Δ/U_e, Q_e at $\omega_{O6} > 600$ (figure 79). Each scaling combination was only successful for the higher Re_θ flow. However, a scaling combination based on outer boundary layer variables that collapses the *p* spectra at high frequency does not make physical sense since the source of high frequency *p* is small-scale, near-wall turbulence.

The lack of scaling parameters that collapse the *p* spectra is not surprising given the complexity of these 3-D flows. In 2-D equilibrium boundary layers similarity parameters exist that scale the velocity (e.g. law-of-the-wall, defect law). In the 3-D flows of the present study, the only scaling which collapses any part of the velocity profile is $U^+ = y^+$ near the wall ($y^+ < 5$) when the velocity is expressed in wall-shear-stress coordinates. Additionally, the frequency/wavenumber dependence of the wave speed of p is exacerbated in this 3-D flow because turbulent structures travel in different directions depending on the distance from the wall (Ha and Simpson, 1993). In order to be successful, scaling parameters for p beneath 3-D flows must incorporate more detailed velocity field information through the Poisson equation.

Previous analysis of 2-D flows (Bradshaw, 1967; Panton and Linebarger, 1974; Blake, 1986) have shown that the Poisson integral is dominated by the mean-shear-turbulence term in the form

$$p \approx \frac{\rho}{\pi} \oint_{\Omega} \left[\frac{\partial U}{\partial y} \frac{\partial v}{\partial x} \right] \frac{d\Omega}{r_S} \tag{52}$$

For the present flow, it is assumed that the high frequency p is generated by small-scale velocity fluctuations near the wall. In a study of three-dimensional boundary layers, Ölçmen and Simpson (1992) showed that the near-wall mean region of the boundary layer follows a two-dimensional wall law reasonably well. Therefore, it is assumed here that, as with 2-D boundary layers, high frequency contributions to the Poisson integral are dominated by the mean-shear-turbulence term and that derivatives of the mean velocity in the x- and z-direction are negligible. Since the y-derivative of the W-component of velocity is not always negligible in the present flow, the 2-D approximation of the Poisson integral (equation 52) is modified here, in the form

$$p \approx \frac{\rho}{\pi} \oint_{\Omega} \left[\frac{\partial U}{\partial y} \frac{\partial v}{\partial x} + \frac{\partial W}{\partial y} \frac{\partial v}{\partial z} \right] \frac{d\Omega}{r_S} \tag{53}$$

Consider the variation of equation (53) from station to station with the goal of collapsing the high frequency end of the p spectra beneath the 3-D flows of the present study.

Some simplifying assumptions must be made in order to evaluate equation (53) with the data available. Similar to a recent model for the p spectrum under a 3-D boundary layer that was proposed by Panton (1998), it is assumed that the small-scale turbulent structures near the wall are homogenous in planes parallel to the wall and behave as traveling waves. Therefore,

$v = v \cos(\omega t - k_1 x - k_3 z)$, where $k_1=\omega/U_{c1}$ and $k_3=\omega/U_{c3}$ are the wavenumbers in the x- and z-direction, respectively. The traveling wave model results in

$$\frac{\partial v}{\partial x} = k_1 v \sin(\omega t - k_1 x - k_3 z) \quad \text{which varies like} \quad k_1 v_\omega$$

$$\frac{\partial v}{\partial z} = k_3 v \sin(\omega t - k_1 x - k_3 z) \quad \text{which varies like} \quad k_3 v_\omega \tag{54}$$

where v_ω is v at a particular frequency. High frequency contributions to the p spectrum primarily originate in the near-wall region where the flow roughly scales on the wall variables ν/u_τ and u_τ. Rewriting equation (53) with the above considerations in mind results in

$$\frac{p}{\tau_W} = \frac{1}{\pi}\oint_\Omega \left(k_1^+ v_\omega^+ \frac{\partial U^+}{\partial y^+} + k_3^+ v_\omega^+ \frac{\partial W^+}{\partial y^+} \right) \frac{d\Omega^+}{r_S^+} \tag{55}$$

Since near-wall turbulent structures have small spatial extent and in light of the $1/r_S^+$ dependence of equation (55), it is assumed that the variation of p/τ_W at a particular high frequency results mainly from the variation of the integrand of equation (55). Furthermore, it is assumed that the variation of the integrand of equation (55) at a particular frequency may be approximated by the variation of $\overline{v^{+2}}(\partial U^+/\partial y^+ + \partial W^+/\partial y^+)^2$ at a particular distance from the wall.

Modification of the inner variable scaling shown in figures 54 and 55 is required to account for the variation of the Poisson integrand (approximated by $\overline{v^{+2}}(\partial U^+/\partial y^+ + \partial W^+/\partial y^+)^2$) near the wall from station to station. To this end, a *Poisson Equation Term Ratio* (Π_R) is formed as

$$\Pi_R = \frac{\left[\overline{v^{+2}}\left(\dfrac{\partial U^+}{\partial y^+} + \dfrac{\partial W^+}{\partial y^+}\right)^2\right]_{3-\mathrm{D}}}{\left[\overline{v^{+2}}\left(\dfrac{\partial U^+}{\partial y^+}\right)^2\right]_{2-\mathrm{D}}} \tag{56}$$

Two issues must be addressed in order to evaluate Π_R with velocity data. First is the coordinate system to use to express the velocity terms. Ideally, Π_R would be coordinate system independent, however, Π_R is not. In the present study, the wall-shear-stress coordinate system was used since it is aligned with the near wall flow. Therefore, phase errors that are introduced by the approximations of the turbulent velocity structure in the x and z-direction are minimized. The second issue is where (distance from the wall) to evaluate the velocity terms. In the present study, a spectral ratio (Φ_R) of $\Phi^+(\omega^+=1)$ at each measurement station in the 3-D flow to $\Phi^+(\omega^+=1)$ in the 2-D flow at comparable Re_θ is used as a measure of the variation of the high frequency pressure spectral levels. The variation of Π_R closely tracks the change in Φ_R from station to station. Figures 84 and 85 show Π_R as a function of Φ_R with each ratio expressed in decibels. The candidate y^+ locations shown in figures 84 and 85 where selected based on the following criteria. The locations $10 \leq y^+ \leq 50$ where selected because they are near the wall. Small-scale fluctuations that are near the wall are sources of high frequency *p*. The locations $y^+ \geq 50$ were selected by assuming several values for the convection velocity, $10 \leq (U_C^+ = U_C/u_\tau) \leq 18$ and using

$$\omega^+ = k^+ U_C^+ = \left(\frac{2\pi}{y^+}\right) U_C^+ \tag{57}$$

to calculate the y^+ values at $\omega^+ = 1$ for the various U_C^+ values. If Π_R at some y^+ tracked the variation of Φ_R from station to station perfectly, all points in figures 84 and 85 for that y^+ would lie along a line with a slope of 1 and passing through the origin (solid line in figures 84 and 85).

Two quantities are used to measure which $\Pi_R(y^+)$ best fit the ideal linear relationship with $\Phi_R(\omega^+)$. The first measure is the range of $\Phi_R(\omega^+=1) / \Pi_R(y^+)$ at the different stations. In other words the scatter in values of $10 \log_{10}\left[\Phi^+ / \Pi_R\right]$ at $\omega^+ = 1$ with Π_R evaluated at the various candidate y^+ locations (figures 86 and 87). The second measure is the correlation coefficient between Φ_R / Π_R and y^+. The correlation coefficient is unity if a linear relationship exists between the two, but gives no information concerning the slope. Figures 86 and 87 indicate that the best fit is at $y^+ = 50$ for both Re_θ. The high frequency *p* spectral collapse (figures 88 and 89), where Π_R is evaluated at $y^+=50$, show that the variation of the high frequency spectra in the present non-equilibrium 3-D flows result from features of the near-wall velocity field which change Π_R from station to station. It is significant that the complex variations in the high frequency *p* spectrum are tracked by a relatively simple term (Π_R) which only requires mean velocity and Reynolds stress data.