6. CONCLUSIONS

6.1. Two-Dimensional Boundary Layer

Surface pressure fluctuation measurements beneath two zero pressure gradient, 2-D turbulent boundary layers, each at a different Reynolds number, were presented. There is not a universal scaling that collapses the *p* spectra of different Reynolds number flows at all frequencies. However, the *p* spectra collapse at high frequencies ($\omega^+ > 0.15$) and decay as ω^{-5} when normalized using τ_W as the pressure scale and ν/u_τ^2 as the time scale. Since τ_W and ν/u_τ^2 are inner boundary layer scales, the collapse of the *p* spectra using these scales indicates that sources of high frequency *p* are small scale turbulent motions near the wall. The present analysis was not designed to address the effects of transducer size on spatial resolution in detail. Nevertheless, high frequency spectral levels of *p* that were measured using transducers with a small sensing area were consistently greater than the spectral levels that were measured using larger transducers.

The *p* spectra collapse within a middle frequency range ($0.7 < \omega_{O1} < 2.5$; $20 < \omega_{O3} < 70$; $100 < \omega_{O5} < 500$; $4 < \omega_{O7} < 20$) when normalized using τ_W as the pressure scale independent of the time scale used. The middle frequency region of *p* spectral collapse overlaps (in frequency) the high frequency region of *p* spectral collapse and decays as $\omega^{-0.8}$. None of the pressure- time scale combinations used in the present study collapsed the *p* spectra at low frequencies. However, *p* spectra have been shown by others (Farabee and Casarella, 1991) to collapse when normalized on outer boundary layer variables within a frequency range lower than presented here.

The *p* spectrum within the middle frequency range, also called the *overlap* frequency range, was shown to be the largest contribution to *p*' through the $\overline{p^2}$ integral. The size of the overlap frequency range was shown to increase with Reynolds number. Therefore, the increase in *p*' with Reynolds number is due to an increase in the size of the overlap frequency range within which the *p* spectrum decays slowly. Dimensionally, the Reynolds number Re_δ is the most appropriate measure of the size of the overlap region since Re_δ is the ratio of the outer layer length scale to the inner length scale. As this ratio increases, so does the size of the overlap region. The data presented here is consistent with a logarithmic increase of $\overline{p^2}/\tau_W^2$ with Re_δ. Also, the favorable comparison of the present investigation with the previous work of other researchers on two-dimensional, turbulent, boundary layers confirms the quality of the experimental apparatus and supports the validity of the experimental techniques used in the present investigation.

6.2. Wing-Body Junction Flow

Surface pressure fluctuation measurements at 10 locations beneath two 3-D turbulent boundary layers *away* from a wing-body junction, each at a different Reynolds number, were presented. Scaling parameters that collapse the pressure spectra within a given frequency range beneath 2-D flows do not collapse the pressure spectra beneath the present 3-D flows. However, the p spectra decay as ω^{-5} at the highest frequencies ($f > 10$ kHz) and decay as ω^n within the frequency range 100 Hz $< f <$ 900 Hz. The exponent, n, changes with measurement station ($-0.6 < n < -1.3$).

At both Reynolds numbers, the flow decelerates at measurement stations upstream of the wing which increases the magnitude of low frequency p significantly, but has little effect on the high frequency p. The flow turns and accelerates at stations to the side of the wing which decreases the magnitude of low frequency p and increases the magnitude of high frequency p. Spectral levels of p at these measurement stations are nearly constant and do not change appreciably with Reynolds number within a middle frequency range (1 kHz $< f <$ 5 kHz). Analysis based on the Poisson integral (equation 25) shows that the variation of high frequency p from measurement station to measurement station is tracked by the variation of mean velocity gradients and $\overline{v^2}$ structure near the wall. The increased spectral levels at high frequencies due to the near constant spectral levels at middle frequencies increases p' significantly. Therefore, accurate measurement of p' requires the accurate measurement of high frequency p particularly when large changes in near-wall mean velocity gradients and $\overline{v^2}$ structure is present.

6.3. Flow Around a 6:1 Prolate Spheroid

The flow around a 6:1 prolate spheroid is complex and three-dimensional. It contains crossflow separations and shed vortices. The wall-shear-stress magnitude decreases to a local minimum at crossflow separation locations and a local maximum at reattachment and under the shed vortices. The *TKE* levels near the wall follow these same trends. The updrafts around regions of separation carry *TKE* away from the wall while secondary reattachments bring some *TKE* back toward the wall. Outer region mean velocities on the windward side of the primary separation increase monotonically to the inviscid free-stream, but increase and then decrease as r increases within the vortices.

Despite the three-dimensional nature of the mean flow, the p spectra and p' at low angle of attack are comparable to that beneath an equilibrium boundary layer. The p spectra at $\alpha = 10°$ collapse at high frequencies when normalized on inner boundary layer variables. The p spectra do not collapse as well when normalized on outer boundary layer variables, however, the p spectral levels are comparable to those beneath a 2-D, separating boundary layer. When normalized on mixed inner and outer boundary layer variables, the spectral collapse of the p spectra is confined to select ranges of ϕ.

The three-dimensionality of the flow is readily apparent in the p spectra at $\alpha = 20°$. High p spectral levels extend to high frequencies underneath the shed vortex and at the most leeward ϕ locations (near $\phi = 90°$). The elevated p spectral levels at high frequencies are due to the nearly constant p spectral levels at middle frequencies.

The flat mid-frequency spectral region is believed to occur because of (1) the lack of overlapping frequency structure between the larger-scale motions and the viscous-dominated region and (2) the decrease of low frequency content with a substantial increase in the high frequency levels. The first reason may be due to the three-dimensional flow structure where the near-wall and outer layer flows have different flow histories and low spatial correlations. The second reason just reflects the need for a flatter spectrum to connect the low and high frequency contributions.

The p spectra at $\alpha = 20°$ does not collapse when normalized on inner boundary layer variables. However, only the p spectra near separation (where u_τ is low) were measured at non-dimensional frequencies (ω^+) high enough in order to exhibit an ω^{-5} decay, which is where spectral collapse would occur. There is p spectral collapse at high frequency near primary separation and windward of primary separation at both $\alpha = 10°$ and $\alpha = 20°$ when the p spectra are normalized using τ_W as the pressure scale and δ^*/U_e as the time scale. The success of this scaling combination, albeit limited, suggests that the high frequency p spectra are affected by both the inner and outer layer flow, however, this scaling combination (τ_W, δ^*/U_e) is not sufficient to fully capture the effect.

The correlation coefficient, R_{pv}, shows the strong relationship between p and v within the log layer that has been theorized and observed beneath equilibrium boundary layers. Windward of the primary separation and leeward of the primary vortex, relatively large negative levels of R_{pv} occur around $100 < r^+ < 250$ and indicate the strong influence of v in this region. In the outermost part of the measured flowfield, relatively positive values of R_{pv} occur, especially in the updraft of the primary separation. Negative R_{pv} is large upstream of the formation of the secondary separation and within the secondary separation and reattachment. Deceleration of the flow are also a source of p through w' near $\phi = 90°$ and $\phi = 180°$.

The topological structure of the surface pressure-velocity correlation coefficient at $\alpha = 20°$, $x/L = 0.600$ is especially interesting. It is very similar topological structure at $\alpha = 20°$, $x/L = 0.772$ near the separations, reattachment, and secondary vortex even though these mean flow features are not present at $\alpha = 20°$, $x/L = 0.600$. Zero R_{pu} and R_{pw} along a line of constant ϕ out to $r^+ \sim 200$ at $\phi = 145°$, $x/L = 0.600$ appears to be a precursor to the secondary separation at $\phi = 145°$, $x/L = 0.772$. It is unclear whether the correlations are low because sources of p are convected away from the surface by the secondary separation, or sources of p that are leeward of the secondary separation are out of phase with sources of p that are windward of the secondary separation, thereby canceling each other. Near the secondary vortex at $r = 0.6$ cm, $\phi = 140°$, $x/L = 0.772$, all three correlation coefficients (R_{pu}, R_{pv}, and R_{pw}) are high at both $x/L = 0.600$ and $x/L = 0.772$ even though the secondary vortex is only present at $x/L = 0.772$. This suggests that the secondary vortex is due to the pressure fluctuations and Reynolds stresses rather than the other way around.

The *p* at low angle of attack is comparable to measurements in equilibrium flows. Around separations, where τ_W is low, the high frequency spectral content of *p* is small, while low frequency contributions from the outer layer are relatively large. In regions with large τ_W, the wall region produces strong high frequency spectral content. There are smaller low frequency contributions at locations with relatively small gradients in the outer region mean velocity distribution. Both of these features occur around ϕ = 90° and under the large vortices. Therefore, at these locations spectral values are nearly constant at middle and high frequencies. The resulting *p*' distributions over the surface reflect the importance of the high frequency wall region contributions. Around separations there is a local minimum in *p*'. Around reattachments and under the large vortices there is a local maximum in *p*'.

6.5. General Conclusions

Two data sets have been measured in three-dimensional flows of practical interest. The data show features of *p* unique to three-dimensional flow. In that regard, the present data base can serve as a test case for the computational investigations of others.

Three-dimensional, skewed flows can have nearly constant *p* spectral levels within a middle frequency range that significantly increases *p*'. The nearly constant spectral levels are due to a lack of overlapping frequency structure between the large-scale motions and the viscous-dominated motions since each of these types of motion may have different flow histories due to the three-dimensional flow structure. This effect amplifies the importance of the middle frequency range to *p*' as compared to two-dimensional flows. Also, from an instrumentation point of view, accurate *p*' measurements in a three-dimensional flow require accurate high frequency (f > 20 kHz) *p* measurements.

Scaling parameters for the *p* spectra beneath three-dimensional flows must incorporate local flow structure, through the Poisson integral, in order to be successful. Analysis based on the

Poisson integral shows that high frequency *p* is mainly due to the mean velocity gradients and $\overline{v^2}$ structure near the wall.

Measurements of the correlation coefficient between surface pressure and velocity fluctuations show that there can be sources of *p* away from the wall in three-dimensional flows. Sources of *p* away from the wall are significant in terms of fluid-structure interaction since they contribute low frequency fluctuations. Structures typically have low resonant frequencies. Sources of *p* away from the wall are also significant in terms of radiated sound since they are likely to interact with the free-stream and be radiated away as sound.

6.6. Suggestions for Future Work

Spectral power densities of *p*, *p*' values, and some surface pressure-velocity correlation coefficients beneath three-dimensional flows of practical interest were presented and discussed in the present study. The logical next step is to obtain more detailed information, such as wave speeds and length scales of *p* in three-dimensional flows of practical interest as has been done beneath two-dimensional boundary layers (Willmarth and Roos, 1965; McGrath and Simpson, 1987; Farabee and Casarella, 1991). Such data can be best acquired using multiple pressure transducers that are spatially separated and simultaneously sample the fluctuating surface pressure. The use of multiple transducers in this way is also known as *wave-vector filtering* and is discussed in detail by Blake (1986). A wave-vector filter can be used to calculate the wavenumber-frequency spectrum, from which the wave speed can be determined. Also, spatial coherence length scales can be calculated using the *p* data from a wave-vector filter.

The success of the Poisson Equation Term Ratio presented in §4.3 highlights the value of identifying sources of *p* within the fluctuating velocity field. Correlation coefficients between surface pressure and velocity were presented here. The logical next step is to obtain more detailed information through surface pressure-velocity cross-spectra. Cross-spectra between the surface pressure and velocity fluctuations at various points within the flow will show the locations within the fluctuating velocity field that are the dominant source of pressure fluctuations within a given frequency range. This type of data and the wave speed data mentioned above can be used, along with the Poisson equation, to further the understanding of, and possibly model, the pressure fluctuations in three-dimensional, turbulent, boundary layers.