Pressure and shear stress measurements at the wall in a turbulent boundary layer on a cylinder

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(Received 14 February 1996; accepted 7 May 1997)

The fluctuating wall shear stress, wall pressure, and streamwise velocity were measured simultaneously in a cylindrical boundary layer at a momentum thickness Reynolds number of $Re_\theta=2160$ and a boundary layer thickness to cylinder radius ratio of $\delta/a=5$ using a hot wire wall shear stress probe mounted just upstream of a hearing aid microphone and a hot wire velocity probe. Variable Interval Time Averaging (VITA) event detection on streamwise velocity indicates that streamwise accelerations are associated with positive wall pressure peaks and sudden increases in wall shear stress. Likewise, positive pressure peak events are associated with streamwise accelerations and sudden increases in wall shear stress. VITA detection on wall shear stress reveals that increasing wall shear stress corresponds to streamwise accelerations and small-amplitude pressure rises, not distinct intense pressure peaks. Detection of strong adverse and favorable instantaneous pressure gradients indicates that a shear layer at $y^+=13$ coincides with a positive peak in the wall pressure, suggesting that a positive wall pressure peak event is the key wall pressure signature associated with the burst cycle. Measurements of the cross-correlation indicate that the pressure–shear stress relationship is about two times weaker than the pressure–velocity relation and about ten times weaker than the shear stress–velocity relation. Thus, a strong relationship exists between wall pressure and streamwise velocity as well as between wall shear stress and streamwise velocity, but the relationship between wall shear stress and wall pressure is quite weak. Because of the similarity of the near-wall structure of all wall-bounded turbulent flows, regardless of transverse curvature, these conclusions should be applicable to planar boundary layers. © *1997 American Institute of Physics.* [S1070-6631(97)02009-6]

I. INTRODUCTION

Turbulent velocity fluctuations in the boundary layer adjacent to a wall give rise to shear and normal stresses at the wall. Considerable effort has been expended over the last decades to understand the fluctuating wall pressure and wall shear stress, both of which are quite difficult to measure. But little is understood about the relationship between the wall pressure and the wall shear stress. The pressure and shear stress at the wall are related to the flow in the boundary layer above the wall in quite different ways. The wall shear stress τ_w is locally determined by the velocity gradient immediately adjacent to the wall. On the other hand, the wall pressure is a weighted integral of the effects of the velocity field over the half-space above the wall.[1]

The fluctuating wall pressure has been studied in great detail over the last few decades.[1–3] Wall pressure fluctuations result from both large-scale disturbances that originate in the outer portion of the boundary layer[4–6] and small-scale disturbances near the wall, presumably related to the burst-sweep cycle.[6–12] Wilczynski, Casarella, and Kammeyer provide an excellent review of conditionally sampled simultaneous measurements of wall pressure and velocity near the wall.[13] Large positive peaks in the wall pressure are related to accelerations in the streamwise velocity and negative peaks are related to decelerations in streamwise velocity.[10–13] Favorable pressure gradients are associated with ejection events, while adverse pressure gradients correspond to sweep events.[7,13,14] Direct measurements of the streamwise velocity gradient indicate that positive pressure peaks are related to shear layers about 20 viscous units above the wall.[15,16]

The fluctuating wall shear stress has been studied less extensively than the wall pressure. It is generally accepted that the rms level of streamwise wall shear stress fluctuations is about 40% of the mean value,[17] although this value is highly dependent upon the shear stress measurement technique.[18] Eckelmann showed similarities in the signals of the streamwise velocity and the wall shear stress for the velocity probe positioned above the wall at $y^+\leqslant 25$,[19] where the + superscript denotes nondimensionalization using the friction velocity u_τ and the kinematic viscosity ν. Cross-correlations between the wall shear stress and the streamwise velocity indicate the existence of large-scale coherent structures, or ''backs,'' [20] inclined at an angle of 13°–18° with respect to the wall.[18,21,22] Conditionally sampled signals obtained by applying variable interval time averaging (VITA) to the wall shear stress appear similar to those for VITA detection on the streamwise velocity near the wall, except that the deceleration of the fluid just prior to the detected event is substantially less for the wall shear stress than for the streamwise velocity.[18,23,24] The streamwise velocity near the wall leads the wall shear stress, presumably because the turbulent structure is inclined to the wall.[18,25]

Given that strong shear stress events are related to strong streamwise velocity events and strong wall pressure events are related to strong streamwise velocity events, one might hypothesize that wall pressure events and wall shear stress events should be related to one another. Our objective was to determine the nature of the relationship between the wall

 1070-6631/97/9(9)/2732/8/$10.00

shear stress, wall pressure, and streamwise velocity in a turbulent boundary layer by simultaneously measuring these three quantities. We are aware of only one study[7] in which all three quantities were measured simultaneously. Unfortunately, in this study the microphone and hot-film shear probe had wide streamwise separation, making interpretation of the measurements quite difficult because structures appearing at one probe advected a significant distance before encountering the second probe. Crucial to the success of our measurements was the small size of the transducers to provide adequate spatial resolution and the close spacing of the wall pressure microphone and the wall shear stress hot-wire transducer to minimize the problems related to the advection of turbulent structures over significant distances between the probes.

The experiments were conducted in a turbulent boundary layer on a cylinder in axial flow. While the canonical flat plate boundary layer is often used for studies of the structure of turbulence, the turbulent boundary layer on a cylinder models many practical engineering applications (for example streamlined vehicles, submarines, aircraft, missiles, and sonar arrays) and has been studied extensively over the past few years both experimentally and computationally.[12,18,26–28]

II. EXPERIMENTAL SETUP

This investigation was conducted in the Northwestern University low-speed, low-noise wind tunnel described in detail in our previous work,[12,18] except that the muffler on the blower outlet was removed after finding that it did not reduce noise contamination in the test section. The 4.57 m long, 0.953 cm o.d. cylinder was suspended along the centerline of the test section with its ellipsoidal nose cone 20 cm downstream of the last inlet screen by a wire attached to an airfoil located above the last four screens of the inlet section. The support airfoil was oriented at right angles to the side of the cylinder containing the wall pressure and shear stress measurement probes to minimize any possible effect of turbulence downstream of the support. The cylinder consisted of an ellipsoidal nose cone at the upstream end of a 3.35 m long by 0.953 cm o.d. acrylic tube with lengths of brass tubing inside to add rigidity. The 1.22 m long downstream instrumented section was 0.953 cm o.d., 0.076 cm wall stainless steel seamless tubing. The cylinder was tensioned to assure straightness, and spring-loaded, foam-lined gripper located 0.55 m downstream from the probes and sewing thread 8 cm downstream from the probes held the cylinder in position and minimized vibration.

To ensure a fully developed turbulent boundary layer, a 1.7 mm high O-ring trip was used 2.13 m upstream of the measurement probes (0.40 m downstream of the beginning of the test section). This distance corresponds to over 1250 trip heights or about 87 boundary layer thicknesses between the trip and the measurement location. The alignment with the cylinder with the test section was confirmed using four 0.056 cm o.d., 0.015 cm wall, Preston tubes every 90° around the cylinder 1 cm downstream of the measurement probes. The wall shear stress measured using the Preston tubes varied by less than 2.3% from the mean, indicating that the boundary layer was essentially axisymmetric. The streamwise mean velocity profile measured using a hot wire agrees well with the cylindrical log law of Lueptow *et al.*[29]

The wall pressure and wall shear stress measurement probes were contained in an insert located halfway between the ends of the downstream instrumented section. The wall pressure and wall shear stress probes were mounted with a center-to-center streamwise spacing of 0.11 cm ($x^+=33$) in a plastic insert machined to match the cylinder's wall curvature. The shear stress probe was installed upstream of the microphone, since data taken with the opposite configuration suggested that the microphone pinhole may disrupt the flow just downstream of it. The hot-wire-on-the-wall shear probe was similar to that used by Wietrzak and Lueptow.[18] The spanwise width of the element was $W^+=7.7$, well within the range of widths of 3–45 used successfully by Shah and Antonia for measuring the wall shear stress.[24] The wall shear stress probe was calibrated against a 0.056 cm o.d. Preston tube taped to the cylinder and aligned with the flow at the same streamwise position as the shear probe, but offset 90° in the spanwise direction following the calibration procedure of Wietrzak and Lueptow.[18] The fluctuating wall pressure was measured using a Knowles EM 3068 electret condenser-type hearing aid microphone like that used by Snarski and Lueptow.[12] The dimensionless microphone diameter of $d^+=21$ provided adequate resolution to minimize spatial averaging and attenuation due to zeros in the wave-number response function of the microphone.[30,31] The frequency response (magnitude and phase) for the Knowles microphone was obtained by performing a comparison calibration in a diffuse random sound field with an adjacent Bruel and Kjaer Model 4134 1.27 cm ($\frac{1}{2}$ in.) pressure-response microphone using the method of Snarski and Lueptow.[12] The mean and fluctuating streamwise velocities were measured using a custom-built, hot wire probe mounted to the end of a streamlined strut similar to that used in our previous work. The data from the velocity probe, wall shear probe, and microphone were simultaneously digitized at 20 kHz for 5.0 s using a 12-bit data-acquisition board after low pass filtering at the 10 kHz Nyquist frequency. Both the hot wire probe and the shear probe were operated at a 30% overheat ratio. All measurements were performed at a free-stream velocity of $U_\infty=10.6$ m/s. Details of the flow conditions at the axial location of the wall pressure and wall shear stress transducers are included in Table I.

III. RESULTS: EVENT DETECTION

Variable interval time averaging (VITA) and peak detection were used for conditional sampling. VITA detects a large short-time variance in the signal that indicates a steep temporal gradient.[32] VITA is typically applied to the fluctuating streamwise velocity, but we also applied VITA to the wall shear stress and the wall pressure. Applying VITA to these signals is somewhat unusual, although physical significance can be attached to steep temporal gradients in the wall shear stress and wall pressure, as described later in this paper. We use the traditional threshold of $k=1$ times the variance to detect bursts.[24,32–34] The averaging time was set to $T^+=15$, a time indicative of the time scale of the structures

TABLE I. Experimental conditions and flow parameters.

Experimental conditions:	
Free-stream velocity	$U_\infty = 10.6$ m/s
Density	$\rho = 1.180$ kg/m^3 (26 °C)
Kinematic viscosity	$\upsilon = 1.57\times10^{-5}$ m^2/s
Cylinder diameter	$2a = 9.53\times10^{-3}$ m
Boundary layer parameters:	
Boundary layer thickness	$\delta = 2.45\times10^{-2}$ m
Momentum thickness	$\theta = 3.2\times10^{-3}$ m
Curvature ratio	$\delta/a = 5.14$
Reynolds number	$\mathrm{Re}_\theta = 2160$
Mean wall shear stress	$\overline{\tau_w} = 0.273$ Pa
Friction velocity	$u_\tau = 0.481$ m/s
rms wall shear stress	$\tau_{\mathrm{rms}} = 0.102$ Pa
rms wall pressure	$p_{\mathrm{rms}} = 0.624$ Pa
Resolution parameters:	
Sampling frequency	$f_s = 20\,000$ Hz
Dimensionless sample time	$\Delta t^+ = 0.74$
Streamwise probe separation	$x^+ = 33$
Shear probe spanwise width	$W^+ = 7.7$
Velocity probe spanwise width	$l^+ = 20$
Microphone port diameter	$d^+ = 21$

being detected and within the range of 10–24 that is commonly used for VITA detection on the streamwise velocity and wall shear stress.[8,18,24,33]

Peak detection identifies high-amplitude peaks in the fluctuating signal that exceed a particular threshold. We used a threshold of $k=2.5$ times the rms value, a level that is within the range of 1.25–4 commonly used for peak detection on the wall pressure signal.[8,10–12,30] For both VITA and peak detection, the ensemble-averaged conditionally detected events are plotted versus inner-scaled time, $t^+ = tu_\tau^2/\nu$, with $t^+=0$ corresponding to the instant that the event is detected. The mean portions of the signals are removed. To compensate for the shear probe being positioned 33 viscous units upstream of the wall pressure and velocity probes, the shear stress signal was delayed by three viscous time units based on a convection velocity of $U_c/u_\tau = 11$.[18]

We consider the conditionally averaged signature of two signals upon the occurrence of a positive event in a third detection signal, shown in Fig. 1. In all cases, the detection signal is the bold curve. The velocity probe was positioned at $y^+=13$, directly above the wall pressure probe. To be assured that the upstream position of the wall shear probe and the close proximity of the velocity probe above the microphone did not degrade the wall pressure measurements, the hot wire velocity probe was removed altogether, the wall shear stress probe was turned off, and the instrumented section of cylinder was reversed so the microphone was upstream of the wall shear probe. The wall pressure spectrum for this setup was nearly identical to that for the measurements presented here, indicating that probe interference was not a problem. The detection of shear layers using positive VITA detection on the fluctuating streamwise velocity u_1 is shown in Fig. 1(a). The ensemble-averaged fluctuating streamwise velocity $\langle u_1\rangle$ and fluctuating wall shear stress $\langle \tau_w'\rangle$ are similar to previous results for both flat plate boundary layers[23,24] and cylindrical boundary layers.[18] Both signals

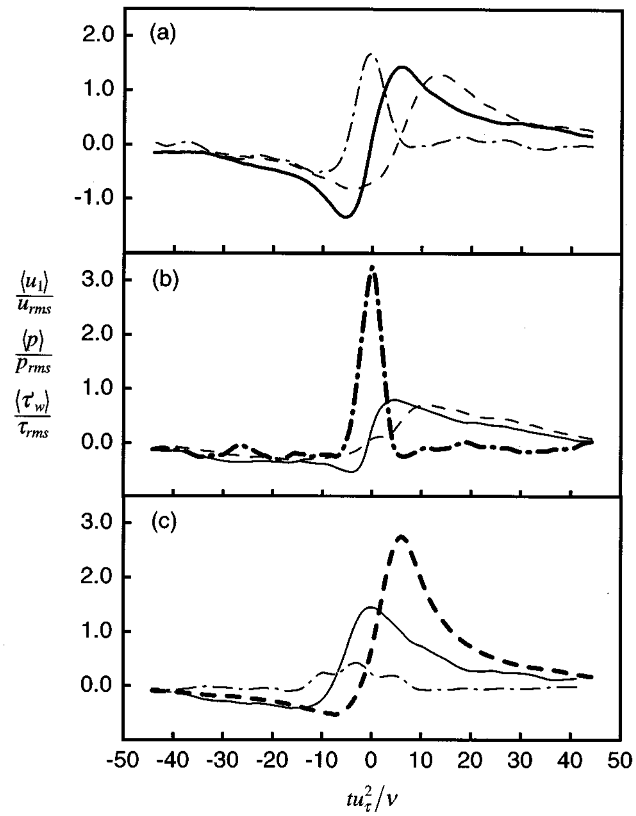

FIG. 1. Conditional averages of positive events detected using VITA and peak detection techniques. Here —, $\langle u_1\rangle/u_{\mathrm{rms}}$; ---, $\langle \tau_w'\rangle/\tau_{\mathrm{rms}}$; –-–, $\langle p\rangle/p_{\mathrm{rms}}$. Detection signals are bold. (a) VITA detection on u ($k=1$, $T^+=15$, 236 events); (b) peak detection on p ($k=2.5$, 294 events); (c) VITA detection on τ ($k=1$, $T^+=15$, 179 events).

drop below the mean, indicating the passage of a low-speed streak and then rise steeply corresponding to the passage of a shear layer to a high level associated with a sweep. The shear stress is delayed with respect to the streamwise velocity, indicating the convection of a ''back'' turbulent structure inclined to the wall.[20] The sharp increase in velocity indicative of a shear layer is associated with a peak in the ensemble-averaged wall pressure $\langle p\rangle$, similar to previous results.[10–12,35]

Upon the detection of a positive wall pressure peak, shown in Fig. 1(b), the corresponding streamwise velocity signature shows a sharp increase. The simultaneous occurrence of a pressure peak with a sharp increase in velocity for both detection on streamwise accelerations [Fig. 1(a)] and wall pressure peaks [Fig. 1(b)] indicates a bidirectional relationship between positive pressure peaks and shear layers like that found by Snarski and Lueptow,[12] indicating that positive wall pressure peaks and shear layers just above the wall are related through a turbulence structure. The pressure peak in Fig. 1(b) occurs slightly ahead of the midpoint of the more gradual increase in wall shear stress, as would be expected from an inclined shear layer. Since an inclined shear layer passes the velocity probe at $10<y^+<20$ at the same instant that a wall pressure peak occurs,[12,35] the impact of the

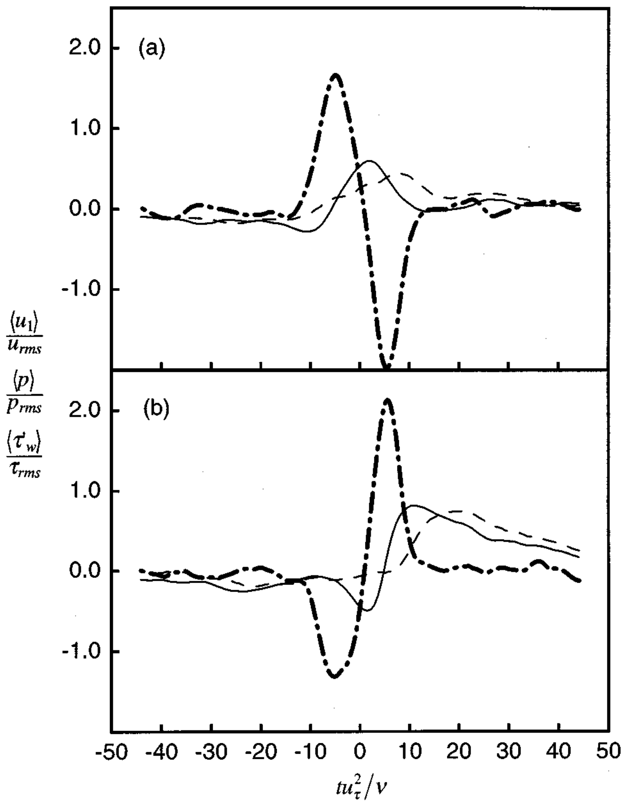

FIG. 2. Conditional averages of pressure gradient events detected using VITA on p. Here —, $\langle u_1 \rangle / u_{\rm rms}$; ---, $\langle \tau'_w \rangle / \tau_{\rm rms}$; –-–, $\langle p \rangle / p_{\rm rms}$. Detection signals are bold. (a) Adverse pressure gradient ($k=2$, $T^+=15$, 281 events); (b) favorable pressure gradient ($k=2$, $T^+=15$, 228 events).

shear layer at the wall shear stress probe would be felt slightly after it passes the velocity probe and, hence, the wall pressure peak. The lead of wall pressure peak with respect to the midpoint of the increase in wall shear stress is about three viscous time units less for pressure peak detection [Fig. 1(b)] than for VITA-on-u detection [Fig. 1(a)]. This discrepancy may be related to the ''flattening'' in the shear stress signal that occurs just after the pressure peak in which the rise in shear stress is momentarily interrupted for about three viscous time units, then continues to increase. The brief flattened portion of the shear stress signature is delayed slightly after the pressure peak, suggesting that it might be related to the part of the inclined shear layer very near the wall that would reach the shear probe shortly after it encounters the velocity probe at $y^+=13$. Haritonidis, Gresko, and Breuer [Fig. 2(a)] found a feature of similar duration and character in the sharply decreasing wall–normal velocity signature obtained upon VITA-on-u event detection,[10] but they did not discuss it and it is not clear that it is related the flattening in the wall shear stress signature in Fig. 1(b).

Detection of sharp increases in shear stress using VITA-on-τ, shown in Fig. 1(c), shows that the sharp increase in wall shear stress lags behind the sharp increase in streamwise velocity by approximately seven viscous time units, the same as that for the VITA-on-u detection. The difference in amplitude of the wall shear stress signal in Figs. 1(a) and 1(c) results from different detection signals in each case. The similarity between the streamwise velocity conditional averages in Figs. 1(a) and 1(c) and the wall shear stress conditional averages in Figs. 1(a) and 1(c) clearly shows a bidirectional relationship between the wall shear stress and the streamwise velocity, confirming the results of Wietrzak and Lueptow for a boundary layer on a cylinder.[18] On the other hand, a sharp increase in the wall shear stress corresponds to only a weakly elevated wall pressure that is qualitatively different from the pressure peak for VITA-on-u or pressure peak detection. The pressure rise lasts about 24 viscous time units, approximately twice as long as a positive pressure event in Fig. 1(c). A small pressure rise appears before and after the central pressure maxima that is not evident in either VITA-on-u or pressure peak detection. Thus, the wall pressure and the wall shear stress have only a very weak bidirectional relationship, compared to the relationships for the streamwise velocity and wall shear stress or the streamwise velocity and the wall pressure.

Although positive wall pressure events can be related to the streamwise acceleration resulting from a sweep following an ejection, the amplitude distribution of negative and positive wall pressure fluctuations about the mean is nearly identical,[9] and the frequency of negative and positive events is similar.[36] Thus, positive and negative events appear equally important. Wilczynski *et al.*[13] suggested that positive and negative wall pressure events may actually be subsets of a single composite event characterized by a negative peak upstream of a positive peak. They explored such a possibility by detecting nearby positive and negative peaks and constructing an average temporal positive–negative event. Although they found an order of magnitude fewer dual peak events than single peak events, the ensemble-averaged dual peak event indeed looks like a composite of a positive pressure peak followed in time by a negative pressure peak. Further evidence of a dual peak event was provided by Astolfi and Forestier detecting on strong shear layers.[16] When their shear layer detection probe was close to the wall ($y^+=10$), they found a positive peak followed in time by a negative peak of nearly equal magnitude.

An effective detection method for composite events is the detection of regions of large adverse pressure gradient, $\partial p/\partial x > 0$. A method to detect local pressure gradients is to apply VITA to the wall pressure signal. The application of VITA to the wall pressure is quite unusual. Steep temporal gradients in the wall pressure, however, can be related to the velocity field as follows. The streamwise pressure gradient at the wall can be related to the spanwise vorticity ω_z at the wall and, hence, to the streamwise velocity, $U=U_1+u_1$,[9,37]

$$\frac{\partial p}{\partial x} = -\left.\frac{\partial \omega_z}{\partial y}\right|_{y=0} = \mu \left.\frac{\partial^2 U}{\partial y^2}\right|_{y=0}. \tag{1}$$

Assuming that the streamwise wall pressure gradient can be related to the time derivative by $\partial p/\partial x = -(1/U_c)\partial p/\partial t$,[38] where U_c is the local convection velocity, the temporal wall pressure gradient can be related to the velocity field by

$$\frac{\partial p}{\partial t} = -\mu U_c \left.\frac{\partial^2 U}{\partial y^2}\right|_{y=0}. \tag{2}$$

When the local pressure gradient is adverse ($\partial p/\partial x > 0$ or $\partial p/\partial t < 0$), the second derivative of the streamwise velocity with respect to the wall–normal coordinate is positive ($\partial^2 U/\partial y^2 > 0$). The positive curvature of the velocity profile at the wall requires an inflection point at some distance above the wall. Although the classic unstable inflectional velocity profile requires the assumption of steady, inviscid, two-dimensional flow, it is not unreasonable to interpret any inflectional profile as a local shear layer instability.[39] Consequently, an adverse pressure gradient event detected using negative VITA-on-p should coincide with a shear layer in the velocity field. Favorable wall pressure gradients are thought to correspond to ejections, and adverse wall pressure gradients are believed to be related to sweeps.[7,13,14] Here we propose that an adverse wall pressure gradient is directly related to the shear layer in a burst cycle based on the instability of an inflectional velocity profile.

Figure 2(a) shows the resulting streamwise velocity and wall shear stress for negative VITA-on-p ($\partial p/\partial t < 0$), which detects on adverse pressure gradient events ($\partial p/\partial x > 0$). The VITA detection scheme used the same averaging time, $T^+ = 15$, as used for VITA-on-u detection, and the trigger level was set at $k = 2$ to obtain approximately the same number of events as found with the previous detection schemes. The steep decrease in wall pressure does indeed seem to be associated with an acceleration in streamwise velocity and a moderate increase in the wall shear stress. Like positive VITA-on-u and positive wall pressure peak detection, the positive peak in the wall pressure signal occurs simultaneously with the midpoint of the sharp streamwise acceleration. Again the increase in the wall shear stress is slightly delayed with respect to the streamwise acceleration.

If, instead, positive VITA-on-p events are detected ($\partial p/\partial t > 0$), corresponding to favorable pressure gradients ($\partial p/\partial x < 0$), the signature of the streamwise velocity and the wall shear stress is similar to that for negative VITA-on-p events, as shown in Fig. 2(b). The streamwise flow accelerates at nearly the same instant as the positive peak in wall pressure occurs, and the wall shear stress increase is slightly delayed with respect to the increase in the streamwise velocity. In fact, the streamwise acceleration for favorable pressure gradient events is stronger than for adverse pressure gradient events.

The crucial result obtained from Fig. 2 is that the wall pressure peak and the streamwise acceleration at $y^+ = 13$, which is related to a shear layer, occur simultaneously. This suggests that the positive wall pressure peak itself, not the adverse pressure gradient upstream of it nor the favorable pressure gradient downstream of it, is directly related to the burst cycle. Clearly, any positive peak in wall pressure will have pressure gradients of opposite signs preceding and following it. This idea fits nicely with the results of Fig. 1, which shows a strong bidirectional correlation between positive wall pressure peaks and streamwise accelerations that are related to the shear layer in a burst cycle. Furthermore, Eq. (2) clearly indicates that adverse pressure gradients ($\partial p/\partial t < 0$) should be related to an inflectional profile that would likely result from a shear layer. Such a shear layer is detected for both the detected adverse pressure gradient in Fig. 2(a) and for the adverse pressure gradient following the pressure peak in Fig. 2(b).

Negative wall pressure peaks are apparently not directly related to the burst cycle. VITA-on-p detection of pressure gradients indicates that negative wall pressure peaks occur either before or after the positive pressure peak. In fact, aligning negative and positive VITA-on-p events on the positive pressure peaks would result in a negative pressure depression leading and following the pressure peak. A small depression in the wall pressure on both sides of the pressure peak is evident in Fig. 1(b), and other researchers have typically found such regions of negative wall pressure leading and following positive wall pressure peaks.[7,12,13,30,35,40] This suggests that positive wall pressure peaks, which are related to the burst cycle, are either preceded or followed by negative wall pressure peaks. Because of the random nature of the turbulence and the burst cycle itself, the negative wall pressure that leads or follows the positive pressure peak may be either quite large or nearly insignificant. The appearance of a negative wall pressure peak alone,[11–13,30,40] like that detected using negative pressure peak detection, is probably just a remnant of the peak detection sampling method, since there exists only a weak bidirectional relationship between negative pressure peaks and the velocity field.[12] Thus, we can conclude that the negative wall pressure peaks are not the direct result of a specific turbulence structure. Instead, negative wall pressure peaks typically appear in conjunction with positive wall pressure peaks, and it is these positive wall pressure peaks that are directly related to coherent turbulence structures, specifically the burst cycle.

IV. RESULTS: CROSS-CORRELATIONS AND SPECTRA

The normalized cross-correlation coefficient between the fluctuating wall shear stress τ_w' and the fluctuating streamwise velocity u_1 is defined as

$$R_{\tau u}(t) = \overline{\tau_w'(\zeta) u_1(\zeta + t)} / \tau_{\mathrm{rms}} u_{\mathrm{rms}}, \tag{3}$$

where the overbar denotes a time average, t is the delay time between the signals, and the rms subscript denotes the rms value of the particular quantity. The cross-correlation is similarly defined for wall pressure/streamwise velocity and wall pressure/wall shear stress. In all cases, the wall shear stress signal was shifted by three viscous time units to compensate for the shear probe being positioned upstream of the wall pressure microphone and velocity probe. The cross-correlations were computed using fast Fourier transforms with 100% zero padding.

The cross-correlation between the wall shear stress and the streamwise velocity measured above the wall pressure probe, shown in Fig. 3(a), weakens as the wall–normal position of the velocity probe increases. The positive peaks indicate that the wall shear stress and streamwise velocity have the same sign, consistent with event detection results, which show that the wall shear stress and the streamwise velocity have similar signatures. The negative lag times indicate that the streamwise velocity leads the wall shear stress, suggesting a turbulence structure that is inclined to the

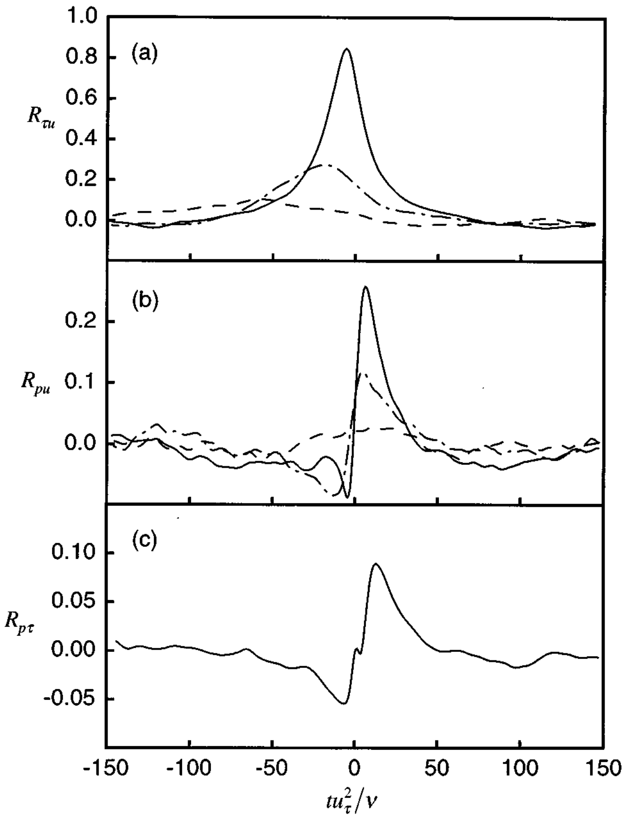

FIG. 3. (a) Cross-correlation between wall shear stress and velocity, $R_{\tau u}$; (b) cross-correlation between wall pressure and velocity, R_{pu}; (c) cross-correlation between wall pressure and wall shear stress, $R_{p\tau}$. Note the vertical scale change. Wall–normal locations of velocity probe —, $y^+=13$; –-–, $y^+=83$; ---, $y^+=349$.

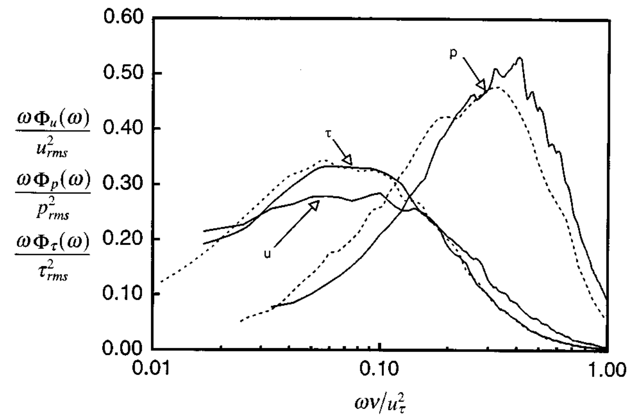

FIG. 4. Spectra of the streamwise velocity u (at $y^+=13$), wall pressure p, and wall shear stress τ_w; — current results; ---, previous measurements (Refs. 12, 18).

wall.[18,21] The cross-correlation between the wall pressure and the streamwise velocity, shown in Fig. 3(b), is much weaker than that for the wall shear stress and the streamwise velocity, and the cross-correlation weakens as the velocity probe is positioned farther from the wall. (Note the change in scale for the vertical axis.) The negative correlation for negative lag times is consistent with the positive pressure peak lagging the negative peak in streamwise velocity in Fig. 1. Similarly, the positive pressure peak leads the positive peak in the streamwise velocity, resulting in a positive cross-correlation peak at a positive lag time. Similar results have been obtained in planar boundary layers.[5,6]

Our key interest here is the cross-correlation between the wall pressure and the wall shear stress. This correlation has the same shape as the pressure–velocity correlation but is an order of magnitude weaker than the shear–velocity correlation and about one-half as strong as the pressure–velocity correlation (for the velocity probe at $y^+=13$ in all cases), as shown in Fig. 3(c). This result is somewhat surprising given that the wall shear stress is directly related to velocity at the wall and that the pressure–velocity correlation increases in strength as the velocity probe is moved closer to the wall as shown in Fig. 3(b) for $y^+\geqslant 13$. The weak pressure–shear correlation is unlikely to result from the streamwise separation between the probes of 33 viscous units, since a streamwise separation of 680 viscous units is needed for a similar reduction in the magnitude of the pressure–velocity correlation for a velocity probe at $y^+=14$.[41] Instead, the weak bidirectional relationship between wall shear stress events and wall pressure events evident in Fig. 1 must account for the weak pressure–shear correlation. A curious aspect of the pressure–shear correlation is the kink evident near a delay time of zero. The physical origin of this kink in the event detection and cross-correlation is unknown, although it might be related to the flattening of the shear stress signature shown in Fig. 1(b).

Spectra of the streamwise velocity, wall shear stress, and wall pressure were computed using fast Fourier transforms after applying a Hanning window to 97 subrecords of 1024 points each, with a resulting frequency resolution of $\Delta\omega=123$ rad/s, or $\Delta\omega^+=\Delta\omega\nu/u_\tau^2=0.0083$. The spectra are plotted in Fig. 4 so that equal areas under the curve contribute equally to the mean square energy to permit easy analysis of which band in the spectrum contributes most to the rms of the measurement.[42] The spectra measured here match previous measurements of the spectra quite well, given slight differences in the boundary layer parameters. The wall shear stress and streamwise velocity spectra are similar to each other. Both spectra have maxima at $\omega^+\approx 0.06$. The maximum in the wall pressure spectrum occurs at $\omega^+\approx 0.4$, nearly an order of magnitude higher in frequency. The relatively tall and narrow peak in the wall pressure spectrum indicates that the energy is distributed over a narrower logarithmic frequency band than the energy of the wall shear stress or the streamwise velocity. Thus, the wall shear stress and wall pressure have very different energy distributions in the frequency domain.

V. DISCUSSION

Turbulence events in the boundary layer above a wall give rise to both pressure (normal stresses) and shear stresses at the wall. Our key interest here is the relationship between the wall pressure and the wall shear stress, given that both arise from the velocity field adjacent to the wall. Event detection and correlation results all indicate that there is a strong relationship between the wall shear stress and the streamwise velocity and there is a moderately strong relationship between the wall pressure and the streamwise velocity. Based on these results and the knowledge that the wall shear stress and the wall pressure both arise from the adjacent velocity field, a reasonably strong relationship between the wall pressure and the wall shear stress would seem likely. Instead, the relationship between the wall pressure and the wall shear stress is quite weak, as indicated by the lack of a bidirectional relationship between wall pressure events and wall shear stress events, as well as weak correlation between the wall pressure and wall shear stress.

The question that arises is why should the relation between the wall pressure and the wall shear stress be so weak when each are the direct result of the flow field above the wall? The character of the relationship of the wall pressure and the wall shear stress to the velocity field provides some insight. The wall pressure is related to the weighted integral of the effects of the velocity field in the half-space above the wall.[1] Kim calculated the contribution to the mean-square wall pressure of the linear and nonlinear terms in this relation as a function of distance from the wall and found that the greatest contribution of both terms occurs near $y^+ \approx 13$ (based on Kim's Fig. 19).[9] Thus, turbulence action in this region, where our streamwise velocity probe was positioned, strongly contributes to the wall pressure. As a result, we found a moderately strong correlation and a bidirectional event relationship between the wall pressure and the streamwise velocity at this wall–normal position.

The direct relationship between streamwise velocity fluctuations and fluctuations in the wall shear stress is most easily demonstrated as follows. In the viscous sublayer, $\overline{\tau_w} + \tau_w' = \mu \partial(U_1 + u_1)/\partial y$ instantaneously and $\overline{\tau_w} = \mu\ \partial U_1/\partial y$ on average, where $\overline{\tau_w}$ and τ_w' are the average and fluctuating wall shear stress and μ is the dynamic viscosity. The difference between these two equations results in $\tau_w' = \mu\ \partial u_1/\partial y \approx \mu u_1/y$, since u_1 and y are zero at the wall. While the direct relation between velocity fluctuations (u_1) and wall shear stress fluctuations (τ_w') is strictly true only in the sublayer, an increase in velocity just outside of the sublayer (at say $y^+ = 13$) will typically result in an increased wall shear stress. Thus, fluctuations in the wall shear stress should follow fluctuations in the streamwise velocity, resulting in a strong bidirectional event relationship and cross-correlation between the wall shear stress and the streamwise velocity at $y^+ = 13$.

The weak relationship between the wall pressure and the wall shear stress may arise from the very different ways in which the two are related to the velocity field. The wall shear stress is only related to the velocity field along the wall–normal line originating at the measurement location. On the other hand, the wall pressure depends on the velocity field in the half-space above the measurement point, so that contributions are felt from velocity fluctuations directly above the measurement point as well as from fluctuations surrounding the measurement point in the streamwise and spanwise directions. Furthermore, the nature of the wall shear stress requires that it be directly related to the streamwise velocity within the viscous sublayer through the velocity gradient at the wall. On the other hand, the wall pressure is not closely related to the streamwise velocity very near the wall (say $y^+ < 3$) based on the results of Kim (Fig. 19),[9] even though the results presented in this paper and by others[10–13] indicate a relationship between the wall pressure and the streamwise velocity for $5 \leqslant y^+ \leqslant 85$. As a result, the wall pressure and the wall shear stress are only weakly related to each other, even though both are closely related to the streamwise velocity at $y^+ > 5$.

A second issue is the characteristic, or fundamental, wall pressure event that is related to a coherent structure in the velocity field. Several different characteristic wall pressure events can be detected, including positive and negative wall pressure peaks and favorable and adverse pressure gradients. While Eq. (2) indicates that a local adverse pressure gradient should correspond to an inflectional velocity profile that may be related to a shear layer, the shear layer at $y^+ = 13$ always coincides with a positive peak in the wall pressure, regardless of whether the positive peak is associated with a favorable or adverse pressure gradient detected using VITA-on-*p* (Fig. 2) or a positive pressure peak found using peak detection [Fig. 1(b)]. Figure 2 further indicates that the shear layer is stronger for a stronger positive pressure peak. These results indicate that the critical feature in the wall pressure field that is related to a burst cycle is a sharp positive peak in pressure. Any positive peak in wall pressure will necessarily have an adverse pressure gradient upstream of it and a favorable pressure gradient downstream of it. Furthermore, a positive wall pressure peak may be related to the growth of a wall pressure wave cluster, as evidenced by the development of wall pressure peaks tracked in a direct numerical simulation of channel flow.[40] The wave cluster will have negative pressures as well as positive pressures associated with it. Although the positive pressure peak is associated with the burst cycle, negative pressures in the wave cluster may exist upstream or downstream of the positive pressure peak. But VITA-on-*p* detection shows that a negative pressure peak occurs in conjunction with a positive pressure peak that is, in turn, related to a shear layer. Thus, positive pressure peaks are the ''fundamental'' event in the wall pressure field that can be related to turbulent structures above the wall, particularly the shear layer associated with the burst cycle.

These results are based on measurements of a turbulent boundary layer on a long slender cylinder. Nevertheless, because the structure of turbulence very near the wall is quite similar to that for a flat plate,[12,18,28,43] these conclusions should be applicable for all wall-bounded turbulent flows.

ACKNOWLEDGMENT

This work was supported by the Naval Undersea Warfare Center, New London, CT, Dr. Marilyn Berliner and Dr. David Hurdis program managers.

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