BRIEF COMMUNICATIONS

The purpose of this Brief Communications section is to present important research results of more limited scope than regular articles appearing in Physics of Fluids. Submission of material of a peripheral or cursory nature is strongly discouraged. Brief Communications cannot exceed four printed pages in length, including space allowed for title, figures, tables, references, and an abstract limited to about 100 words.

Relationship between wall pressure fluctuations and streamwise vortices in a turbulent boundary layer

Joongnyon Kim, Jung-II Choi, and Hyung Jin Sung

Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, 373-1, Kusong-dong, Yusong-ku, Taejon, 305-701, Korea

(Received 1 August 2001; accepted 2 November 2001)

A direct numerical simulation is performed to examine the relationship between wall pressure fluctuations and near-wall streamwise vortices in a spatially developing turbulent boundary layer. It is found that wall pressure fluctuations are closely linked with the upstream quasistreamwise vortices in the buffer region. The maximum correlation occurs with the spanwise displacement from the location of wall pressure fluctuations. The space–time correlation reveals that wall pressure fluctuations lag behind streamwise vorticity in the upstream, while streamwise vorticity lag behind wall pressure fluctuations in the downstream. The contributions of high-amplitude wall pressure event to the turbulent energy production mechanism are examined by the quadrant analysis of Reynolds shear stress. © 2002 American Institute of Physics. [DOI: 10.1063/1.1429964]

It is known that the generation of wall pressure fluctuations is governed by the dynamics of velocity fluctuations through a Poisson’s equation. Thomas and Bull found that a region of high pressure associated with the sweep motion is due to the passage of inclined near-wall shear layers. Johansson et al. also showed that the shear layer structures in the buffer region are responsible for the generation of large positive wall pressure peaks. A literature survey reveals that both shear layer structures and quasistreamwise vortices are primary turbulent structures beneath turbulent boundary layers. From the visualization of turbulence structures by direct numerical simulation (DNS), quasistreamwise vortices are associated with the generation of wall pressure fluctuations. Bernard et al. found that the sweep motions due to streamwise vortices can generate a region of positive wall pressure, while negative wall pressure occurs beneath vortex core and ejection motions. Kim examined the source terms in the Poisson’s equation for pressure to assess the relative importance of each term. Among the source terms, it was found that \((\partial u_i/\partial x_j)\langle \partial w/\partial y \rangle\) is the largest term, which is large at the core of streamwise vortices. Recently, the convolution of the Green’s function with source terms in various regions of turbulent channel flow was computed by Chang et al. They found that the most important source term is closely linked to quasistreamwise vortices.

Our objective in the present study is to obtain a more quantitative statistical description of the relationship between wall pressure fluctuations and streamwise vortices in a turbulent boundary layer. The locations and length scales of streamwise vortices highly correlated with wall pressure fluctuations are scrutinized in terms of two-point correlations. The phase relations between wall pressure and streamwise vorticity fluctuations are examined by utilizing the space–time correlations. Based on the wealth of DNS data, averaged features of coherent structures are deduced from the conditionally averaged vorticity field. To secure information on the contributions to the turbulent energy production mechanism, a quadrant analysis of Reynolds shear stress is conducted.

In the present study, a direct numerical simulation is performed on a spatially developing turbulent boundary layer. The unsteady three-dimensional Navier–Stokes equations are integrated in time by using a fully implicit decoupling method, which has been proposed by Kim et al. All terms are advanced with the Crank–Nicolson method in time, and they are resolved with the second-order central difference scheme in space. Time-dependent turbulent inflow data are provided at the inlet based on the method by Lund et al. A convective boundary condition at the exit has the form \((\partial u_i/\partial t) + c(\partial u_i/\partial x) = 0\), where \(c\) is the local bulk velocity. The no-slip boundary condition is imposed at the solid wall, and the boundary conditions on the top surface of the computational domain are \(u = U_x\), \((\partial u/\partial y) = (\partial w/\partial y) = 0\). A periodic boundary condition is applied in the spanwise direction.

# Author to whom correspondence should be addressed. Telephone: 82-42-869-3027; fax: 82-42-869-5027. Electronic mail: hjsung@kaist.ac.kr
and

\[ R'_{p,w} = R''_{p,w} \frac{(\Delta x, y, \Delta z)}{p_{\text{rms}} \omega_{\text{rms}}} \]

respectively. All the results presented in this study are obtained at the center of the computational domain \( x_0 = 100 \theta_0 \). The bracket denotes an average over the spanwise direction and time. A typical isosurface of \( R'_{p,w} \) in a three-dimensional view exhibits two highly correlated structures upstream of the location at which the wall pressure fluctuations are obtained. The contour lines of \( R'_{p,w} \) truncated at the planes are exhibited in Fig. 1. The contours in the \( y-z \) plane are presented in Fig. 1(a), where the maximum correlation coefficient occurs with the spanwise displacement \( \Delta z^+ = \pm 20 \) from the location of wall pressure fluctuations. The large value of the correlation coefficient at the wall is a kinematic consequence of the interaction between the streamwise vortices above the wall and the no-slip boundary condition. Note that the spanwise displacement at the wall is also \( \Delta z^+ = \pm 20 \) [Fig. 1(b)], indicating that the strongest correlation coefficients in the vicinity of the wall are observed directly above the locations of those at the wall. Figure 1(c) discloses that the location of the maximum correlation coefficient moves away from the wall with increasing \( \Delta x^+ \). This confirms the existence of a tilted structure in the vicinity of the wall. The tilted structure was observed by Kravchenko et al., who examined the relationship between wall skin friction and streamwise vortices from a direct numerical simulation database of turbulent channel flows. It is seen that the \( y^+ \) location of the maximum correlation coefficient increases from \( y^+ \approx 10 \) at \( \Delta x^+ = -50 \) to \( y^+ \approx 15 \) at \( \Delta x^+ = -25 \), which gives a tilted angle of about 11.3°.

The correlation coefficients at the wall and above the wall are represented in Fig. 2. The location of \( y^+ = 20 \) corresponds to the average location of the center of streamwise vortices. The positive and negative maxima are clearly seen at \( \Delta z^+ = \pm 20 \) for both \( y^+ \) locations. As mentioned earlier, the streamwise vortices exist directly above the locations of high correlation coefficients at the wall. Furthermore, these locations are with spanwise displacement \( \Delta z^+ = \pm 20 \) from the point of high wall pressure fluctuations. Note that the correlation coefficient at \( \Delta z^+ = 20 \) in Fig. 2(b) is negative at

![FIG. 1. Contours of the correlation coefficient between \( p_w \) and \( \omega_z \): (a) at \( \Delta x^+ = -20 \) in the \( y-z \) plane; (b) at \( y^+ = 0 \) in the \( x-z \) plane; (c) at \( \Delta z^+ = -20 \) in the \( x-y \) plane. The contour levels are from -0.35 to 0.35 with the increment of 0.05, and the negative correlations are dashed.](Image)

![FIG. 2. The correlation coefficient between \( p_w \) and \( \omega_z \): (a) at \( y^+ = 0 \); (b) at \( y^+ = 20 \).](Image)
negative $\Delta x^+$ but becomes positive at certain positive $\Delta x^+$. This indicates that the vortical structures highly correlated with wall pressure fluctuations have alternating signs of streamwise vorticity. These are consistent with the dominant structures educed by Jeong et al.,$^{11}$ which are quasistreamwise vortices with alternating signs of $\omega_x$. One could conclude from the correlations results that high wall pressure fluctuations are directly linked with the upstream streamwise vortices located at $y^+=20$ and $\Delta z^+=\pm 20$.  

The space–time correlation between wall pressure fluctuations and streamwise vorticity is computed, which is defined as

$$R_{\bar{p}_w, \bar{\omega}_x}(\Delta x, \Delta y, \Delta z, \Delta t) = \langle p(x_0,0,z,t) \times \omega_x(x_0+\Delta x, y, z+\Delta z, t+\Delta t) \rangle.$$  

(3)

The bracket denotes an average over the spanwise direction. All the correlations at $\Delta z^+=0$ are equal to zero. The space–time correlations at $\Delta z^+=-20$ are presented in Fig. 3, where four streamwise locations are chosen to display the correlations. The most distinct feature in Fig. 3 is the phase shift between wall pressure fluctuations and streamwise vorticity. In the upstream of the location of wall pressure fluctuations, the positive peak of the correlation is located at negative $\Delta \tau^+$ [Fig. 3(a)]. This means that wall pressure fluctuations lag behind streamwise vorticity in the upstream. On the contrary, the peak is obtained at positive $\Delta \tau^+$ in Fig. 3(d), where streamwise vorticity lag behind wall pressure fluctuations in the downstream. In particular, an “in-phase” location where the peak is at $\Delta \tau^+=0$ is observed upstream of the location of wall pressure fluctuations [Fig. 3(b)]. Here, the “in phase” means that the phase of streamwise vorticity is the same as that of wall pressure fluctuations. For example, the phase of streamwise vorticity at $(\Delta x^+, y^+)$ $=(-20,20)$ is equivalent to that of wall pressure fluctuations without any time lag. This suggests that high wall pressure fluctuations are directly linked with the upstream streamwise vortices. A closer inspection of the peak locations of the correlation in Fig. 3 indicates that the “in-phase” location moves away from the wall with increasing $\Delta x^+$, confirming the existence of tilted structure.

In order to examine the averaged features of coherent structures, the conditionally averaged streamwise vorticity fields are calculated for various threshold levels of wall pressure fluctuations. The streamwise vorticity near the position of high wall pressure fluctuations are averaged for positive and negative pressures, respectively. The conditional averages of streamwise vorticity are constructed, satisfying the condition

$$p_w > k \rho_{rms},$$

(4)

for the positive wall pressure fluctuations, and

$$p_w < -k \rho_{rms},$$

(5)

for the negative wall pressure fluctuations. Here, $k$ is a threshold value. The results in the case of $k=2$ are exhibited in Fig. 4. The contours of the conditional averages are truncated at $\Delta x^+=-20$ in the $y-z$ plane. It is evident in Fig. 4(a) that the region of high positive wall pressure is related with the inward motion of fluid particles due to the streamwise vortices above the wall. On the contrary, the high negative wall pressure fluctuations occur beneath the outward motion of fluids in the vicinity of the wall [Fig. 4(b)]. Note that the $y^+$ location of the local maximum of the vorticity for the negative wall pressure fluctuations is closer to the wall than that for the positive wall pressure fluctuations. This suggests that the streamwise vortices associated with negative wall pressure fluctuations are closer to the wall. A comparison of the conditionally averaged results for different threshold values reveals that the shapes and sizes of vortices are almost the same, while the strengths for the case of lower threshold values are much weaker than those of higher threshold values.
The Reynolds shear stress is divided into four categories according to the signs of \( u' \) and \( v' \), namely four quadrants. The quadrant analysis of the Reynolds shear stress is performed for various threshold levels of wall pressure fluctuations. Since most of the turbulent energy production comes from \( -u'v' \partial U/\partial y \), the analysis divides the Reynolds shear stress into four categories according to the signs of \( u' \) and \( v' \). The Reynolds shear stress from each quadrant is averaged satisfying the same condition with Eqs. (4) and (5). The average over the spanwise direction and time is directly constructed above the location of the wall pressure fluctuations.

In summary, the maximum correlation occurs with the spanwise displacement \( \Delta z^+ = \pm 20 \) from the location of wall pressure fluctuations. The correlation coefficient has a maximum at \( \Delta x^+ = -20 \), which is upstream of the location of wall pressure fluctuations. The streamwise vortices related to high-amplitude wall pressure fluctuations are tilted from the wall and have alternating signs of streamwise vorticity. The space–time correlation shows that wall pressure fluctuations lag behind streamwise vorticity in the upstream, while streamwise vorticity lag behind wall pressure fluctuations in the downstream. The “in-phase” location is observed upstream of the location of wall pressure fluctuations. The region of high positive wall pressure is associated with the inward motions due to the streamwise vortices above the wall. On the contrary, the high negative wall pressure fluctuations occur beneath the outward motion in the vicinity of the wall. The contribution of high-amplitude wall pressure events to the turbulent kinetic energy production is larger than that of small-amplitude wall pressure events.

**ACKNOWLEDGMENTS**

This work was supported by a grant from the National Research Laboratory of the Ministry of Science and Technology, Korea. The partial support from the Underwater Acoustics Research Center of Agency for Defense Development is acknowledged.