11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

CHARACTERISTICS OF POSITIVE AND NEGATIVE PRESSURE FLUCTUATIONS IN THE NEAR-WALL REGION OF A TURBULENT FLOW

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ABSTRACT

Distributions of instantaneous positive and negative pressure fluctuations in the near-wall region of a turbulent flow have been determined. The relationship between these distributions and the seven terms that make up the pressure equation are described. A few of these terms are dominant and these dominant terms are related to physical features of the flow. A Direct Numerical Simulation (DNS) data base was used for this investigation.

INTRODUCTION

Pressure measurements in turbulent flows are very difficult to make; only wall pressure measurements have been reported in the literature and even these measurements are fraught with difficulties. Eckelmann (1990) has a recent summary of pressure measurement experiments.

Most measurements have been made at a single position in the wall and this does not allow a spatial description of the pressure fluctuations to be made. A valiant effort to obtain spatial information of wall pressure fluctuations was that of Dinkelacker et.al. (1977).

With the advent of Direct Numerical Simulation (DNS) – a direct solution of the Navier–Stokes equations without resource to modelling – an opportunity has been provided to investigate pressure distributions in more detail since pressure values at each grid point are available. The data base used here was developed by Kim et.al. (1987) and reference should be made to this article for computational details. The flow used was a channel flow with an R_θ of 280, this being quite a low Reynolds number and a reflection of the limitations of current computers. A number of experimental investigators have not found any serious error in the DNS data for quantities that could be measured by the experiments. Reynolds number effects may change some of the relative magnitudes of the pressure distributions but it is possible that the fundamental physical relationships found at this low Reynolds number will also apply to higher Reynolds number flows.

Kim (1989) reported in some detail on pressure fluctuations in this flow. He gives distributions of rms, pdf, skewness, flatness and power spectra. Also presented are certain pressure correlations, contours of the fluctuations at the wall and centre–line and contours of vorticity.

In this current work, emphasis is placed on a description of the distribution of the instantaneous values of the pressure fluctuations and some of the physical relationships that contribute to such distributions.

COMPUTATIONAL FIELD

The computational field for the DNS data is shown in Figure 1. Flow is between two parallel plates and the region is divided into 128 x 129 x 128 nodes (2,113,536 total).

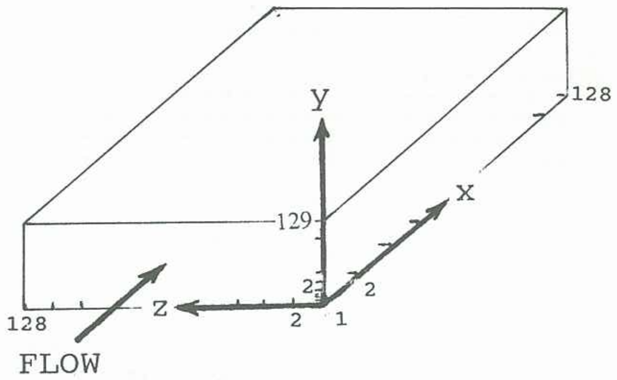

Figure 1. Computational Field

The nodal spacing, in wall units, is 11 in the *x* direction, 4 in the *z* direction and variable in the *y* direction (there are 15 nodes out to $y^+ = 10$ with the closest node to the wall being at $y^+ = 0.05$ while at the centre–line the spacing is approximately 4 wall units). At each node the DNS calculations provided instantaneous values of the velocity components (U,V,W), the pressure (P) and the vorticity components (ω_x, ω_y, ω_z).

RESULTS

(a) Pressure Fluctuation Pockets

Typical pockets of positive and negative pressure fluctuations in the *y–z* plane, at a sequence of *x* positions, are shown in Figure 2. Pressure magnitudes are indicated by the length of line drawn; an arrow to the right indicates positive fluctuations while an arrow to the left indicates negative fluctuations. This convention for showing pressures (and other quantities) gives a clearer picture of the pockets than does contour plotting. To emphasise high values, arrows are only used for pressure fluctuations of magnitude more than $2P_{rms}$, where P_{rms} is the rms of the wall pressure fluctuations. A line running from one grid point to the next in Figure 2 would indicate a pressure fluctuation of $7P_{rms}$. The pressure fluctuation peaks in Figure 2 are thus generally quite high – of the order of 5 to $6P_{rms}$.

Positive pressure pockets always seem to be well delineated; they have clear starting and finishing positions (in the *x* direction) and do not appear to amalgamate with other pockets or divide into smaller pockets. The one shown in Figure 2, from $x = 35$ to $x = 41$ is about 80 wall units long in the *x* direction, and 50 x 50 wall units maximum size in the *y–z* plane. Although in contact with the wall for most of its length, the peak fluctuations are generally not at the wall.

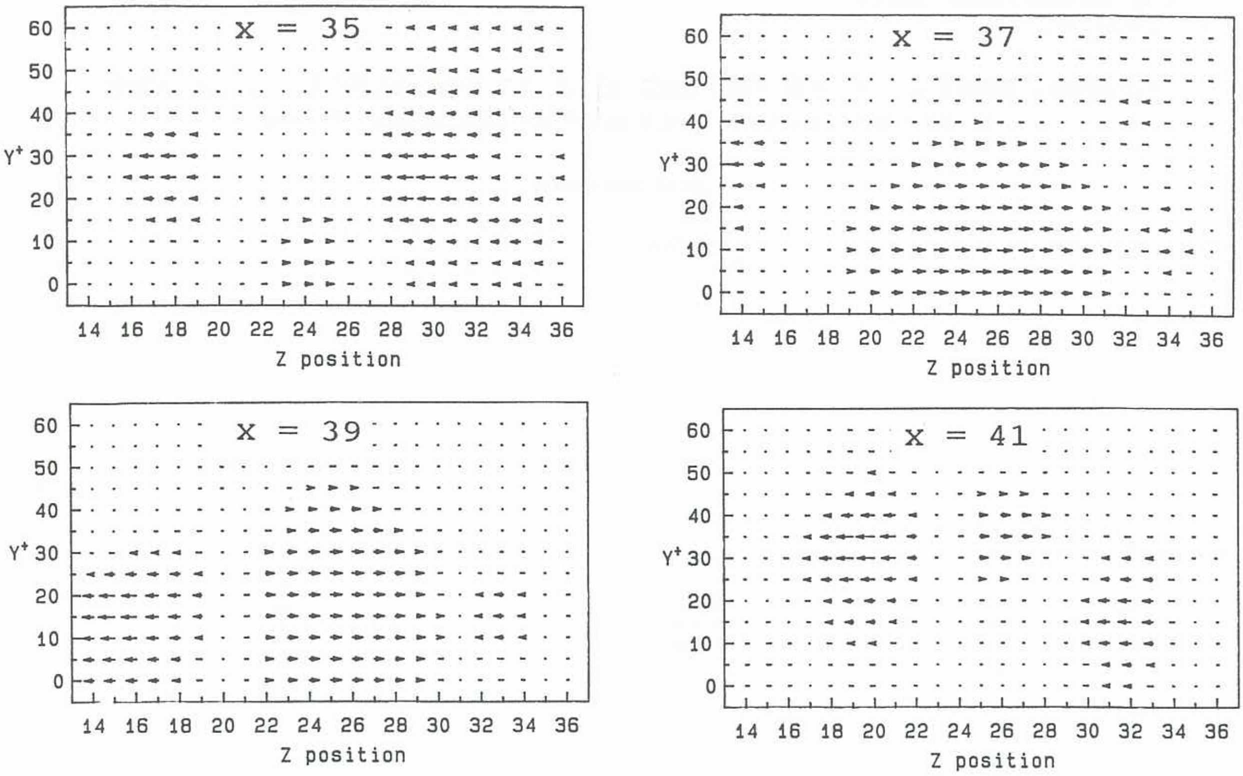

Figure 2
Instantaneous pressure fluctuations in the y–z plane for x = 35, 37, 39 and 41.
Line lengths indicate fluctuation magnitudes.
This line, —, represents a fluctuation of magnitude 7 x (P_{rms}) wall.
→: positive fluctuations; ←: negative fluctuations

Negative pressure pockets on the other hand appear to be continually separating or combining and a clear start and end to a pocket, in the x direction, is difficult to find. Thus, the larger negative pocket shown at $x = 35$ in Figure 2, thins out at the bottom at $x = 36$ (not shown) and separates completely at $x = 37$. It then becomes progressively larger up to $x = 41$. The positive pressure pocket gets smaller and has almost disappeared and at $x = 43$ (not shown here). The two negative pressure pockets, shown at $x = 41$ merge later and then at $x = 48$ (also not shown here) this combined pocket combines with another pocket. Peaks in negative pressures in the pockets invariably occur away from the wall, generally between $y^+ = 20$ to 40, although high negative peaks are not uncommon at $y^+ = 80$ to 100. Many of the negative pressure pockets do not extend to the wall.

(b) Possible Sources of the Pressure Pockets

Using tensor notation, a turbulent flow pressure field satisfies the equation:

$$\nabla^2 P = -U_{i,j}\,U_{j,i} \qquad (1)$$

where here U indicates an instantaneous velocity component, i and j (= 1,2 & 3) indicate the component direction, and the comma indicates differentiation.

Using $U_i = \overline{U}_i + u_i$ where $\overline{U}_i$ is the mean velocity and u_i the fluctuating component, equation (1) becomes –

$$\nabla^2 P = -2\overline{U}_{1,2}\,u_{2,1} - u_{i,j}\,u_{j,i} \qquad (2)$$

Using now U, V & W for the instantaneous velocity components and u, v & w for the fluctuating components in the x, y & z directions, equation (2) becomes –

$$-\nabla^2 P = \overset{①}{2\frac{d\overline{U}}{dy}\frac{\partial v}{\partial x}} + \overset{②}{\left(\frac{\partial u}{\partial x}\right)^2} + \overset{③}{\left(\frac{\partial u}{\partial y}\right)\left(\frac{\partial v}{\partial x}\right)} + \overset{④}{\left(\frac{\partial u}{\partial z}\right)\left(\frac{\partial w}{\partial x}\right)}$$
$$+ \overset{⑤}{\left(\frac{\partial v}{\partial y}\right)^2} + \overset{⑥}{\left(\frac{\partial v}{\partial z}\right)\left(\frac{\partial w}{\partial y}\right)} + \overset{⑦}{\left(\frac{\partial w}{\partial z}\right)^2} \qquad (3)$$

All the derivatives in equation (3) were evaluated from the data base using simple central difference formulae. For $x = 40$, the pressure fluctuations are shown in Figure 3 (a) for the same y–z region as used in Figure 2. The positive pressure pocket has been enclosed with a solid line while the two negative pressure pockets have been enclosed with a broken line. For these pockets, $-\nabla^2 P$ and the sum of the seven terms of equation (3) are also shown, using the same scale, in Figure 3. Considering the possible errors in evaluating the derivatives, the agreement between $-\nabla^2 P$, Figure 3(b), and the sum of the seven terms of equation (3), Figure 3(c), are in remarkably good agreement. In comparing $-\nabla^2 P$, Figure 3(b), with the pressure distributions, Figure 3(a), it is to be noted that the peak pressure values coincide with the peaks in $-\nabla^2 P$ and that the $-\nabla^2 P$ peaks are more localised. This latter comment is particularly true for the positive pressure fluctuations.

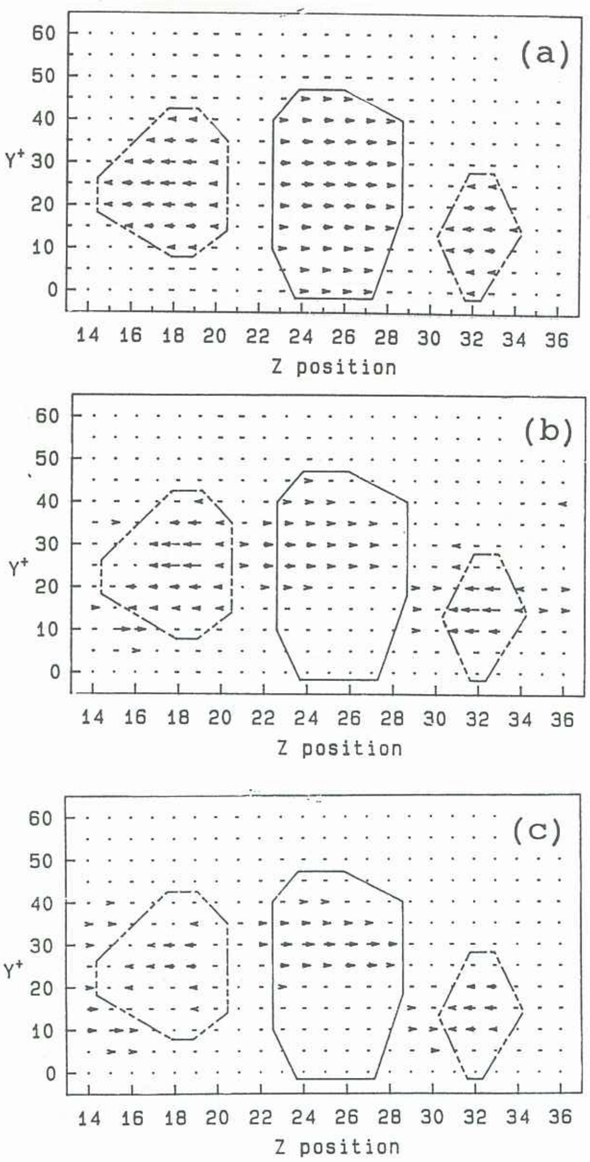

Figure 3. $x = 40$
a) Pressure fluctuations as in Figure 2
b) $-\nabla^2 P$ using simple central differences
c) RHS of (3) using central differences

To determine which of the seven terms of equation (3) make a major contribution to $-\nabla^2 P$, each term was plotted for $x = 40$ for the same region as shown in Figure 3, and the results are presented in Figure 4. The same scale has been used for each term and the pocket outlines of Figure 3 have been used.

High positive pressure fluctuations coincide with large values of terms ② and ⑦ of equation (3) i.e. with large values of $\left(\frac{\partial u}{\partial x}\right)^2$ and $\left(\frac{\partial w}{\partial z}\right)^2$; $\left(\frac{\partial u}{\partial x}\right)^2$ being the dominant term.

Contributions to the peak negative pressures are due mainly to large values of terms ④ and ⑥ of equation (3) i.e. with large values of $\left(\frac{\partial u}{\partial z}\right)\left(\frac{\partial w}{\partial x}\right)$ and $\left(\frac{\partial v}{\partial z}\right)\left(\frac{\partial w}{\partial y}\right)$; $\left(\frac{\partial v}{\partial z}\right)\left(\frac{\partial w}{\partial y}\right)$ being the dominant term. These derivatives occur in the vorticities:

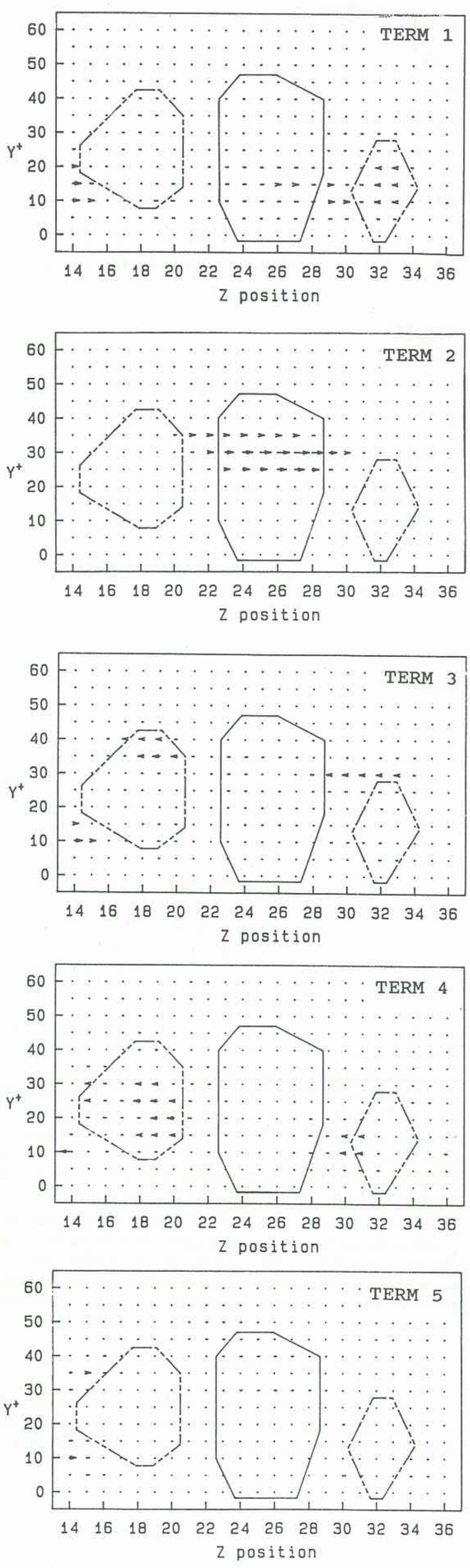

Figure 4 (see next page)

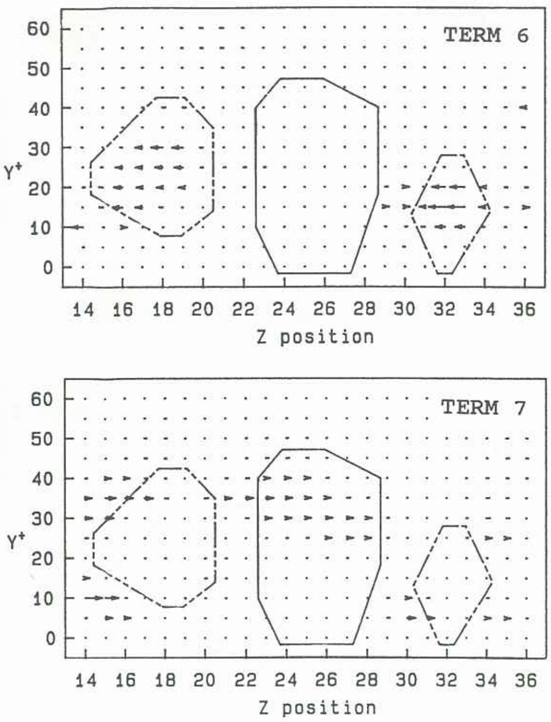

Figure 4. $x = 40$. Terms 1 to 7 of equation (3)

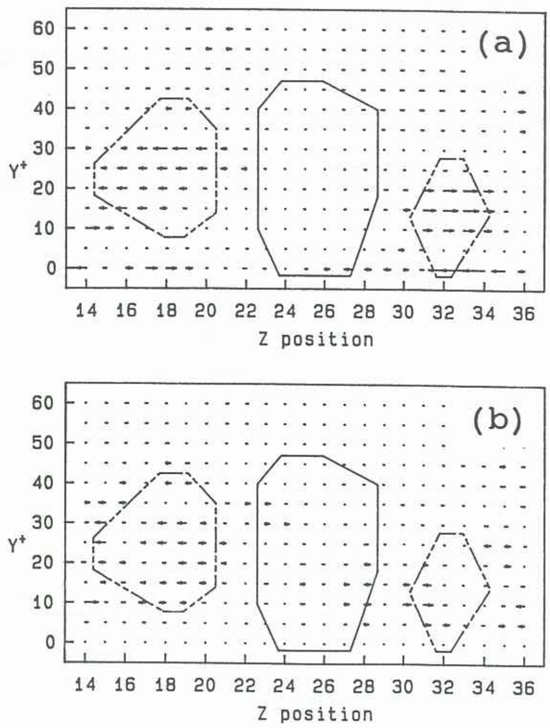

Figure 5. $x = 40$
a) ω_x b) ω_y

$$\omega_x = \left(\frac{\partial w}{\partial y}\right) - \left(\frac{\partial v}{\partial z}\right)$$

and $$\omega_y = \left(\frac{\partial u}{\partial z}\right) - \left(\frac{\partial w}{\partial x}\right)$$

The magnitudes of these two vorticities, for the same $x = 40$, are shown in Figure 5 and it is apparent that the peak negative pressures coincide with a vortex that is pointing in the direction of flow but slightly inclined away from the wall. Note that the two vortex regions of Figure 5 have opposite signs. The coincidence of the centre of streamwise vortices with regions of high negative pressure has already been noted by Robinson et. al. (1990) using the same DNS data and is emphasised here by the vector plot in the $y - z$ plane, at $x = 40$, shown in Figure 6.

An important feature to note from Figure 6 is that the peak positive pressure fluctuation occurs at a saddle, and that the $\partial w/\partial z$ values are necessarily large near this point. Above, it was shown that the $(\partial w/\partial z)^2$ term of equation (3) contributed significantly to high positive pressures. From the continuity equation, and noting that the $\partial v/\partial y$ values are negligible, large values of $\partial w/\partial z$ will result in large values of $\partial u/\partial x$ and thus of $(\partial u/\partial x)^2$, a major contributor to peak positive pressures. If it is postulated that the saddle region of Figure 6 is a direct consequence of the nearby vortices then the single physical phenomena which gives rise to both peak positive and negative pressure fluctuations are streamwise vortices.

ACKNOWLEDGEMENTS

The data tapes used in the analysis were kindly supplied by John Kim during a visit to the Centre of Turbulence Research (NASA–Ames/Stanford University) in 1990.

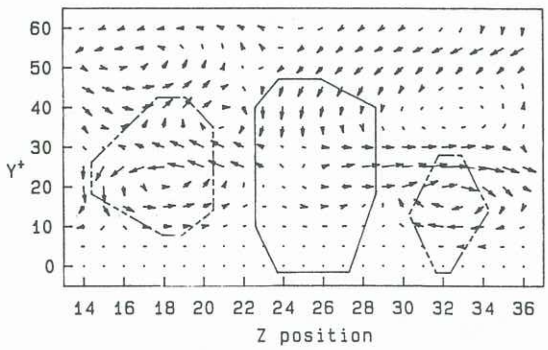

Figure 6. $x = 40$. Velocity vectors in the $y–z$ plane.

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