OBSERVATIONS OF THE FORMATION OF STREAMWISE VORTICES

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ABSTRACT

Streamwise flow-oriented vortices play an important, if not dominant, role in generating Reynolds stresses. A new mechanism has been identified for forming these vortices. This involves the turning of spanwise arch vortices that occur at locations where the streamwise velocity profile develops a strong inflection.

INTRODUCTION

Streamwise vortices are observed to play a major role in the production and maintenance of wall turbulence. A critical issue is the determination of how these vortices are formed. This paper uses direct numerical simulations of turbulent flow in a channel at H=150. Here H is the half-height of the channel made dimensionless with respect to wall parameters. Vortex identification methods and conditional averaging are used as tools. Streamwise vortices have been found to be created (a) in downdrafts of streamwise vortices that lie very close to the wall, (b) in updrafts that appear to be associated with large scale motions that impinge on the wall and (c) by the turning of "arch" vortices at the outer part of the viscous wall region. The first of these has been discussed earlier by Brooke & Hanratty (1993). The latter two mechanisms are new observations.

Particular attention will be given to mechanism (c) in this paper. Arch vortices have been identified previously by Robinson (1991) and others. The novel aspect of the results presented in the paper is the observation of the turning of these vortices because of the inherent asymmetries in a turbulent field.

NUMERICAL PROCEDURES

Simulation with DNS

The time dependent, three-dimensional velocity field for turbulent channel flow is obtained by direct numerical simulation of the Navier-Stokes equations,

$$\frac{\partial \mathbf{u}}{\partial t} = (\mathbf{u} \times \omega) - \nabla \Pi - P_x \mathbf{e}_x + \nabla^2 \mathbf{u} \tag{1}$$

$$\nabla . \mathbf{u} = 0 \tag{2}$$

where $\mathbf{u}$ is the fluid velocity, ω is the vorticity $(= \nabla \times \mathbf{u})$, P is the static pressure, $\mathbf{e}_x$ is the unit vector in the x-direction, and all terms are non-dimensionalized using the friction velocity u* and the kinematic viscosity of the fluid, ν. Π is given by

$$\Pi = P - P_x x + (\mathbf{u}.\mathbf{u})/2 \tag{3}$$

The velocity is subject to rigid boundary conditions at the walls. The velocity and Π fields are assumed to be periodic in the streamwise (x) and spanwise (z) directions. The domain size is 1900 wall units in the streamwise direction, 950 in the spanwise direction, and the half-width of the channel is 150. The numbers of grid points in the x, y, and z directions are 128, 193 and 128, respectively.

Vortex Identification Method

To visualize the vortices and to follow their evolution, iso-surfaces of the imaginary part of the eigenvalue of the velocity gradient tensor are used (Chong et al., 1990; Zhou et al., 1997). This method is preferred over the location of low-pressure regions as used by Robinson (1988), because it is free of the non-local effects associated with pressure variations.

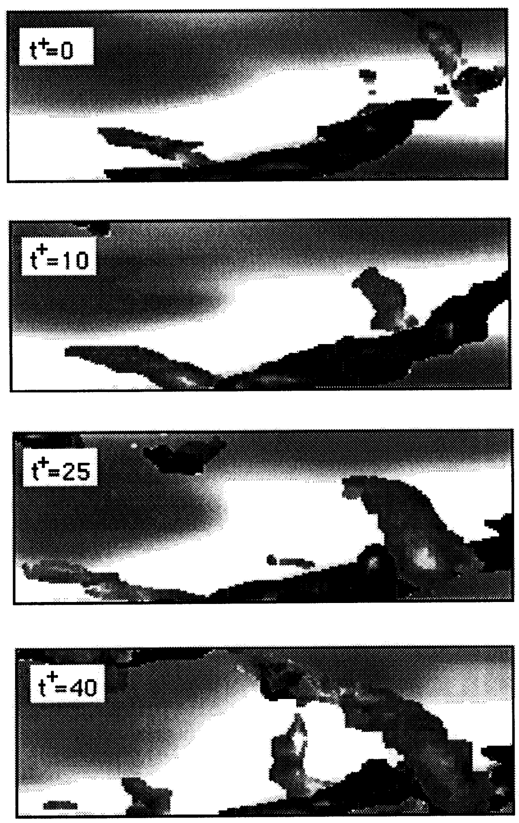

Figure 1. Formation of an arch vortex viewed from above

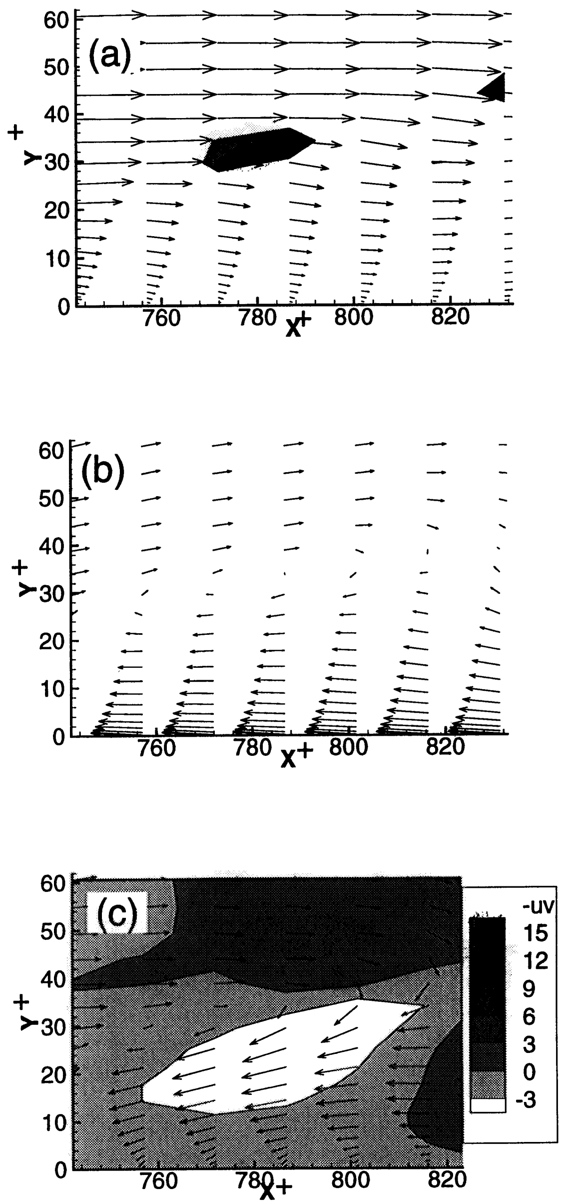

Figure 2. t^+=10 (a) Instantaneous velocity (vectors) and vortex indicator (contour). (b) Instantaneous velocity with convection velocity subtracted. (c) Instantaneous velocity fluctuations (vectors) and -uv (contours).

FORMATION OF ARCH VORTICES

Figure 1 shows the formation of an arch vortex that rotates to form a streamwise vortex. Vortices are colored black when $\omega_x > \omega_z$ and gray when $\omega_x < \omega_z$. The arch is found to form at $t^+ = 10$ in an updraft of a wall vortex and to start to rotate at $t^+ = 40$.

Figure 2a shows the instantaneous velocity field at $t^+ = 10$. The shaded regions in 2a show contours representing the magnitude of the vortex identifier. The arch vortex has just formed at the inflectional point of the velocity profile. If the convection velocity is subtracted from the velocity field a vortex is seen (figure 2b). Figure 2c shows the fluctuating velocity vectors and contours of -uv.

TURNING OF ARCH VORTICES

Figure 3 shows the fluctuating velocity in the y-z plane at $t^+ = 40$; that is, after the vortex starts to turn. Shaded regions indicate contours of -uv. Examination of plots such as these show that large -uv are not observed until the arch vortex starts to turn. Observations indicate that once the arch vortex turns it can 'attach' to the wall and evolve into a quasi-streamwise vortex.

To determine the frequency of vortex formation by this mechanism an instant of time was chosen and 91 vortices longer than 50 wall units in the streamwise direction were identified. Each of these vortices was traced backward in time to determine that 26 of these originated from spanwise arches. The positions above the wall of the upstream ends of the vortices varied between

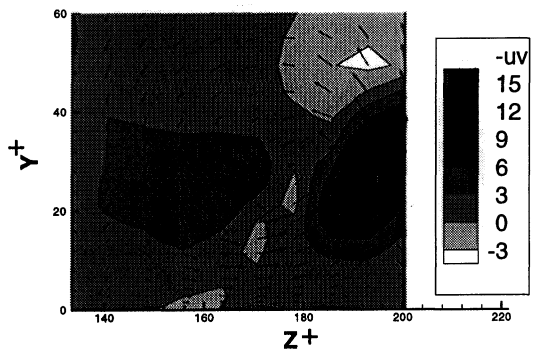

Figure 3. $t^+=40$. Instantaneous velocity (vectors) and -uv (contours).

$y^+=9$ to 45. No preferential location was identified for the arch vortices that turned.

INTERPRETATION

The mechanism for the formation of the arch vortices, therefore, seems to be associated with wall vortices that pump low momentum fluid from the wall to form an inflectional velocity profile. If the shear rate at the inflection point is large enough a vortex can form. If this vortex turns, large Reynolds stresses can be observed. For flow over a flat plate it would seem that both mechanisms (a) and (c) discussed in the beginning of this abstract, depend of the existence of elongated vortices at the wall. The wall vortices, therefore, appear to recreate themselves.

For flow over a surface which is roughened with waves, vortices need to be generated by a different mechanism. Mechanism (c) could be the dominant one. In this case shear layers are formed by the separation of the flow behind the crest.

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