Near-Wall Bursting Phenomena and Quasi-Streamwise Vortex Models*

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Near wall bursting phenomena have been detected both by the VITA technique and by a quadrant analysis. In addition to these detection schemes, visual burst detection has been performed in order to characterize the difference between VITA events and Q2 (second quadrant) events. It is shown that the spanwise yaw angle of visualized low-speed streaks for VITA events is greater than for Q2 events. Based on the experimental findings and the Euler equation, quasi-streamwise vortex models are proposed, and the results are compared with the experiments. Fluctuating velocity signals computed from the models are in good agreement with the experimental data for VITA events. Contour plots of the calculated axial velocity, spanwise vorticity and instantaneous Reynolds shear stress are presented. The generation processes of shear layer structures and Q2 and Q4 motions are demonstrated.

Key Words: Turbulent Flow, Turbulence, Shear Flow, Vortex, Wall Turbulence, Bursting Phenomena, Quasi-Streamwise Vortex, Shear Layer, Low-Speed Streak, Conditional Sampling

1. Introduction

The well-organized motions can be observed in the near-wall region of wall-bounded turbulent shear flows. One of the most outstanding coherent motions is so-called "bursting", which is believed to be a dominant factor in the production of turbulent kinetic energy^{(1),(2)}.

There has been much effort devoted to the search for and examination of the structure and origin of near wall bursting. The structure of bursting has been investigated using the VITA (Variable Interval Time-Averaging) technique⁽³⁾ and quadrant analysis⁽⁴⁾, and it was reported that a main ingredient is a pair of counter-rotating quasi-streamwise vortices. However, there is discrepancy between flow structures detected by these schemes, i.e., streamwise

vortices detected by the VITA technique associate with internal shear layers while those by the quadrant analysis not^{(5),(6)}. Recently, using numerically simulated flow fields, it was shown that bursting events are predominantly associated with a single quasi-streamwise vortex rather than a pair of vortices^{(7),(8)}. Despite the large effort devoted to the subject, the structure of bursting is not well understood. As concerns the origin of bursting, its connection with the inflexional instability was pointed out by Blackwelder⁽⁹⁾ who found that the streamwise velocity profile is highly inflexional at and before the burst detection. Since the inflexional profile corresponds to the internal shear layer, bursting phenomena are conjectured to be caused by the vortex layer instability. However, there are few theoretical explanations for the generation of vortex layers and their relation to quasi-streamwise vortices.

The main objectives of this study are to demonstrate the source of discrepancy between the burstings detected by the VITA technique and quadrant analysis, and to theoretically explore quasi-streamwise vortical motions and their relation to the generation of vortex layers. In the experiments, simultaneous

* Received 30th May, 1995. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 60, No. 579, B(1994), pp. 3805-3813 (Received 7th March, 1994).

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dye flow visualization and LDV (Laser-Doppler Velocimeter) measurement were performed at the wall bisector in a fully developed turbulent square-duct flow to detect near-wall bursting by the visualization, VITA technique and quadrant analysis. By using the visual data the spanwise yaw angle of low-speed streaks is evaluated at the VITA and second quadrant event detection, and the difference is shown between these events. Based on the experimental findings, a model for quasi-streamwise vortices is proposed using the exact solution to the Euler equation, and the results are compared with the experiments. The generation processes of vortex layers, ejection and sweep motions are demonstrated through quasi-streamwise vortical motions.

2. Experimental Apparatus and Procedures

The experiments were performed in the straight square duct previously described by Ayukawa et al.⁽¹⁰⁾ The square duct is nearly 9 m in length and 100 mm in width, and the water is used as the working medium. The test section is located 6.8 m downstream of the duct inlet, where the velocity field is fully developed⁽¹⁰⁾, and turbulence statistics⁽¹⁰⁾, the mean streak spacing⁽¹¹⁾ and streamwise vortical structures⁽¹²⁾ in the vicinity of the wall bisector are similar to those for boundary layers and two-dimensional channel flows. The mean flow parameters are listed in Table 1. A Reynolds number Re is based on a half of duct width and mean centerline velocity. u_τ is a local friction velocity, the value of which is obtained from the Clauser's chart on the wall bisector⁽¹⁰⁾.

Fluorescein was used for flow visualization. A dye was diluted with ethanol and water, so that its specific gravity was 1.00. A $5\nu/u_\tau$ wide slit is located in the bottom wall of the duct upstream of the test section, through which the dye was injected at a very small flow rate of $330 \text{ mm}^3/\text{s}$ to visualize sublayer flow structures. Visualized structures were filmed with a 16 mm movie camera BOLEX H16SBM from above the LDV measuring point (Frame intervals are $1.4\nu/u_\tau^2$). Two one-component LDV systems (DISA 55 system and KANOMAX 27 system) were used to obtain the streamwise and wall-normal velocity com-

ponents, u and v . The measuring point was located at $y^+ = 35$ on the bottom wall bisector $500\nu/u_\tau$ downstream of the dye slit (Hereafter a superscript + denotes variables scaled by ν and u_τ). At this streamwise location visual data are available for full burst detection⁽¹³⁾, and the wall-normal position $y^+ = 35$ corresponds to the core height of quasi-streamwise vortices⁽¹¹⁾. In the experiments the visual and LDV data were synchronized and taken simultaneously, and LDV signals were digitized and registered on a magnetic disk with a sampling frequency of 100 Hz. The total of recording periods was 540 s.

3. Low-Speed Streaks at the Burst Detection

Using the visual data we shall characterize the difference between the VITA events and the second quadrant events. In the VITA technique⁽¹⁴⁾ the local square deviation is defined for the streamwise velocity fluctuation u' as follows:

$$\widehat{\text{var}}(t; T) = \frac{1}{T} \int_{t-T/2}^{t+T/2} (u'(s))^2 ds - \left(\frac{1}{T} \int_{t-T/2}^{t+T/2} u'(s) ds \right)^2, \quad (1)$$

and then bursting events are detected when $\widehat{\text{var}} > k_{\text{th}} u_{\text{rms}}^2$ (Hereafter this detection scheme is referred to as VITA.). Here T is an interval for time-averaging, k_{th} the threshold parameter, and u_{rms} the streamwise turbulence intensity. In this work, the condition, $du'/dt > 0$ or $du'/dt < 0$ is added to the above criterion [Hereafter the former is referred to as VITA(+), and the latter VITA(-)]. In the case of the quadrant analysis⁽¹⁵⁾ ejections, i.e. second quadrant events, are detected in the (u', v') -plane when $|u'v'| > H_{\text{th}} u_{\text{rms}} v_{\text{rms}}$ (Hereafter this detection scheme is referred to as Q2.). Here v' is the wall-normal velocity fluctuation, v_{rms} its intensity and H_{th} the threshold parameter. We set $k_{\text{th}} = 1$, $T^+ = 10$ and $H_{\text{th}} = 3$ so that the bursting frequencies evaluated by VITA and Q2 can be identical. In the visual study the burstings are detected when the dye-filled low-speed streak⁽¹¹⁾ is lifted within $150\nu/u_\tau$ upstream and $100\nu/u_\tau$ downstream of the LDV measuring point in the streamwise direction and within $50\nu/u_\tau$ of the measuring point in the spanwise direction.

Table 2 shows the rates of numbers of the visually detected events to the corresponding total numbers of those detected by VITA(+), VITA(-) and Q2. It can be seen that for any event the visual burst detection

Table 1 Mean flow parameters

Kinematic viscosity ν	$0.99 \times 10^{-6} \text{ m}^2/\text{s}$
Mean centerline velocity U_c	8.0 cm/s
Friction velocity u_τ	5.1 mm/s
Reynolds number Re	4000

Table 2 Rates of visually detected events

VITA(+)	VITA(-)	Q2
0.72	0.65	0.73

Fig. 1 Yaw angle of low speed streaks

Fig. 2 Histogram of the yaw angle of low-speed streaks

covers over 60%. In this study, using the visual data the spanwise yaw angle of low-speed streaks, θ is evaluated at the VITA and Q2 event detection to characterize the difference between these events. θ indicates the maximum angle between the streamwise direction and a tangent to the low-speed streak on the plane parallel to the bottom wall of the duct as shown in Fig. 1, and it was measured with a 16 mm film analyzer NAC SPORTIALS 300 for the frames at peak time of $\widehat{\text{var}}$ and $|u'v'|$. Figure 2 shows histogram of θ for the Q2 events, ones also detected by VITA(+), ones not detected by VITA, and the VITA(+) events, respectively. Comparing the histogram for the Q2 and VITA(+) events, it can be seen that the histogram for the VITA(+) events has the broader tail and has a peak in the range of $5^\circ < \theta \leq 10^\circ$. Also comparing the histogram for the Q2 events detected by VITA(+) and not detected by VITA, we can see that the former has a remarkable peak of 79% in the range of $0^\circ < \theta \leq 5^\circ$ while the latter peak value is reduced to 57%. It is clear from these results that the yaw angle of low-speed streaks for the VITA(+) events is greater than for the Q2 events and that low-speed streaks for the Q2 events not detected by VITA are nearly oriented to the streamwise direction. In a word, the difference between the VITA and Q2 events originates from the presence of the spanwise inclina-

Table 3 Mean yaw angles of low-speed streaks

VITA(+)	9.8°
VITA(-)	9.2°
Q2	5.2°
Q2 with VITA(+)	6.8°
Q2 without VITA	3.7°

tion of low-speed streaks, which is also confirmed in the mean yaw angles shown in Table 3.

Since low-speed streaks are tilted for the events detected by VITA(+), which is known to be a detector for internal shear layers⁽¹⁶⁾, their spanwise inclination is conjectured to be connected with the generation of internal shear layers. As commonly accepted low-speed streaks are formed through their pumping action of quasi-streamwise vortices⁽¹⁰⁾, which suggests that the spanwise inclination of a rotation axis of streamwise vortices has the connection with the generation mechanism for internal shear layers.

4. Models for Quasi-Streamwise Vortices

Recently, in their investigation based on the direct numerical simulation Bernard et al.⁽¹⁷⁾ showed that both streamwise vortices and their vorticities are often tilted toward the spanwise direction. In order to demonstrate the connection of the inclination of streamwise vortices with the shear layers generation we shall consider idealized "building-block" flows. We introduce the following assumptions to make a theoretical approach to the subject:

- (a) Fluid is incompressible and inviscid.
- (b) There is no variation of any flow parameter in the direction parallel to the vortex axis.
- (c) The wall is infinitely removed from the vortex.

- (d) The contour of a cross section of the vortex is elliptic, and axial vorticity therein is uniform.

The problem considered is a shear flow with the imbedded streamwise vortex tube, as shown in Fig. 3. We employ the three coordinate systems $Oxyz$, $O'x_1x_2x_3$ and $O'x'_1x'_2x'_3$. Let the coordinate system $Oxyz$ be at rest, and x , y and z represent the coordinate corresponding to the streamwise, wall-normal and spanwise directions, respectively. We set the initial shear profile $\mathbf{U}_0 = U_0\mathbf{e}_x + Sy\mathbf{e}_x$, where $\mathbf{e}_x$ is the unit vector in the x direction and $S (>0)$ the initial shear rate. The vortex axis is located on the plane $y=0$ and moving to the x -direction at a speed of the local shear velocity U_0 . Let the coordinate system $O'x_1x_2x_3$ move with the vortex tube, and let the x_1 -, x_2 - and x_3 -axis be parallel to the x -, y - and z -axis,

Fig. 3 Coordinate system

respectively. The origin O' is located on the tube axis. The vortex axis is tilted at an angle of θ toward the x_3 -direction, and the x'_1 -axis in the coordinate system $O'x'_1x'_2x'_3$ is aligned with the tube axis. We can take the inclination angle θ in the range of $0^\circ < \theta \leq 90^\circ$ without loss of generality. Because of the spanwise inclination the vortex feels a transverse shear $2\gamma = -S \sin \theta (< 0)$, i.e. the x'_1 -component of the background-shear vorticity, $-S e_z$ outside the ellipse E defining the vortex. The ellipse E has the radius a in the x'_2 -direction, and has the radius b in the x'_3 -direction. Let ω_0 denote the uniform axial (x'_1 -) component of vorticity inside E. Since assumption (b) means $\partial/\partial x'_1 = 0$, velocity components u'_1 , u'_2 and u'_3 in the moving coordinate system $O'x'_1x'_2x'_3$ are described by

$$\frac{\partial u'_1}{\partial t} + u'_2 \frac{\partial u'_1}{\partial x'_2} + u'_3 \frac{\partial u'_1}{\partial x'_3} = 0, \quad (2.a)$$

$$\frac{\partial u'_2}{\partial t} + u'_2 \frac{\partial u'_2}{\partial x'_2} + u'_3 \frac{\partial u'_2}{\partial x'_3} = -\frac{1}{\rho} \frac{\partial p}{\partial x'_2}, \quad (2.b)$$

$$\frac{\partial u'_3}{\partial t} + u'_2 \frac{\partial u'_3}{\partial x'_2} + u'_3 \frac{\partial u'_3}{\partial x'_3} = -\frac{1}{\rho} \frac{\partial p}{\partial x'_3}, \quad (3.c)$$

$$\frac{\partial u'_2}{\partial x'_2} + \frac{\partial u'_3}{\partial x'_3} = 0, \quad (3)$$

where p is the pressure and ρ the fluid density. We note that u'_2 and u'_3 are governed by the two-dimensional Euler equation and continuity equation, and that u'_1 is frozen in the fluid particles. Near-wall streamwise vortices maintain their identities for relatively long times, and propagate downstream at a nearly constant speed, as demonstrated by Guezennec et al.⁽⁷⁾ Thus, we shall find the steady solution to Eqs. (2.b), (2.c) and (3). We then set the following boundary conditions:

(a) $u'_2 \rightarrow 0$, $u'_3 \rightarrow 2\gamma x'_2$ at infinity.

(b) The normal velocity component vanishes on the ellipse E.

(c) The tangential velocity component is continu-

ous across E.

Condition (c) implies the continuity of the pressure across E. Under boundary conditions (a) and (b) the steady solution to Eqs. (2.b), (2.c) and (3) is equivalent to that for a two-dimensional flow, obtained by Moore and Saffman⁽¹⁸⁾. Inside E the streamfunction Ψ ($u'_2 = \partial\Psi/\partial x'_3$, $u'_3 = -\partial\Psi/\partial x'_2$) is given by

$$\Psi = -\frac{1}{2} \Omega ab \left(\frac{x'^2_2}{a^2} + \frac{x'^2_3}{b^2} - 1 \right), \quad (4)$$

where

$$\Omega = \frac{\omega_0 ab}{a^2 + b^2}. \quad (5)$$

Outside E the solution depends on a sign of ω_0 . In the case of $\omega_0 < 0$ Ψ is given by

$$\begin{aligned} \Psi = & -\frac{\gamma c^2}{4} (\cosh 2\xi + \cos 2\eta) \\ & + \frac{\gamma c^2}{4} \cosh 2\xi \cos 2\eta \\ & + \frac{\gamma c^2}{4} (1 - \cosh 2\xi_0) e^{-2(\xi - \xi_0)} \cos 2\eta \\ & - \frac{\Gamma}{2\pi} (\xi - \xi_0) + \frac{\gamma c^2}{4} \cosh 2\xi_0, \end{aligned} \quad (6)$$

where

$$x'_2 = -c \sinh \xi \sin \eta, \quad (7.a)$$

$$x'_3 = c \cosh \xi \cos \eta, \quad (7.b)$$

$$c = \sqrt{b^2 - a^2}. \quad (7.c)$$

Here $b > a$, $b = c \cosh \xi_0$ and $a = c \sinh \xi_0$. In the case of $\omega_0 > 0$ Ψ is given by

$$\begin{aligned} \Psi = & -\frac{\gamma c^2}{4} (\cosh 2\xi + \cos 2\eta) \\ & - \frac{\gamma c^2}{4} \cosh 2\xi \cos 2\eta \\ & + \frac{\gamma c^2}{4} (1 + \cosh 2\xi_0) e^{-2(\xi - \xi_0)} \cos 2\eta \\ & - \frac{\Gamma}{2\pi} (\xi - \xi_0) + \frac{\gamma c^2}{4} \cosh 2\xi_0, \end{aligned} \quad (8)$$

where

$$x'_2 = c \cosh \xi \cos \eta, \quad (9.a)$$

$$x'_3 = c \sinh \xi \sin \eta, \quad (9.b)$$

$$c = \sqrt{a^2 - b^2}. \quad (9.c)$$

Here $a > b$, $a = c \cosh \xi_0$ and $b = c \sinh \xi_0$. On the right-hand side of Eqs. (6) and (8), the first terms describe a solid body rotation, the second a pure straining motion, the third an irrotational flow responsible for boundary condition (b), and the fourth an irrotational flow induced by a vortex filament of strength Γ . Boundary condition (c) requires the following relation between the parameters in the above solutions:

$$\frac{2\gamma}{\omega_0} = \frac{\Theta^{-1}(\Theta^{-1} - 1)}{\Theta^{-2} + 1}, \quad (\omega_0 < 0) \quad (10.a)$$

$$\frac{2\gamma}{\omega_0} = -\frac{\Theta - 1}{\Theta^2 + 1}, \quad (\omega_0 > 0) \quad (10.b)$$

$$\Gamma = \pi ab(\omega_0 - 2\gamma), \quad (11)$$

where $\Theta = a/b$. In the case of $\omega_0 < 0$, $\Theta < 1$ and Eq. (10.a) implies

$$0 < \frac{2\gamma}{\omega_0} < 1. \quad (12)$$

In the case of $\omega_0 > 0$, $\Theta > 1$ and Eq. (10.b) implies

$$-\frac{\sqrt{2}-1}{2} < \frac{2\gamma}{\omega_0} < 0. \quad (13)$$

Finally, we can derive u'_2 and u'_3 from Ψ . Now consider the time-evolution of the axial velocity u'_1 . Given the cross-flow components of the fluid velocity u'_2 and u'_3 , u'_1 is frozen in the flow induced by u'_2 and u'_3 . At $t=0$ u'_1 is identical with the x'_1 -component of the initial shear velocity $Sx'_2\mathbf{e}_x$, i.e. $u'_1 = Sx'_2 \cos \theta$. Let X'_1 and X'_2 denote the x'_1 - and x'_2 -coordinates of the fluid particles. The equation of motion of particles is of the form

$$\frac{dX'_2(\mathbf{X}'_0, t)}{dt} = u'_2(X'_2(\mathbf{X}'_0, t), X'_3(\mathbf{X}'_0, t)), \quad (14.a)$$

$$\frac{dX'_3(\mathbf{X}'_0, t)}{dt} = u'_3(X'_2(\mathbf{X}'_0, t), X'_3(\mathbf{X}'_0, t)), \quad (14.b)$$

where $\mathbf{X}'_0$ is the particles' position at $t=0$. Ordinary differential Eqs. (14) are backward integrated from $t > 0$ in order to fix $\mathbf{X}'_0$, and u'_1 is then obtained from the values of $u'_1|_{t=0}$ at the initial particles' position. In this work the improved Euler method was used for numerical integration of Eqs. (14). There are four control parameters S^+ , ω_0^+ , a^+ and θ in this model. The values of these parameters are taken to be consistent with those in real turbulent flows, as shown in Table 4. S^+ represents the local mean shear⁽²⁰⁾ in the buffer layer where quasi-streamwise vortices often exist. $2a^+$ is taken from Robinson's⁽¹⁹⁾ data for the diameter of near-wall streamwise vortices. In order to find the values of ω_0^+ we use the streamwise vorticity of near-wall vortical structures. In Robinson's⁽¹⁹⁾ results its magnitude is roughly 0.16. We then take $\omega_0^+ = -0.16/\cos \theta + 2\gamma^+$ in the case of $\omega_0^+ < 0$ and $\omega_0^+ = 0.16/\cos \theta + 2\gamma^+$ in the case of $\omega_0^+ > 0$, where $2\gamma^+ = -S^+ \sin \theta$. Here we set $\theta = 10^\circ$ which corresponds to the mean yaw angle of low-speed streaks for the VITA events (see Table 3). Note that in this evaluation of ω_0^+ , vorticity intensity of the quasi-streamwise vortex $|\omega_0^+ - 2\gamma^+|$ is the same between the cases of $\omega_0^+ < 0$ and $\omega_0^+ > 0$, and Eqs. (12), (13) are satisfied. Hereafter, the

Table 4 Control parameters in the models

Velocity gradient S^+	0.11
Vorticity in vortex core $\omega_0^+ (> 0)$	0.14
Vorticity in vortex core $\omega_0^+ (< 0)$	-0.18
Vortex core diameter $2a^+$	25
Vortex yaw angle θ	10°

model of $\omega_0^+ = 0.14$ in Table 4 is referred to as model A, and the one of $\omega_0^+ = -0.18$ model B. In model A the vortex tube is tilted toward the spanwise direction with its spanwise vorticity anti-parallel to mean shear vorticity while in model B the vortex tube is tilted with its spanwise vorticity parallel to mean shear vorticity.

5. Comparison of Models with the Experiments

In this section the results from models A and B will be compared with the experiments for the VITA (+) and VITA (-) events. The conditionally averaged bursting signals of $u'^+_{i^+}$ and $v'^+_{i^+}$, $\widehat{u'}(\tau^+)$ and $\widehat{v'}(\tau^+)$ were obtained by using VITA (+) and VITA (-). The origin of a signal phase $\tau^+ = 0$ is taken to be identical to the peak time of the local square deviation $\widehat{\text{var}}$. Since the experimental data have been obtained near the core height of quasi-streamwise vortices, in the models we translate spatial variations of u'_1 and u'_2 on the plane $x_2 = 0$, at which the vortex axis is located, into temporal variations of those. $|\partial u'_1 / \partial x'_1|$ on $x_2 = 0$ takes a maximum at the vortex center $x'_1 = 0$, so the relation $\tau^+ = -x'_1 / U_0^+$ is used for the translation, where we set $U_0^+ = 14$ corresponding to the

(a) Streamwise velocity

(b) Wall normal velocity

Fig. 4 Comparison of model A with the VITA (+) event

(a) Streamwise velocity

(b) Wall normal velocity

Fig. 5 Comparison of model B with the VITA(-) event

streamwise mean velocity⁽²¹⁾ at $y^+ = 30$. Note that in the following comparison of the models with the experiments, t^+ will be fixed at the peak time of $|\partial u_1^+ / \partial x_1^+|$ on $x_1^+ = 0$, which is reasonable from the fact that the moving time-scale of the vortex $b^+ / (U_0^+ \sin \theta)$ is much smaller than its rotating time-scale $4\pi / |\omega_0^+|$.

Figures 4 and 5 show the comparison of model A and model B with the VITA(+) event and the VITA(-) event, respectively. In Fig. 5 Mochizuki's⁽²²⁾ experimental data for a boundary layer are also shown (His measuring position and threshold parameters are the same as ours.). The models are in good agreement with the experiments. However, there are some discrepancies between them: (a) The low-speed portion of the streamwise velocities is remarkable in the experiments, and (b) the amplitude of the wall-normal velocities is greater in the models. The sources of these discrepancies would be in (a) the linearization of the initial shear profile, and in (b) near-wall reduction in the wall-normal velocity in reality. The results support that model A represents the VITA(+) event and model B represents the VITA(-) event, which implies that the difference between the VITA(+) and VITA(-) events originates only from the yawing direction of a streamwise

(a) Model A ($\omega_0 = 0.14$) (b) Model B ($\omega_0 = -0.18$)Fig. 6 Time evolution of contours of axial velocity in the (x_2', x_3') -plane

vortex of the same vorticity sign.

6. Time-Evolution of Flow Fields around Vortices

Time-evolution of contours of u_1^+ is shown in Fig. 6 (Contour increment is 0.5 and negative contours are dashed.). Contours of u_1^+ are identical with material lines as discussed in Section 4, so the contours in Fig. 6 are equivalent to (x_2', x_3') projection of vorticity lines. It can be seen that both model A and B induce ejections and sweeps [the regions of low axial velocity with upward motions, and of high axial velocity with downward motions in Fig. 6 ($t^+ \geq 30$)]. At later times it is found that the contours are denser on the upper left and lower right of model A [Fig. 6 (a) ($t^+ = 60$)]. This high density of the contours suggests significant material and vorticity stretching through the wrapping process⁽²³⁾ by the vortex of $\omega_0^+ > 0$. The vortical motions rotate the vorticity lines in the core regions, which causes a deviation in the direction of the vortex tubes and the fluctuating vorticity vectors therein. Similar deviations are also found in near-wall quasi-streamwise vortices (see figure 4 of Bernard et al.⁽¹⁷⁾).

Figure 7 shows time-evolution of contours of the spanwise (x_3 -) component of the fluctuating vorticity (Contour increment is 0.2 and negative contours are dashed.). At the initial state ($t^+ = 0$) vorticity fluctuation vanishes. As time passes ($t^+ = 30$), negative vorticity appears on the upper and lower sides. In

(a) Model A ($\omega_0^+ = 0.14$) (b) Model B ($\omega_0^- = -0.18$)Fig. 7 Time evolution of contours of spanwise vorticity fluctuation in the (x_1, x_2) plane

model A, these regions of negative vorticity develop into sheet-like structures of concentrated vorticity regions, i.e. vortex layers, as a consequence [Fig. 7(a) ($t^+ = 60$)]. These vortex layers are generated by background-vorticity stretching due to the streamwise vortical motion [see Fig. 6(a)]. The intense vorticity of a negative sign can be seen on the upper left and lower right of model A [Fig. 7(a) ($t^+ = 60$)], and these locations represent those of strong vorticity stretching in Fig. 6(a) ($t^+ = 60$). Note that the spanwise component of the background shear is

(a) Model A ($\omega_0^+ = 0.14$) (b) Model B ($\omega_0^- = -0.18$)Fig. 8 Time evolution of contours of the instantaneous Reynolds stress in the (x_1, x_2) plane

negative. The vortex layers in Fig. 7(a) are tilted roughly at a 10° angle with respect to the streamwise (x_1 -) direction. Considering that near-wall internal shear layers⁽¹⁶⁾ have the spanwise vorticity of the same sign as that of the mean shear and are tilted at a $10-20^\circ$ angle with respect to the wall, the vortex layers in model A seem to be identical with the shear layer structures. In the model the vertical inclination angle of the vortex layer attains to 0° as $\theta \rightarrow 0^\circ$. Thus, any tilted sheets similar to the internal shear layers are not generated by the vortex tube perfectly

oriented to the streamwise direction, which is consistent with the fact that the Q2 events, without yawing of low-speed streaks, do not associate any shear layers^{(5),(6)}. As contrasted with model A, model B does not generate intense shear layers. This is because background vorticity stretching in model B is much weaker than in model A (see Fig. 6).

The regions of positive vorticity can be observed in the vicinity of the vortex [Fig. 7 ($t^+=60$)]. It is evident from Fig. 6 ($t^+=60$) that they correspond to locations in which the vorticity lines have been deformed enough to be overturned, so that the same vorticity lines represent the spanwise vorticity component opposite to its original sign⁽²³⁾.

Time-evolution of contours of the instantaneous Reynolds shear stress $-u_1^+ u_2^+$ is shown in Fig. 8 (Contour increment is 0.2, negative contours are dashed and the quadrant numbers for contours are shown in the top of each figure.). In model A it can be observed that through a vortical motion, the strong ejection (Q2) and sweep (Q4) are generated on the downstream side and upstream side, respectively. As time passes ($t^+=60$), the outward interaction (Q1) and inward interaction (Q3) appear on the lower right and upper left of the vortex, respectively. Similar Q1 - Q4 motions are also found in model B. However, in the case of model B the strong ejection is located on the upstream side and the strong sweep is located on the downstream side.

7. Conclusions

We have examined the source of discrepancy between the burstings detected by the VITA technique and quadrant analysis using simultaneous flow visualization. It is shown that the spanwise yaw angle of low-speed streaks for the VITA events is greater than for the second quadrant (Q2) events and that low speed streaks for the Q2 events not detected by the VITA technique are nearly oriented to the streamwise direction. These findings suggest the connection of the spanwise inclination of low-speed streaks and streamwise vortices with the generation mechanism for internal shear layers. In order to demonstrate this connection, we have proposed the tilted streamwise vortex models. The models are in good agreement with the experiments and also show the generation processes of shear layers and Q2 and Q4 motions similar to those in real turbulent flows. In the models, the difference in the presence of internal shear layers between the VITA and Q2 events originates from the presence of the spanwise inclination of streamwise vortices, and the difference between the VITA(+) and VITA(-) events originates from the yawing direction of a streamwise vortex of the same vorticity

sign.

Quasi-streamwise vortical motions can generate vortex layers through their background vorticity stretching⁽²³⁾, and particularly in the case that the spanwise vorticity of tilted streamwise vortices is anti-parallel to mean shear vorticity (model A), vorticity stretching is much stronger, so that vorticity intensity of the resulting vortex layers is much greater.

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