The Regeneration of Quasi-Streamwise Vortices in the Near-Wall Region*

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Regeneration of quasi-streamwise vortices is investigated using a data base obtained by high-resolution LES (Large Eddy Simulation) for channel flow. It has been revealed that quasi-streamwise vortices are regenerated both at the upstream of the upstream end of a parent vortex and at the downstream end of a parent vortex. In both cases, the new vortex has a vorticity of opposite sign to that of the parent vortex and comprises a chain line of vortices in the flow direction with the parent vortex, which is one of the basic organized structures in the near-wall region. It has also been revealed that the main contribution to the generation of new vortices at their infant stage is the tilting of wall-normal vortices, and that to their sustenance at grown-up stage is stretching effect.

Key Words: Turbulent Flow, Near-Wall Turbulence, Vortex, Quasi-Streamwise Vortex, Coherent Structure, Regeneration

1. Introduction

Several kinds of elementary structures are embedded independently and/or in combination⁽¹⁾, in near-wall turbulence. The key ones among them are quasi-streamwise vortices, i.e., vortex filaments having a large vorticity component in the streamwise direction. Since the quasi-streamwise vortices control most of the turbulent events such as the generation of turbulent kinetic energy, it is expected that management of these vortices will allow us to control the near-wall turbulence.

Ejection and burst which are the most fundamental phenomena caused by quasi-streamwise vortices have been extensively investigated using VITA and VISA. However, the available informations regarding such vortices is confined mainly to static structures⁽²⁾. What is needed for turbulence control is knowledge of

dynamic behaviors rather than static ones. In particular, the flow structures and their mechanisms in the early stage of generation of a quasi-streamwise vortex are of keen interest.

Since vorticity is generated only at the wall surface, the quasi-streamwise vortices in the near-wall flow are due to a combination of viscous diffusion and conversion of cross-flow vorticity to the streamwise vorticity. The simplest way of such a vortex is a 'hairpin' vortex, and the configuration of quasi-streamwise vortices determined by VISA supports this idea. However, individual quasi-streamwise vortices identified by applying suitable conditions from field data of numerical simulations of wall turbulence, hairpin structures are less common than single quasi-streamwise vortices without counter parts.

Recent investigations have revealed that a quasi-streamwise vortex can bear a new vortex of the same kind. That is, regeneration is possible. This regeneration is an important means of generation of new vortices. The present authors have pointed out that this regeneration takes place at upstream end of a parent vortex⁽³⁾, whereas Brooke and Hanratty⁽⁴⁾ concluded, based on the hypothesis that streamwise

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vortices must be sustained by regeneration, that regeneration occurs at the downstream end of a parent vortex. Furthermore, Bernard et al.⁽⁵⁾ discussed the continuous regeneration and the sustenance mechanism of Reynolds stresses and pointed out that the regeneration can occur both at the upstream end and downstream end of parent vortices.

In this work, a high-resolution LES for channel flow was used with a conditional sampling technique to construct a database for a group of typical quasi-streamwise vortices and the dynamic evolution of one of these vortices as well as its structure was investigated in detail. Strong inrush toward the wall is used as a condition of vortex sampling, and it is demonstrated here that vortices thus sampled undergo continuous regeneration in the upstream direction and exhibit a zig-zag pattern arrangement which persists long. Some aspects of this phenomenon were discussed individually in separate works but the whole scenario of the global system has not been discussed. In this respect, it is intended here to present a new fundamental idea regarding the physics of near-wall turbulence and its control.

2. Database

For obtaining field data regarding a three-dimensional turbulent flow in a channel, an LES code of high resolution which was developed by the present authors and colleagues⁽⁶⁾ is used. In this code, the contribution of the SGS (sub-grid scale) model to the total turbulent stresses is so small that the simulation is regarded as almost a DNS. The Reynolds number based on the mean friction velocity at the walls u_τ and the separation of the walls H is $Re_\tau = u_\tau H / \nu = 300$ where ν is the kinematic viscosity. The computational box is $6.8H$, H and $2.54H$ in the streamwise (x), the wall-normal (y) and the spanwise (z) directions, respectively, and the grid numbers are $256(x) \times 117(y) \times 128(z)$ which correspond to a box of size $2040(x) \times 300(y) \times 762(z)$ in a wall unit which is a non-dimensional quantity normalized by u_τ and ν . Accordingly, the grid separations in a wall unit are $\Delta x^+ = \Delta x u_\tau / \nu = 8$, $\Delta y^+ = 0.704 \sim 4.447$, $\Delta z^+ = 6$.

The boundary conditions are periodic conditions in both x and z directions and no slip at the walls. The time advancement in the simulation is $\Delta t^+ = \tau u_\tau^2 / \nu = 0.045$ and the data for the whole flow field for every $\Delta t^+ = 3.6$ are stored for analysis of the flow evolution. The time of the shots in the following is the elapsed time from the arbitrarily chosen initial time $t^+ = 0$.

3. Conditional Sampling

Around the upstream part of the body of a quasi-streamwise vortex, one finds usually strong down-

Fig. 1 Instantaneous distribution of skewness factors (a) S_v and (b) S_{ω_x} of wall-normal velocity and streamwise vorticity ω_x on a plane parallel to the wall, $y^+ = 15$

wash. The strong relationship between wall-normal velocity v and streamwise vorticity ω_x is confirmed by comparison of maps of the skewness factors of the fluctuation of these two quantities $S_v = \overline{v'^3} / v_{rms}^3$ and $S_{\omega_x} = \overline{\omega_x'^3} / \omega_{x,rms}^3$ where a prime (') indicates a fluctuation component. In the following, quantities having only fluctuation component such as v and ω_x are denoted without a prime unless otherwise stated. Figure 1, which shows maps of (a) S_v and (b) S_{ω_x} at an instant on a plane parallel to the wall, $y^+ = 15$, demonstrates that the distributions of these two quantities are quite similar, meaning that S_v is a good detector of quasi-streamwise vortices. The reason why one uses S_v in place of v' itself is to strengthen the detection signal.

The intensity of fluctuation of vorticity components ω'_x and ω'_y which are defined as $\omega'_i = \sqrt{\overline{\omega_i'^2}}$, ($i = x, y$) peaks value at $y^+ \sim 15$. Moreover, the convection velocities V_{c,ω_x} and V_{cp,ω_x} for ω_x and $D\omega_x/Dt$ are nearly same and slightly smaller than the local mean flow velocity, in the region $y^+ > 15$. This suggests that in this region, individual vortices evolve on within a group of vortices which convect jointly. In the region $y^+ < 10$, or in the viscous sublayer, the convection velocity is nearly constant, suggesting that here, no inherent activities of vortices such as generation are induced and the fluctuation observed here is only that transmitted as a viscous wave from the layer above. These considerations lead us to choose $y^+ = 15$ where we pick up detection signal S_v .

Typical streamwise vortices satisfying the following two conditions are sampled.

$$\alpha = \begin{cases} 1, & \text{when } S_v = \overline{v'^3} / v_{rms}^3 < k \text{ and } \partial u / \partial x > 0, \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where k is a suitable threshold value and

$$48 \leq l^+ \leq 80, \quad (2)$$

where l^+ is the distance between the upstream end and the downstream end of $S_v=0$ of a vortex, in the plane of $y^+=15$. The number of samples which give $\alpha=1$ in Eq. (1) and at the same time satisfy Eq. (2) is about 150 when the threshold value is $k=-15$. To prevent inclusion of a vortex twice, the sampling is performed at time intervals Δt^+ greater than 90.

Figure 2 shows a plan view of a representative pair of quasi-streamwise vortices at $t^+=28.8$ with vortex contours of $|\omega_x^+| \geq 0.2$ appearing in several planes parallel to the wall superposed. The solid lines are for $\omega_x > 0$ and the broken lines, $\omega_x < 0$. The thinnest lines indicate the countours on $y^+=15$ and the thickest ones those on $y^+=45$; the lines of intermediate thickness indicate the contours of on $y^+=25$ and 35. In addition, the white and black circles show the points where $S_v \geq 15$ and $S_v \leq -15$, respectively. It is found that a strong negative S_v corresponds to strong downwash at the upstream end of a quasi-streamwise vortex.

Figure 2 also shows an interesting fundamental structure in which two vortices of opposite sign (A_1 : downstream-side vortex, A_2 : upstream-side vortex) are arranged in the streamwise direction in a zig-zag pattern, a conceptual model⁽⁷⁾ for which is given in Fig. 3. The number of vortices in this chain is not necessarily three as in Fig. 3; in some cases, only two

Fig. 2 A plan view of representative quasi-streamwise vortices obtained by conditional sampling using S_v as a detector

vortices of combinations (A, B) and/or (B, A) are found.

4. Regeneration of a Quasi-Streamwise Vortex

A quasi-streamwise vortex is convected downstream, maintaining its configuration for a long time. The vortices sampled under the conditions given by Eqs. (1) and (2) show various kinds of behavior as investigated by Bernard et al.⁽⁶⁾ Upon tracing of the time evolution of these vortices with storage of the data for the whole flow field every $\Delta t^+=3.6$, it is found that most of the sampled vortices can be classified as one of the following three types.

(1) a parent vortex bearing new vortex at its upstream end,

(2) a parent vortex bearing new vortex at its downstream end,

(3) a straight streamwise vortex undergoing attenuation without bearing a new vortex.

Note that the ratio of the number of sampled vortices to the total is not known.

The generation mechanism of the type (2) vortices is the same as that described by Brooke and Hanratty⁽⁴⁾. In the following, the time evolutions of the vortices of type (1) and (2), the former in particular, will be described.

4.1 A vortex born at the upstream end grows to upstream direction

Figure 4 shows the time evolution of a sampled vortex pair in the period between $t^+=18.0$ and $t^+=72.9$. The figures are plan views and the vortices are visualized by taking the threshold value of the vorticity as $|\omega_x^+|=0.2$. The dark filaments are negative vortices and light ones are positive ones. The streamwise location of the vortices at each instant is determined by referring to the scale of the straight line at the top of the figure. Because of convection, the vortices shift to the right as time proceeds.

In Fig. 4(a) which is for $t^+=18.0$, vortex A_2 is of negative rotation, $\omega_x < 0$ and A_1 is of positive rotation, $\omega_x > 0$ and the tail of the former shifts to the left as viewed from upstream to downstream and that of

Fig. 3 A conceptual model of a basic structure of quasi-streamwise vortices

Fig. 4 Time evolution of quasi-streamwise vortices regenerating a new vortex at the upstream end of a parent vortex (light filament: $\omega_x > 0$, dark filament: $\omega_x < 0$)

Fig. 5 (a) A perspective view and (b) a side view of an instantaneous configuration of quasi-streamwise vortices ($t^+ = 72.0$)

the latter, to the right. As a result, the chain of vortices becoming arranged in a line in the mean flow direction constitutes a zig-zag pattern, as conceptually sketched in Fig. 3. At $t^+=18.0$, the tail of vortex A_2 is located above the upstream end of vortex A_1 and vortex A_2 extends to upstream, thus composing the structure in Fig. 3. At $t^+=25.2$, A_1 is slightly smaller but A_2 is larger than at $t^+=18.0$. At $t^+=32.4$, new vortex A_3 appears at the upstream end of A_2 , and A_3 grows as time proceeds until it becomes mature at $t^+=57.6$ when it composes the structure shown in Fig. 3 jointly with A_2 and A_1 has almost completed its life. Thus, a regeneration of a quasi-streamwise vortex which started at $t^+=32.4$ is completed at $t^+=57.6$.

At $t^+=64.8$, new vortex A_4 appears at the upstream end of A_3 , and it becomes mature at $t^+=79.2$. That is, the structure in Fig. 3 is generated once again. At this instant, new vortex layer A_5 appears beneath the upstream end of A_3 . This vortex layer A_5 is not a vortex tube as is obvious in Fig. 5, which shows (a) a perspective view and (b) a side view of the shot of Fig. 4(h) at $t^+=72.0$. Although one finds an area of high negative vorticity, A_5 , in Fig. 5(a), no corresponding tube is found in Fig. 5(b). That is, A_5 is a vortex layer attached to the wall surface. The above-mentioned evolution of a chain of vortices shows the process of regeneration of a young vortex from a

parent vortex, and it is concluded that the time needed for one regeneration is about $\Delta t^+ \sim 20$ and that the regeneration recurs numerous times.

The velocity maps around the vortices A_2 and A_3 in a few cross-flow sections at $t^+=32.4$ (Fig. 4(c)) are shown in Fig. 6., in which (a), (b), (c) are the sections at $x^+=1256$, 1304, 1352, respectively, and show that the new vortex A_3 is located above and at the side of the lift-up flow of vortex A_2 . In addition, it is observed that the vortices are lifted up themselves gradually in the downstream direction and the center of the vortex at the upstream end is as low as $y^+=10$.

The regeneration of a vortex at the upstream side has been mentioned by Bernard et al.⁽⁵⁾ but their concern was a vortex which appears beneath the upstream end of a parent vortex and not the regeneration described above. Their indication is interpreted as that a vortex layer located close to the wall has a possibility to be converted to a vortex tube.

In order to discuss the mechanism of the growth of a quasi-streamwise vortex, the transport equation of streamwise vorticity ω_x , which is given by $D\omega_x/Dt$ and is

$$\frac{D\omega_x}{Dt} = \omega_x \frac{\partial u}{\partial x} - \frac{\partial w}{\partial x} \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \frac{\partial u}{\partial z} + \frac{1}{Re_\tau} \nabla^2 \omega_x, \quad (3)$$

is considered. The right-hand side of the above equation is production rate of vorticity ω_x due to the stretching of streamwise vortex itself, due to tilting of wall-normal vorticity, due to yawing of cross-stream vorticity and due to viscous diffusion, in the order from the first term to the right, respectively.

Figures 7 show an example of a plan view of the surface distribution of the production rate for each component, namely, that for (a) stretching, (b) tilting, and (c) yawing and (d) the sum of these three, for $t^+=28.8$. In the figures, the solid lines are the contour lines of $D\omega_x^+/Dt \geq 0.15$ in a plane parallel to the wall, and the broken lines, $D\omega_x^+/Dt \leq -0.15$. The thinnest lines are on the plane $y^+=15$, the thickest ones, on $y^+=45$ and the lines of intermediate thickness are on $y^+=25$ and 35. Looking at Fig. 7, it is found that to the production rate, stretching and tilting contribute most, and that at the early stage of regeneration, tilting in the lift-up side region contributes greatly. At the tail of vortex A_2 , since production rate is low, A_2 attenuates. Meanwhile, at the tail of A_1 , production due to tilting of negative vorticity tends to result in generation of a new vortex, as suggested in Fig. 4(a) and (b), but this regeneration which is considered to be of category (2) ends shortly after this instant.

For investigation of the mechanism of sustained

Fig. 6 Velocity maps and cross sections of quasi-streamwise vortices ($\omega_x^+ = \pm 0.2$) in cross-flow sections at (a) $x^+=1256$, (b) $x^+=1304$ and (c) $x^+=1352$ at an early stage of regeneration ($t^+=32.4$)

Fig. 7 An instantaneous surface distribution of production rate of streamwise vorticity on the planes parallel to the wall, $y^+ = 15, 25, 35, 45$

vorticity in the evolution of a vortex, integrated production rate P_{ω_x} which is an integrated value of the production rate in a cross-section of a vortex in the area having high vorticity of $|\omega_x^+| \geq 0.2$ is calculated. The area of high production rate of vorticity and that of high vorticity do not exactly superpose on one another, especially in the tail region, but the above-mentioned method of estimating integrated production rate can give an idea of the mechanism of sustenance and regeneration of vortices. Figures 8 show the results and show the time evolution of a streamwise distribution of the vortex, namely, (a) A_2 and (b) A_3 . Dotted lines show the integrated production rate due to stretching, broken lines, due to tilting, chained lines, due to yawing and solid lines are the sum of these three.

From Fig. 8(b), one finds that in the early stage of growth, the contribution of tilting is major but after a vortex has grown to a certain size, stretching becomes dominant. This observation confirms that of Bernard et al.⁽⁵⁾ qualitatively. As for a fully grown vortex, the total production rate is almost thoroughly accounted for by the stretching effect, which balances the viscous diffusion effect which always tends to cause attenuation of vorticity. The mechanism of sustenance of a fully grown vortex is the same for both A_2 and A_3 as has been suggested by Kim and Hamilton⁽⁸⁾. However, since stretching does not result

Fig. 8 Time evolution of streamwise distribution of integrated production rate P_{ω_x} for the vortices (a) A_2 and (b) A_3 (Solid lines: total production rate, dotted lines: due to stretching, broken lines: due to tilting, chained lines: due to yawing)

in an increase in the total circulation, more detailed investigation of its mechanism is needed.

Fig. 9 Time evolution of quasi-streamwise vortices regenerating a new vortex at the downstream end of a parent vortex (light body: $\omega_x > 0$, dark body: $\omega_x < 0$)

Fig. 10 Side view of time evolution of the centerline of a parent vortex bearing a new vortex beneath its downstream end

4.2 A vortex born at the downstream end of a parent vortex

In Figs 9, a typical time evolution of a vortex of category (2) every $\Delta t^+ = 7.2$ from $t^+ = 61.2$ to 90.0 is shown, in a manner identical to that for Fig. 4. The center of parent vortex B_1 is located as high as $y^+ = 50 \sim 60$ and before $t^+ = 61.2$, no new vortex is found beneath it. At $t^+ = 61.2$, new vortex B_2 appears and it grows gradually until it matures at $t^+ = 90.0$. Figure 10 shows the convection of the centerline of the parent vortex which is shown by broken lines in a side view. In this type of regeneration, a parent vortex remains distant from the wall.

The velocity maps as well as the location of the cross sections of the vortices are shown in Fig. 11, for $t^+ = 61.2$. The lines in the figures indicate the contour lines of $|\omega_x| = 0.2$, and the solid lines and broken ones are for $\omega_x > 0$ and $\omega_x < 0$, respectively. New vortex B_2 is generated at the splatting flow region where the

Fig. 11 Velocity maps and cross sections of quasi-streamwise vortices ($\omega_x^* = \pm 0.2$) in cross-flow sections at (a) $x^+ = 808$, (b) $x^+ = 856$ and (c) $x^+ = 904$ at an early stage of regeneration ($t^+ = 61.2$)

strong downwash of parent vortex B_1 produces a high shear layer of streamwise vorticity to meet with the no-slip condition on the wall. This regeneration

mechanism is exactly the one pointed out by Brooke and Hanratty⁽⁴⁾ and occurs on the downwash side and when a parent vortex is located at a high position.

5. Conclusion

Strong downwash was used to detect quasi-streamwise vortices, in this work. The time evolution of the conditionally sampled vortices was investigated carefully and the following conclusions were reached.

(1) A quasi-streamwise vortex is regenerated by a mature parent vortex. The newly born vortex has opposite rotation to the parent one and forms a zig-zag line in the direction of streaming jointly with the parent one.

(2) The regeneration can occur both at the upstream end and at the downstream end of a parent vortex. In the former case, the new vortex appears in the ejection flow and in the latter, in the downwash flow of the parent vortex.

(3) For the generation of circulation of a quasi-streamwise vortex, tilting of a wall-normal vorticity generated in the flow due to the parent vortex contributes the most in the infant stage of the growth of a new vortex, and in the fully grown stage, stretching of the streamwise vorticity itself contributes overwhelmingly.

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