Analysis of Clusterization of Quasi-Streamwise Vortices in Near-Wall Turbulence*

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Our aim is concerned with clustering or grouping of quasi-streamwise vortices. A fact that quasi-streamwise vortices are not distributed homogeneously but intermittently populated in space in a wall layer, is shown at first by referring to a Direct Numerical Simulation (DNS) data for a channel flow. Then, Regeneration property of quasi-streamwise vortices is one of the crucially important possible mechanisms for this clustering is shown by a simplified non-dynamical simulation. Next, a wavelet decomposition of quasi-streamwise vortices in two scale-based groups is shown. The interaction between vortices of two groups indicates that individual quasi-streamwise vortices can not survive long without assistance of surrounding large scale structure which is adapted for them. Thus, it is pointed out that large scale structure around a cluster of vortices is an important coherent structure to be investigated more in detail.

Key Words: Shear Flow, Turbulence, Quasi-Streamwise Vortex, Near-Wall Turbulence, Coherent Structure, DNS, Cluster

1. Introduction

In order to establish the active control technique of turbulence, it is necessary to put information about the turbulent structure in order and to understand the its mechanism. When observing the micro structure of the wall turbulence, the existence of the quasi-streamwise vortices which have their axis nearly in the mean-flow direction, is recognized in the near wall region. In view of attenuation of the individual quasi-streamwise vortex, recently Choi et al.⁽¹⁾ demonstrated numerically that the wall shear stress is reduced effectively by local suction / blowing on the wall. Also, Jung et al.⁽²⁾ found out that the effective reduction rate is realized by spanwise oscillation of the wall. Further the authors explained its drag reduction

mechanism based on the detailed examination^{(3),(4)} of the regeneration and the maintenance of individual quasi-streamwise vortex. The important role accomplished by the quasi-streamwise vortices in near-wall turbulence was made clear by a series of these studies.

On the other hand, when looking at the whole wall region once more, a fact that quasi-streamwise vortices are distributed not homogeneously but densely and concentrated in some places of near-wall region is shown. Hence defining such a structures as the cluster of quasi-streamwise vortices, it is expected that the understanding about the global nature of the near-wall turbulence deepens and that the new active-control technique will be developed. Then when analyzing the behavior of this cluster, since the streamwise length of them is larger than that of a quasi-streamwise vortex, it becomes necessary to conduct the simulation having a long enough length in streamwise direction.

In this study, First, based on the data base of which it is conducted the DNS of channel flow having streamwise-long volume, the characters of the cluster of quasi-streamwise vortices are investigated. Second, as for the clusterization, it is demonstrated that

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regeneration property of quasi-streamwise vortices is one of the crucially important mechanisms by a simplified non-dynamical simulation. Furthermore introducing a wavelet transform to decompose flow field into large and small scale groups, in view of the interaction between vortices of two groups, it turns out that the individual quasi-streamwise vortex can not survive long without assistance of surrounding large scale structure which is adjusted for them.

2. Numerical Methods

A direct numerical simulation (DNS) of a channel flow was carried out using a computational volume which is long enough in streamwise direction to avoid interference of inlet and outlet sections possibly caused by periodic condition and to allow us to observe long evolution of vortical field. A coordinate system and a computational volume are shown in Fig. 1. The size $h^+ = h\bar{u}_\tau/\nu$ in wall unit, of the computational box in each direction is $h_x^+ = 4608$, $h_y^+ = 300$, $h_z^+ = 576$ where x, y, z are streamwise, wall-normal and spanwise direction, respectively and $\bar{u}_\tau$ is mean wall friction velocity and ν , kinematic viscosity. $\bar{u}_\tau$ is defined as $\bar{u}_\tau = \sqrt{(\bar{\tau}_L + \bar{\tau}_U)/2\rho}$, where $\bar{\tau}_U, \bar{\tau}_L$ are wall friction stress on the upper and the lower walls, respectively. The Reynolds number $Re_\tau = \bar{u}_\tau H/\nu$ which is defined by $\bar{u}_\tau$ and channel half width H , is 150. The grid number is $256 \times 64 \times 64$ in x, y, z direction, respectively. As boundary condition, periodic conditions are applied in the streamwise and spanwise directions. Both walls are subjected to a no-slip condition. The numerical scheme used in the code is described in Kajishima et al. (1997). After the calculation long enough to reach statistically steady state, the physical quantity of the whole flow field such as velocity and pressure are stored at every 1000 step ($\Delta t^+ = 30$). In the following, superscript “+” denotes the non-dimensionalized quantities by $\bar{u}_\tau$ and ν .

3. Computational Results

3.1 The characteristic of the cluster of quasi-streamwise vortices

The spatial distribution of the quasi-streamwise vortices in the whole flow field is shown in Fig. 2(a). Based on the argument of the identification of the quasi-streamwise vortex in authors' report⁽⁷⁾, the threshold value $|\omega_x^+| > 0.2$ as indices of the streamwise

Fig. 1 Computational volume

vortex is adopted here. The gray part in Fig. 2 is to be positive ω_x and the black part is negative one. The quasi-streamwise vortex is distributed intermittently in the space.

Enlarging a rectangular box in Fig. 2(a) to Fig. 2(b), it is observed that the quasi-streamwise vortices having a opposite sign rotation are assembled along the streamwise direction with each other^{(3),(4)} and are densely populated. Below, the area where these quasi-streamwise vortices are populated densely is named a cluster of quasi-streamwise vortices (CQV). Then to make clear the things about the behavior of the CQV, it introduces the filter quantity $\hat{f}$ which is smoothed by the filter of top-hat type defined as following.

$$\hat{f} = \frac{1}{S} \int_{-\Delta\xi}^{\Delta\xi} \int_{-\Delta\zeta}^{\Delta\zeta} f(x+\xi, y, z+\zeta) d\xi d\zeta \quad (1)$$

$$(S = 4\Delta\xi\Delta\zeta, \Delta\xi^+ = 50, \Delta\zeta^+ = 20)$$

Figures 3 show the time evolution of plane view of quasi-streamwise vortices observed below the center of channel. In the figures, each long strip is the plane view at $\Delta t^+ = 30.0$ after to its left and dark

Fig. 2 Plane and side view of quasi-streamwise vortices, (a) full volume, (b) a rectangular volume in Fig. (a), light color: $\omega_x^+ > 0.2$, dark one: $\omega_x^+ < -0.2$

color denotes streamwise vorticity $|\omega_z^+| > 0.2$ and its filter quantity $|\bar{\omega}_z^+| > 0.135$. $|\bar{\omega}_z^+|$ agree well with the area where the quasi-streamwise vortices are clustered. Observing about the area (A, B, C) which are

Fig. 3 Evolution of distribution of quasi-streamwise vortices. Each long strip is a plan view at the time instant $\Delta t^+ = 30$ after that of the one next to its left, (a) : quasi-streamwise vortices of $|\omega_z^+| \geq 0.2$, (b) : filtered quasi-streamwise vortices of $|\bar{\omega}_z^+| \geq 0.135$ by Eq.(1)

surrounded with the rectangular box in the figure, all of them move to the downstream at the same speed and this movement speed is approximately the same as that of individual quasi-streamwise vortex.

Although the streamwise length of the matured quasi-streamwise vortex is $l^+ = 100 - 200$ in wall unit, the CQV in area B has about $l^+ = 1200$ that means several times of that of the quasi-streamwise vortex. In the box A, B and C, the CQV moves to the downstream while some are growing and some others are decaying. Since the life time of individual quasi-streamwise vortex is about $\Delta t^+ = 100$, that of the CQV is longer, it is suggested that individual quasi-streamwise vortex is generated and becomes extinct in the volume of the CQV. The filter quantity of pressure fluctuation $\bar{p}'$ on the wall that is defined by Eq.(1), is shown in Fig.4(b). The left end strip of Fig.3(b) is inserted in Fig.4(a) to be compared. The closed curve in the Fig.4(b) is an area above rms value ($\bar{p}'_{rms} \sim 1.4$). The existence of the CQV corresponds to the area with high pressure fluctuation value on the wall. While it is well known that high pressure region is formed spotty on the wall due to the downwash of each quasi-streamwise vortex, such a high pressure spot concentrates in the closed curve of Fig.4(b), i.e. it is suggested that the individual quasi-streamwise vortex is vitalized in the volume of the CQV.

3.2 Formation of the CQV

In order to find out a substantial property concerning how vortex clusters are formed, a simulation which is not based on dynamical condition but on probability condition was carried out. The simulation is done in two-dimensional plane of the same rectangular box as shown in Fig.3 under the following procedure and assumptions.

1. 30 pieces of straight line vortices are supplied to the flow field at every $\Delta t^+ = 20$.

Fig. 4 Similarity of distribution of fluctuating pressure on the wall and quasi-streamwise vortices, filtered by Eq.(1), (a) : Quasi-streamwise vortices of $|\omega_z^+| \geq 0.135$ (the left-end strip in Fig.1(b)).(b) : Fluctuating pressure $|\bar{p}'^+| \geq 1.4$, both at the instant of the left-end strip of Fig.1

2. The locations of the supplied vortices are determined randomly, consulting for random number table.

3. The vortices are convected to downstream at speed $u_c^+ = 15$.

4. Each vortex has lifetime of $\Delta t^+ = 100$ and in its first half, it grows linearly and attains the maximum length $l^+ = 200$ at $t^+ = 50$ from its supply and then shrinks linearly, in the latter half.

5. The supplied vortices are allowed only in a certain distance around existing vortices. That is, influential area of each vortex which is $\Delta s^+ = 20$ from a vortex is defined, only within which a new vortex can be supplied.

Condition [3] mimics the DNS data that vortices are convected with the speed slightly lower than local mean velocity, maintaining its configuration long time. Since we are considering quasi-streamwise vortices in the layer $y^+ = 10 - 35$, most probable mean convection velocity is $u_c^+ = 15$. Condition [4], i.e., both mean lifetime and mean scale of quasi-streamwise vortices are also brought from the DNS data. If we do not apply the last condition, that is, if new vortex is allowed to be born at any place, no clusterization occurs as shown in Fig. 5(a) which is depicted in the same manner as Fig. 2. But with the last condition, Fig. 5(b) is obtained. The left-end strip of Figures 5(a), (b) is at an arbitrary time instant enough long time after the start of simulation and each strip is for $\Delta t^+ = 20$ after the one next to its left. Fig. 5(b) is quite similar to Fig. 1(a) and we find that clusters grow as time marches. Since the last condition mimics the fact that a new vortex is usually born under the influence of an existing vortex, or by regeneration, the result indicates strongly that regeneration inherently generates clusterized structure of vortices. Although the clusterization may have other mechanism, it is substantially important that commonly observed properties of behavior of quasi-streamwise vortices itemized above can reproduce the process of cluster formation.

3.3 The extraction of the CQV-scale structure

Since it is supposed that the scale which is larger than that of the quasi-streamwise vortex contributes to the clusterization, it divides the flow field into two scale groups using a Wavelet transform. First, the discretized Wavelet transform to utilize for the analysis is simply explained (the details are referred to a volume⁽⁶⁾) and further it shows the flow structure decomposed into two scale groups.

3.3.1 The discretized Wavelet transform

When one dimensional spatial data $f(x)$ is given, the discretized Wavelet transform is as following

$$d_k^{(j)} = 2^{j/2} \int_{-\infty}^{\infty} \overline{\psi(2^j x - k)} f(x) dx \quad (2)$$

Fig. 5 Cluster formation of quasi-streamwise vortices by means of simple probability model on a two-dimensional plane, (a) : Case of random supplied vortices, (b) : case of conditionally supplied vortices according to above-described [5]

where $\overline{}$ denotes conjugate relation.

Inverse transform corresponding to above definition is written as

$$f(x) \sim \sum_j \sum_k d_k^{(j)} \psi(2^j x - k) \quad (3)$$

where the function ψ is named Mother wavelet and function $f(x)$ is expressed by the liner combination of the scaled one with $1/2^j$ and the shifted one with $k/2^j$

along x .

Double sum in Eq.(3) is defined as

$$g_j(x) = \sum_k d_k^{(j)} \phi(2^j x - k) \quad (4)$$

$$f_j(x) = \sum_k C_k^{(j)} \phi(2^j x - k) \quad (5)$$

(As for coefficient $C_k^{(j)}$, it omits).

ϕ is named a scale function and Mother wavelet ψ is composed of combination with them. Moreover, Eqs.(4), (5) are expressed in the recursion form of the following equation.

$$f_j(x) = g_{j-1}(x) + f_{j-1}(x) \quad (6)$$

Above equations, subscript ' j ' denotes the order (the level) and $f_j(x)$ is expressed at the base function with $1/2^j$ scale. Also, The level j -th function is resolved by low-wave number component, f_{j-1} and high-wave one, g_{j-1} .

if $f(x)$ equals to $f_0(x)$

$$\begin{aligned} f_0(x) &= g_{-1}(x) + f_{-1}(x) \\ &= g_{-1}(x) + g_{-2}(x) + f_{-2}(x) \\ &= \sum_k g_{-k} + f_{-1} \end{aligned} \quad (7)$$

So any function is decomposed into the the data structure layered according to the scale. (So called the multiple scale analysis).

Below, we discuss about the flow structure which is decomposed into two scale groups, i.e. $\sum_k g_{-k}$ (the small scale) and f_{-1} (the large scale).

3.3.2 The extraction of the CQV scale by the discretized Wavelet transform Has been proposed several kinds of wavelet, for this study it is adopted third order B-spline function⁽⁸⁾ shown in Fig. 6. Figures 7 show the one-dimensional wavelet decomposition of ω_x along x, z direction, respectively at some position ($y^+ = 15$). Quickly fluctuating line is the original signal representing ω_x^+ and slowly fluctuating one corresponds to the extracted large scale fluctuation. Although according to the decreasing j , the signal data is smoothed more and the obvious peaks appear. In case that the level j is -3 and -4 for x, z direction, respectively, the extracted scale length become approximately $\Delta x^+ = 600$ and $\Delta z^+ = 100$. Compared with the visualized result of the CQV in Fig. 3, it is supposed that the former scale corresponds to the streamwise-length scale of the CQV and the latter one, to the spanwise spacing of streaky structure.

According to the usual procedure of the Wavelet analysis, the contour map of the transform coefficient which is defined by Eq.(2), is shown in Fig. 8. The signal data of Fig. 7(a) is considered. In the figure, the vertical and horizontal axis denote the scale $a^+ (= 2^j H_x Re_\tau)$ and trans rate $b^+ (= k/2^j H_x Re_\tau)$, respectively and the solid line means a position with the scale of $j = -4$. The portions of which the contour lines concentrate on the smaller scale side ($j < -4$) correspond to the existence of quasi-streamwise vortices in

Fig. 6 3rd order Wavelet, (a) Mother wavelet, (b) Scaling function

Fig. 7 An example of one dimensional wavelet decomposition of ω_x^+ , in a plane $y^+ = 15$ and for the time instant of Fig. 2(a). (a): Streamwise (level=-4), (b): spanwise (level=-3)

Fig. 2(a).

The one-dimensional spectrum of the original and the large scale streamwise vorticity in a plane $y^+ = 15$ is shown in Fig. 9. In the figure, the solid and broken lines denotes original and large-scale spectrum, respectively and the difference of them is small scale one. The characteristic of the adopted Wavelet transform seems to be a sharp-cut filter. Therefore, as for the separation of the scales, it is not inconvenient for the use of Sharp-cut filter. However since it is possible to decide the separation scale based on the local-structure information, it is more favorable to use the wavelet transform. Below, the above transform is extended to two-dimensional space of x - z plane and it extracts various physical quantity such as the ω_x^+ field of above-mentioned time instant. Then $(\sim)$ denotes the extracted quantity is defined as the CQV scale structure, and a difference between original and the CQV scale is defined as the small scale structure. Figure 10 shows the wall-normal distribution of mean absolute value of fluctuating vorticity in plane parallel to the wall. The solid line is for the whole vorticity and the broken line is for the CQV scale vorticity and the chained line for the small scale vorticity. In most

Fig. 8 Example of one dimensional wavelet decomposition of ω_x^+ for the example of Fig. 7(a) on the plane defined by a scale and translate. Solid line denotes scale $j = -4$

Fig. 9 Decomposition of ω_x^+ in one dimensional spectrum at $y^+ = 15$

part of mean values, the small scale vorticity occupies and the strength of the CQV scale vorticity is weak. The small scale vorticity becomes isotropic near $y^+ = 50$, but the CQV one does not even such as the position $y^+ = 70$. Thus it demonstrated that the large-scale structure exists further away from the wall compared with the quasi-streamwise vortex.

Fig. 10 Wall normal distribution of mean absolute value of fluctuate vorticity averaged in a plane parallel to the wall, (a) ω_x^+ (b) ω_y^+ (c) ω_z^+ . Solid line: total, chained line: small scale and broken line: large scale

The small scale of streamwise vorticity $\Delta\omega_x = \omega_x - \tilde{\omega}_x$ and the CQV scale $\tilde{\omega}_x$ at the time of Fig. 2(a) is visualized in Figs. 11. To be compared with Fig. 2(a), the threshold values $\Delta\omega_x^+ = 0.2$ and $\tilde{\omega}_x^+ = 0.07$ are chosen. Although the strength of the CQV scale is weak, they agree with the plane distribution of small scale $\Delta\omega_x$ for the most part. On the other hand, the small scale structure agrees very well with the plane distribution of Fig. 2(a). A streamwise vorticity and a velocity vector on the y - z plane at the position A in the Fig. 11 are shown in Figs. 12. In the figures, fine solid line is velocity vector and thick solid one is iso-contour line of streamwise vorticity. As shown these distribution, it is reconfirmed that the small scale structure agrees very well with the original one. That is, it finds that quasi-streamwise vortices which are identified in general are small scale structure. Since the large-scale rotational motion is observed from the

Fig. 11 Plan view of decomposed larger and smaller scale quasi-streamwise vortices, (a) Larger scale vortices for the level $j=4$ in x and $j=3$ in z direction, obtained by wavelet transform. $|\omega_x^+| \geq 0.07$. (b) smaller scale vortices obtained by subtracting larger scale components of Fig. 11(a) from total vortical field. $|\omega_x^+| \geq 0.2$

velocity vector plot, the CQV scale structure is specified as some kind of vortex. On the other hand, the center of rotation of large-scale vortex does not always coincide with that of iso-contour line of vorticity in Fig. 12(c), thus the movement of the CQV scale structure is not identified by the streamwise vorticity which used for the identification of small scale structure. We are going to investigate about the technique for the identification at present. As our comments, drawing the iso-contour surface of the helicity density $h_n(=\boldsymbol{\omega} \cdot \mathbf{u}/|\boldsymbol{\omega}||\mathbf{u}|)$ (not shown here), they wrap the rotational motion of the CQV scale and their volume stretch for streamwise direction and exist further away from the wall, so the CQV scale motion may be a swirling motion.

3.4 The role of the large-scale structure to form the CQV

Since the small-scale structure is the predominant one in the flow field, it demonstrates that the large-scale structure plays an important role for their maintenance as follows. For that purpose, numerical experiments are conducted for the large or small scale groups. That is, as a initial condition it is used several velocity components u , v and w that are decomposed into two scale groups by above transformation. However in the case of small scale, not including the mean velocity component, that of a fully developed channel flow is added to streamwise velocity compo-

Fig. 12 Cross sectional distribution of original, small and large scale flow. Velocity vector and contours of vorticity are drawn based on the each scale, (a) Original (solid: line $|\omega_x^+| > 0.2$), (b) Small scale flow (solid: line $|\omega_x^+| > 0.2$), (c) Large scale flow (solid: line $|\omega_x^+| > 0.07$)

ment. Although the continuity equation must be nearly zero, it is enough to be satisfied in both cases at initial instant. Figure 13 shows the result where the distribution of vortices are depicted in the same manner as in Fig. 3(a). That is, the left-end strip is for the initial instant and each strip is for $\Delta t^+ = 30$ after to its left. Since it attenuates cascading process by removing the small scale, large scale vortical field can live long in Fig. 13(a). On the other hand small scale structure disappears quickly in Fig. 13(b) though the mean flow exists. Although it is confirmed that a single quasi-streamwise vortex has self-sustaining mechanism⁽⁴⁾, the mean shear of arbitrary velocity distribution is not useful in sustaining the small scale vortices as showing these results. That is, small scale structure necessitates its own large scale structure

Fig. 13 The time evolution of each decomposed initial large and small scale vortices embedded in mean turbulent Poiseuille flow, (a) : Large scale ($|\omega_x^+| \geq 0.07$), (b) : small scale ($|\omega_x^+| \geq 0.2$)

around it which is inherent to itself, in order to be able to generate new vorticity to live long.

In order to get an idea how large and small scale vortices are interacting with each other, vorticity production is investigated.

Vorticity equation is given by

$$\frac{D\omega}{Dt} = \mathbf{A} \cdot \omega + \frac{1}{Re_\tau} \nabla^2 \omega = \mathbf{f}_e + \mathbf{f}_t + \frac{1}{Re_\tau} \nabla^2 \omega \quad (8)$$

$$\mathbf{f}_e = (\mathbf{A} \cdot \omega) \cdot \mathbf{e}_\omega \quad (9)$$

$$\mathbf{f}_t = \mathbf{A} \cdot \omega - \mathbf{f}_e \quad (10)$$

where $\mathbf{e}_\omega = \omega/|\omega|$, $\mathbf{A} = \partial u_i / \partial x_j$ and D/Dt is material derivative. $\mathbf{f}_e$ is the production rate of vorticity by stretching and $\mathbf{f}_t$ is that by turning.

Denoting the quantities of large scale vortex by over bar as $\bar{f}$ and that of small scale vortex by prime as f' , one has four components of $\mathbf{A} \cdot \omega$.

Namely, as for the stretching part of it,

$$A_e: [(\bar{\mathbf{A}} \cdot \bar{\omega}) \cdot \bar{\mathbf{e}}_\omega], B_e: [(\mathbf{A}' \cdot \bar{\omega}) \cdot \bar{\mathbf{e}}_\omega]$$

$$C_e: [(\bar{\mathbf{A}} \cdot \omega') \cdot \bar{\mathbf{e}}_\omega], D_e: [(\mathbf{A}' \cdot \omega') \cdot \bar{\mathbf{e}}_\omega]$$

and for turning part, A_t :

$$A_t: \bar{\mathbf{A}} \cdot \bar{\omega} - [(\bar{\mathbf{A}} \cdot \bar{\omega}) \cdot \bar{\mathbf{e}}_\omega] \cdot \bar{\mathbf{e}}_\omega$$

$$B_t: \mathbf{A}' \cdot \bar{\omega} - [(\mathbf{A}' \cdot \bar{\omega}) \cdot \bar{\mathbf{e}}_\omega] \cdot \bar{\mathbf{e}}_\omega$$

$$C_t: \bar{\mathbf{A}} \cdot \omega' - [(\bar{\mathbf{A}} \cdot \omega') \cdot \bar{\mathbf{e}}_\omega] \cdot \bar{\mathbf{e}}_\omega$$

$$D_t: \mathbf{A}' \cdot \omega' - [(\mathbf{A}' \cdot \omega') \cdot \bar{\mathbf{e}}_\omega] \cdot \bar{\mathbf{e}}_\omega$$

A and D mean production rate of large scale vorticity and small scale one by themselves, respectively, B is production rate of large scale vorticity by small scale strain rate and C , that of small scale vorticity by large scale strain rate.

Wall-normal distribution of above A_e , A_t , etc., for streamwise vorticity component ω_x , averaged in a plane parallel to the wall are shown in Fig. 14(a) for stretching part f_{ex} and Fig. 14(b) for turning part f_{tx} .

In the figures, thick solid lines are for A , broken lines, for B , thin solid lines, for C , thin dotted lines, for D and symbols are for total production rate. It is demonstrated that the large scale structures are not self-sustainable since both A_{ex} and A_{tx} are negligible small in whole section. But since B_{ex} is positive rate and B_{tx} , negative one, they are produced by stretching of small scale vortices and are changed to other vorticity components by the small scale strain, namely the large scale structure is deformed by small scale one.

As for the small scale vortices, major field of production is buffer layer, as is known widely and both stretching and turning due to straining by large scale vortices contribute parallel, though the latter is much larger than the former. The property that turning is the largest contributor is interpreted as that supply of new streamwise vorticity by tilting of wall-normal vorticity due to velocity gradient of large scale flow field is the major source of ω_x . On the other hand, since D_{ex} shows the negative rate around the

Fig. 14 Wall-normal distribution of the splitted production rate for x -wise vorticity component ω_x , (a) : stretching part f_{ex} , (b) : turning part f_{tx} . Thick solid line : A, broken line : B, thin solid line : C, thin dotted line : D and symbols : total

position $y^+ = 10 - 30$ where the most of the quasi-streamwise vortices exist, it is found that the small scale structures attenuate their own stretching rate with each other, that is, each quasi-streamwise vortex weaken oneself by the interaction with the other one.

Also such a feature of production rate explains the above numerical experiments' result ; in the case of large scale, since the production rate A terms only contribute to the generation of vorticity and at the same time viscous diffusion term is small, the large scale structure dissipate gently. And in the case of small scale, though D_{tx} terms produce vortex to a certain extent in near wall layer, D_{ex} is negative rate, i.e. vorticity is not stretched enough to be matured, thus small scale structure dissipate quickly.

5. Conclusions

Based on a particular DNS using a long streamwise computational box, it analyzed using the

discrete Wavelet transformation about the cluster of quasi-streamwise vortices. The conclusion are as follows :

1) The cluster of quasi-streamwise vortices exists intermittently in flow field and their size become about several times of length of individual quasi-streamwise vortex. Also, the cluster moves to the downstream while it shows the characteristic by which it develops, it maintains and attenuates.

2) The clustering is confirmed to be inherent in the near wall turbulence. Regeneration property of quasi-streamwise vortices is substantial mechanism in cluster formation using a simplified numerical experiment.

3) By decomposition of vortical field into large scale and small scale structures, it turned out that usually observed quasi-streamwise vortices are small scale ones and are covered by large scale structure.

4) Large scale vortices can survive long if they do not interact with small scale vortices though they are not self-sustainable. But small scale vortices necessitate assistance of large scale vortices which is not arbitrary one but inherent to themselves, to sustain.

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