NEAR-WALL STRUCTURE IN A FULLY DEVELOPED TURBULENT PIPE FLOW

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ABSTRACT

This paper investigates the near wall structures of a turbulent pipe flow at Reynolds numbers ranged from 5000 to 10000. The LIF technique is used for the visualization of the flow patterns which are recorded by a CCD camera at the speed of 25 frames per second. The longitudinal vortices and bursting rates are evaluated from the time series of the images. The results show that both average spacing of the longitudinal vortices and mean time interval of the bursts are greater than those at plate wall of turbulent flows. The Fourier Descriptor technique is used for reconstruction of the vortical structures near the wall, it provides a new tool to explore the spatial evolution of the coherent structure.

INTRODUCTION

It is now well known that for wall-bounded flows, the majority of the turbulence production occurs in the inner region. The flow in near-wall region has some important characteristics as the low velocity streaks and subsequent ejection of low velocity fluid away from the wall to the outer region. This overall process called burst phenomena plays a significant role in the generation of turbulence as well as in the heat and mass transfer in wall-bounded turbulent flows.

Most of studies about the burst phenomena concern turbulent boundary layer and channel flows. (Head and Bandhyopadhyay, 1981; Blackwelder and Haritonidis, 1983; Bogard and Tiederman, 1986, 1987; Luchik and Tiederman, 1987) The aim of this paper is to characterize the burst phenomena in a turbulent pipe flow. We could expect that the curvature of the wall will act on the bursts and so all the induced physical processes.

* A project cosponsored by Chinese National Natural Science Foundation, Sino-French Laboratory (LIAMA) and Dassault Aviation.

The experimental technique adopted in this study is flow visualization and image processing. Taking advantage of the Fourier Descriptors theory, we developed a heuristic scheme for the three-dimensional reconstruction of structures from the two-dimensional images. Both qualitative and quantitative results can then be extracted.

EXPERIMENTAL FACILITY AND VISUALIZED STRUCTURES

The experiments were performed in a circular smooth water pipe flow of inner diameter 40mm at Reynolds number 5000 and 10000, based on the bulk velocity and the diameter of the pipe. The friction velocity u_τ is estimated as 0.0102m/s and 0.0186m/s at corresponding Reynolds numbers by the Blasius semi-empirical law. (Schlichting, 1979)

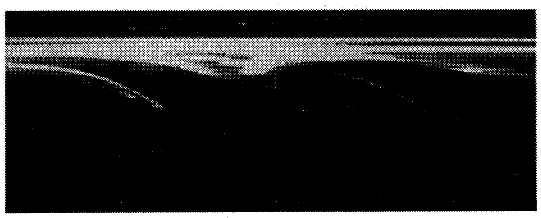
Fluorescent dye was used for visualization and injected at the wall nearly tangentially by means of a circular slot with a with of 0.3mm. The injection rate of the dye was low enough to ensure that it does not disturb the turbulent pipe flow and it marks quite well the near-wall structures.

Both longitudinal and cross planes are illuminated by a 1 mm laser light sheet. The images are stored in the video tape by means of a standard CCD camera with a lens of 55 mm focal length. The images are then digitized and processed on WorkStation.

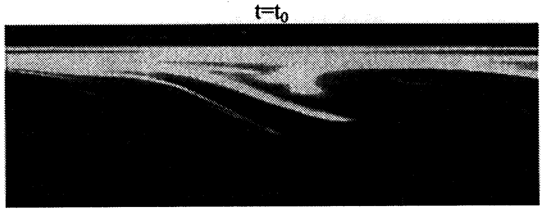
Figure 1 shows the typical pictures of the near wall structures on the longitudinal plane in which the inclined dyes reveal the lifting and ejection events as well as the spanwise vortices. These near-wall turbulent structures are similar to those of plate wall turbulence.

Figure 1. Flow structure on longitudinal plane
Re=5000

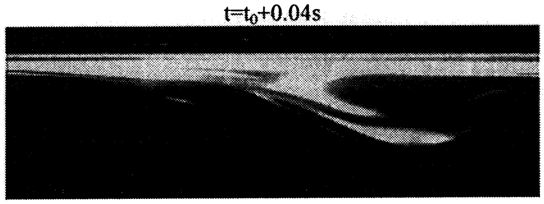
The burst frequency is evaluated from the two-dimensional images by searching the ejection events frame by frame in the near wall region. Three successive images during the ejection are shown in Figure 2 in which the dye is ejected at $y^+=10$.



$t=t_0$



$t=t_0+0.04s$

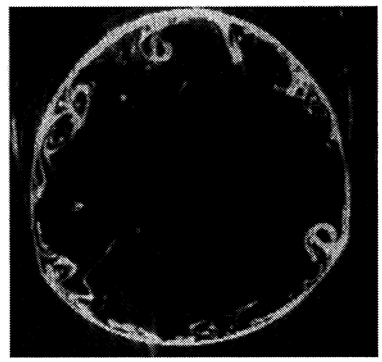


$t=t_0+0.08s$

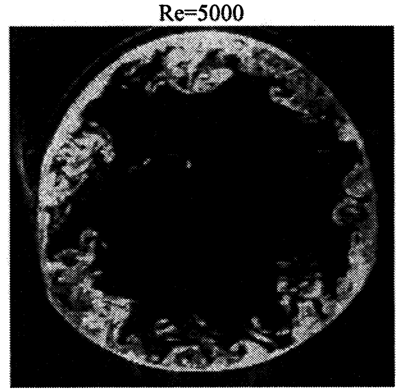
Figure 2. A typical ejection in three successive time

Bursts are identified visually in terms of the criterion suggested by Bogard and Tiederman (1986). The average burst rate is about $(8\sim10)U_m/R$ at $y^+=10$.

Figure 3 shows the evolution of near-wall structures in a cross section at Reynolds number 5000 and 10000 respectively. There are six or eight longitudinal vortices at Re=5000, ten or twelve vortices at Re=10000.



Re=5000



Re=10000

Figure 3. Flow structures in cross section

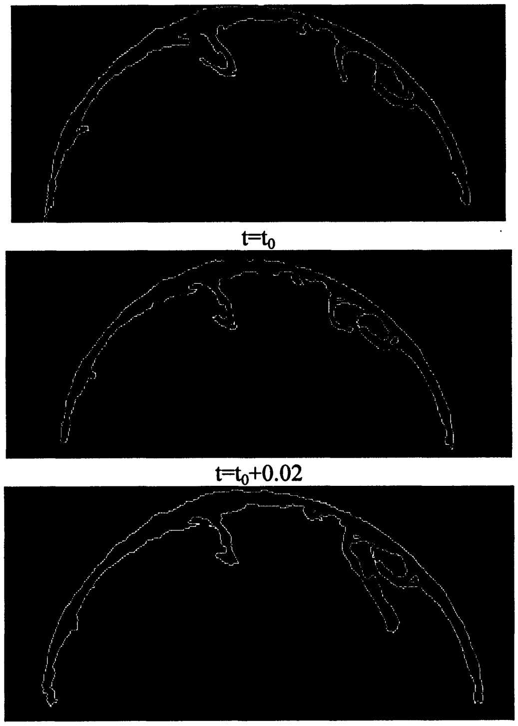
The average spacing at $y^+=10$ is estimated around 180 based on the wall scales and is much larger than the average spacing of streaks, usually 100, at plane wall of turbulent flows. The visualized pictures in the cross section clearly demonstrate the focusing effect on longitudinal vortices by the circular section of the pipe when they are moving towards the core region of the pipe. (Sabot and Comte-Bellot, 1976)

RECONSTRUCTION OF THE STRUCTURES

From the time series of the two dimensional images on cross plane, we are able to reconstruct the three-dimensional configuration of the near wall structures by use of the frozen hypothesis. The time interval between two consecutive images (fields) is 0.02s which should be compared to the integral time scale, $T_L=D/U_b$, estimated as 0.026s and also to the inner layer time scale $\nu/u_\tau^2\sim0.01s$.

With these time characteristics, the images are not so closely taken in time so that only three or four successive two-dimensional images can be used for considering the turbulence as nearly frozen in time. To reconstruct the three-dimensional configuration of the structure from few 2D images we use the Fourier Descriptors technique.

From the two-dimensional images, we can extract by image enhancement the edges and contours of the structures. Figure 4 shows the contours of the structure in a cross section at three successive instants.



$t=t_0$

$t=t_0+0.02$

$t=t_0+0.04$

Figure 4. Three successive contours of flow structures in cross section

Fourier Descriptor Coefficients (FDC) and Fourier Descriptor are defined from the Fourier Transform and the Inverse Fourier Transform of the complex coordinates $z_{s,P}$, the points on the contours, as

$$A_{r,P} = \sum_{s=-M/2}^{M/2-1} z_{s,P} \exp\left\{-\frac{2j\pi}{M} sr\right\} \tag{1}$$

$$z_{s,P} = \frac{1}{M} \sum_{r=-M/2}^{M/2-1} A_{r,P} \exp\left\{\frac{2j\pi}{M} sr\right\}, \quad r,s \in \left[-\frac{M}{2}, \frac{M}{2}-1\right] \tag{2}$$

In the Fourier space, we can define a quantitative measure of the geometrical differences between two successive contours C_k and C_{k+1} as

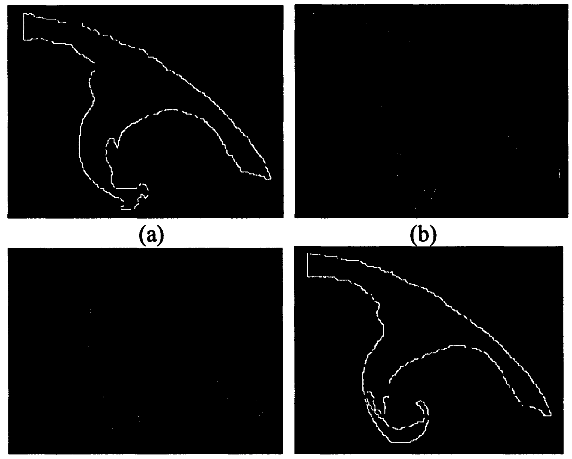
$$d(C_k, C_{k+1}) = \left[\sum_{s=-R/2}^{R/2-1} \left(A_{s,P} - A_{s,Q}\right)^2\right]^{1/2} \tag{3}$$

where $A_{s,P}$ and $A_{s,Q}$ represent the FDC of contours C_k and C_{k+1} respectively. R is the minimum number of the points of the two contours. If the distance $d(C_k, C_{k+1})$ is large, some intermediate contours are created by linear interpolation in the Fourier space as follows

$$A^{\lambda_i}_{r,(P,Q)} = \lambda_i A_{r,P} + (1-\lambda_i) A_{r,Q} \quad \lambda_i = \frac{i}{n+1} \tag{4}$$

in which n is the number of intermediate plane.

An illustration of this possibility is presented in Figure 5 in which two successive contours of a wall sturcture with a distance of 25 are presented. Figure 5(a) and (d) are the original successive images and Figure 5(b) and (c) are the interpolation.



(a) (b)

(c) (d)

Figure 5. Illustration of the interpolation of the contour by Fourier Descriptor

A general three-dimensional reconstruction procedure is then established in the following way. We first determine which successive contours are matching together. Then we evaluate deformations and differences between these contours in order to link them directly or to create some intermediate contours. Finally, all contours are connected points by points using a minimum criterion.

Figure 6 shows the images of a near-wall structure at three successive instants and Figure 7 its three-dimensional reconstruction.

(a) (b) (c)

Figure 6. Three successive images of flow structures at cross section (Re=6000)

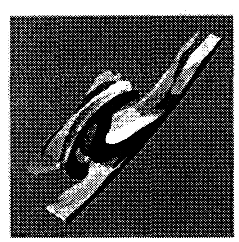
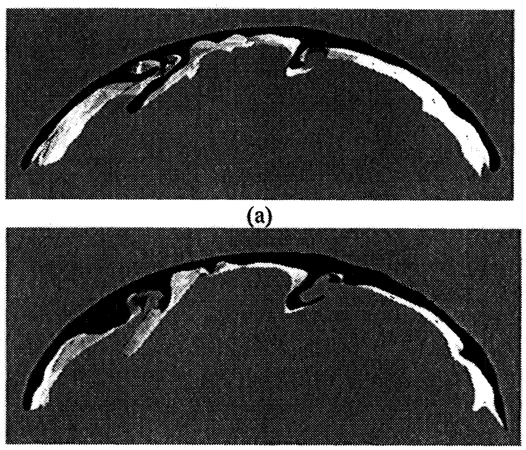


Figure 7. Three dimensional reconstruction of a near wall structure from the images shown in Figure 6.

Moreover, the reconstruction of the near-wall structure in half pipe can be realized from the successive image contours of Figure 4. The spatial streaks and ejection effect can then be demonstrated as shown in Figure 8.



(a)

(b)

Figure 8. Three dimensional reconstruction of structures in half pipe from the images shown in Figure 4.

CONCLUDING REMARKS

1. The visualized pictures of the turbulent pipe flow show the similar near wall structures to those at plane wall turbulence, i.e. streaks or longitudinal vortices and ejection events etc. However it has different characteristic quantities, greater spacing of streaks and less bursting rates.
2. The reconstruction of the near wall structure by Fourier Descriptor technique is adequate and it creates a new tool to explore the turbulent coherent structures.
3. To have more detailed understanding of the turbulent characteristics a combination of visualization and measurements of the near wall turbulence is necessary and it is in progress now.

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