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n xperimental Study on the Structure of uncture lows

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***Abstract*:** The structure of juncture flows caused by a flat plate mounted a short cylinder on has been experimentally studied through visualization and measurement. The experiment was conducted in a water tunnel with low turbulence intensity which is less than 0.3%. The test Reynolds number was changed from 1,000 to 32,000. The results suggested that (a) four typical flow patterns were visualized clearly, which correspond to four Reynolds number ranges respectively; (b) there are strong correlations between the oscillation of the juncture horseshoe vortex system and the velocity fluctuation of upstream separated shear layer.

***Keywords*:** juncture flow, horseshoe vortex, flow pattern, fluorescent dye.

1. Introduction

Juncture flow in front of a bluff body mounted on a flat plate or on a curved surface with small curvature is a common kind of flow such as wing-body juncture flow, building-ground juncture flow, pier-riverbed juncture flow and so on. In general, juncture flow is a very complex, three-dimensional and non-stationary one, which contains three-dimensional boundary layer separation, attachment, and vortex shedding, convection, wrapping and merging.

In the past decades, juncture flow has been investigated quite extensively. Earlier flow visualization by Schwind (1962) and Baker (1978, 1979) showed some of typical flow pictures. The detailed experiment by Baker (1979) first revealed that, with the increase of Reynolds number, the flow pattern of juncture flow evolves from a single primary horseshoe vortex to multiple vortices, and from steady horseshoe vortex system to unsteady one. Thomas (1987) suggested that the periodic phenomenon does not strongly depend on the characteristics of the incoming flow, and is not related to the familiar Karman vortex shedding, which was also found by Visbal with numerical simulation (1991). Recently, Ahmed and Khan (1995) observed vortex wrapping and engulfing near the cylinder as well as the vortex shedding from upstream shear layer in unsteady case. The viscous dissipation of the unsteady horseshoe vortex was studied by Tobak and Peake (1979). Also, Measurements of pressure and velocity have been carried out (Dargahi, 1989; McMahon et al., 1982; Pierce and Harsh, 1988; Menna and Pierce, 1988; Khan, 1995). One of the notable characteristics of juncture flow is the oscillatory behavior of horseshoe vortex, which is considered as a characteristic to plot flow patterns. Baker (1991) analyzed the oscillatory behavior of horseshoe vortex may be due to the oscillations of the upstream separated shear layer and the oscillations of the vortex core itself. A recent work of Wei et al. (1998) proved that the oscillatory behavior of horseshoe vortex was due to the incessant shedding of vortex from the shear layer and convection toward the cylinder, and merging each other. Most of results from numerical simulation concentrated on the topology and vortex system evolvement with

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changing Reynolds number. To the present, simulation of laminar juncture flow was more successful. Briley et al. (1985) simulated steady horseshoe system. Kaul et al. (1985) simulated horseshoe vortex system and analyzed topology structures. Visbal (1991) not only simulated juncture vortex evolvement and revealed the periodic process at *Re* = 5,400, but also first illustrated the existence of saddle-point-of- attachment flows. And later, Coon and Tobak (1995) proved that the new topology could occur over a range of Reynolds number with experiment.

To describe the horseshoe vortex system in detail, this paper addresses an experimental study with wide Reynolds range (1,000-32,000). The main objectives of this work is to study juncture flow from laminar to turbulent: (1) with fluorescence dye, visualize the flow field to observe the evolvement of horseshoe vortex system with changing Reynolds number; (2) with hot-wire anemometer, measure the frequency characteristic of oscillating horseshoe vortex system and finally, to classify the flow patterns according to the behavior of horseshoe vortex.

2. xperiment Setup

2.1 Water Tunnel

Experiments were conducted in Peking University SKLTR (The State Key Laboratory for Turbulence Research) in a 400mm × 400mm × 6,000mm low turbulence intensity water tunnel, capable of velocity of 30mm/s to 1,300mm/s approximately with the turbulence intensity less than 0.3%.

2.2 Models

Square, circular and prismatic cylinders with 80mm in characteristic length and 160mm in height, made of plexiglass, were used respectively. In the experiment, the test Reynolds number based on the side length of the square cylinder is changed from 1,000 to 32,000. A flat plate with an elliptic leading edge and a tapered trailing edge, 8mm thickness, 395mm span and 2,000mm length, is horizontally mounted on the test section with a distance 100mm from the section bottom. The cylinder is mounted on the flat plate, which is on the plate centerline and 700mm apart from the plate leading edge. Several narrow holes are made on the flat plate and located upstream of the cylinder for dye (Fig. 1).

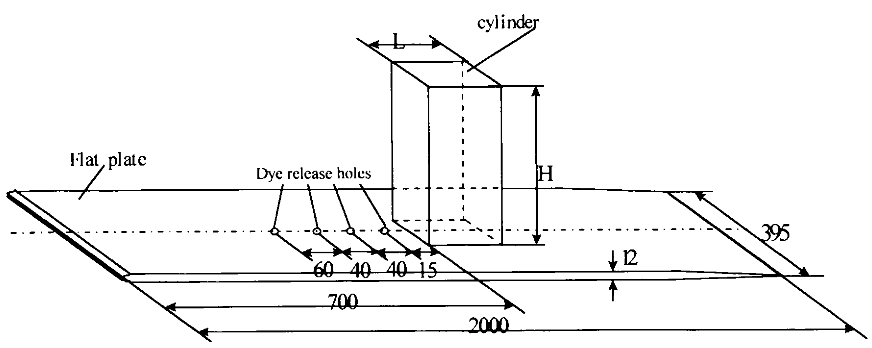


Fig. 1. Model (Unit: mm).

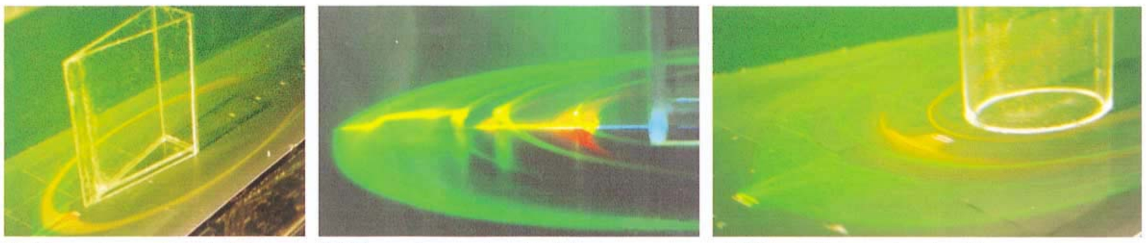
2.3 Experimental Devices

A set of equipment including fluorescent dye conductor and laser sheet was used. The fluorescent dye has two colors; red and green. The former is released from the hole which is nearest to the cylinder to visualize the primary vortex and the latter is released from other holes to visualize the vortex shedding and separated boundary layer. The laser light sheet is formed by an Argon-ion laser source with power 5W and a cylinder lens. Besides, a hot-wire anemometer with a single hot-film probe was used to measure the fluctuating velocity.

3. xperimental esults

3.1 Flow Visualization

With fluorescent dye, the configuration of the juncture flow with changing Reynolds number was visualized. Figure 2 shows that the flow configurations of three models at *Re* = 4,000 are similar, which all constituted the complex three-dimensional horseshoe vortex system. It can be observed that the horseshoe vortex extends to the wake of the cylinder (Fig. 2(a)), and the flow is separated from the upstream and forms a shear layer where the horseshoe vortex comes into being and sheds constantly (Fig. 2(b) and 2(c)). Figure 3(a) shows the side view of the vortex system on the symmetry section of the juncture flow in front of a square cylinder. Both the horseshoe vortices and the secondary vortices near the plate can be recognized obviously. The largest one, close to the cylinder, is called primary horseshoe vortex (Fig. 3(b)). Therefore, the topology of juncture flow can be shown in Fig. 3(c).



(a)Horseshoe vortex stretch to the wake (prism cylinder) (b)Horseshoe vortex shed from upstream shear layer (square cylinder) (c)Horseshoe vortex shed from upstream shear layer (circular cylinder)

Fig. 2. Picture of the vortex system in Juncture flow (top view).

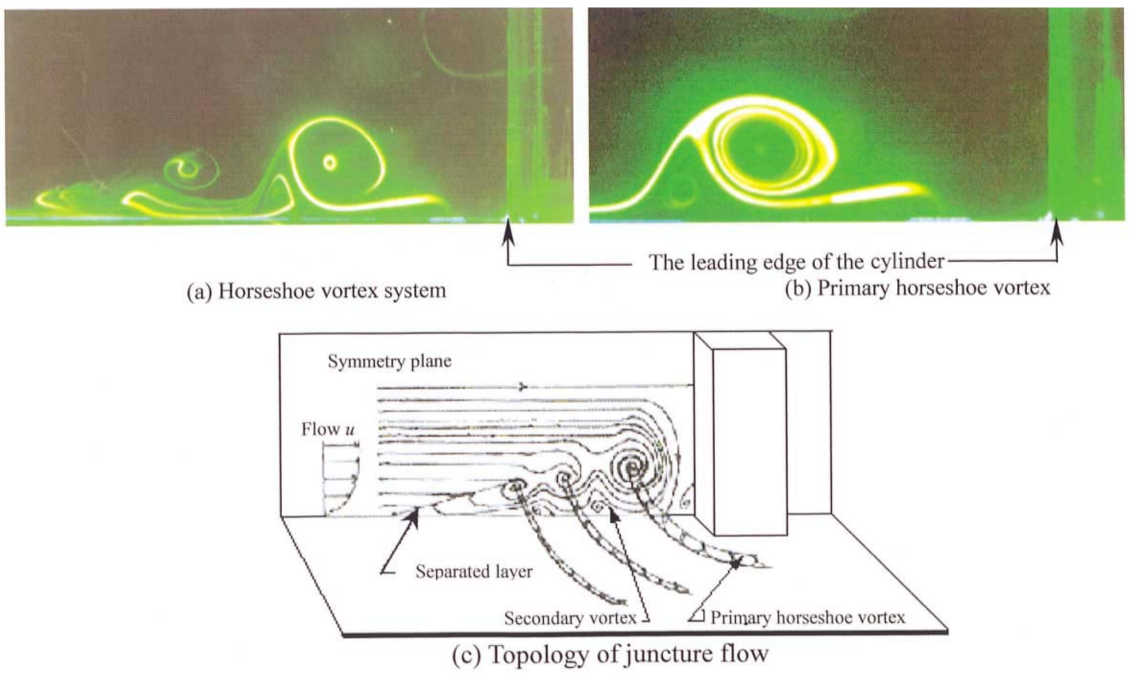


Fig. 3. Picture of the vortex system in juncture flow (side view).

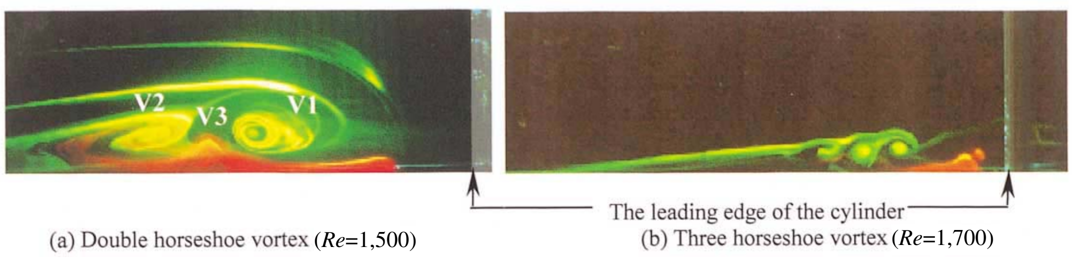


Fig. 4. Steady horseshoe vortex system.

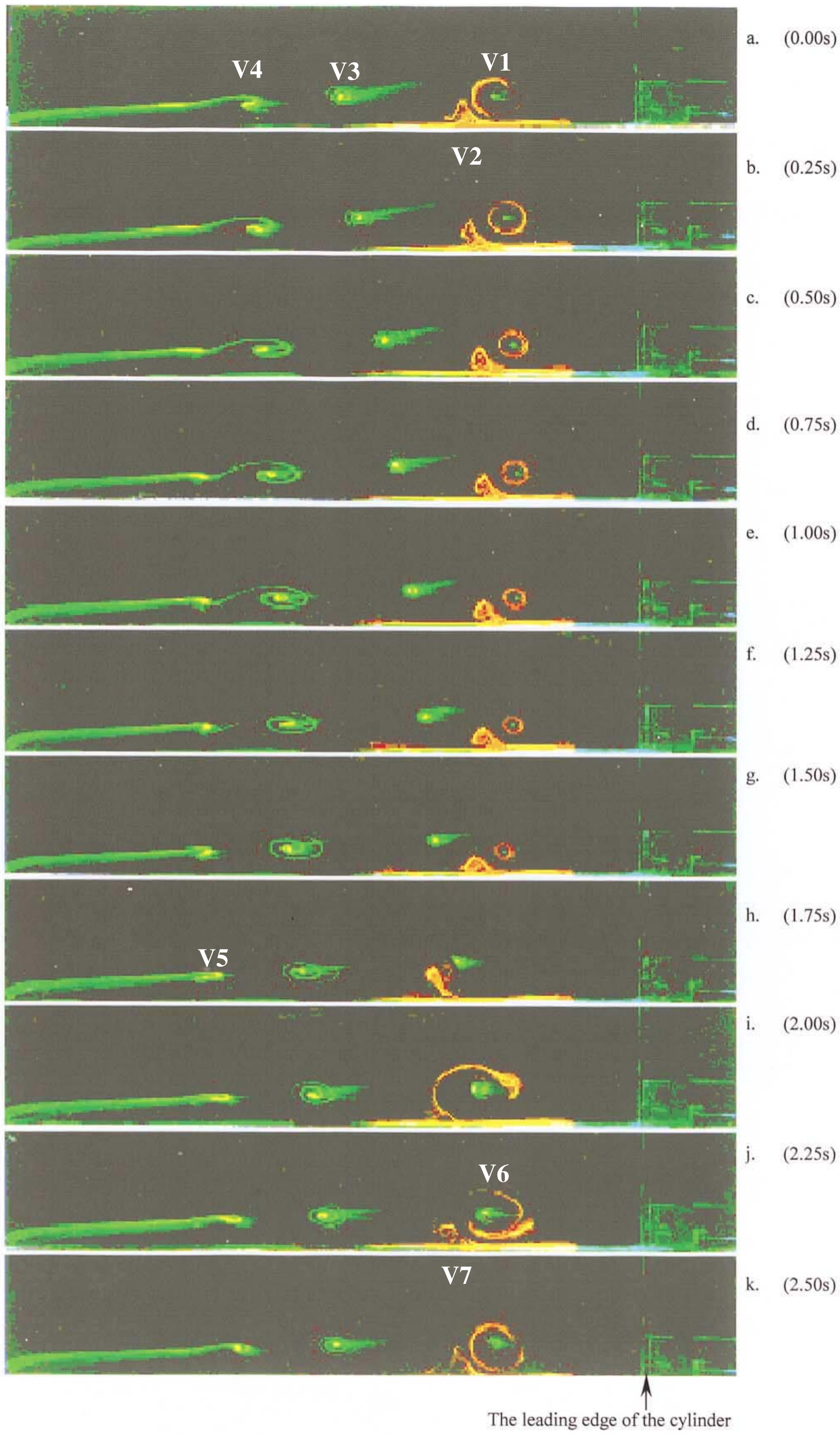


Fig. 5. The periodically oscillating horseshoe vortex system (side view, Re = 4,000).

The following four typical flow patterns are observed in the range of test Reynolds number from 1,000 to 32,000. For simplicity, only the case of juncture flow of a square cylinder is discussed below.

Pattern I: Steady horseshoe vortex system

The horseshoe vortex exists at the minimum achievable Reynolds number of 1,000 in the water tunnel. The observed vortex system is steady and seems to be spatially fixed at the same location. Figure 4(a) shows the horseshoe vortex system of two vortices (V1, V2) and one counter rotating secondary vortex (V3) at *Re* = 1,500. The numbers of "steady" vortex system increase with the increasing Reynolds number. The vortex system of three vortices and two secondary ones are also observed at *Re* = 1,700 (Fig. 4(b)). This pattern has been observed until Reynolds number reaches to about 2,000. Further increasing in Reynolds number the vortex system exhibits oscillating behavior.

Pattern II: Periodically oscillating horseshoe vortex system

With the increasing Reynolds number from 2,000, the oscillation of vortex system became more acute, and sometimes the shedding of vortex from separated shear layer was observed. Moreover, these shedding vortices orderly wrap and merge the former primary vortex and corresponding second vortex in front of the cylinder and form new primary vortex. In the process the primary vortex moves forth and sways back, showing oscillatory characteristics.

Figure 5 is sequential pictures of the flow patterns at interval of 0.25 second taken on the symmetry section of the juncture region using a laser light sheet at *Re* = 4,000. The flow pattern shown in Fig. 5k is almost the same as the one shown in Fig. 5a, therefore Figure 5 shows the vortex motion in a period of 2.5 second. It can be seen from Fig. 5 that (1) the vortices V3 and V4 are shed from the tip of separated shear layer and flows down; (2) near the front edge of the cylinder the shed vortex V3 induces the former primary vortex V1 and the second vortex V2 to move upstream (pictures e, f and g of Fig. 5) and wraps them and lastly forms a new primary vortex V6 and a

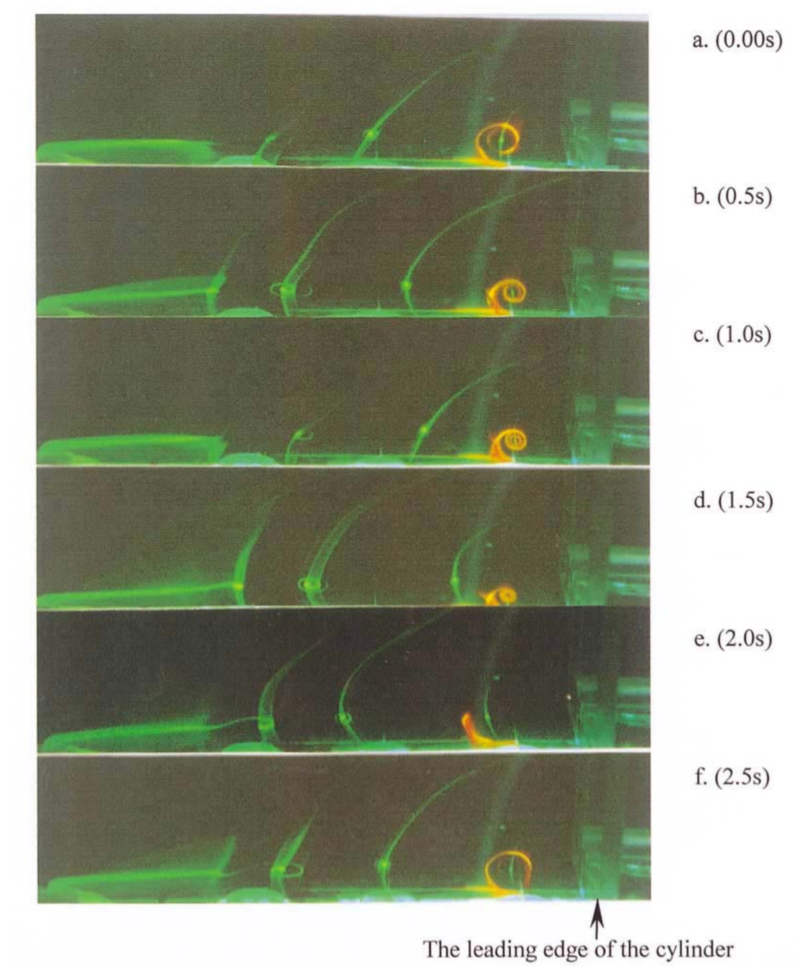


Fig. 6. The periodically oscillating horseshoe vortex system (top view, *Re* = 4,000).

second vortex V7 (pictures h, i and j of Fig. 5). In this period the primary vortex fulfils an update and does oscillation one time.

Figure 6 is also sequential pictures at interval of 0.5 second under the same conditions as that of Fig. 5, but taken at a different moment and from a top visual angle. As a spatial view, Figure 6 shows the same procedure as that shown by Fig. 5 more clearly. It can be observed that the separated shear layer and the shed horseshoe vortices are very smooth at the Reynolds region 2,000-5,000.

Pattern III: Unsteadily oscillating horseshoe vortex system

When Reynolds number is between 5,000 and 8,000, the separated shear layer and the shedding horseshoe vortices become irregular, and the periodicity of the oscillation of the juncture vortex system becomes unstable. The smooth vortex core observed in pattern II becomes tortuous (Fig. 7). Sometimes, the vortices merging earlier can be observed during their travelling toward the cylinder. The separated shear layer was also observed to be irregular.

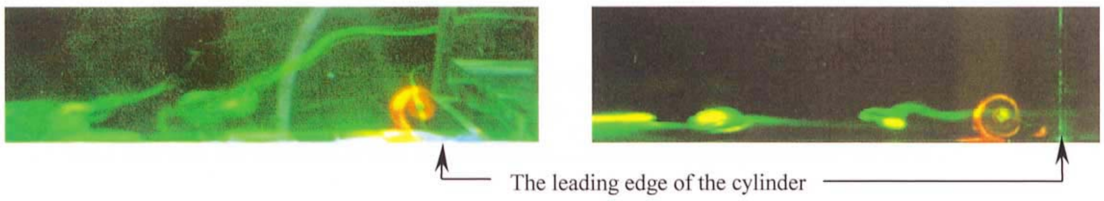


Fig. 7. Unsteady oscillating horseshoe vortex (*Re* = 7,000).

Pattern IV: Intermittent or continuous turbulence juncture flow

With the increase of Reynolds number, the oscillation of the vortex system becomes unsteadier. Sometimes, the vortex was difficult to be discerned, and intermittent phenomena were observed (Fig. 8). This pattern can be thought as the intergrade from laminar juncture flow to turbulent one. When the Reynolds number is greater than 9,000 approximately, the distinct separated shear layer cannot be observed, and the flow patterns showed a turbulent character. Figure 9 (*Re* = 11,000) showed the intermittent turbulent juncture flow. The process of vortex shedding has not been observed, and only one primary vortex can be discerned. This intermittent phenomenon exists until Reynolds number 14,000. The juncture flow exhibits continuous turbulent behavior for $Re \geq 14{,}000$ (Fig. 10). In this case a lot of vortices in the separation region flow down rapidly, interact with each other and form the primary horseshoe vortex lastly that oscillate more acutely and stochastically.

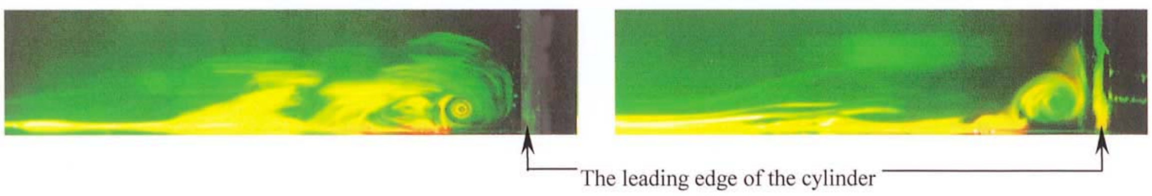


Fig. 8. Unsteady oscillating horseshoe vortex with intermittent phenomenon (side view, *Re* = 8,500).

Fig. 9. Intermittent turbulence juncture flow (side view, *Re* = 11,000).

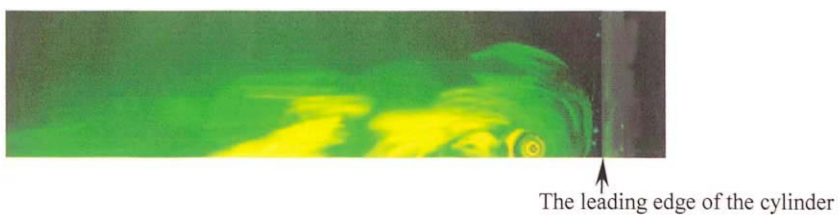


Fig. 10. Continuous turbulence juncture flow (side view, *Re* = 24,000).

3.2 Measurements of Vortex Oscillations

The power spectrum of the velocity fluctuation at two positions in the juncture flow has been measured. One of the measurement positions is at the vortex shedding region denoted by s-position. Another is at the primary vortex region denoted by "c-position." Let F^* be characteristic frequency which corresponds to a peak of the power spectrum and $F = F^*L/U$ be its dimensionless value, where L the characteristic scale of a cylinder, U the mean velocity of incoming flow at the entrance of the test section and let $<F_s>$ and $<F_c>$ be the set of these characteristics frequency measured at s-position and c-position, respectively. It has been found that three typical relationships between $<F_c>$ and $<F_s>$ correspond to three zones of Reynolds number. Figure 11 shows the results obviously.

Zone I: 2,000 < *Re* < 5,000, both $<F_s>$ and $<F_c>$ are single-valued and very close.

For the Reynolds number at the zone 2,000 < Re < 5,000, both the $<F_s>$ and $<F_c>$ have only one main frequency F_s and F_c respectively, and are very close, and even equal (zone I of Fig. 11). The horizontal distance X from s-position and c-position to the leading edge of the cylinder is 150mm and 10mm respectively. As an instance, the dimensionless frequencies of F_s and F_c are equal to the same value 0.42 at Re = 3,900. Actually this result proves that the oscillation of primary horseshoe vortex is entirely due to the periodic vortex shedding from the upstream separated shear layer and periodic vortex merging in front of the cylinder. This zone corresponds to the typical flow pattern II.

Zone II: 5,000 < *Re* < 8,000, $<F_s>$ is single-valued, but $<F_c>$ is multiple-valued.

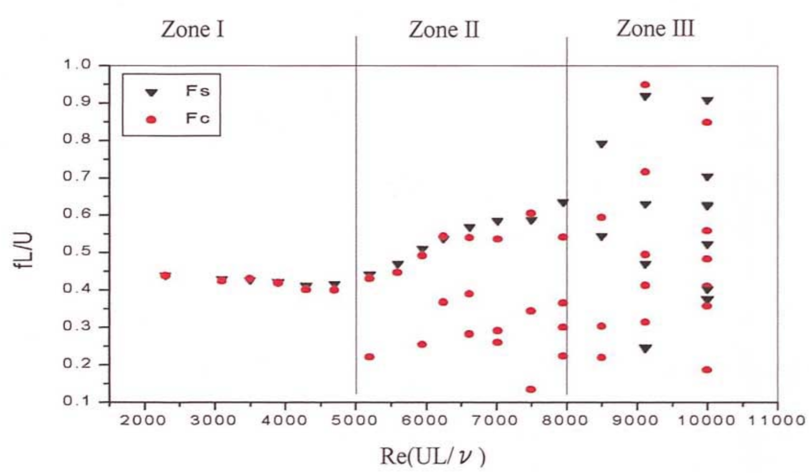


Fig. 11. Relationship between F_s and F_c with changing Reynolds number.

For Reynolds number in the range of about 5,000-8,000, $<F_s>$ retains single-valued F_s, but $<F_c>$ becomes multiple-valued, and $<F_c>$ contains some of divisions of F_s (zone II of Fig. 11). The horizontal distance X from s-position and c-position to the leading edge of the cylinder is 130mm and 10mm respectively. In this zone one value of $<F_c>$ is close to F_s, and the others of $<F_c>$ may be equal to or close to F_s/N, N = 2, 3, ..., for example, at Re = 5,900, F_s is equal to 0.5, while $<F_c>$ has two values 0.507 and 0.25. The last one is just equal to $F_s/2$, i.e. 1/2 division frequency of F_s. This relationship between $<F_s>$ and $<F_c>$ is due to the vortices merging ahead of time during their travelling downstream in the juncture. This zone represents the phase where the laminar flow is becoming unstable, corresponding to the typical flow pattern III.

Zone III: *Re* > 8,000, both $<F_s>$ and $<F_c>$ are multiple-valued.

For Reynolds number larger than 8,000, both $<F_s>$ and $<F_c>$ are multiple valued and $<F_c>$ has some values which are close to some components of $<F_s>$ (zone III of Fig. 11). The horizontal distance X from s-position and c-position to the leading edge of the cylinder is 100mm and 20mm respectively. This zone corresponds to the flow pattern IV. The separated shear layer has become unstable, and periodicity is entirely destroyed. The flow has become intermittent or continual turbulence.

4. onclusions

From the results of visualization and measurements it can be found that the juncture flow in front of a short cylinder mounted on a flat plate appears four typical flow patterns corresponding to four ranges of Reynolds number. They are as follows:

I steady separation flow and horseshoe vortex system, for Reinolds number less than about 2,000;

II periodical vortex shedding from separated shear layer and periodical oscillation of the primary vortex with the same frequency as the vortex shedding, for Reinolds number at about 2,000-5,000;

III basically periodical vortex shedding and unsteady multiple-valued periodical oscillation, for Reinolds number at about 5,000-8,000;

IV turbulent separarion and stochastic primary votex oscillation, for Reinolds number bigger than 8,000.

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