Fluid Forces Acting on a Circuler Cylinder with Single Semi-Circuler Cylindrical Tripping Wire

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Abstract

The purpose of this paper is to investigate the effect of a semi-circuler tripping wire on the aerodynamic character of a circuler cylinder as basic research for study on Rain-wind induced vibration. As a results of experimental investigation on the fluid forces acting on a circuler cylinder with a semi-circuler tripping wire, it became evident that there were bi-stable flows in the limiting condition of R_e number and relative height of a trippig wire to diameter of cylinder d/D. In a state of the bi-stable, the mean values of lift forces in short times show rectanguler change intermittently. It is decided the condition convereted into the bi-stable flows by statistic characters of flactuating lift and the change of fluid forces with the switching of two flow patterns by analysis of the measured fluctuation of fluid forces transformed into low frequency fluctuation through the low pass filter with 2 or 3 times period of eddy shedding from a circuler cylinder.

1. INTRODUCTION

One of the important factors of Rain-Wind induced vibration is aerodynamical instability induced by a path of rain-water on the cable of bridges (13),(14). Concidering a semi-circuler cylindrical tripping wire as a model of a rain-water path, we have investigated experimentally the fluid forces acting on a circuler cylinder with single semi-circuler cylindrical tripping wire.

This problem is a result of natural phenomina and can be dealt with the control of flow around a circuler cylinder. There are two ways to control the flow around a circuler cylinder. One is to control boundary layer (4),(5),(7),(8), and another is to control wake flow (2),(3),(8). As concrete examples, the way to control unstable vibration by setting up a V-strive on a cable (15) and the way to control excessive vibration of aqueduct by setting up small cylinders (15) are proposed. Our research concerns the way to control the boundary layer around a circuler cylinder with two tripping wires being set symmetrically with respect to the stagnation point. It has been cleaned already that when setting angle of tripping wires is less than a certain value, the drag coefficient reduces to 0.5 by the cause that shear layer separated from the re-attaches to the surface of a cylinder (7). As the result of our present experiment

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setting a single tripping wire, the drag coefficient reduction was about 1/2 of that of single cylinder with two wire setting symmetrically. On the other hand, the maximum lift coefficient was great, specifically, about 0.4 ~0.45. This value agrees well with one obtained by supposing that pressure profiles on the side without tripping wire may be the same as that of single cylinder. At re-attachment region of separated bubble, it has been cleared that three dimensional larege scale vortex structure flows away (11),(12). It has been considered that this three dimensional vortex has effects upon separation of flow from the surface of a circuler cylinder in down stream and forms a singuler flow field. We have found already that rectanguler-like fluctuation of lift forces caused by switching of two different flow fields alternating intermittentley under the conditions of setting angle of a single tripping wire and Reynolds number from distribution function analysis of fluctuating lift forces. This paper reports the results of investigation on the occurence conditions of this singuler lift force and switching period and mean amplitude of rectanguler like wave of lift forces.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The experiment was carried out with wind tunnel having working section 1m wide × 10cm hight and 1m long. Side walls of the test section are made 10mm thick acrylic resin plate, the ceiling is made of 9mm thick glass and the floor is made of 15mm thick Bakelite plate. A 50mm diameter test circuler cylinder was set on the centerline 20cm away from the entrance of the test section. Static pressure distribution was uniform at the section where the cylinder was set. The static pressure reduced lineary in down stream direction and equaled to atmospheric pressure at the exit of test section (9). A cylinder for measurement of fluid forces is made of acrylic resin pipe of 60mm length by 47mm in inside diameter. Above and under the test cylinder, 20mm length dummy cylinders were set at intervals of 0.1mm. These two dummy cylinders were connected by four small cylinders runnning through the test cylinder to maintain relative position. The length of the dummy cylinders and the gaps between the dummy cylinder and the test cylinder were decided by making preliminary experiment. The preliminary experiment changed Reynolds numbers and gaps between cylinders that the surface pressure distributions on axial directions become uniform and circumferential pressure profiles agree with the results of experiment in which the aspect-ratio is large enough, because the space of 0.1mm between the dummy and main cylinder divides the flow (9).

Fluid forces acting on the main cylinder were measured by strain guages on a 7mm × 7mm and 25mm length brass rectanguler pole. The center of gravity of the main cylinder was fixed with the upper part of the pole. Four KSP type semi -conductor strain guages (the guage factor=225) were put on the each side of the rectanguler pole. One pair of strain guages on the opposite sides composed four gauge Wheatstone bridge and measured the drag and lift forces simultaneously. Natural frequency of the fluid forces measurement system was nearly 1500 Hz, it is 10 times greater than the Strouhal frequency of the test cylinder.

As tripping wire, we used semi-circuler cylinders. The height of a tripping wire are 1.0mm,1.45mm and 2.0mm. And the ratios to cylinder diameter d/D equall 0.02,0.029, and 0.04 respectively. The boundary layer thickness estimated with our experiment are nearly 0.2~0.3 mm in the range of $\theta=30^\circ \sim 60^\circ$. This value is calculated according to Thwaites' approximation method using momentum thickness of the boundarly layer calculated based on non-dimensional velocity distribution u_e/u along the surface of a circuler cylinder. The velocity u_e was estimated by Bernoulli's theorem using the experimental pressure values measured by Fujita et al.(4). Then the height of a tripping wire d is 3~10 times as much as boundary layer thickness, it is higher than outer edge of boundary layer.

In this experiment, fluid forces were measured on the following condition : (a) setting angle of a tripping wire from front stagnation point $\theta$was changed in steps 1°~5°in the range of θ between 30° and 90° and (b) approaching velocity U was changed into seven cases between 8 and 20 m/s ($Re=2.56\times10^4 \sim 7\times10^4$) at each setting angle$\theta$. The signals obtained from strain gauges were degitized using A/D converter with sampling frequency 500 Hz and were analized to obtain the statistical characteristics of mean fluctuation of fluid forces.

3. EXPERIMENT RESULTS AND DISCUSSION

Fig. 1 shows the coordinate system. Each arrow difines the positive directions of drag and lift forces.

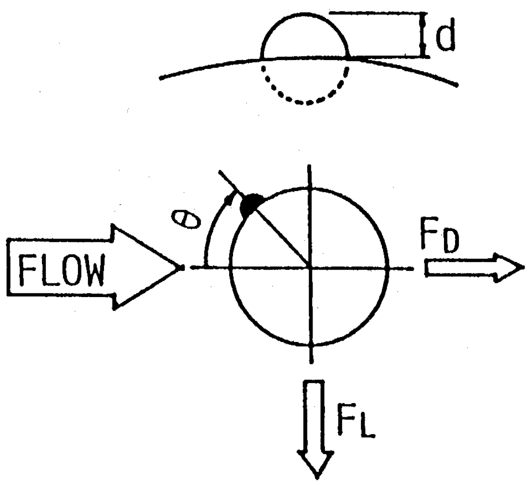

Fig. 1 Definition of fluid forces

3.1 Drag and lift coefficient

Fig. 2 and 3 show the changes of drag and lift coefficient against setting angle of a tripping wire θ for the three values of d/D. Each symbol is divided in groupes of Reynolds number. The definitions of both coefficients are the same as used in general. Drag coefficient C_d decreases with increasing θ, becomes minimum in the range of $\theta=50^\circ \sim 60^\circ$, increases remarkably within the limit of $\theta=10^\circ$ after and becomes maximum. As θ increase further, drag coefficient decreases asymptotically to that of a circuler

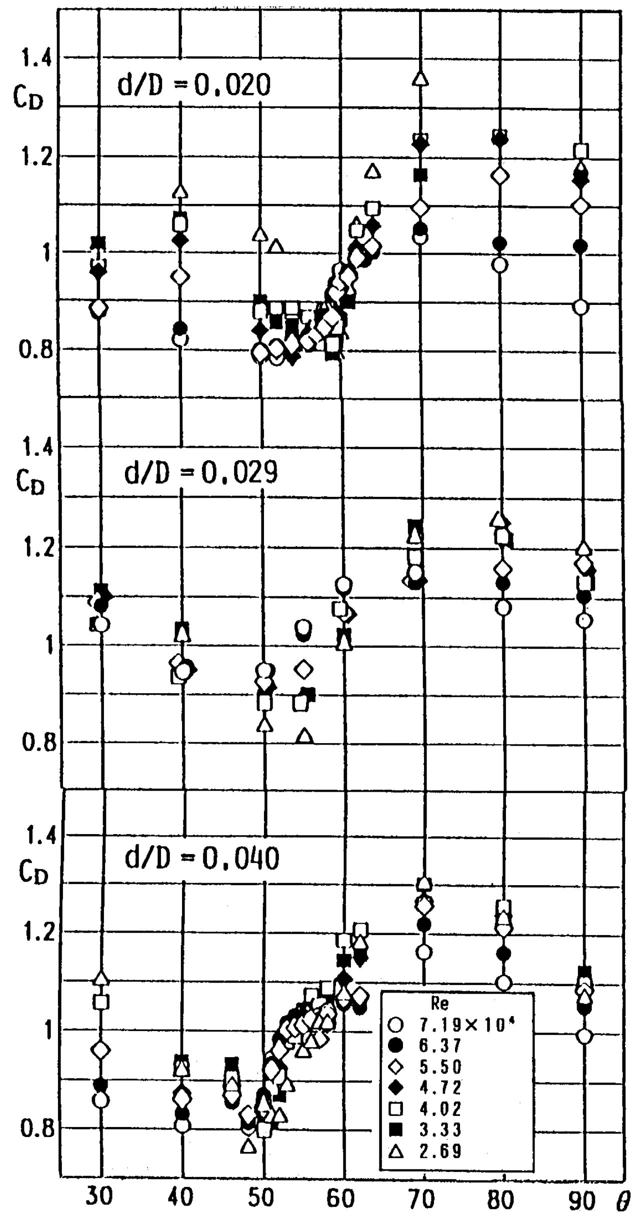

Fig. 2 Drag coefficient

cylinder with no-tripping wire.

The setting angle of a tripping wire θ at which drag coefficient takes the minimum value decreases with the increases of d/D and Reynolds number. The above change of drag coefficient with θ has a tendency toward concurring the experimental results of Fujita et al.(7) who have set tripping wires symmetrically. However, in their experiments, the smallest drag coefficient was 0.5, while in our present experiments, the smallest value of C_D is 0.8 and drag reduction rate was about half of theirs. Fujita et al.(4) measured the mean surface pressure profiles of a cylinder with two tripping wire and classified the pressure distributions into three groupes at lined in fig.4 (Dotted lines show the pressure profiles of a circuler cylinder without the tripping wires). Refering to Fig. 4, if we suppose that the separation of flow at the side without a

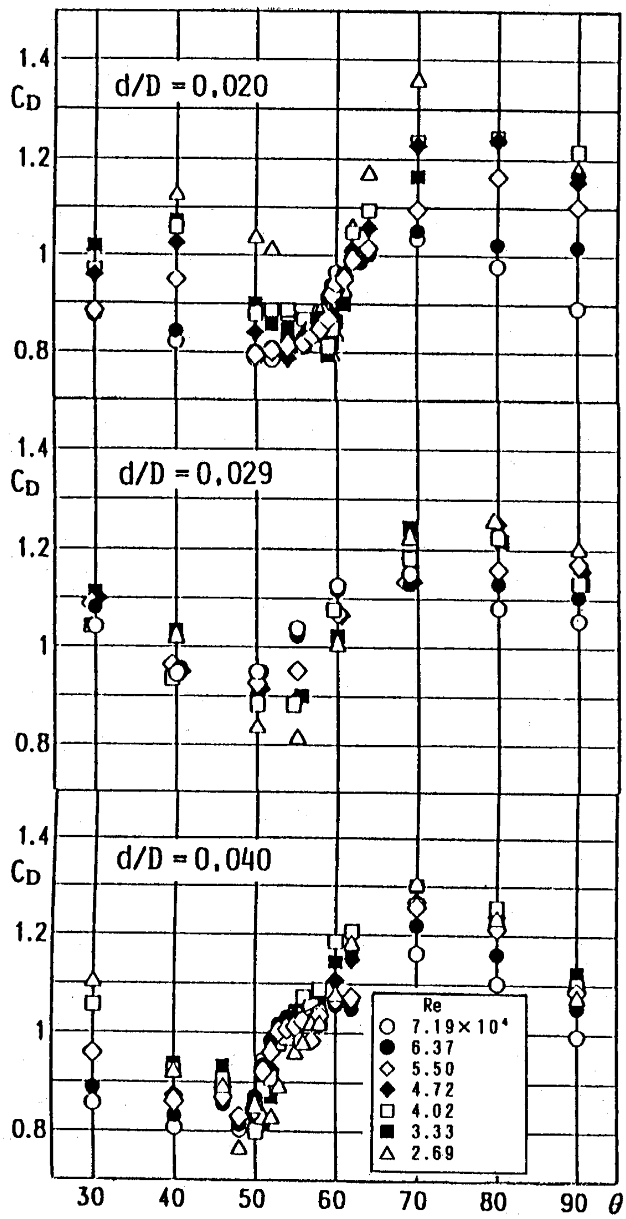

Fig. 3 Lift coefficient

tripping wire is similar to as that of a circuler cylinder, the scale of separation region will differ from each other, and the back pressure will be the middle value of both conditions. Then, it is reasonable to consider that the drag reduction rate in our present experiment is about half of that of the cylinder setting tripping wire symmetrically.

The length of separation bubble behind the wire differs with Reynolds number, from a fact that Reynolds number R_{ed} defined by the height of wire d and velocity at setting wire u_e is smaller 2nd order than Reynolds number R_e defined by the cylinder diameter D and approach velocity U. As a result, the value of drag coefficient C_d differ with R_e number.

As compared Fig. 3 with Fig. 2, the changes of drag and lift coefficient are most strongly dependent upon setting angle of a tripping wire θ. That is to say, in the region

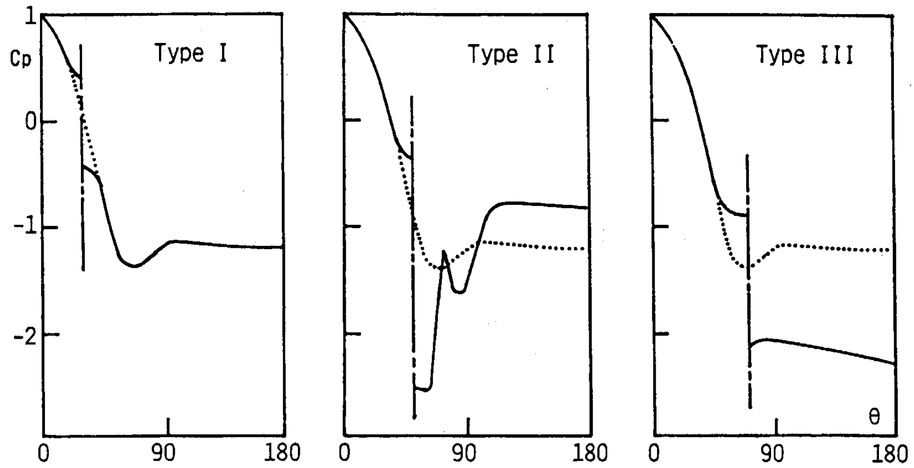

Fig. 4 A general condition of pressure profiles on surface of circuler cylinder with tripping wires setting up in symmetric with respect to the main flow direction

where drag coefficient decreases with θ, the absolute value of lift coefficient increases, and the absolute value of lift coefficient is the maximum at θ where drag coefficient is the minimum.

In the region where drag coefficient increases steeply, the absolute value of lift coefficient decreases steeply and the value of lift coefficient changes from negative to positive, because the acting directions of lift inverse. As compared with the experimental conditions by Fujita et al.(4), inversion of lift coefficient will occur at θ in Type III

From the results in Fig.4, the cause of inversion of lift coefficient in this experiment can not be explained. However, it can be explained by assuming that the separation of flow on the side without a tripping wire will be similar to that of a single circuler cylinder and back pressure does not decrease as shown in type III. Now,in order to confirm the above, we are preparing for the measurements of mean and fluctuation of pressure on the surface of the cylinder.

3.2 Fluctuating patterns of fluid forces

We examined fluctuating patterns and a probability mass function of fluctuating lift force, since it fluctuates unstably with time in the region of θ where the absolute value of lift coefficient decreace steeply and the direction of lift inverses. Fluctuating patterns of lift forces are divided into four basic groups shown in Fig.5 . As θ increase, fluctuating patterns of fluid force are converted into the following four types A,B,C and D.

Type A: A probability mass function is nearly normal distribution, it is observed in the region where θ is small and drag coefficient decreases and the absolute value of lift coefficient increases as θ increases.

Type B: This pattern is observed in the region where θ is smaller by about 10° than the setting angle where drag coeffisient has a minimum and very large lift force occurs instantaneously.

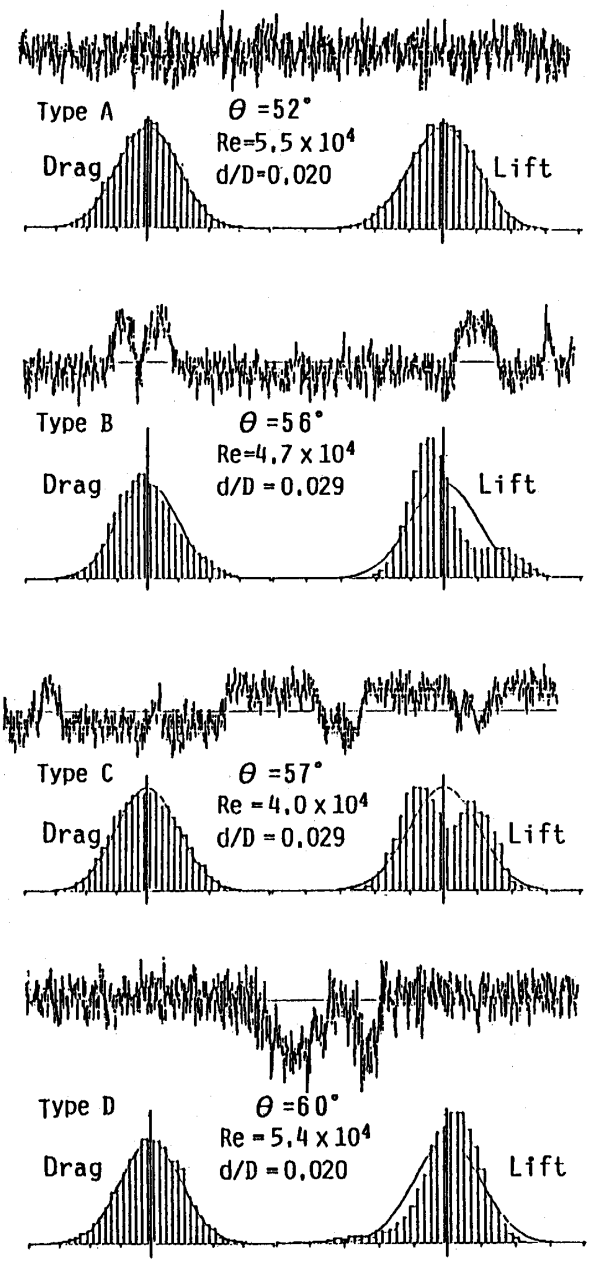

Fig. 5 Fluctuating pattern of fluid forces and probability mass function

Type C: Remarkable changes on the short time averaged values of lift forces take place intermittently. Probability mass function has two peaks. It is observed in the region where drag and lift coefficient change drastically with θ increase.

Type D: This is observed in the region where θ is about 10° larger than the setting angle where drag coefficient has a maximum. This pattern is the opposite of Type B.

Based on pressure profile in Fig.4, let us investigate the relations between flow around a cylinder and fluctuating fluid forces. When θ is under 30°, a separated flow field behind the tripping wire is stable and a stable pressure profile as type I is formed. As θ increases, the absolute value of lift increases and drag coefficient decreases. As θ increases, the re-attachment point of flow separated from the top of tripping wire approaches to the separation point of main flow from the test cylinder, and the instability of separation bubble is induced by three dimensional structure of a large vortex formed in vicinity of the re-attachment point (11). In this stage, wake region reachs in the separated bubble, so internal pressure of separation bubble rises instantaneously and fluctuating pattern converts into Type B. θ increases further, the forming period of independent separation bubble behind a tripping wire and the period of separation flow occurring from the top of a tripping wire are in equilibrium, so that fluctuating pattern converts into Type C. In this case, the state of flow field around a cylinder turns alternately into two flows having a different separation point from each other. This is a bi-stable flow in which re-attachment flow and separated flow take turns intermittently. By the degree of stability in re-attachment flow and separated flow, fluctuating patterns convert into some one of Type B,C,D. When separated bubble is not formed behind the tripping wire and there is no re-attachment of flow separated from the top of a tripping wire, the probability mass function becomes normal distribution in Type A.

3.3 Occurence conditions of bi-stable flow

Fig.6 shows an example of changes of skewness α_3 and peakness α_4 of fluctuating lift and correlation coefficients between fluctuation of drag and lift against setting angle of a tripping wire θ. It is the purpose of these statistical calculations to clear the conditions creating bi-stabe flow. In order to extract spike-like fluctuation without an error caused by vortex shedding from a circuler cylinder as well as rectanguler wave, we analysed the measuerd fluctuation of lift forces transformed into low frequency

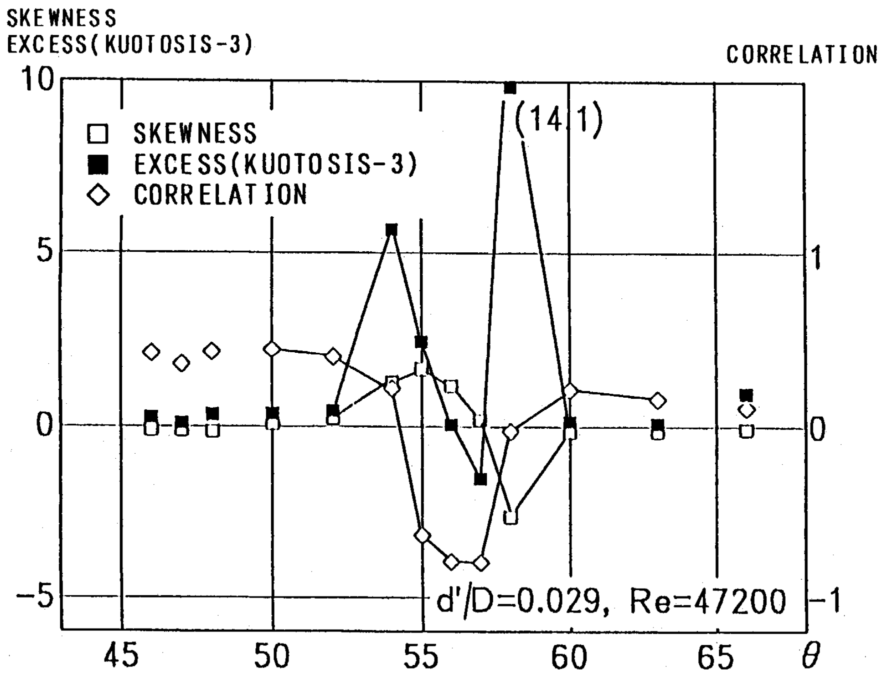

Fig. 6 Variation of statistic values of fluctuating fluid forces with setting angle θ

through the low pass filter with two or three times of the Strouhal period given by Strouhal number $S_t=0.2$. An ideal example of the results shown in Fig.6 is drawn in Fig.7. Considering the characteristics of fluctuating pattern of fluid forces and the changes of each statistical value with θ, we show the notates of types fluctuating patterns defined in Fig.5, under the transverse axis in Fig.7. Fig.8 shows each type of fluctuating pattern determined by the relations based on Fig.7, on the coordinates of Reynolds number and θ. The region of θ where bi-stable flow takes place is more up stream as diameter ratio d/D increases. This result is natural, since the length of separated bubble is larger as the tripping wire is higher. The region of θ where bi -stable flow takes place is narrow with decreasing Reynolds number. These results may be explained as follows. The scale of separation bubble behind a tripping wire should be prescribed by Reynolds number R_{ed} defind by the height of tripping wire d and velocity u_e at the tripping wire. As mentioned above, the length of separation bubble becomes small with decreasing R_{ed}, so that the point of θ where bi-stable flow takes place moves down stream and the region of θ where bi-stable flow takes place becomes narrow.

3.4 Characteristics of low frequency fluctuation of lift in bi-stable flow

We introduce the definition related to the flow pattern. That is to say, the flow pattern of state formed independently separation bubble behind a tripping wire is termed " re-attachment flow " and the flow separated from the top of a tripping wire and formed wake flow field is termed " separation flow". As the result of converting into both flow patterns intermittently, the time records of short time-mean values of lift force which are calculated according to the moving average method and answer to each flow pattern, show the rectanguler like waves.

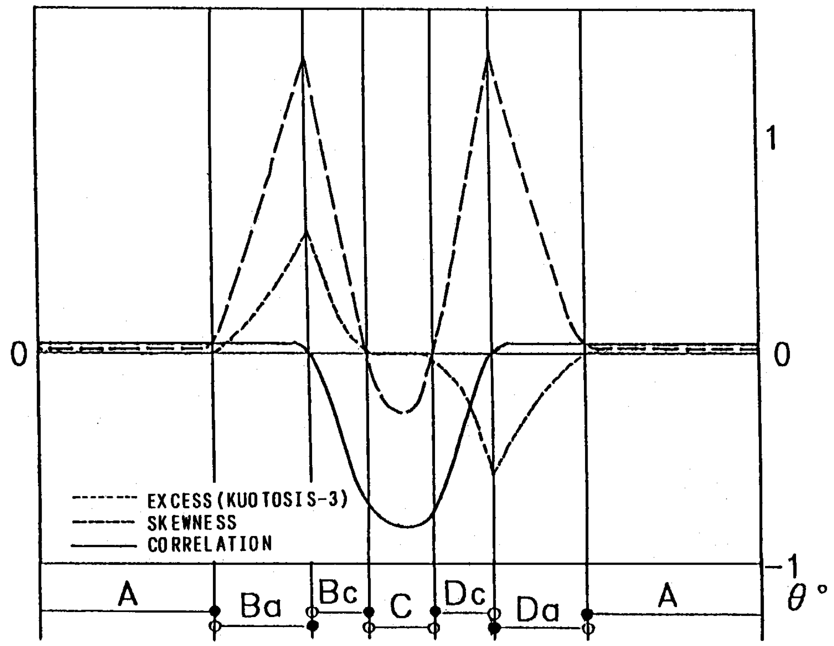

Fig. 7 A standard on classification of fluctuating patterns

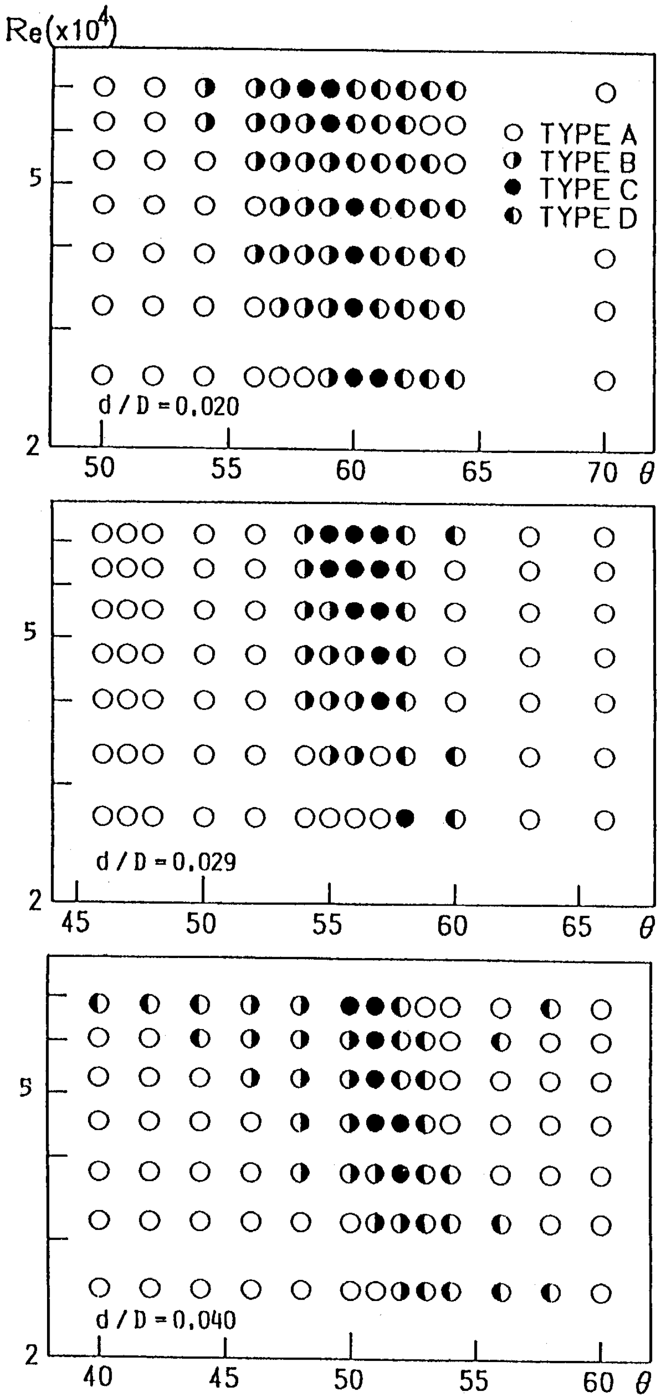

Fig. 8 The condition each fluctuating patterns take place

We also calculated the long time-mean values of fluctuating lift smoothed by moving average method as mentioned above. The instantaneous lift forces are devided into two groups on a standard whether the value is larger than the mean value or not. We defined the mean amplitude of rectanguler like waves fluctuation of lift force F' to the difference between mean values of each group. Finally, We transformed F' into the non-dimensional fluid force coefficient C_{ls} using the mean value of approaching velocity U and the area of cross-section to $C_{ls}=F'/(\rho AU^2/2)$

Fig.9 shows as example of the relation between C_{ls} and setting angle of a tripping wire θ for the case of $R_e=7\times10^4$. This result is naturally expected from the fluctuating patterns shown in Fig. 5 compared with Fig. 8, the relation between fluctuating patterns and θ is more clearer. In the case of Type B, separated flow in short time takes place intermittently, so that intensity of fluctuation become large. In the case of type C, e.i., bi-stable flow, the intensity of fluctuation has a maximum value. In the case of Type D, the period of re-attachment flow decreases so that the intensity of fluctuation decreases.

Fig. 10 shows the relation between dimensionless coefficient of fluctuating intensity of C_{ls} and Reynolds number in bi-stable flow, for the several ratio of height of tripping wire d to the diameter of test cylinder D. The C_{ls} seems to have the maximum value

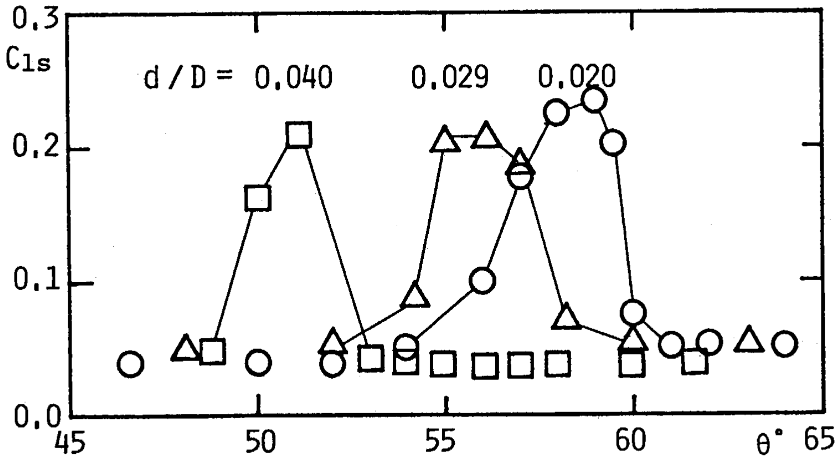

Fig. 9 Variation of Fluctuating intensity on lift force with setting angle θ

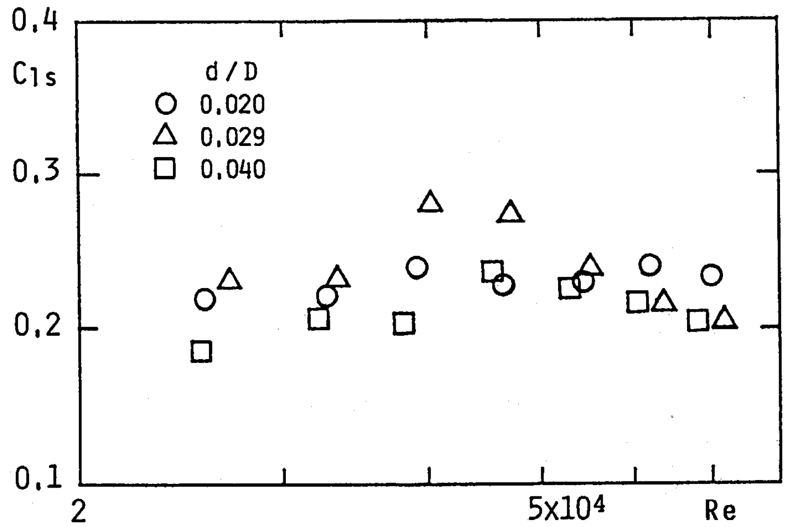

Fig. 10 Fluctuating intensity on lift forces in the state of bi-stable flow

at $R_e=4\sim5\times10^4$. In bi-stable flow, considering that the mean value of the largest and the smallest of instantaneous lift almost agree with the time averaged value and the periods maintaining each flow pattern are nearly equal, the difference between mean lift forces in state of re-attachment flow and separated flow can be estimated $2^{1/2}$ times of C_{ls} roughly. The magunitude of lift force changed at the flow converted from re-attachment flow into separated flow or vice versa, is evaluated based on the above estimation. This value is 0.35~0.45 in the form of lift coefficient,a notably large value.

It is considered that stability in separated bubble formed behind a tripping wire plays important rolls in switching re-attachment flow and separated flow. In a state of bi-stable flow, the mean turning period that re-attachment flow converted into separated flow and becoming re-attachment flow again is calculated. The mean period may be transformed in non-dimensional form of Strouhal number S_{td} which is defined by the height of the tripping wire d and velocity u_e along surface of a cylinder given by potential flow at θ. Fig. 11 show the relation between Strouhal number S_{td} and

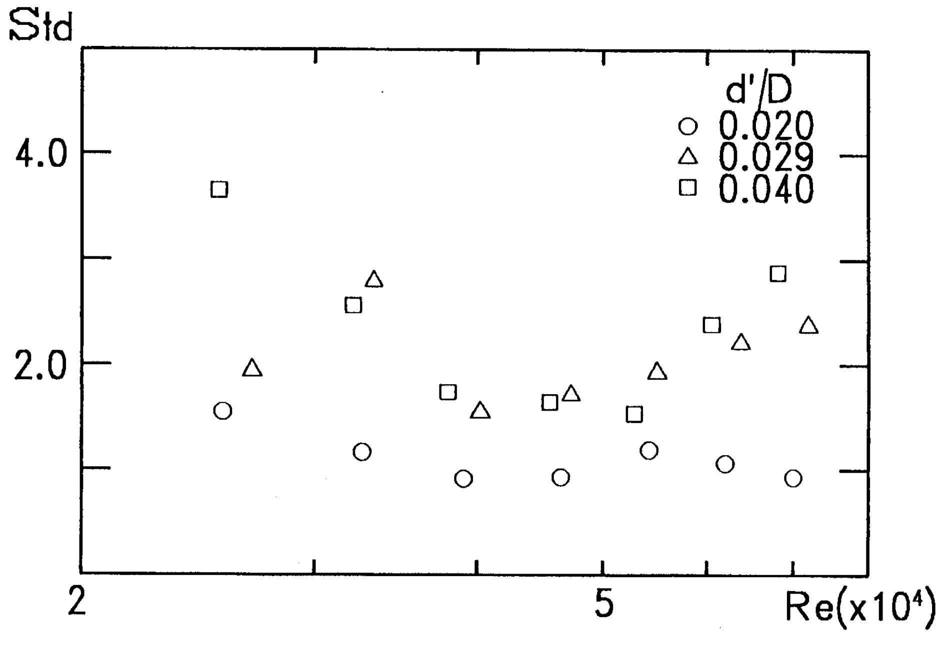

Fig. 11 Dimensionless period of lift forces in low fluctuation frequency

Reynolds number R_e. It is remarkable that S_{td} has a smallest value at $R_e=4\sim5\times10^4$ at which intensity of fluctuation of lift is the largest.(Fig. 10)

4. CONCLUSION

As the most fundamental study for the instabillity by a path of rain water formed on cables, which is one of the facters creating rain-wind incuced vibration of cable-stayed bridges, drag and lift acting on a circuler cylinder with single semi-circuler cylinder was measured simultaneously, and mean value of drag and lift forces and the characterlistics of fluctuation of lift was investigated. Summaries of the results obtained in this study are as follows:

1. Drag and lift coefficients change with θ as shown in Fig.2 and Fig.3. They have the same tendency in the case that tripping wires are set symmetrically to the front stagnation point. However, the reduction ratio of drag force is nearly half. The strongest dependance between the changes of lift coefficient and of drag coefficient with θ was observed, at the angle of θ where drag coefficient is the smallest and lift coefficient is the largest, the value is $C_L=0.4\sim0.45$.

2. Bi-stable flow in which flow pattern converted into re-attachment flow and separated flow alternatively, takes place at the setting angle of a tripping wire where the drag and lift coefficients change remarkably. The conditions of bi-stable flow taking place are shown in Fig.8, the setting angle where bi-stable flow takes place is more down stream as the diameter ratio of a tripping wire d/D is smaller.

3. In the state of bi-stable flow, the intensity of lift fluctuation and the mean turning period are shown in Fig.10 and Fig.11. The magnitude based on roughly estimating the intensity of lift force changed at re-attachment flow converted into separated flow or vice varsa, is $0.35\sim0.45$ in non-dimensional form. This value is very large.

To summarize the above, we expect that a circuler cylinder will be unstable aero-dynamically by inducing such a large fluctuatig intensity of lift forces, adding to changing ratio of drag and lift coefficient with θ.

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