Fluctuating Fluid Forces Acting on Two Circular Cylinders in a Tandem Arrangement at a Subcritical Reynolds Number

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The fluctuating and time-averaged aerodynamic forces acting on two circular cylinders and characteristics of flow over the cylinders in a tandem arrangement were investigated experimentally at a Reynolds number of 6.5×10^4 . The position of the downstream cylinder was varied systematically up to the spacing of 5 diameters and time-averaged drag, fluctuating pressure, fluctuating lift and drag forces acting on the cylinders were measured. Two peaks in each of the distribution of the fluctuating lift and drag forces acting on the downstream cylinder were observed when the cylinders were placed before the critical spacing. The value of the fluctuating lift and drag forces at the larger peak that occurred at a spacing ratio of 1.4 was about 2 and 2.8 times, respectively that of a single cylinder. The magnitude of the fluctuating lift and drag forces acting on the downstream cylinder was related very sensitively with the reattachment position of the separated shear layers from the upstream cylinder onto the downstream one and the fluctuating lift and drag forces became maximum when the reattachment position of the shear layers reached to minimum.

1. INTRODUCTION

The interference between two closely arranged bodies drastically changes the flow around them; as a result, aerodynamic characteristics such as the drag and lift forces, the pressure distribution, the Strouhal number, and vortex shedding patterns differ significantly and depend strongly on the spacing between the two bodies. Such arrangement of two bodies can be found in many cases, such as cooling system for nuclear power plants, chimney stacks, power transmission lines, heat exchanger tubes, suspension bridges, radar mast vibrations, and structures on land and in the ocean. In many of these engineering applications, the periodic shedding of Karman vortices causes the fluctuating aerodynamic forces on the bodies. Due to having many engineering applications of two bodies in various arrangements, many researches have been done on two circular cylinders in a tandem, side-by-side and staggered arrangements. Previous studies of such configurations, by Biermann and Herrnstein [1], Hori [2], Zdravkovich and Pridden [3, 4], Okajima [5], Igarashi [6, 7], and Hiwada et al. [8] have revealed considerable complexity in the fluid dynamics. All of these researches are concerned with only time-averaged drag force, pressure distributions, and flow

visualization. There have been few studies on the fluctuating lift and drag forces that are responsible for the major problems like vibrations and noise. Arie et al. [9] evaluated the fluctuating lift and drag forces acting on two circular cylinders in a tandem arrangement only for certain spacings from the distribution of rms surface pressure and the circumferential correlation coefficients.

Comparing previous investigations on two circular cylinders in a tandem arrangement, many disagreeable points among them were perceived. Igarashi [6] noted some disagreeable points in this regard. However, compared with studies on two circular cylinders, systematic measurements of the fluctuating lift and drag forces acting on the cylinders are very scant, and still many unknowns remain. Also, mutual interference of two cylinders is strong in a tandem and is weak in a side-by-side arrangement [2] and intermediate tendency can be expected in a staggered arrangement.

Hence the aim of this study was to examine the characteristics of fluctuating lift and drag forces acting on two circular cylinders in a tandem arrangement and to clarify flow patterns over the cylinders. Measurements of time-averaged drag, fluctuating lift and drag forces acting on the cylinders were carried out systematically.

2. EXPERIMENTAL ARRANGEMENT AND PROCEDURES

Experiments were conducted in a low-speed, closed-circuit wind tunnel with a test section of 0.6 m high, 0.4 m wide, and 5.4 m long. The free-stream turbulence intensity in the working section was about 0.19% at the free-stream velocity of 20 m/s, which was the velocity employed in the present experiment. Three types of circular cylinder were used for the experiment; a cylinder with two load cells installed inside the body was used for the measurement of fluid forces, and a cylinder with a semiconductor pressure transducer installed inside the body was used for the measurement of time-averaged and fluctuating pressures. The other cylinder was used as a dummy one. The cylinders tested were machined brass with 49 mm diameter with smooth surface finish.

The cylinder for the measurement of fluid forces was composed of two parts, namely an active ('live') section and a dummy section, and a load cell on which four semiconductor strain gauges were installed was set inside each section. The load cell

installed inside the active section measured a combination of the fluid forces and the forces due to vibration transmitted from the outside through the cylinder support. The load cell installed inside the dummy section measured the forces due to vibration transmitted from the outside through the cylinder support. Hence, the fluid forces acting on the active section could be calculated by subtracting the output of the load cell installed inside the dummy section from that of the load cell installed inside the active section. To measure the surface pressure, a semiconductor pressure transducer (TOYODA DD104A) with a range of ± 10 kPa was used and the transducer output was calibrated to give a reading of 6.22 Volt for 1 kPa of applied pressure. The pressure transducer responded to the pressure fluctuation up to 500 Hz with a gain factor 1 ± 0.06 , the phase lag being negligible. The geometric blockage ratio and aspect ratio of the cylinder at the test section were 8.1% and 8.2, respectively. None of the results presented were corrected for the effects of wind-tunnel blockage. The placement of the two circular cylinders, the coordinate system and the definitions of the symbols are shown in Fig. 1.

Fig. 1. Two cylinders in tandem arrangement with coordinate system and definition of symbols.

3. RESULTS AND DISCUSSION

3.1 Time-averaged drag force

Variations of the time-averaged drag coefficient, C_D , of the upstream and the downstream cylinders against spacing ratio, L/D , are shown in Fig. 2 together with the results of Biermann and Herrstein [1] and Zdravkovich and Pridden [4]. The drag coefficient of the upstream cylinder decreases gradually with the increases of the spacing between the cylinders. On the other hand, the drag coefficient of the downstream cylinder forms a peak at $L/D=1.40$. This type of peak was also found in the previous reports [3, 6, 8]. Zdravkovich & Pridden [3] placed a third cylinder behind the downstream cylinder in order to exclude the effect of the wake of the downstream cylinder and the second cylinder was monitored but the peak did not disappear completely. Thus, it seems that the peak is not only due to the effect of the wake of the downstream cylinder but also due to the effect of flow in the gap between the cylinders. The well-known bistable flow occurs at $L/D=3.0$ (critical spacing) where two values of the drag coefficient are seen for two different flow patterns, namely: reattachments flow and jump flow. Beyond $L/D=3.0$, though two cylinders form vortices individually behind them, the drag coefficient of the downstream cylinder exhibits a much smaller value than that of the upstream cylinder or a single one. This is due to fact that the downstream cylinder is exposed to a wake velocity less than free-stream velocity, U_0 , and more highly turbulent flow created

by the upstream cylinder. As the spacing increases, the downstream cylinder leaves gradually the wake of the upstream cylinder. So, C_D of the downstream cylinder increases gently.

Fig. 2. Effect of tandem spacing on time-averaged drag of two cylinders.

3.2 Fluctuating pressure

In order to get a concept about the flow patterns around the cylinders, rms pressure coefficients, $C_{p,rms}$, on the surface of the cylinders were measured for certain spacings, and are shown in Figs. 3(a, b). First for $L/D < 3$, the magnitude of the rms pressure on the surface of the upstream cylinder is much lower than that for a single cylinder and decreases with increasing spacing. In this range of spacing, the shear layer separated from the upstream cylinder reattaches onto the surface of the downstream cylinder and divides into two shear layers at the reattachment point. One shear layer indicated by ① (hereafter referred to as the downstream shear layer) flows to the downstream and the other shear layer indicated by ② (hereafter referred to as the upstream shear layer) flows to the upstream direction. The rms pressure distribution for $L/D=0.10$ has two peaks: the first one is near the separation point, and the second one is on the rear surface and is due to reattachment of the upstream shear layer. The reattachment of the upstream shear layer was also confirmed by the surface oil-flow patterns. For $L/D=2.50$ where the shear layer separated from the upstream cylinder reattaches almost steadily onto the surface of the downstream cylinder, the both peaks vanish and the profile becomes flat. Immediately after the critical spacing, say, $L/D=3.5$, the fluctuating pressure sharply increases to a level higher than that of a single cylinder.

The pressure fluctuation on the surface of the downstream cylinder is very large compared with that of a single cylinder or corresponding upstream cylinder. In case of $L/D=0.30$, three peaks are self-evident in the fluctuating pressure distribution. The middle peak is near the reattachment of the shear layer separated from the upstream cylinder, and the first peak is due to separation of the upstream shear layer formed from the main shear layer, and the downstream shear layer separation causes the third peak on the rear surface. The fluctuating pressure on the surface of the cylinder increases with increasing spacing up to $L/D=1.40$. At this spacing, $C_{p,rms}$ on the whole surface becomes maximum and decreases

again as the spacing increases. It is obvious that in case of $L/D=1.40$, C_{pr} is strong not only on the top surface but also on the front and rear surfaces. Thus in this case, the upstream and the downstream shear layers roll strongly in the gap between the cylinders and behind the downstream cylinder, respectively.

Fig. 3. Distribution of rms pressure fluctuation around: (a) upstream cylinder, (b) downstream cylinder.

3.3 Fluctuating lift and drag forces

Variations of the fluctuating lift coefficient, C_{Lr} , and the fluctuating drag coefficient, C_{Dr} , plotted against the spacing ratio, L/D , are shown in Fig. 4 and 5, respectively including the measurement of Arie et al. [9]. From the figures, it is seen that fluctuating lift and drag coefficients of the downstream cylinder are very sensitive to the spacing between the cylinders especially before the critical spacing. The figures show that there exist two noteworthy peaks in each of the figures at $L/D=0.35$ and 1.40 for the downstream cylinder and a peak at $L/D=0.35$ for the lift coefficient of the upstream cylinder. The abovementioned peaks are not self-evident in the result of Arie et al. The value of the fluctuating lift and drag coefficient of the downstream cylinder at $L/D=1.40$ where the second peak occurs is 2 and 2.8 times, respectively that of a single cylinder. Also it has been discussed in the previous section that fluctuating pressure on the whole surface of the downstream cylinder is maximum for $L/D=1.40$. The value of the fluctuating lift coefficient of a single cylinder for the present case is 0.445 and that for Lesage et al. [11] case is 0.45. Both values are very close to each other due to same Reynolds number. But the value for the case of Arie et al. [9] and Batham [10] is quite different from the value of the present case. This is due to fact that the

fluctuating fluid force acting on a circular cylinder strongly depends on Reynolds number [12]. By observing the figures, it is clear that the fluctuating lift and drag forces of the downstream cylinder are much higher than that of the upstream cylinder not only before the critical spacing but also beyond the critical spacing.

Fig. 4. Variations of rms lift coefficient against L/D .

Fig. 5. Variations of rms drag coefficient against L/D .

3.4 Reattachment position

It is well-known that before the bistable flow spacing, the shear layer separated from the upstream cylinder reattaches somewhere onto the surface of the downstream cylinder. The reattachment position, θ_R , obtained from surface oil-flow techniques and the peak of the time-averaged pressure distribution is shown in Fig. 6 together with the result of Zdravkovich and Pridden [4] and Hiwada et al. [8]. The result obtained from the peak of the pressure distribution has a good accord with the result obtained from surface oil-flow patterns. By comparing Figs. 4, 5 and 6, it is obvious that there is a dormant relationship of the values of the fluctuating lift and drag coefficients of the downstream cylinder with the reattachment position of the shear layers. For $L/D=0.10$, the reattachment position of the shear layers is 75° . As the spacing increases, θ_R precedes forward sharply and C_{Lr} and C_{Dr} increases at the same rate. When the distribution of θ_R creates a valley at $L/D=0.35$, the C_{Lr} and C_{Dr} distributions create a peak at the same spacing. Again, when θ_R recedes backward for the spacings $0.35 < L/D < 0.8$, the C_{Lr} and

Fig. 6. Variation of reattachment position against L/D .

C_{Df} decrease and when θ_R again precedes forward for the spacings $0.8 < L/D < 1.40$, the C_{Lf} and C_{Df} increase highly. At $L/D=1.40$, the C_{Lf} and C_{Df} reach to a maximum value of 0.86 and 0.28, respectively, and the θ_R reaches to a minimum value of 55° . Beyond $L/D=1.40$, the reattachment position recedes backward again. Therefore, it can be concluded that the fluctuating fluid forces acting on the downstream cylinder strictly depend on the reattachment position and are found to be increased when the reattachment position of the shear layer precedes forward and vice versa.

3.5 Time-averaged pressure at reattachment point

Fig. 7. Relationship between time-averaged pressure at reattachment point and position of reattachment.

The figure 7 shows the relationship between the magnitudes of the time-averaged pressure, C_{PR} , at the reattachment position and the reattachment position, θ_R , of the shear layers when the spacing between the cylinders is changed. From the figure, it is seen that C_{PR} has the inverse relationship with position of reattachment, that is, C_{PR} increases when θ_R precedes forward, and C_{PR} decreases when θ_R recedes backward. At $L/D=0.35$ and 1.40 where the θ_R reaches to minimum, the C_{PR} reaches to maximum. It is comprehensible that when a shear layer attaches on a surface with a smaller incidence angle (angle between the approaching shear layer and a normal to the surface at the reattachment point), the pressure at the reattachment point becomes higher. Thus, for the present case, when the reattachment position precedes forward, the incidence angle of the shear layers becomes smaller and vice versa. As the C_{PR} is maximum at $L/D=1.40$, the incidence angle of the shear layers on the surface seems to be minimum. Therefore, at $L/D=1.40$, the approaching shear layers confront the downstream

cylinder having more bluntness than that of the other positions and that results a stronger rolling of the divided shear layers in the gap and behind the downstream cylinder. Due to strong rolling of the divided shear layers, the fluctuating fluid forces become maximum at $L/D=1.40$.

4. CONCLUSION

Main results of this study may be summarized as follows:

- (1) The fluctuating lift and drag forces acting on the downstream cylinder are greater than that of the upstream one and the time averaged drag force of the downstream cylinder is less than that of the upstream one for any spacing.
- (2) The fluctuating lift and drag forces of the downstream cylinder are very sensitive to the spacing between the cylinders especially before critical spacing. Each of the fluctuating lift and drag coefficient distributions of the downstream cylinder shows two peaks: one is at $L/D=0.35$ and the other is at $L/D=1.40$. The peak at $L/D=1.40$ is larger and the values of the fluctuating lift and drag forces are about 2 and 2.8 times, respectively that of a single cylinder.
- (3) There exist a clear relationship between the fluctuating fluid forces acting on the downstream cylinder and the reattachment position, θ_R , of the shear layer. The fluctuating lift and drag forces on the downstream cylinder are found to be increased when the reattachment position of shear layer precedes forward and vice versa.
- (4) First, the reattachment position, θ_R , of the shear layers onto the downstream cylinder precedes forward up to a spacing ratio of $L/D=0.35$, then recedes backward up to a spacing ratio of 0.8 and precedes forward again up to a spacing ratio of 1.40. Beyond this spacing, reattachment position recedes backward again.

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Spanwise Coherence Characteristics of Surface Pressure Field on 2-D Bluff Bodies

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1. INTRODUCTION

The spanwise coherence of buffeting forces is thought to be described by that of the turbulent velocity components of the oncoming flow. Buffeting response of line-like structures such as long-spanned bridges and tall buildings has been based on this idea. Whereas, the higher spanwise coherence of surface pressure than that of oncoming flow was pointed out in several papers.¹⁾⁻⁴⁾

On the other hand, the observed coherence of the oncoming flow velocity indicates lower value than unity in the lower frequency³⁾. While, it gives nearly 1.0 in the conventional exponentially decaying type coherence function. The uncertainty in evaluating buffeting forces caused by the higher spanwise coherence may be compensated properly in the buffeting response analysis by this reason.

In order to obtain the information to clarify the mechanism of the spanwise higher coherence, the surface pressure fluctuation on 2-D rectangular and 2-D hexagonal cross sections were measured simultaneously in three different flow conditions: in smooth flow, in turbulent flow and in 2-D sinusoidal vertically fluctuating flow. The coherence of approaching flow was also evaluated to compare with that of the surface pressure.

2. EXPERIMENTAL APPARATUS

The wind tunnel used in this study has 1.0m width (W) x 1.8m height (H) in cross section. Wind velocity can be controlled continuously from 0.5m/s up to 30m/s in smooth flow. Turbulent flow was generated by the grid at about 1.2m upstream from the model. (see Fig.1) The 2-D rectangular cross

Fig.1 Sketch of wind tunnel experiment setup and coordinates, velocity components

Fig.2 Model configuration. Triangular fairings can be attached on front and rear surface to form the model hexagonal.

section model with the width $B = 300\text{mm}$, the depth $D = 60\text{mm}$ and 900mm in span length is supported horizontally in the wind tunnel. The model surface is made of aluminum. 342 pressure taps are installed on a model side surface as shown in Fig.2. The triangular fairings are attached on

windward and leeward surface to make the cross section hexagonal. The coordinate system is shown in Fig.1.

The surface pressure fluctuation is measured at two points being separate only in the spanwise (y) direction in most cases. The used equipment is the pressure transducer (DD-101K, TOYODA Co.Ltd.) which can subtract the static pressure in the wind tunnel pneumatically. Wind velocity fluctuation was measured by the hot wire anemometer (model 1011, 1013, 1008, Kanomax Co.,Ltd.) with x-type probe (model 0252-R5, Kanomax Co.,Ltd.).

3. RESULTS AND DISCUSSION

Fig.3 indicates the power spectra of u -component in the oncoming turbulent flow. It was confirmed that each velocity component shows good agreement with Karman type spectrum⁵⁾ using the integral scale of turbulence for corresponding component. The intensity of turbulence is $I_u = \sigma_u / U = 10.3(\%)$, $I_v = \sigma_v / U = 9.1(\%)$ and $I_w = \sigma_w / U = 7.9(\%)$ at the origin of spatial coordinate system without the model. The scale of turbulence is $L_u = 0.12(\text{m})$, $L_v = L_w = 0.05(\text{m})$. The spatial distributions of these quantities in y - and z - direction are confirmed to be uniform, whereas the slight trend is observed in x - direction due to the decay of turbulence level

Fig.3 Power spectrum of u -component at $(x,y,z)=(0,0,0)$. The Karman type spectrum is represented by thicker solid line. Model is not set in wind tunnel.

along the longitudinal distance from the grid. It was also confirmed that the coherence for each velocity component is well approximated by the Karman type formula provided that the length scale L in the formula is chosen $1/2 L_u$ for u -, L_u for v - and $1/3 L_u$ for w -component, respectively. The lateral v -component indicates higher coherence level than other components. An example of coherence of the longitudinal velocity component in the oncoming

Fig.4 Coherence of u -component at $(x,y,z)=(0,0,0)$ when model is not set in wind tunnel.

grid turbulence is shown in Fig.4. The coherence is expressed by the following equation:

$$\text{coh}(\Delta y; f) = \frac{|S(\Delta y; f)|}{\sqrt{S_{y=0}(f)} \sqrt{S_{y=\Delta y}(f)}} \quad (1)$$

where, $\text{coh}(\Delta y; f)$: coherence of the physical quantity (velocity component or surface pressure) with the spanwise separation of Δy , $S(\Delta y; f)$: cross spectrum with the spanwise separation of Δy , $S_{y=0}(f), S_{y=\Delta y}(f)$: power spectrum at $y=0, \Delta y$.

The Strouhal number for the models in each flow conditions is listed in Table 1. The number is evaluated from the pressure signal on model surface.

Table 1 Strouhal number

	rectangular	hexagonal
In smooth flow	0.132	0.18, 0.28
In turbulent flow	0.197	0.19, 0.25

As for the hexagonal model in smooth and in turbulent flow, since broad band spectral peaks were observed in two different frequencies, the corresponding two Strouhal numbers are shown in the Table.

The reattaching point of the separating shear flow on the side surface is evaluated based on the distribution of the time averaged pressure $\bar{C}_p$, and rms value $\tilde{C}_p$. The point locates between the minimum point of $\bar{C}_p$ and the peak of $\tilde{C}_p$ by the literature. Consequently, the reattaching point should be $7B/8$ from the leading edge in smooth flow and $3B/8$ in turbulent flow in case of the rectangular cross section. For the hexagonal cross section, it is evaluated that the reattachment occurs almost at the leading edge in both flow conditions.

Figs.5 to 8 show the coherence of surface pressure between two pressure taps with the spanwise

separation of Δy for each model and flow condition. The two pressure taps are at the same distance from the leading edge, that is, in the line of the same pressure tap position.

In case of the rectangular cross section in turbulent flow, higher coherence level in lower frequency than the Karman vortex shedding frequency ($f = 33\text{Hz}$) is observed in the upstream half surface, position 1 to 7 (where, "position i " corresponds to the i -th pressure tap from the leading edge.). (see Fig.5(a)) In the downstream half surface, the coherence tends to decrease. (see Fig.5(b)) This chordwise trend of coherence level may correspond to that the pressure near the leading edge is significantly controlled by the separating flow which is uniform in spanwise direction, and that the coherence level decreases due to the flow reattachment of the model surface at around $3B/8$ from the leading edge. It should be noted that the coherence in lower frequency increases again near the trailing edge and even reaches to almost the same level at the leading edge. (see Fig.5(c))

When the model is in smooth flow, the same characteristics as in turbulent flow can be observed. As shown in Fig.6, the coherence shows higher level in lower frequency from position 1 to 7, and gradually decreases up to the trailing edge. The Karman vortex shedding frequency is evaluated as 22Hz in this case. The recovery of coherence level at

Fig.5 Coherence of surface pressure in spanwise direction for the rectangular section in turbulent flow.

Fig.6 Coherence of surface pressure in spanwise direction for the rectangular cross section in smooth flow.

Fig.7 Coherence of surface pressure in spanwise direction for the hexagonal cross section in turbulent flow.

the trailing edge is not, however, recognized clearly.

For the hexagonal cross section, the plateau from 30 to 45Hz is recognized in each coherence diagram from position 9 to 19 in smooth and turbulent flow conditions. It must be due to the Karman vortex shedding, but the identification of Strouhal number was not possible. Fig.7 shows some examples of coherence in turbulent flow. The coherence takes 0.8 at position 1 in the lower frequency region, then reaches to 0.9 at position 3 and keeps the high coherence level to near the trailing edge. In case of smooth flow as shown in Fig.8, the coherence in the lower frequency decreases at position 2 and 3, then increases significantly. At position 9 to 17, the value is almost 1.0. These high coherence can be seen even in the large distance of $\Delta y = 275\text{mm}$. Since the reattaching point is evaluated near the leading edge according to the $\bar{C}_p$ and $\tilde{C}_p$ distribution, the flow attaching on the side surface is developing towards the trailing edge. The higher coherence of the surface pressure described above implies that the flow after the reattachment has uniform property in spanwise. The coherence recovery at the trailing edge observed in the rectangular cross

(a) at position 2, $(x,y) = (-127.2, 0) - (-127.2, \Delta y)$
 Fig.8 Coherence of surface pressure in spanwise direction for the hexagonal cross section in smooth flow.
 — $\Delta y = 25\text{mm}$
 — $\Delta y = 60\text{mm}$
 — $\Delta y = 125\text{mm}$
 — $\Delta y = 275\text{mm}$

section in turbulent flow may support these flow characteristics.

By the definition, the coherence indicates the cross-correlation coefficient of a specified frequency component of the two signals and does not give the power of each frequency component. To discuss the contribution of pressure fluctuation to the buffeting force, more useful information can be obtained from the cross spectrum. In case of the rectangular cross section, the maximum power on the surface is appeared at position 13 for smooth flow and at position 4 for turbulent flow. (see Fig.9) The spectrum at position 1 shows larger power. But since the pressure fluctuation at this point is thought to be sensitively affected by the approaching flow, this point should be expected from the discussion. In consequence, the surface pressure fluctuation at the slight upstream position from the reattaching point gives most significant contribution to the buffeting force from the viewpoint of its magnitude. The higher coherence observed in the buffeting force is, therefore, caused by the spanwise uniform nature of the separation bubble.

On the other hand, there is no big difference in the

(a) in turbulent flow at position 4, $(x,y) = (-95.4, 0) - (-95.4, \Delta y)$
 Fig.9 Cross spectrum of surface pressure in spanwise direction for the rectangular cross section
 — $\Delta y = 25\text{mm}$
 — $\Delta y = 60\text{mm}$
 — $\Delta y = 125\text{mm}$
 — $\Delta y = 275\text{mm}$

magnitude of the cross spectrum of the hexagonal cross section over the surface from the leading edge to the trailing edge. In other words, not only the cross spectrum but the coherence also specifies the most important position which contributes significantly to the buffeting force. Based on the previous observation in Figs.7 and 8, it is concluded that almost the entire side surface contributes the higher coherence buffeting force characteristics.

These flow characteristics which determine the coherence of the surface pressure, and buffeting force in consequence, consist of two factors: one is the effect of separation and reattachment which are formed by the model itself, the other is the effect of the approaching flow.

4. CONCLUSION

Some concluding remarks are indicated as follows:

- 1) For the rectangular cross section, the pressure on the side surface shows higher coherence level in the upstream of the reattaching point. This tendency is identical in smooth and in turbulent flow. The spanwise two-dimensional properties of the separation bubble play most important role.
- 2) For the hexagonal cross section, the coherence keeps higher level in almost entire side surface. The flow after the reattachment may also have spanwise two-dimensional nature.
- 3) The contribution to the higher coherence of the buffeting force is discussed by the cross spectrum. The most significant point for the rectangular cross section is evaluated as the slight upstream position from the reattaching point. This tendency is observed also in smooth flow. On the contrary, there is no big difference in the cross spectrum for the hexagonal cross section. This leads that the pressure field on the entire surface plays important roles on the two-dimensional buffeting force characteristics.

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Pressure Correlation on Cylinders in a Turbulent Wind

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1. INTRODUCTION

In the buffeting analysis of a bridge deck, aerodynamic admittance function is measured in a turbulent wind. Experimental studies show that aerodynamic admittance varies with turbulence scale of a wind and a cross sectional shape of a deck^(1,2). The aerodynamic admittance for a section with large ratio of depth to width tends to become larger than theoretical value⁽²⁾. Larose and Mann⁽²⁾ supposed that body-induced turbulence also caused the additional aerodynamic force. They also suggested that lift force is produced by separated and reattached flow as well as vertical fluctuating wind speed. However the creating mechanism of gust force for a bluff bridge section is not yet clarified. Pressure measurement and flow visualization may give some information.

In this paper cross sections of bridge decks are simplified into hexagonal and rectangular sections. Unsteady surface pressure on cylinders with those cross sections is measured in a turbulent wind. An active gust generator generates turbulent wind speed. The time series of turbulent wind speed given by the active gust generator is the same at every test run, and which enables us to compare the time series of wind and pressure. Characteristics of pressure at each point are surveyed comparing with pressure at

another point and with the applied wind fluctuation. Fluctuating flow produced by an active gust generator is almost 2-dimensional.

2. EXPERIMENTAL SETUP

Turbulent flow in the experiment was generated by an active gust generator installed in the outlet of wind tunnel as shown in Fig. 1. The plate array and wing array driven by an actuator gave an along wind and vertical fluctuation of wind speed respectively. The along wind and vertical speed were controlled up to 5 and 10 Hz. The power spectrum of wind speed measured at the point downstream from the mesh C by 700mm, at which the center of the model is located as shown in the figure, are shown in Fig. 2.

Cross sections of bridge deck were simplified into hexagonal and rectangular section as shown in Fig. 3. The sections have 30 pressure taps on the surface.

3. RESULT

Pressure measurement was conducted under the mean wind speed $U=5.0\text{m/s}$, along wind turbulence intensity $I_u=8.5\%$, vertical turbulence intensity $I_w=5.1\%$. The integral turbulence scales were $L_u=1.7\text{m}$ and $L_w=0.49\text{m}$ for along wind and vertical wind respectively.

Fig.1 Turbulence generator in wind tunnel

Fig.2 Power spectrum of generated wind

(a) B/D=8

(b) B/D=9

Fig.3 Model sections and pressure taps

(a) B/D=8

(b) B/D=9

Fig.4 Vertical wind speed, pressures and aerodynamic force [$\bar{U}=5\text{m/s}$]

The examples of the time series of pressure sampled at 200Hz are shown in Fig.4. In which P2 through P14 indicates the tap numbers. The vertical wind was previously measured at the position planned to be the center of the model in the wind tunnel without the model. The same time history of wind gust shown at the top of the figures was used for both models. The lift forces obtained by integration of pressure distribution are shown in the bottom of the figures. Characteristic patterns of fluctuating pressure similar to vertical wind speed are seen in the upstream taps, P2 and P4 for the hexagonal section, P2, P4 and P6 for the rectangular section. In the down stream taps, P10, P12 and P14, no significant pattern is found. The lift force induced by fluctuating wind speed may be produced mainly at the upward portion of the cylinder. The hexagonal

section has small pressure fluctuation compared with the rectangular cylinder.

Mean and rms pressures are shown in Fig. 5. Pressure fluctuations governed by the fluctuation of approaching flow, seen in Fig.4, appear in the separation region. Random pressure fluctuations, seen in Fig.4, appear after reattachment of flow.

Cross correlation coefficients between different pressure taps were calculated. The maximum values were picked up and plotted as contour lines in Fig. 6. Relatively high correlation region is seen among the upstream taps, taps in the separated region. In the down stream region, reattachment region, small correlation appears. The highly correlated pressures at the separated region produce the gust force dominantly.

Cross correlation coefficients between vertical

Fig.5 Pressure distribution

Fig.6 Maximum correlation value among pressures

Fig.7 Maximum correlation between wind and pressure

wind speed and each pressure were calculated and the maximum values were picked up. The results are plotted in Fig. 7. The figures seem like the distributions of rms pressure in Fig. 5(b). This figure shows that the pressure governed by vertical wind appears at separated region. After reattachment the characteristics of vertical wind in the surface pressure is gradually diminished.

4. CONCLUSION

Unsteady pressures, which create gust force, on hexagonal and rectangular cylinder were measured. Characteristics of pressure were discussed related both another pressure and vertical wind speed. The result showed that the fluctuating pressure at the separated region is governed by vertical wind speed, after the reattachment of flow pressure has small correlation with vertical wind speed. Gust force is dominantly produced from the pressure at the separated region.

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key words: pressure, cylinder, turbulent flow, gust force

Experimental Study on Surface Pressure and Flow Structure around a Triangular Prism Located behind a Porous Fence

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1. INTRODUCTION

Atmospheric dispersion of wind-blown dust particles from an open coal storage yard causes serious air-pollution and environmental problems. This also leads to loss of raw materials.

Wind erosion is closely related to the flow characteristics of the atmospheric surface layer, such as pressure fluctuations, wind speed and turbulent shear stress, etc. Especially, the lift force that ejects dust particles from the coal pile surface is closely related to the magnitude of the oncoming flow speed and viscous friction velocity near the surface. This implies that the surface pressure fluctuations on the coal-pile surface are dependent on the surface flow characteristics.⁽¹⁾

Many wind simulation studies have been carried out to reduce the dust emission or to analyze the wind erosion mechanism^(2,3). During the last decades, many kinds of wind fence have been used as windbreaks to protect coal piles from mass loss and wind erosion. A wind fence blocks the oncoming flow and reduces the wind speed of the wind behind the fence.

Borges and Viegas⁽⁴⁾ investigated the shelter effect of windbreaks by measuring the mean velocity and shear stress behind the windbreaks. Perera⁽⁵⁾ found that the separation bubble formed behind the fence disappeared when the porosity was larger than $\epsilon=30\%$, and the shelter effect occurred at small porosity condition.

The main objective of this study is to investigate the surface pressure and flow structure around the fence and a triangular prism model with varying the oncoming flow condition and fence porosity. In addition, the relationship between the surface pressure and flow structure was also investigated.

2. EXPERIMENTAL APPARATUS AND METHODS

The experiments were performed in a closed return type subsonic wind tunnel having a test section of $0.72(W) \times 0.6(H) \times 6(L)$ (m^3). Spires and roughness elements were installed in front of the test section to create atmospheric boundary layers. The schematic diagram of the wind tunnel test section and measurement system is shown in Fig. 1.

Fig.1 Wind tunnel test section and measurement system

Six porous wind fences with different porosities ($\epsilon=0, 20, 30, 40, 50$, and 65%) were tested in this study. The experimental set-up and the coordinate system used in this study are shown in Fig. 2. The coal pile model was simulated as a triangular prism with an inclination angle of 40° .

Figures 3 and 4 show the mean velocity and turbulence intensity profiles measured at prism location and the power spectra of blown-wind. During the experiments, the freestream velocity was fixed at $U_0 = 14.5$ m/s, corresponding Reynolds number based on the model height h was 3.9×10^4 .

Fig.2 Experimental set-up and coordinate system (unit : mm)

To measure the surface pressure on the coal pile model and ground plate, sixty-one pressure taps were installed along the mid-span ($Z=0$) of the prism in the range from $X/B=-4.5$ to $X/B=4.5$. The

Fig.3 Mean streamwise velocity and turbulence intensity profiles at fence location($X=0$)

Fig.4 Power spectra of longitudinal velocity fluctuations at $Z=0.26$ m ($U_0=14.5$ m/s)

pressure taps were connected to the transducer of Electronic Scannivalve (ZOC 23B) system with vinyl tubes of 0.8 mm inner diameter. For each channel, 32,768 pressure data points were acquired at a sampling rate of 200 Hz. Surface pressure difference between the surface pressure and the reference static pressure was non-dimensionalized by the dynamic pressure, using a velocity at the prism crest height and an air density.

The PIV velocity field measurement system was used to analyze the flow field around the coal pile model. The PIV system was consisted of a high-resolution CCD camera, a dual-head Nd:Yag laser, a frame grabber, a synchronizing device and a computer as shown in Fig. 5. The velocity field measurement system was synchronized with the

Fig.5 Schematics of PIV velocity field measurement system and electronic pressure scanning system

surface pressure scanning system to measure both simultaneously. For the PIV measurements, the interrogation window size was 64×64 pixels and overlapped in 50%.⁽⁶⁾

3. RESULTS AND DISCUSSION

Figure 6 shows the mean and rms pressure distributions around the fence and prism model with varying oncoming flow condition. When there is no fence ($\epsilon=100\%$) in front of the prism, the oncoming flow is decelerated slightly as approaching to the triangular prism and the mean pressure increases due to the blockage effect of the prism model. When a porous fence of $\epsilon=40\%$ is installed in front of the prism model, the mean pressure ahead of the fence is increased, compared with that of no fence case.

The rms pressure fluctuations for ABL of $n=0.22$ have larger values for both cases of with and without a wind fence compared with other upstream flow conditions due to high turbulence intensity of oncoming flow with a thick boundary layer thickness.

The mean and rms pressure distributions on the bottom plate and prism surface are shown in Fig. 7

Fig.6 Effect of oncoming flow condition on the surface pressure as a function of fence porosity. In front of the fence, the mean pressure on the ground plate is increased as the fence porosity decreases.

When the fence porosity ϵ is larger than 30%, the rms pressure fluctuations have a similar distribution, irrespective of the fence porosity, even though the porosity variation may change the turbulence structure behind the fence.

Fig.7 Effect of fence porosity on the surface pressure

Figure 8 shows the instantaneous velocity vector field and surface pressure distribution around the triangular prism measured simultaneously within a small coincidence time window. When a fence of porosity $\varepsilon=40\%$ is installed in front of the prism, the flow speed behind the fence is largely decreased down to about 1/3 compared with that of without the fence as shown in Fig. 8(b).

The instantaneous surface pressure at $X=-25\text{mm}$ is increased because a large-scale eddy impinges on the windward surface. The sudden decrease of the surface pressure measured at $X=-20\text{mm}$ may be resulted from the divergence of flow along the prism surface, increasing the wind-speed near the prism surface. The third pressure at $X=-15\text{mm}$ is increased slightly again because the diverged flow is partly reattached on the prism surface, before it is accelerated along the windward surface toward the prism crest.

4. CONCLUSION

The effects of porous wind fences on the surface pressure and flow structure around a 2-D triangular prism embedded in atmospheric boundary layers were investigated experimentally with varying the

oncoming flow condition and fence porosity.

The wind fence with porosity $\varepsilon=40\sim 50\%$ seems to be most effective for attenuating the pressure fluctuations on the prism surface. When a wind fence of porosity $\varepsilon = 40\%$ is installed in front of the prism, the speed of bleed-flow behind the fence is largely decreased down to 1/3 compared with that of without the fence.

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key words : wind fence, porosity, triangular prism, surface pressure, PIV(Particle Image Velocimetry)

Fig.8 Instantaneous velocity field and surface pressure on the up-hill slope of the triangular prism

End effects on cylinder wake transition process

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1. INTROCUCTION

The wake of a stationary circular cylinder, placed in an uniform flow perpendicular to its axis, is a classic problem in bluff body aerodynamics. It is well known that the first instability of a circular cylinder wake occurs at a Reynolds number (Re) of around 47. Above that Reynolds number, the wake becomes time-independent, which is characterized by two rows of opposite-signed vortices, known as the von Karman vortex street. At a slightly higher Re (usually less than 200), the 2-D wake becomes unstable to three-dimensional disturbances. The transitional process of a circular cylinder wake has attracted much attention recently, and due to the extensive and in depth research work of Williamson, it becomes well known that the circular cylinder wake transition regime involves two modes of small scale three-dimensional instabilities, referred to as modes A and B. Modes A and B occur in different Reynolds number ranges, and associated with different spanwise wavelengths. The existences of modes A and B correspond to the two discontinuities on the S- Re Curve for a circular cylinder. At the same time, it should be clarified whether the three dimensional transitional process is due to the intrinsic instability of the flow, or due to the three dimensional conditions of the experimental set-up. It was recognized earlier that different end conditions had dramatic effects on the flow past a circular cylinder. Williamson¹, Hammache & Gharib² and Noberg³ etc. had done much work in this area. By modifying the circular cylinder's end conditions, two-dimensional parallel shedding can be maintained by different methods. They include the use of angled endplates (Williamson¹), coaxial end cylinders (Eisenlohr & Eckelmann⁴), novel control cylinders which are orthogonal to test cylinder (Hammache & Gharib²), and downstream suction tubes (Miller & Williamson⁵). For square cylinder, Robichaux *et al*⁶ and Sohankar *et al*⁷ had obtained

some valuable information about the square cylinder wake transition by employing Floquet analysis method and DNS, respectively. Both of them found that although some differences exist, there were much similarity between the wake transitional processes of square and circular cylinders. In the present paper, hot film anemometry and flow visualization are used to investigate the effects of end conditions on both circular and square cylinder wakes. Angled endplates were installed at the ends of cylinder. It will be shown that different endplate inclinations have substantial effects on the S- Re curve for flow past a circular cylinder, and parallel shedding for both circular and square cylinder wakes can be maintained with endplates inclined at certain angles.

2. EXPERIMENTAL SETUP AND PROCEDURE

The measurements were carried out in a low speed vertical water tunnel specially designed for the present research. This tunnel has a square cross section with a side length of 200mm. The cylinder was placed horizontally in the test section. Careful attention was paid to isolate the vibration caused by pumps.

In this water tunnel, in the velocity range of 24-70mm/s, the free stream turbulence intensity is less than 1%, and the velocity beyond the wall boundary layer is uniform across the test section to within 3% of the free-stream speed U_0 . The coordinate system was shown in Fig.1, defined with the x-axis in the streamwise direction, y-axis perpendicular to the flow and cylinder axis, and the z-axis coincident with the cylinder axis. The origin was taken to be at the center of the cylinder.

For hot film measurements, a polished stainless steel circular cylinder with a diameter (D) of 4.76mm was used in the present investigation. End plates with diameter of 70mm were placed at 170mm apart on the

cylinder to promote two-dimensional flow. In the present experiment, four different pairs of endplates (all with a diameter of 70mm) were used. When installed, they are inclined inwards (toe-in) at angles of 0° , 7° , 14° and 22° to the free stream. Since we define the aspect ratio as the distance between the leading edges of the end plates over the diameter of the cylinder, with the different inclined angles mentioned, the aspect ratio in the present investigation varies from 30.7 to 35.7. Since the blockage in the present experiment is less than 5%, no blockage correction was applied to the data measured. As for the measurements of square cylinder wake, a stainless steel square cylinder (with a side length of 4mm) and 60mm diameter endplates inclined at 14° were used. The aspect ratio is about 42.

Figure 1 Sketch of the test section and the coordinates system.

A Dantec hot film and CTA system was used in present experiment. The hot film was positioned outside the separating shear layers in the near wake region ($y/D \approx 1.5$ and $x/D \approx 2$), and very close to the middle span (i.e. $z/D \approx 0$) of the cylinder. The time traces of the streamwise velocity were recorded and processed by the HP VEE software. By using fast Fourier transformation (FFT), a spectrum can be obtained from the time trace of wake velocity. For each time trace, 65,536 samples were recorded at 800 samples per second. The shedding frequency (f) was taken as the frequency that corresponds to the peak in the calculated spectra. In the present investigation, each spectrum was actually the arithmetic mean of about eight spectra. The Strouhal number is defined as $S = fD/U_0$.

For flow visualization experiment part, dye was ejected from a spanwise slot on the surfaces of the hollow circular and square cylinders. The diameter of the circular cylinder and the side length of the square cylinder are both 70mm. Endplates inclined

at 0° and 14° to the free stream were used to demonstrate the end effects on cylinder wake transition.

Flow the visualization results were recorded by a Panasonic AG-7355 video cassette recorder through a Sony CCD-IRIS camera, model DXC-107P. Photographs were then extracted by a video capture software.

3. EXPERIMENTAL RESULTS AND ISCUSSION

3.1. Hot film anemometer measurement

S-Re relations for a circular cylinder wake with different end plate angles are shown in fig.2. The effects of endplates are clearly demonstrated. For the cylinder with 0° endplates, its S-Re curve is lower than that of the 14° endplates cylinder at both the laminar ($Re < 176$) and transitional flow region ($176 < Re < 240$). The S-Re curve for the cylinder with 7° endplates is between the two above curves, but is closer to the 14° endplates S-Re curve. It should also be pointed out that the S-Re curve for the cylinder with 14° endplates is very close to the curve given by the parallel shedding formula (Williamson & Brown⁸) at Reynolds number larger than 100.

Figure 2 Effects of endplate on the S-Re curves of a circular cylinder. Note that the parallel shedding curve is based on the equation proposed by Williamson & Brown⁸.

For all of the three S-Re curves above, there are two discontinuities that take place at different Reynolds numbers. These discontinuities mark the different instability modes, namely mode A and mode B. For the cylinder with a 14° endplate, mode A appears at about $Re_c = 176$. Above $Re = 250$, only mode B can be detected (no large-scale dislocations appear). For the cylinders with 0° and 7° end plates, these two critical Reynolds numbers are a little lower than those of the 14° endplates cylinder (near 170 and slightly lower than 250). This is likely to be a consequence of the oblique shedding when the end plates inclinations are smaller than 14° . From the three sets of S-Re results shown above, it is natural for one to wonder if the S-Re curve will continue to rise with further increase in the endplates inclination.

In fact, the S-Re curve for a cylinder with 22° end plates coincides with the curve for parallel shedding from $Re=80-140$. However, when the streamwise velocity increases further (i.e. $Re>140$), the flow becomes unstable. Since for the other three smaller end plates angles, Re_c is much higher than 140, this three-dimensional flow is not likely to be related to mode A instability, but could be caused by flow separation from the highly inclined endplates. According to results shown in Fig. 2, 14° is therefore thought to be the most suitable endplates angle for the present investigation. Also, based on the good agreement between the 14° endplates data and the parallel shedding curve of Williamson⁸, it can be concluded that with 14° endplates, in the laminar region, the wake is two-dimensional, and any three dimensionalities due to experimental setup had been reduced to a minimum. With the above situation, the transitional process can be studied more accurately.

In fig.3, the time traces of wake velocity at different Reynolds number (all with 14° endplates) are shown. From fig.3, one can clearly see that there are three distinct types of time traces in the Reynolds region of 80 to 290. For laminar flow ($Re<176$), the velocity fluctuation is almost perfectly periodic. When the mode A transition appears ($176\leq Re\leq 250$), the velocity fluctuation is characterized by the existence of low frequency fluctuations which causes intermittent and sudden decrease in the amplitude of the velocity. When the Reynolds number exceeds 260, there is no more sudden reduction in the velocity amplitude, and wake gradually becomes turbulent.

Figure 3 Three distinct patterns of time trace of wake velocity (U) at different Re's (circular cylinder).

The detailed S-Re relation curve for a square cylinder with 14° endplates is shown in fig.4. Like

the case of the circular cylinder, two discontinuities exist which are identified as the indicators of mode A and mode B instabilities. From the curve shown in fig.3, mode A instability commences at $Re\approx 165$, and mode B instability starts at $Re\approx 210$. Both the above critical Reynolds numbers are substantially lower than the values of a circular cylinder, but are close to the values reported by other researchers: Robichaux *et al*⁶ had shown that mode A appears at a Reynolds number of around 161 and mode B appears at a higher Reynolds number of around 190, while Sohankar *et al*⁷ indicated the transition was between $Re=150$ and $Re=200$.

Figure 4 The S-Re relation curve for square cylinder with 14° toe-in end plates.

Similarly for a square cylinder with 14° endplates, fig.5 shows that there also exists three distinct patterns for the time traces of wake velocity, but the Reynolds numbers are different from those of the circular cylinder wake.

Figure 5 Three distinct patterns of time trace of wake velocity (U) at different Re's (square cylinder).

3.2. Flow visualization

Flow visualization approach is recognized as one of the best investigation tools for flow field or flow structure studies. It can provide the information for the whole flow field. For both the circular and square cylinders, 0° and 14° endplates were used to

identify the effects of end conditions. From fig.6, it can be clearly seen that the angled endplates have strong effects on the entire span for both circular and square cylinders. When the 0° endplates were used, due to the end effects, the streamwise velocity along the span is not uniform. This most likely causes the base pressure to become non-uniform too. It can be seen from the recorded video that there is a spanwise flow from the ends of the cylinder to the mid-span region. This causes an “arch” shape shedding pattern (fig.6 a (i) and b(i)), and as confirmed by the hot film measurements, the corresponding Strouhal number becomes lower than their parallel shedding counterpart. When 14° inclined endplates were installed, the flow at the end region was accelerated, and the base pressure along the span becomes more uniform. It can also be seen clearly from the recorded video that there is less spanwise flow at the ends of the cylinder. All these changes cause the shedding to become parallel to the axis of cylinder, as are clearly seen in fig 6 a(ii) and b(ii).

a) Circular cylinder wake
i) $Re=120$ (with 0° endplates).

ii) $Re=120$ (with 14° endplates).

b) Square cylinder wake
i) $Re=120$ (with 0° endplates).

ii) $Re=120$ (with 14° endplates).

Figure 6 The effects of different endplates' angles.

4. CONCLUSIONS

From hot film measurements and flow visualization, it can be concluded that for both the circular cylinder and square cylinders, inclined endplates are useful for maintaining parallel shedding, as they can be used to isolate the effects of end contaminations. For circular cylinder, the S-Re curves for 0° , 7° endplates cylinder are lower than that of 14° endplates cylinder. The S-Re curve for the latter was found to be in good agreement with the parallel shedding curve reported in Williamson & Brown⁸.

With 14° endplates installed, both circular cylinder and square cylinder wake were measured. The transitional processes for both cylinders are similar in that mode A and mode B exist in both cylinders' wakes. There are two discontinuities in the S-Re curve for both of them. There are also three distinct patterns for the time traces of (both) cylinder wake velocity, which correspond to the laminar, mode A and mode B regions. On the other hand, the two critical Reynolds numbers (which correspond to the two discontinuities in the S-Re curves) are different for the two cylinders. In the present investigation, they are about 176 & 250 and 165 & 210 for circular and square cylinder, respectively.

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Keywords: cylinder wake, transition, end effects

Field Experiment on the Drag of Circular Cylinders

- Is the atmospheric flow around a bluff body turbulence ? -

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1. INTRODUCTION

The aerodynamic characteristics of bluff bodies in the atmospheric turbulence are one of the most important problems in wind engineering and have been extensively studied both in the academic and practical points of view¹⁾. In order to evaluate the aerodynamics of bluff bodies, wind tunnel tests in a smooth and uniform flow are widely conducted. Next, if it is needed, turbulent flows generated by using turbulence grids or other turbulence generators are employed to investigate the effects of turbulence on the aerodynamics of bluff bodies. The differences in the results from a smooth flow and various turbulent flows are examined and the bluff body aerodynamics in the atmospheric turbulent flows are predicted.

We have made a series of experiments on the effects of turbulence on the mean flow past two- and three-dimensional bluff bodies. The following results are obtained with emphasis placed on finding possible effects of turbulence scale as well as turbulence intensity²⁻⁵⁾: the flow in the bluff-body near wake is governed by the two basic flow phenomena; one is flow separation and reattachment, and the other is vortex shedding; if either or both of these two phenomena are influenced by the disturbances introduced into the flow field, any flow parameters related to the near wake may be subjected to significant changes; the length scales that are associated with these two phenomena can be the shear-layer thickness on the one hand, and on the other, the spacing between the two shear layers, or

more simply, the body size; therefore, turbulence can exert a strong influence on the near wake flow if the scale is comparable to either of these two length scales; conversely, it will no longer control the near wake flow efficiently if the scale is sufficiently away from either of these length scales; it is for this reason that the effect of turbulence is assumed to be negligible small when the turbulence scale is increased beyond the range of body-size scale.

Thus the aerodynamic characteristics of bluff bodies in the atmospheric turbulent flows, in which the turbulence scale ratio Lx/d is very large, are an interesting problem and remain to be clarified. Here, Lx is a longitudinal scale of turbulence and d is a typical length of a bluff body. Recently, we had a chance to make a field experiment to measure the drag of circular cylinders in the atmospheric turbulent flows. The results are described here.

2. DRAG MEASUREMENT FACILITY AND METHOD IN THE FIELD EXPERIMENT

We have selected a site for the experiment in an open field in the south of Kyushu, Japan, referring to the paths of typhoons in the past. There are no tall buildings and houses that can influence the flow around the cylinder models set in the site. We have constructed a tower to measure the drag of circular cylinders as shown in Figure 1. The measurement tower consists of a base with four telegraph poles of 9m high and a measurement frame of 6.5m high by 2.2m wide on the base. Inside the measurement frame, eight circular cylinders with the span length

of 1.6m, which consist of two 23mm-diameter (d) cylinders, two 30mm-diameter ones and four 90mm-diameter ones, are horizontally mounted with separations larger than 5d. In order to avoid any strong interference by the measurement frame, the cylinder models have circular end plates of 32cm in diameter for 23mm- and 30mm-cylinder models and of 50cm in diameter for 90mm-cylinder models as shown in Figure 2. The circular cylinder models have a smooth surface and rough surfaces with three different circular-groove arrays in size. The measurement frame driven by a motor can rotate horizontally on its axis so as to follow the change in wind direction, accordingly the wind direction is always almost normal to the cylinder models. The drag of each cylinder model is measured with two load cells set at the both ends of a cylinder (Figure 2) and the each output is obtained through a strain-amplifier. To measure the wind speed, two three-cup anemometers are set on the top and bottom of the measurement frame and a wind direction vane is set on the top of the frame. The all outputs from load cells, anemometers and a direction vane are recorded with a 32ch analog tape-recorder and three pen-recorders.

3. RESULTS

Measurement was conducted when the typhoon T9806 came close to the site on September 18, 1998. The typhoon did not bring any rain to the site. The maximum and minimum wind speeds for the experiment were approximately 26m/s and 13m/s.

3.1 The turbulence characteristics of the wind

The wind data recorded with two anemometers are digitized with an A/D converter at a sampling frequency of 10Hz. The power spectra of wind velocity fluctuations are analyzed by the auto-regression (AR) method. Figure 3 shows an example of non-dimensionalized power spectra of u-velocity fluctuation (streamwise component). The spectrum shows a wide inertial subrange of the $-5/3$ power law that is a feature of the atmospheric turbulence. In this case, the mean wind speed is 17.6m/s, the turbulence intensity of u-component is 17.2 %, and the longitudinal length of turbulence scale (the streamwise integral scale) L_x is approximately 83m.

3.2 The drag measurement

We have analyzed the drag data of circular

cylinders for approximately six minutes that include the instantaneous maximum wind speed during the severe wind. The time averaging of the fluctuating drag is made at intervals of 3 seconds for the six minutes, and hence a group of time-averaged C_d data with 3 seconds is plotted for each case in Figures 4-7. We have examined the influence of time-averaging intervals of 1 to 10 seconds on the mean drag with Reynold number. The results showed little difference in Figures 4-7. The drag coefficients, C_d , are non-dimensionalized by the air density, ρ , the diameter, d , and length, l , of the cylinder models, and the wind velocity, U . The wind velocity is determined as follows. We have assumed a linear distribution of wind velocity between the top and bottom anemometers. An incorporated value at each model height is, therefore, adopted as the approaching wind velocity for the cylinder. The wind speeds at model positions inside the measurement frame, however, seem to be slightly higher than those at the anemometer positions at the top and bottom because of the blockage of the frame. The blockage effects of the measurement frame on the cylinder models were preliminary examined in the wind tunnel test before the field experiment. The result clearly showed an increase in the wind speed especially near the frame. Finally, we have adopted a correction coefficient of 1.047 for the speed up in the approaching wind at the model positions for the three cylinder models.

Figure 4 shows the results of drag measurement for the smooth-surface cylinders with diameters of 23, 30 and 90 mm. In the figure, the wind tunnel result for 90 mm cylinder model placed in a smooth flow is also shown. Although the C_d data are very scattered in the figure, the overall mean values of these C_d plots for the three models in the field are nearly equal to the values in the wind tunnel for a wide range of Reynolds number, indicating around 1.2. Figure 5 shows the result of a rough-surface cylinder with 90mm diameter, together with the wind tunnel data of the same 90 mm model placed in a smooth flow. The rough-surface cylinder model has 18 small circular grooves in circumference, with a ratio of groove depth to cylinder diameter of 0.01. The result from field measurement, which indicates a rapid decrease in C_d in the high Reynolds number range of around 10^5 , shows a good agreement with

the result from the wind tunnel experiment for a smooth flow. Similarly, Figures 6 and 7 show the results of rough-surface cylinders with medium and large groove arrays. The ratios of groove depth to diameter are 0.013 for medium roughness and 0.016 for large roughness, respectively. Both are also in good agreement with the result from each wind tunnel experiment conducted in a smooth flow.

These results strongly suggest that the aerodynamic characteristics of a circular cylinder in the atmospheric turbulence are almost the same as those in a smooth flow in a wind tunnel. The authors predicted in the previous papers²⁻⁵⁾ that if the turbulence scale ratio Lx/d becomes very large, the effects of turbulence on bluff bodies will disappear. In this field experiment, the turbulence scale ratio Lx/d attains to 900-3600. Therefore, the present field experiment provides a reliable piece of evidence of the disappearance of turbulence effects on bluff bodies in the atmospheric turbulent flows.

4. CONCLUSION

A field experiment on the drag of circular cylinders was conducted when a typhoon approached Kagoshima, Japan. Using a specially designed drag measurement facility, the drag coefficients C_d of circular cylinders were successfully evaluated in high accuracy. The result shows that the C_d values of circular cylinders in a highly turbulent flow in the atmosphere are almost equal to those in a smooth flow in wind tunnel experiments. This implies that the cylinder drag in a very large-scale turbulence approaches the value in a smooth flow.

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Figure 1. Experimental facility in the field

Figure 2. Model arrangement for drag measurement

Figure 3. Non-dimensional power spectrum of u-velocity component

Figure 4. Drag coefficient C_d vs. Reynolds number Re (smooth surface)

Figure 5. Drag coefficient C_d vs. Reynolds number Re (rough surface with small grooves)

Figure 6. Drag coefficient C_d vs. Reynolds number Re (rough surface with medium grooves)

Figure 7. Drag coefficient C_d vs. Reynolds number Re (rough surface with large grooves)

Cross Wind Excitation of a 2D Square Prism with Vibrating Leading Edge Flaps

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INTRODUCTION

Wind effects have caused design problems for engineers in many different ways, especially in tall building design, such as cladding pressures, internal pressures, and pedestrian level winds. Dynamic wind response is an area with growing importance as modern structures are getting taller and "lighter". For sizes of typical skyscrapers, serviceability, which includes the acceleration response of a building, is often the major design criterion.

Ever since the problem of dynamic response was recognized by structural engineers, numerous ways of tackling it have been proposed. Tuned mass dampers [1] and sloshing dampers [2] and their derivatives [1, 3, 4] are the more classic ways of vibration control and utilise only mechanical mechanisms. On the other hand building shapes [5], corner modifications [6], horizontal or vertical slots [6, 7], moving boundary layer control [8], and other aerodynamic appendages [9] are relatively new ways to counter the problem by means of excitation control.

This paper outlines an experimental study on the effects of vibrating leading edge flaps, similar to the ones described by Mizota and Okajima [10], on the cross-wind excitation of a rigid 2D square prism pressure model. Effects of flap frequency, amplitude, and mean flap angle are discussed.

EXPERIMENTAL STUDY

Rigid Pressure Model

In the wind tunnel experiments a rigid 2D square prism pressure model was used. The model had dimensions of 200mm x 200mm x 1000mm. A circular end-plate of diameter 2m was located at each end of the model in order to make the approaching flow two dimensional. The edge of the end-plate was rounded to minimise boundary layer growth on the

end-plate due to initial separation. The size of end-plates, necessary for 2D bluff body model tests, was chosen by following the recommendations of Kubo[11]. Each of the side walls was populated with 20 pressure taps in 5 stream-wise locations with the four pressure taps at each stream-wise location manifolded together using a 4 to 1 pressure manifold. Pneumatically averaged pressures on the opposite faces of the model were connected to the opposite sides of pressure transducers, enabling the measurement of cross-wind differential pressures on the model. More detail can be found in [12]. The distribution of the pressure taps is shown in Fig. 1.

Figure 1 Distribution of pressure taps on the model

The flaps were designed to vibrate about the two leading edge corners of the model where flow separation occurs. They were hinged along these corners. The flapping motion was sinusoidal and was driven by two high frequency linear actuators for a range of frequencies, amplitudes and mean angles. The length of the flaps is believed to play an important role, and while a large chord is believed to have a more significant effect on cross-wind excitation, for practical reasons it is not desirable. The authors chose a flap length of 10% of the model width for this study, a size which was judged to be a good compromise between the two conflicting criteria.

Wind Tunnel Configuration

The pressure model was situated in the middle of a 3m x 6m open jet Twisted Flow Wind Tunnel at The University of Auckland. The twisting vanes were removed and inserts were used to reduce the jet to 3m x 3m during this study. The Reynolds number was kept constant at 1×10^5 throughout the study. Uniformity of the mean flow speed and turbulence intensity were checked using a hot-wire probe.

Data Collection

Pressure data were collected using 5 scanivalve pressure transducers via the manifolded tubing system described. Sixty-four blocks of 8192 pressure samples per channel were collected at 400 Hz. The gain of the overall tubing system was within 10% of unity up to 200Hz and the phase shift was linear up to 250Hz. Details of the response of the tubing system can be found in ref [12]. Electrical signals were amplified and low-pass filtered at 200Hz and then digitised using an analogue-to-digital converter in a PC for later processing.

The Wind Tunnel Tests

The wind tunnel tests were carried out to investigate the effect of flap vibrational parameters on the cross-wind forces developed on a 2D square prism. Details of each test are shown in Table 1 and the definitions of each parameter are illustrated in Fig. 2. These parameters were chosen to cover the range of interest whilst being within the limitations of the equipment. To limit the number of variables and to provide a base-case, the flow in the wind tunnel was smooth and angle of attack was kept at 0 degrees. Only the flap vibrational parameters such as flap reduced frequency (defined using the flap vibrational frequency, the model width, and the mean flow speed), and amplitude were varied in the study described herein. The flaps were worked in pairs throughout the experiment; when one flap swung outward, the other retracted, and vice versa,

hence giving a 180 degree phase difference between the two flaps.

Table 1 Flap parameters

Data set	Flap reduced frequency	Amplitude (deg)	Phase angle between flaps (deg)	Mean angle (deg)
1	No flap			
2	0	0	-	35
3	0.20	2.8	180	35
4	0.27	2.8	180	35
5	0.68	2.8	180	35
6	0.85	2.8	180	35
7	1.00	2.8	180	35
8	1.14	2.8	180	35
9	1.29	2.8	180	35
10	1.29	2.8	180	45
11	1.29	2.8	180	40
12	1.29	2.8	180	37.5
13	0.48	2.8	180	45
14	0.48	4.2	180	45
15	0.48	5.7	180	45
16	0.48	7.0	180	45
17	0	0	-	45

Figure 2 Definitions of vibrating flap parameters

Post Processing

This study focused mainly on the frequency domain analysis of the pressure fluctuations on the sidewalls of the model, although the pressure data were analysed in both the time and frequency domains.

Means and variances of the pressures were calculated and presented in dimensionless coefficient form. They were also combined across different channels to give unsteady cross-wind force coefficients. Results from testing different wind tunnel and vibration parameters were compared.

In the frequency domain analysis, individual power spectra of the 64 blocks of time series data were calculated using normal FFT procedures and then averaged together. Ensemble averaging with varying ensemble size was performed as described in a previous study [12]. The effects of vibrational

parameters on force and pressure coefficients in different frequency bands were investigated.

RESULTS AND DISCUSSION

Time Domain Analysis

Fig. 3 contains the standard deviation of the side-force coefficient, C_{Lrms} , measured from data set 1-9. It shows the effect of flap vibrational frequency on the unsteady lift coefficient of the square prism at a mean flap angle of 35 degrees and with a relatively small flap amplitude. In this figure C_{Lrms} from data set 1 and 2 were both 1.26 and appear in the plot as 1 point. Data set 1 represents a plain square model while data set 2 corresponds to a square model with stationary flaps at 35 degrees. The value of 1.26 is within the range of other measured values [13, 14, 15]. As the reduced flap frequency increases from 0 to 1.29, the unsteady lift coefficient reduces by slightly more than 30% from 1.26 to 0.86.

Figure 3 Variation of C_{Lrms} with flap frequency

Figure 4 Variation of C_{Lrms} with flap amplitude

Fig. 4 shows C_{Lrms} for data sets 13-17 where the flap reduced frequency and mean angle were kept constant at 0.48 and 45 degree respectively. As the flap amplitude increases from 0 to 7 degrees, the unsteady lift on the model decreases almost linearly from 1.29 to 0.38.

Figure 5 Variation of C_{Lrms} with flap mean angle

Fig. 5 is a plot of C_{Lrms} for data sets 9-12 and illustrates the effect of mean angle on the unsteady lift coefficient. The four sets of data have common reduced frequencies and amplitudes of 1.29 and 2.8 degrees respectively. The value of C_{Lrms} is 0.86 at 35 degrees slowly decreasing to a minimum of 0.48 at a mean angle of 40 degrees, and then increases to 0.80 as the mean angle increases to 45 degree. The results show that there appears to be an optimal mean angle of around 40 degrees for reducing the fluctuating lift on a square prism.

Frequency Domain Analysis

Figure 6 Effect of flap reduced frequency on cross wind force spectra

Fig. 6 shows the power spectra of data set 2 and 9, with a mean angle of 35 degree for both, stationary and amplitude of 2.8 degree respectively. The reduced frequency on the horizontal axis is defined using the frequency from spectral analysis, model width, and mean flow speed. The Strouhal number of both data sets was 0.126. Despite the differences in C_{Lrms} , both spectra showed 95% of the total energy between reduced frequencies of 0.11 and 0.14. Hence in small amplitude conditions, flap frequency seems to have similar effect on all frequency components.

Figure 7 Effect of flap amplitude on cross wind force spectra

Fig. 7 shows the power spectra of data sets 13-16 with varying flap amplitude. The Strouhal number of these data varied from 0.120 to 0.124. For a reduced flap frequency of 0.48, increasing the vibrational amplitude from 2.8 to 7 degrees gradually decreases the energy in the reduced frequency band between 0.11 and 0.14, from 89% to 57%. Hence in contrast to the effect of flap frequency, flap amplitude tends to affect the vortex shedding process more than other frequency bands.

CONCLUSIONS

For a square prism with vibrating leading edge flaps:

1. Increasing the reduced frequency of the vibrating flaps from 0 to 1.29 reduced C_{Lms} , by more than 30%.
2. Increasing the vibrational amplitudes from 0 to 7 degrees reduced C_{Lms} , by up to 70%
3. There seems to be an optimal mean angle for reducing the unsteady lift, and for a reduced vibrational frequency of 1.29 and an amplitude of 2.8 degrees, the optimal mean angle is around 40 degrees.
4. Reduction in unsteady cross-wind force with increase in flapping frequency was achieved by weakening the pressure fluctuations over a broad frequency band. Increasing flap frequency seems to have similar effect on pressure fluctuations at different frequency bands.
5. Reduction in unsteady cross-wind force with increase in flap amplitude was caused mainly by weakening of the pressure fluctuations around the shedding frequency. Hence it is believed that large amplitude flap vibrations disrupt the vortex shedding process.

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