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Flow Control by a Short Splitter Plate Asymmetrically Arranged Downstream of a Cylinder

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The flow around a circular cylinder of diameter d was investigated, behind which a short splitter plate with a chord of $1.0d$ was placed horizontally as an interference element. The splitter plate was shifted along a line at several discrete levels. The position of the splitter plate is, therefore, defined by gap G from the cylinder base to the leading edge of the plate and by level Z from the wake ceterline. The Reynolds number mainly used was 1.7×10^4 based on the diameter. For $Z=0$, as the splitter plate approaches the cylinder, a critical drop in Strouhal number and base suction occurs for $G\sim2.0d$ (i.e., "critical gap"), in a similar fashion to Roshko's experiment. For $Z=0.5d$, as the splitter plate reaches $G\sim1.8d$, base suction shows a critical drop, but Strouhal number increases gradually for $G<1.8d$. Similar experiments were performed for a rectangular cylinder (height $h(=d)$, depth $0.1h$) with the splitter plate at different levels. When $Z=1.1h$, Strouhal number increases gradually for gaps less than the critical gap. The curve interpolating the positions of the critical gap for each level indicates that also in the circular cylinder case the separated shear layer is forced to flow into the gap and interact in the nearer wake by the approach of the splitter plate to the cylinder.

1. Introduction

In the wake of a bluff body, a pure-frequency oscillation due to the Karman vortex formation dominates normally at high Reynolds numbers. On the other had, it is well known that the Karman vortex formation can be altered, or attenuated by a solid body or boundary located adjacent to, or within, the inherently unstable near wake. It is practically important to understand such phenomena within the context of wake control. Among numerous methods of wake control, the representative one is insertion of a splitter plate along the plane of symmetry of the wake, as documented by Roshko [1] (short plate) and Unal & Rockwell [2] (wedge plate). In Roshko's experiment, a short splitter plate is shifted along the wake centerline of a circular cylinder. He found a critical drop in Strouhal number and base suction as the plate approaches the cylinder, thereby indicating that the ensuing wide and longer "vortex formation" region exhibits a lower shedding frequency; roughly, the frequency scales inversely with the formation length for a given body as:

$$St\propto d/L_F \quad (1),$$

where St is Strouhal number, d diameter, and L_F formation length.

Bearman [3] also using splitter-plate wake interference, made the discovery that the base suction was very closely inversely proportional to the formation length, an assumption often invoked in subsequent studies:

$$-C_{pb}\propto d/L_F \quad (2),$$

where $-C_{pb}$ is base suction coefficient.

Here, a question might arise naturally concerning whether the critical change by the splitter plate is peculiar only to symmetric situations in which the splitter plate is shifted along the wake centerline. If the splitter plate is placed off the wake centerline (i. e., asymmetric situations), could the critical change occur? At least it should be reasonable to assume that the shear layer separated towards the plate will be impeded somehow by the plate and the dynamics

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of vortices alternately shed from both sides of the cylinder could not be equivalent. Hence it is of primary interest to compare the features between the symmetric and asymmetric cases.

Although in somewhat different situations, there have been a few works concerning asymmetric situations. Bearman & Zdravkovich [4] performed an experiment, in which the flow around a circular cylinder placed at various heights above a plane boundary was investigated. They demonstrated cessation of the Karman vortex formation, when the cylinder is placed sufficiently close to a solid wall. This experiment suggests that even under asymmetric conditions, the critical behavior as found by Roshko could occur.

Strykowski & Sreenivasan [5] noticed that the Karman vortex shedding behind a cylinder could be effectively suppressed by inserting a much smaller control cylinder into the flow, immediately outside the wake shear layer, although the experiment was for low Reynolds numbers. They explored the relation of the suppression mechanism to absolute and convective instability of the modified wake, but it has not yet been established. The asymmetry of the base flow, resulting from the insertion of the control cylinder, may have some relevance to a significant change of local stability properties.

The aim of this study is to investigate the flow characteristics of the symmetric and asymmetric cases using a circular and a rectangular cylinder. Rectangular cylinders have sharp edges, so that the separation point is fixed and the flow characteristics are probably less dependent on Reynolds number. Thus, results of the flow past a rectangular cylinder might be useful for understanding of the mechanism of the flow past a circular cylider.

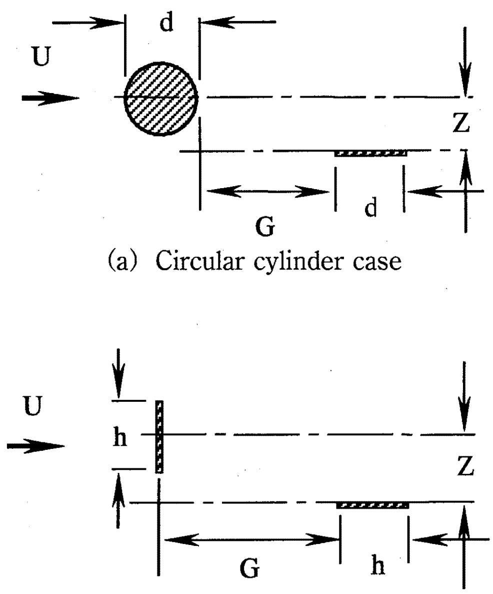
The plan of this study is as follows: Details of the experimental arrangement are described in Section 2. Flow characteristics in which a circular cylinder was used are examined in Section 3.1. Similar measurements using a rectangular cylinder in place of the circular cylinder are presented in Section 3.2. Detailed discussion are provided in Section 4.

2. Experimental set-up

A low-speed wind tunnel was used, which has a rectangular cross section 0.7 cm wide and 3.0 m high. Two kinds of situations were examined and represented in Fig. 1. To increase the degree of two-dimensionality of the flow, wooden end plates were fitted, which had dimensions of 70.0 cm and 50.0 cm parallel and perpendicular to the free stream respectively. At 20.0 mm from either wall giving a separation between the plates of 66.0 cm. The front face of the model was 20.0 cm from the upstream edges of the end plates. The resulting base pressure distribution showed fairly good uniformity. All further measurements were carried out with end plates in position. Reynolds number based on diameter ranged from 6.7×10^3 to 2.5×10^4. The flow speed mainly used was 5.0 m/s (i.e., $Re=1.7\times10^4$). The cylinder occupied about 1.7 % of the total height of the tunnel, but no attempt was made to apply a conventional blockage correction.

2.1 Circular cylinder case

Fig. 1 (a) shows the schematic of the circular cylinder case. A circular cylinder is settled normal to the free stream with its axis parallel to the tunnel floors. The diameter of circular cylinders used were d=5.0 cm and 11.0 cm, the latter of which were adopted for measurements of the surface pressure distribution. A short splitter plate was settled parallel to the free stream behind the cylinder. The splitter



(b) Rectangular cylinder case

Fig. 1 Schematic of the flow configurations plate chosen was 5.0 mm in thickness. The position of the splitter plate relative to the cylinder is defined by distance G from the cylinder base to the leading edge of the splitter plate, and by level Z from the wake centerline to the upper surface of the plate. The splitter plate is traversed along two horizontal lines with $Z=0$ and $0.5d$ behind the cylinder, to examine the variation in Strouhal number and base suction. $Z=0$ means that the splitter plate is shifted along the wake centerline, and hence this situation is reduced to the same situation as Roshko has done [1].

A hot wire probe was positioned in the neighborhood of the cylinder $\sim 3.0d$ downstream and $\sim 2.0d$ beyond the cylinder center. Velocity fiuctuations were detected with KANOMAX constant-temperature hot-wire anemometers and the frequency of vortex shedding was measured on an ONO CF-910 wave analyser.

To measure the pressure distribution around the surface, measurements using a circular cylinder of diameter 11.0 cm was added. The cylinder had pressure tapping at its mid-section, which had internal diameters of 0.3 mm. Transducers were connected to tappings by tubing of nominally 3.0 mm internal diameter.

2.2 Rectangular cylinder case

Fig. 1 (b) shows the schematic representation of the rectangular cylinder case. A rectangular cylinder is settled in place of the circular cylinder, but otherwise the arrangement is almost the same. The rectangular cylinder has a height h of 5.0 cm and a depth of 0.5cm; h has the same length as d. The gap G and level Z are defined similarly to the circular cylinder case. A hot wire probe was positioned $\sim 3.0d$ downstream and $\sim 2.0d$ beyond the upper rear corner. In addition to the basic two levels of $Z=0$ and $0.5h$, the splitter plate was shifted at $Z=0.7h$, $0.9h$ and $1.1h$.

3. Results

3.1 Circular cylinder

Since circular cylinder has no edges, the flow characteristics in general tend' to be dependent on Reynolds number. Fig. 2 shows the variation of base suction coefficient and Strouhal number for different Reynolds numbers. As the splitter plate approaches the cylinder, base suction in Fig. 2a remains almost constant or increases gradually, but at a gap it drops abruptly. Strouhal number behaves quite similarly as shown in Fig. 2b. As Reynolds number increases from 6.7×10^3 to 2.5×10^4, the critical gap approaches the cylinder. This trend is in accord with that of the vortex formation length beyond $\sim 2.0\times10^3$, as was

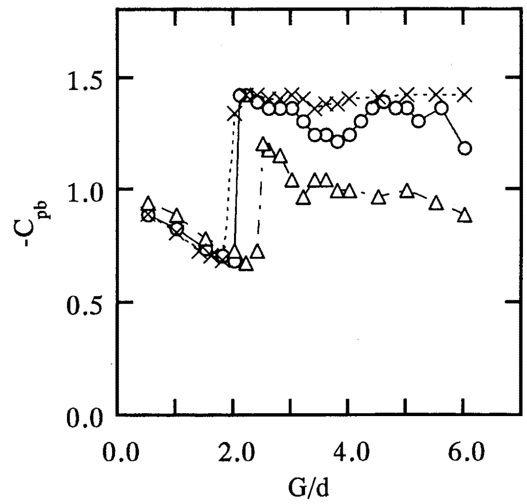


Fig. 2a Variation of base suction coefficient with gap for different Reynolds numbers in the circular cylinder case with $Z=0$. ○, Re$=1.7\times10^4$; △, Re$=6.7\times10^3$; ×, Re$=2.5\times10^4$.

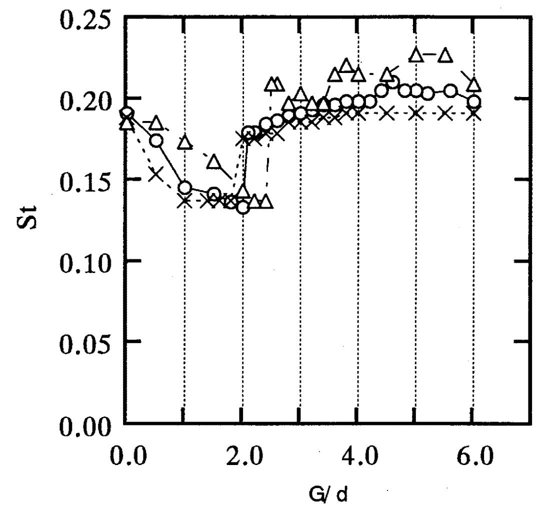


Fig. 2b Variation of Strouhal number with gap for different Reynolds numbers in the circular cylinder case with $Z=0$. ○, Re$=1.7\times10^4$; △, Re$=6.7\times10^3$; ×, Re$=2.5\times10^4$.

demonstrated by visualization in Unal & Rockwell [2]: as Reynolds number increases from 1900 to 5040, the formation length decreases (in their paper, the formation length is defined as the distance downstream of the cylinder at which irrotational fluid is drawn across the centerline).

Fig. 3 shows the variation of Strouhal number and base suction coefficient with G/d, including the results taken from Roshk[1]. When the splitter plate is well-removed from the cylinder, the Strouhal number is around 0.2. As the splitter plate approaches the cylinder, Strouhal number decreases slightly to 0.18. When the splitter plate is located at $G \sim 2.0d$, Strouhal number jumps critically down to 0.13. With further approach of the splitter plate to the cylinder, Strouhal number increases again and tends to 0.19, which is close to the well-removed value. Base suction also shows a similar trend and an abrupt decrease by $\sim$ 50 % occurs at the same location $G \sim 2.0d$. From the reduction in base suction for $G<2.0d$, vortex shedding is found to be suppressed. This is confirmed by the varitation of peak amplitude of velocity fluctuation spectra plotted in Fig. 4.

Our experimental results show good agreement with those of Roshko, but the critical gap ($\sim 2.0d$) is smaller than for Roshko's case ($\sim 2.7d$). There are some possibilities as to the cause such as differences in Reynolds number, aspect ratio and other parameters. In Roshko's experiment, the Reynolds number used was 1.45×10^4, which is smaller than our Reynolds number, $Re=1.7\times10^4$. Consistently this arises partly from the feature that the critical gap approaches the cylinder, with increasing Reynolds number. In Fig. 3, the measurements using a cylinder with a small aspect ratio are included. Little dependence of base suction or Strouhal number on aspect ratio was observed.

Fig. 5 shows the variation of Strouhal number and $-C_{pb}$ with G/d for $Z=0.5d$. When the splitter plate is well removed from the cylinder, St decreases with decreasing G/d in a similar manner to the symmetric case. When $G \sim 1.8d$, the base suction drops abruptly. Interestingly, however, the Strouhal number does not show a large drop, unlike the symmetric case. Although the feature around the critical gap is slightly dependent on aspect ratio, St increases gradually with further approach of the splitter plate to the cylinder except for $G=-0.5d$ in the case of the larger aspect ratio. Apparently, this is inconsistent with the relation (1). From the reduction in base suction for $G<1.8d$, it is clear that vortex shedding is suppressed.

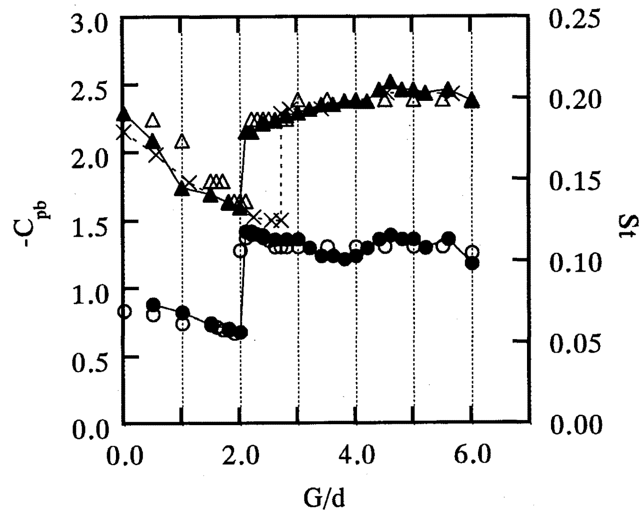


Fig. 3 Variation of base suction coefficient and Strouhal number with gap for the circular cylinder case with $Z=0$. ●, ○, base suction coefficient; ▲, △, Strouhal number. Solid symbols stand for aspect ratio=13.2, and open symbols for aspect ratio=6.0. ×, taken from Roshko [1].

3.2 Rectangular cylinder

Fig. 6 shows the variation of St and C_{pb} with G/d

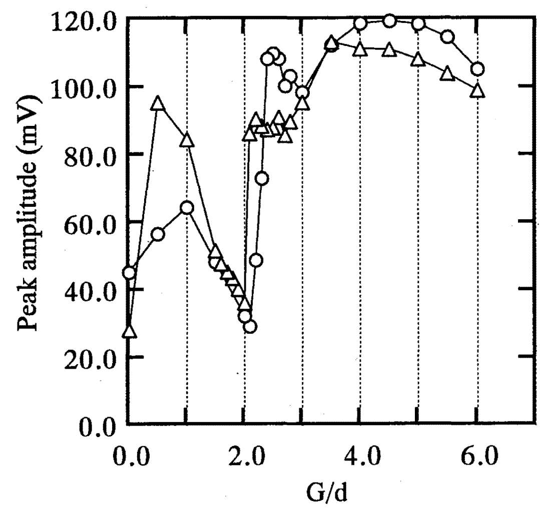


Fig. 4 Variation of peak amplitude with gap for the circular cylinder case. ○, $Z=0.5d$; △, $Z=0$.

for the rectangular cylinder case with $Z=0$. When the splitter plate is positioned sufficiently far from the cylinder, *St* and $-C_{pb}$ remain almost constant. When the splitter plate reaches $G=4.2d$, St critically drops to around 0.1, and at the same time $-C_{pb}$ decreases by 45 %. With further decrease in *G/d*, both *St* and $-C_{pb}$ increase and tend to the respective asymptotic values close to the well-removed value. Fig. 6 includes the data for the asymmetric situation with $Z=0.5d$. Both *St* and $-C_{pb}$ of the asymmetric case are small compared with the symmetric case. However, both curves are very similar.

Fig. 7 shows the variation of base suction with *G/d* for different levels $Z=0.5\sim1.1d$. As the splitter plate is isolated from the wake ceterline, the critical gap approaches the cylinder. Fig. 8 shows the variation of Strouhal number with *G/d* for the different levels. In accordance with the behavior of the critical gap in base suction, the critcal gap of *St* approaches the cylinder, as *Z* increases. Interestingly, however, when $Z=1.1d$, the trend changes significantly. The crtical drop in Strouhal number does not occur. Instead, *St* increases gradually from $G=2.8$ to $2.0d$. For $G<2.0d$, *St* returns to a value to which the other cases are converged to. Fig. 9 shows the variation of peak amplitude in power spectra with *G/d*. From almost the same positions as the critical gap, the peak amplitude falls. This confirms the suppression of the vortex shedding for the gaps less than the critical gap.

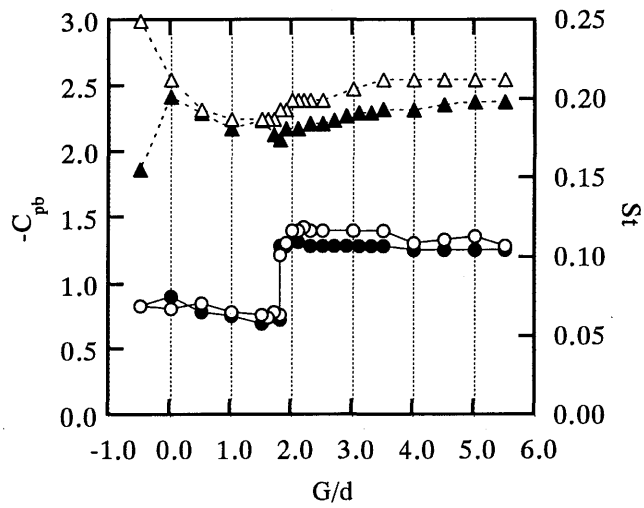


Fig. 5 Variation of base suction coefficient and Strouhal number with gap for the circular cylinder case with $Z=0.5d$. ●, ○, base suction coefficient; ▲, △, Strouhal number. Solid symbols stand for aspect ratio=13.2, and open symbols for aspect ratio=6.0.

4. Discussion

Comparing Strouhal curves of the circular and

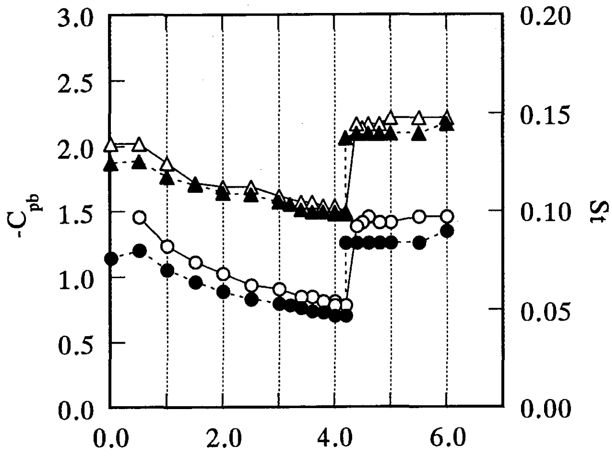


Fig. 6 Variation of base suction coefficient and Strouhal number with gap for the rectangular cylinder case. ●, ○, base suction coefficient; ▲, △, Strouhal number. Open symbols stand for $Z=0$, and solid symbols for $Z=0.5d$.

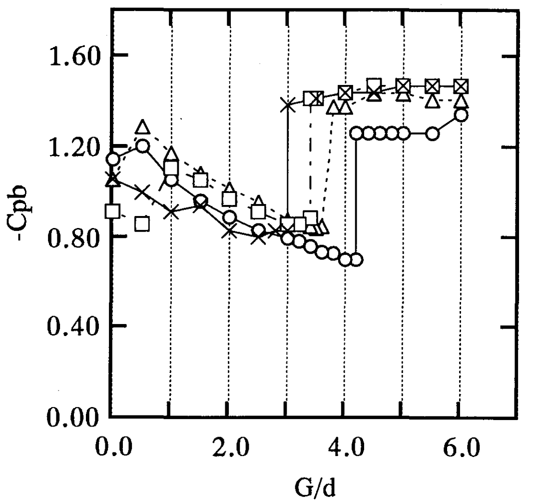


Fig. 7 Variation of base suction coefficient with gap for different levels in the rectangular cylinder case. ○, $Z=0.5d$; △, $Z=0.7d$; □, $Z=0.9d$; ×, $Z=1.1d$.

rectangular cylinder at $Z=0.5$ (i.e., Figs. 5 and 6), we can find a remarkable difference. In contrast to the critical drop in St for the rectangular cylinder case, St does not drop for the circular cylinder case but increases gradually for gaps less than $G \sim 1.8d$. One might question what the origin of this difference is.

Here, instead of the circular cylinder case, our attention was paid to the behavior of the Strouhal curve of the rectangular cylinder case (height h ($=d$), depth $0.1h$) for different levels Z as shown in Fig. 8. It might be useful for a better understanding of the circular cylinder case. The similar variation for $Z=0.5 \sim 0.9$ indicates a common mechanism of vortex shedding should work for those flows, but for $Z=1.1d$ some change in the mechanism should occur. Fig. 10 shows the positions of the critical gap for each level used, and a curve is drawn from interpolating the points. From the curve, it is expected that the critical gap is closely related to the time-averaged path of the separated shear layer. Thus an interpretation of the increase in St for $Z=1.1d$ might be given as follows: The separated-shear layer shed from the gap side engulfs the splitter plate for $Z=0.5$ to $0.9d$. However, when $Z=1.1d$, the splitter palate is sufficiently isolated vertically that the separated shear layer cannot engulf the splitter pate any more, but is forced to flow into the gap and interacts in the nearer wake. A similar mechanism should work also for the circular cylinder case.

This is supported by the fact that from $Z \sim 3.0$ to $2.0d$, Strouhal number increases significantly. This is also consistent with the relation (1). Interestingly, however, the relation (2) does not hold true.

Fig. 11 shows the time-averaged surface pressure coefficient C_p of the circular cylinder for the asymmetric case with the splitter plate located upstream ($G=1.5d$) and downstream ($G=2.5d$) of the critical gap ($G \sim 1.8d$). When the splitter plate is located downstream of the critical gap, the pressure distribution becomes clearly asymmetric. When the splitter plate is upstream of the critical gap, the asymmetry in pressure distribution is not so significant, although C_p on the bottom side are slightly lower than

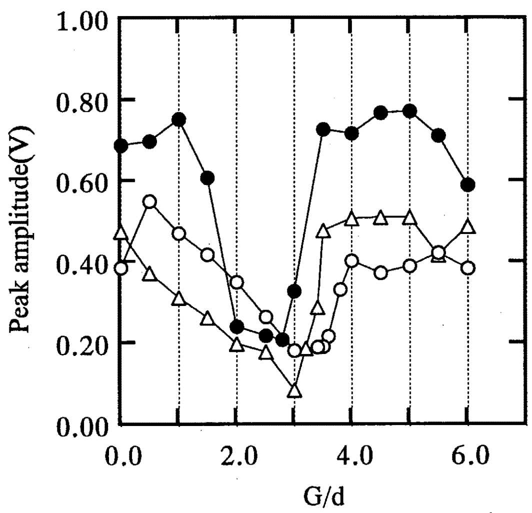


Fig. 9 Variation of peak amplitude with gap for different levels in the rectangular cylinder case. ●, $Z=1.1d$; △, $Z=0.9d$; ○, $Z=0.7d$.

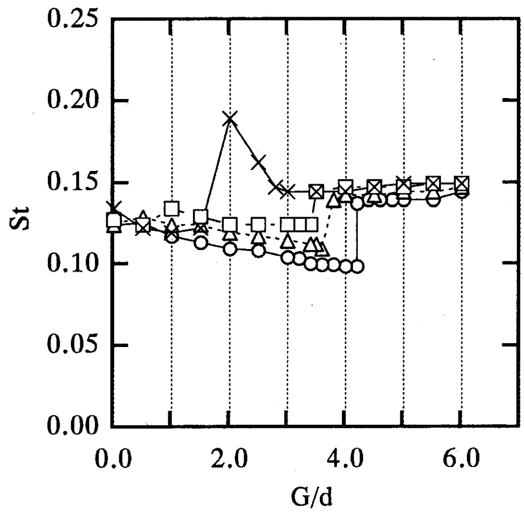


Fig. 8 Variation of Strouhal number with gap for different levels in the rectangular cylinder case. ○, $Z=0.5d$; △, $Z=0.7d$; □, $Z=0.9d$, ×, $Z=1.1d$.

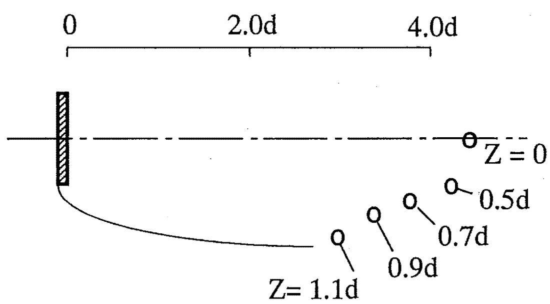


Fig. 10 Trace of the positions of the critical gap for each level in the rectangular cylinder case.

on the top side. This supports again the explanation that the separated shear layer is forced to flow into the gap and interacts in the nearer wake. It should be noted that in the circular cylinder case, the separation point moves upstream to 80° when the splitter plate is located upstream of the critical gap. In other words, by moving separation point, the circular cylinder flow adjusts itself to the approach of the splitter plate.

5. Conclusions

The flow past a circular cylinder was investigated, behind which a short thin splitter plate was inserted as an interference element. Flow characteristics are examined mainly for symmetric ($Z=0$) and asymmetric ($Z=0.5d$) cases.

1) For $Z=0$ in a similar manner to the finding by Roshko [1], as the plate approaches the sylinder, a critical drop in St and $-C_{pb}$ occurs for a gap $G\sim 2.0d$. For $Z=0.5d$, a similar critical drop in $-C_{pb}$ can be seen as the splitter plate approaches the cylinder, but St increases gradually for $G<1.8d$. This is apparently inconsistent with the relation (1) that vortex shedding frequency is inversely proportional to formation length.
2) Similar measurements were performed for a rectangular cylinder with a height h ($=d$) and a depth $0.1h$ in place of the circular cylinder. For the asymmetric case, in which the splitter plate is shifted along a plane $0.5h$ off the center, a similar critical change to the symmetric case can be seen. As the plate is isolated vertically from the wake centerline, the critical gap approaches the rectangular cylinder. Of particular interest is the fact that when the plate is shifted along a line $1.1h$ off the wake centerline, Strouhal number increases significantly as the plate approaches the rectangular cylinder from $Z\sim 3.0$ to $2.0h$.
3) From the curve interpolating the positions of the critical gap for each level, it is expected that the critical gap is closely related to the time-averaged path of the separated shear layer. Thus an interpretation of the increase in St for $Z=1.1h$ can be given as follows: The separated-shear layer shed from the gap side engulfs the splitter plate for $Z=0.5$ to $0.9h$. However, when $Z=1.1h$, the splitter plate is sufficiently isolated vertically that the separated shear layer cannot engulf the splitter plate any more, but is forced to flow into the gap and interacts in the nearer wake. A similar mechanism works also for the circular cylinder case. This is consistent with the relation (1) but interestingly not consistent with the relation (2).

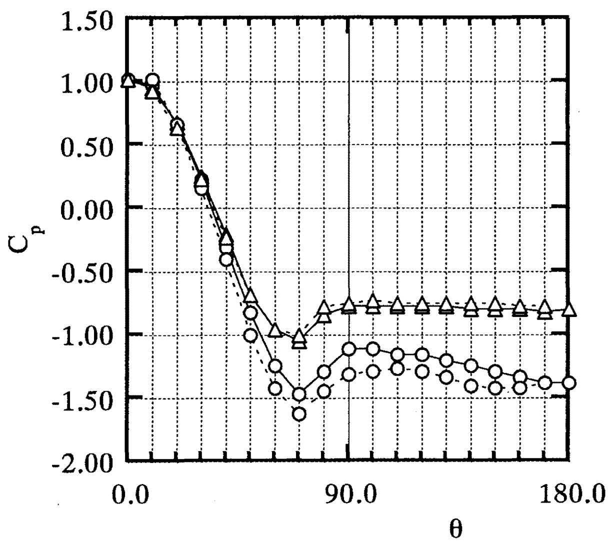


Fig. 11 Distribution of surface pressure coefficient for the circular cylinder case with $Z=0.5$. ○, $G=2.5d$; △, $G=1.5d$. Broken lines stand for the upper side, and solid lines for the lower side.

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