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Flow over a cylinder with a hinged-splitter plate

S. Shukla, R.N. Govardhan*, J.H. Arakeri

Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India

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Abstract

Previous work on rigid splitter plates in the wake of a bluff body has shown that the primary vortex shedding can be suppressed for sufficiently long splitter plates. In the present work, we study the problem of a hinged-splitter plate in the wake of a circular cylinder. The splitter plate can rotate about the hinge at the base of the cylinder due to the unsteady fluid forces acting on it, and hence the communication between the two sides of the wake is not totally disrupted as in the rigid splitter plate case. In our study, we investigate this problem in the limit where the stiffness and internal damping associated with the hinge are negligible, and the mass ratio of the splitter plate is small. The experiments show that the splitter plate oscillations increase with Reynolds numbers at low values of Re, and are found to reach a saturation amplitude level at higher Re, Re $>$ 4000. This type of saturation amplitude level that appears to continue indefinitely with Re, appears to be related to the fact that there is no structural restoring force, and has been observed previously for transversely oscillating cylinders with no restoring force. In the present case, the saturation tip amplitude level can be up to $0.45D$, where D is the cylinder diameter. For this hinged-rigid splitter plate case, it is found that the splitter plate length to cylinder diameter ratio (L/D) is crucial in determining the character and magnitude of the oscillations. For small splitter plate lengths ($L/D \leqslant 3.0$), the oscillations appear to be nearly periodic with tip amplitudes of about $0.45D$ nearly independent of L/D. The nondimensional oscillation frequencies (fD/U) on the other hand are found to continuously vary with L/D from $fD/U \approx 0.2$ at $L/D = 1$ to $fD/U \approx 0.1$ at $L/D = 3$. As the splitter plate length is further increased beyond $L/D \geqslant 4.0$, the character of the splitter plate oscillations suddenly changes. The oscillations become aperiodic with much smaller amplitudes. In this long splitter plate regime, the spectra of the oscillations become broadband, and are reminiscent of the change in character of the wake oscillations seen in the earlier fixed-rigid splitter plate case for $L/D \geqslant 5.0$. In the present case of the hinged-splitter plate, the sudden transition seen as the splitter plate length (L/D) is increased from 3 to 4 may be attributed to the fact that the wake vortices are no longer able to synchronize with the plate motions for larger splitter plate lengths. Hence, as observed in other vortex-induced vibration problems, the oscillations become aperiodic and the amplitude reduces dramatically.

Keywords: Splitter plate; Cylinder wake; Vortex-induced vibrations

1. Introduction

Prior studies have shown that the wake downstream of a cylinder can be greatly influenced by placing a splitter plate along the wake centre-line. These studies in fact show that the vortex formation in the wake can be nearly suppressed by

*Corresponding author. Tel.: +91 80 2293 3232; fax: +91 80 2360 0648.
E-mail address: raghu@mecheng.iisc.ernet.in (R.N. Govardhan).

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the presence of a sufficiently long splitter plate. In these investigations, for example by Roshko (1954) and Apelt and West (1975), a rigid splitter plate is placed behind the cylinder, effectively inhibiting any communication between the two shear layers on either side of the body. In the present work, we investigate the problem of flow over a cylinder with a hinged-rigid (flexibly mounted) splitter plate, as shown in Fig. 1. The splitter plate is allowed to rotate about the hinge point at the base of the cylinder, and hence the communication between the two sides of the wake is not completely inhibited as in the case of a rigid (fixed-) splitter plate. Apart from being an interesting extension to the rigid splitter plate problem and the more recent study of a permeable splitter plate (Cardell, 1993), this problem could also have practical applications in energy extraction (Allen and Smits, 2001) and in suppression of vortex-induced vibrations (VIV) (Assi and Bearman, 2007). This problem is also related to the extensively studied flag flutter problem [e.g. Argentina and Mahadevan (2005), Connell and Yue (2007)], for the case when the flag pole diameter is not negligible compared to the flag/membrane thickness.

A rigid splitter plate can stabilize the near wake and suppress vortex shedding, as has been shown clearly by Roshko (1954). His experiments at Re of about 1.45×10^4 showed that vortex shedding behind a cylinder can be suppressed by a splitter plate $5D$ long, which also resulted in an increased base pressure and a consequent reduction in the drag on the cylinder (D is the cylinder diameter). Apelt et al. (1973) and Apelt and West (1975) continuously varied the length of the splitter plate (L) in their extensive investigations of the effects of a wake splitter plate placed behind a circular cylinder. They report that for short splitter plates ($L/D<5$), the drag coefficient and Strouhal number vary as the splitter plate length is varied due to modifications in the near-wake flow patterns. However, for longer splitter plates ($L/D>5$), vortex shedding is eliminated and the drag coefficient does not vary with the splitter plate length. They suggest this is due to the fact that for longer splitter plates ($L/D>5$), the reattachment point is on the plate surface, and hence any further increase in splitter plate length does not significantly affect the flow pattern. The effects of placing a splitter plate in the wake of other types of bluff bodies have also been studied, for example by Bearman (1965), for a model with a blunt trailing edge, and by Apelt and West (1975) for a flat plate placed normal to the flow. The broad feature of a sufficiently long splitter plate suppressing vortex shedding is also reported in these investigations.

It is clear from the results of rigid splitter plate studies that the near-wake structure can be varied by changing the length of the splitter plate. It should be noted that in these rigid splitter plate cases, no communication is possible across these plates. The work on the effect of a long permeable splitter plate (Cardell, 1993) is an extension of the solid splitter plate investigations discussed above, where some communication is possible between the two shear layers on either side through the permeable plate. Cardell (1993) showed that the near wake can be continuously changed by varying the permeability (or solidity) of the plate. He reported that when the permeability is high, the basic near-wake structure and vortex formation is similar to that when there is no splitter plate present. On the other hand, when the permeability is low, he reported that the near wake is almost disconnected from the vortex formation that occurs further downstream.

In the present work, we are using flexible interfering elements, and one could expect the flexible element to oscillate due to the unsteady pressure forces acting on it. One related study is the work of Allen and Smits (2001), where they placed a piezoelectric membrane or "eel" in the wake of a normal plate, and described the oscillations of the membrane. In their work, the membrane was placed downstream of the base of the bluff body. The purpose of their study was to obtain optimal conditions to achieve the largest possible energy extraction from the flow, to possibly generate power for some autonomous systems. The above problem, in the absence of a bluff body reduces to the extensively studied problem of flag flutter. As mentioned by Connell and Yue (2007), the flag flutter problem involves the study of a thin membrane (flag) that is pinned at the leading edge and is otherwise free. As the fluid travels over the flag surface and into the wake, an instability can occur that results in flapping of the flag. This type of natural flapping behaviour also has applications in understanding the efficient locomotion of swimming fish and other aquatic creatures like eels (Shen et al., 2003).

In the present study, we investigate the problem of flow over a cylinder with a hinged-rigid splitter plate, as shown in Fig. 1. As stated earlier, in this configuration, the communication between the two shear layers on either side is not

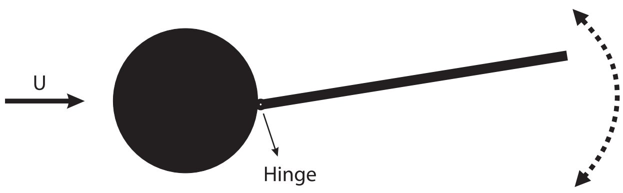

Fig. 1. Schematic of cylinder with a hinged-rigid splitter plate. The rigid splitter plate is free to rotate about the hinge at the base of the cylinder.

Fig. 2. Superimposed image, obtained from a video sequence, showing the extent of splitter plate motions. In this case, splitter plate length to diameter ratio, $L/D = 3.0$, and Re ≈ 7000.

totally inhibited. An integrated effect of the difference in pressures across the splitter plate can cause motions of the plate, which can in turn lead to some communication between the two shear layers on either side of the body.

The main nondimensional parameters in the present problem are the splitter plate length-to-diameter ratio (L/D) and the Reynolds number (Re). In addition, there can be nondimensional parameters that are related to the mass of the splitter plate, the bending stiffness of the hinge and the internal structural damping of the hinge. In the particular case of the experiments here, these additional parameters are very small and do not appear to influence the dynamics, as explained in more detail in the Experimental methods section. Hence, we have effectively two nondimensional parameters; L/D and Re.

One of the most basic questions that one can pose about the present problem is: Do sustained oscillations occur for a hinged-rigid splitter plate? Some recent experiments by Assi and Bearman (2007) with a slightly different configuration, where the hinge point is at the centre of the cylinder, in fact suggest that plate oscillations do not occur. To address this question directly for the present configuration, we present in Fig. 2 the superimposed image obtained from a video sequence of the splitter plate motions. The figure clearly shows that significant oscillations do occur with amplitudes of the order of $0.5D$. The motion of the splitter plate was observed to be reasonably periodic and sustained, as indicated by a series of measurements. We shall present in this paper the measurements of the tip amplitude for such a system, and the effects of varying the two main parameters governing the system: Reynolds number (Re) and the splitter plate length (L/D).

2. Experimental methods

The present experiments were conducted in a $1\,\text{m} \times 1\,\text{m}$ cross-section water-tunnel in the Mechanical Engineering department, IISc, which has a maximum speed of 1 m/s. The cylinder diameter used was 1.78 cm and the flow velocity was varied from 0.04 to 0.60 m/s, resulting in a Reynolds number range, Re $\approx 800-10{,}000$. The aspect ratio of the cylinder used was 13. In all the experiments reported here, end-plates of streamwise length 6 diameters were used to encourage two-dimensional vortex shedding. The hinged-rigid splitter plates were typically made using two plastic sheets of thickness 100 μm with a highly flexible plastic sheet of thickness 30 μm between them. While the rigid sheets were cut to the required splitter plate lengths, the flexible sheet placed in between was longer and extended in between the two halves of the cylinder model. A small part of the flexible sheet was left exposed between the rigid sheets on one side and the cylinder model on the other, and acted as the hinge. The hinge length was typically between 1 and 2 mm. The mass per unit length of the splitter plate was varied by using different types of sheet materials. The effective stiffness of these composite plates was found to be sufficient to resist bending of the plates, and observed motions were purely due to the bending at the hinge. In all cases reported here, the cylinder was mounted vertically so that gravity played no role in the motion (in the horizontal plane) of the splitter plate. The splitter plate motions were visualized at rates up to 40 Hz using a CCD camera in conjunction with a halogen lamp or a PIV Nd-Yag laser. Time traces of the displacement of the trailing edge of the splitter plate were obtained from image processing of the acquired images.

As explained in the Introduction, apart from the Reynolds number (Re) and the nondimensional splitter plate length (L/D), other parameters can affect the system response. These include the stiffness and damping associated with the hinge that connects the splitter plate to the cylinder and the nondimensional mass of the splitter plate. In the particular case of the experiments here with a hinge of thickness 30μ having very low flexural rigidity (EI $\approx 10^{-7}\,\text{Nm}^2$), the stiffness and structural damping are very small and are unlikely to influence the dynamics. These experiments are thus done in the limit where the stiffness and damping of the hinged (flexibly mounted) plate are tending to zero, and hence have similarities with the no restoring force experiments of Govardhan and Williamson (2002) for a transversely oscillating cylinder.

The splitter plate mass can affect the dynamics of the plate, and hence a series of experiments were done with varying splitter plate masses, characterized by the mass ratio, $\rho^* = (\rho_s/\rho_f) \times (t/D)$, where ρ_s is the density of the splitter plate,

ρ_f is density of fluid, t is the thickness of splitter plate and D is the cylinder diameter. The definition of the mass ratio here was taken along the lines of the definitions used in the flag flutter problem, as used for example in Connell and Yue (2007), with the change that the cylinder diameter (D) is used as a characteristic length scale instead of the flap length (L). The measured tip displacement amplitudes for varying mass ratios of the splitter plate at high Re corresponding to the saturation amplitude (discussed in the next section) are shown in Fig. 3 for $L/D = 3.0$. It should be noted that each point in Fig. 3 was obtained from a complete amplitude response plot with Re of the type shown in Fig. 4. Fig. 3 shows that as the mass ratio (ρ^*) is reduced from larger values, the amplitudes do increase. However, for the lower mass ratios ($\rho^* < 0.03$), the amplitude level remains at a nearly constant value as indicated by the lowest two mass ratio cases in the plot. Similar experiments for varying mass ratio were also done for $L/D = 1.0$ and for $L/D = 5.0$, and these experiments also suggest that for small mass ratios, $\rho^* < 0.03$, the amplitude levels are independent of the mass ratio. This insensitivity of the amplitude to the mass ratio, at low mass ratios, may be expected, as at these very low mass ratios the mass of the plate is itself very small compared to the fluid added mass. All the results shown in this paper correspond to this low mass ratio cases ($\rho^* < 0.03$), where the mass ratio no longer appears to be a parameter.

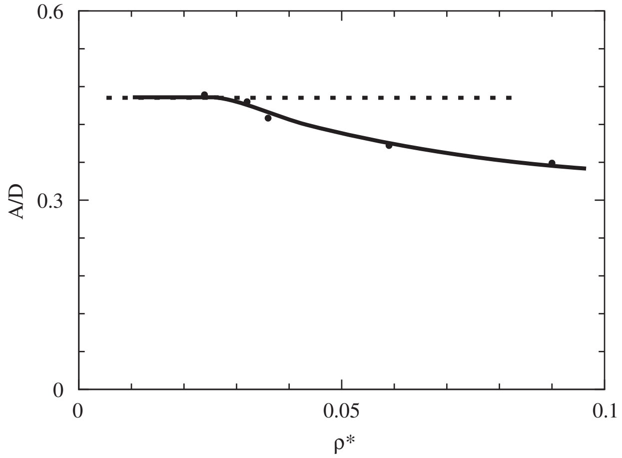

Fig. 3. Variation of the saturation amplitude of plate tip oscillations with mass ratio (ρ^*) for the case $L/D = 3.0$. The amplitude values increase as ρ^* is reduced from larger values, but for $\rho^* < 0.03$, the amplitude appears to no longer be affected by the mass ratio.

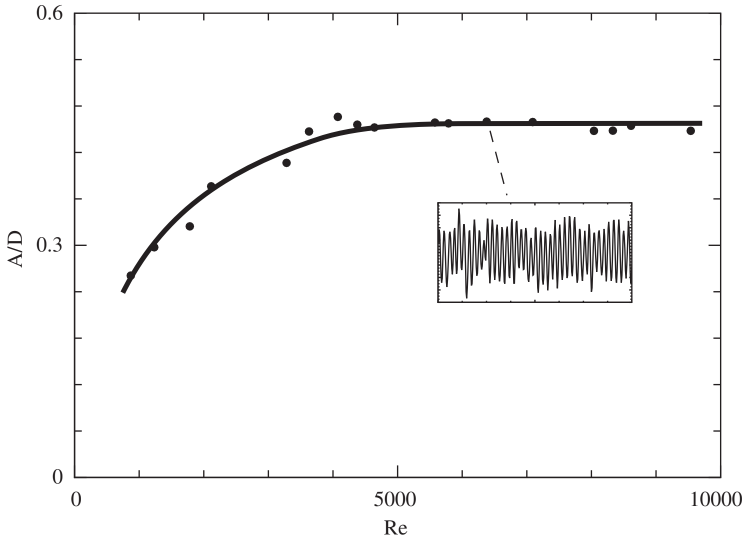

Fig. 4. Variation of the normalized amplitude of tip oscillations of the hinged-splitter plate with Re. The normalized amplitude (A/D) increases rapidly at low Re and attains a saturation amplitude level of $A/D \approx 0.45$ at higher Re. The inset in the figure shows the time trace of the splitter plate motions corresponding to the data point indicated. In this case, $L/D = 3.0$.

3. Tip displacement measurements

Time traces of the tip displacement were obtained from a time sequence of video-images of the splitter plate motions, as explained in the Experimental methods section. An example time trace of measured tip displacement is shown in the inset in Fig. 4 for $L/D = 3.0$. Although there are cycle to cycle variations, the tip oscillations are nearly periodic and these oscillations are sustained. It is clear from Fig. 4 that the plate motions increase gradually at lower Re, and then reach a saturation level at higher Re (Re > 4000) with a normalized amplitude of $A/D \approx 0.45$. This saturation amplitude level is found to extend to the highest flow speeds tested. This kind of saturation level that extends to high flow speeds is reminiscent of the zero restoring force transversely oscillating cylinder experiments of Govardhan and Williamson (2002), where again the response amplitudes were found to remain at a nearly constant level as the flow speed was increased. As discussed in Govardhan and Williamson (2002), it is likely that this type of infinitely wide regime of response would occur for any low mass-ratio VIV cases where there is no stiffness in the system, as in the present case. It should be noted that for systems with restoring forces, and hence systems with mechanical natural frequencies, one would expect a "resonance" only at certain flow speeds and the amplitude would generally decay after reaching the particular flow speed where the shedding frequency is close to the mechanical natural frequency.

An example spectra of tip oscillations is shown in the inset in Fig. 5 for the same conditions as the inset in Fig. 4. The spectra show a clear distinct peak at a normalized frequency (fD/U) of about 0.1. The variation of the dominant or peak frequency found from the spectra with Re is shown in Fig. 5. The normalized frequency of the splitter plate is found to decrease with Re at low Re, and then attain a constant value of approximately 0.1 at higher Re. The constant value of normalized frequency reached is clearly very different from the nominal Strouhal number of about 0.2 for a bare cylinder at these Re. Hence, it is clear that the hinged-splitter plate has a significant effect on the shedding frequency, as one might expect from the earlier fixed-splitter plate study of Apelt and West (1975). It should be noted, however, that the reduction in normalized frequency is more pronounced here than for the wake frequency in the fixed-splitter plate case where $fD/U \approx 0.165$ for the same L/D. We shall see in the next section that this constant value of normalized frequency is strongly dependent on the splitter plate length.

4. Effect of splitter plate length

As discussed above, the results from fixed-rigid splitter plates suggest that for long splitter plates ($L/D \geqslant 5$) the near-wake structure and the vortex dynamics are substantially different from that for short splitter plates, say $L/D = 1$. The marked difference has been attributed to the fact that for long splitter plates, the communication between the two shear layers on either side of the body is completely inhibited, while for small splitter plate lengths, this communication is possible due to the limited extent of the plate. In the present problem of the hinged-rigid splitter plate, both for short or long splitter plates, the communication across the plate is not totally disrupted, and an integrated effect of the pressure

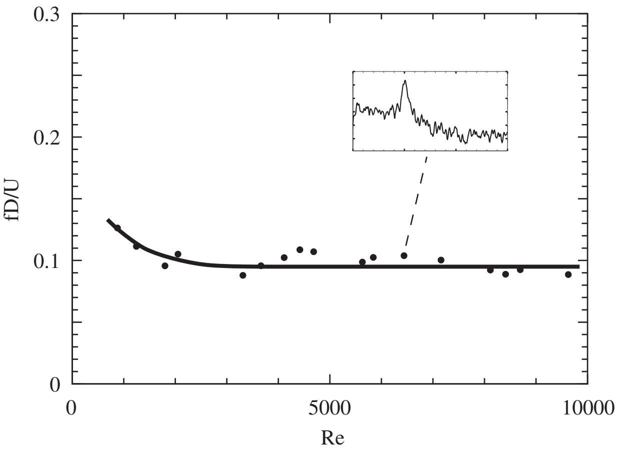

Fig. 5. Plot of the normalized frequency of oscillations of the hinged-splitter plate with Re. The normalized frequency (fD/U) decreases at lower Re and appears to reach a nearly constant value of about 0.1 at higher Re. The inset in the figure shows the spectra of the splitter plate motions corresponding to the data point indicated [$L/D = 3.0$].

difference along the plate can lead to plate motions and hence communication across the plate. It is clear that the larger the plate, the larger the integration length, and hence one would perhaps expect the communication to be less effective.

The variation of the normalized splitter plate amplitude with Re for different splitter plate lengths (L/D) is shown in Fig. 6. The figure contains amplitude data for six different values of L/D ranging from 0.75 to 7.0. Remarkably all the data fall neatly into two sets. The first set with larger amplitudes corresponds to $L/D \leqslant 3.0$, while the second set with smaller amplitudes corresponds to $L/D \geqslant 4.0$. Further, the corresponding time traces, shown in insets in the figure, clearly show nearly periodic oscillations for $L/D \leqslant 3$, while for the larger splitter plate cases, the time traces are qualitatively different and appear to be aperiodic with significantly smaller amplitudes. The change in behaviour between $L/D = 3.0$ and 4.0 cases is dramatic and appears to suggest that there is a sharp transition at a value of L/D between 3 and 4. The

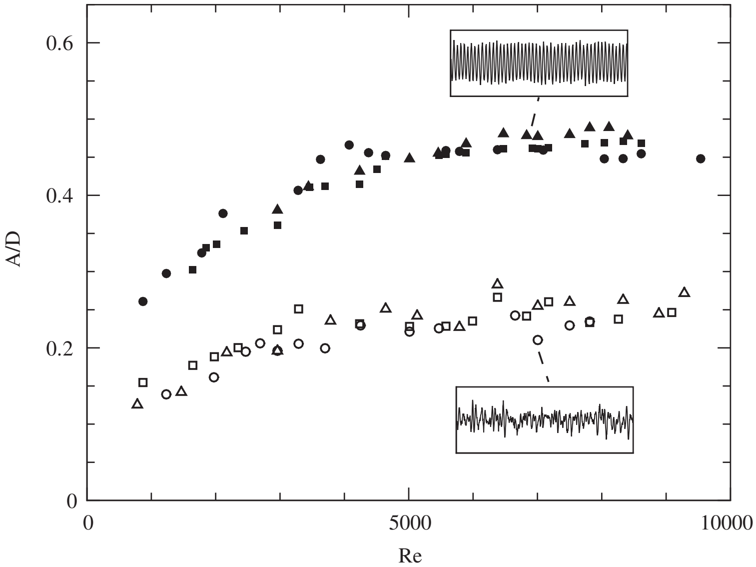

Fig. 6. Amplitude response (A/D) with Re for six different splitter plate lengths. Remarkably, the data fall neatly into two sets with the change over between them occurring for L/D values between 3.0 and 4.0. The time traces shown in the insets also indicate that the oscillations in the higher amplitude case are nearly periodic, while the oscillations in the lower amplitude cases are aperiodic. ▲, $L/D = 0.75$; ■, $L/D = 1.0$; •, $L/D = 3.0$; △, $L/D = 4.0$; □, $L/D = 5.0$; ○, $L/D = 7.0$.

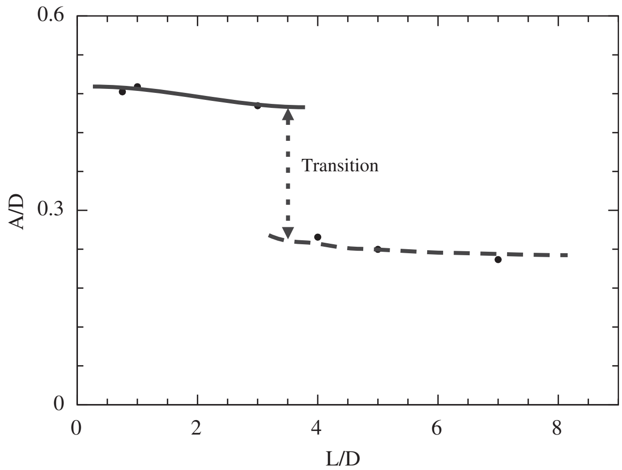

Fig. 7. Overview plot of the amplitude response of the splitter plate showing variation of the saturation amplitude (at high Re) with splitter plate length (L/D). There appears to be a sharp transition in the response between L/D values of 3.0 and 4.0. The solid line indicates the regime of periodic large-amplitude oscillations, while the dashed line indicates the regime where the oscillations are aperiodic with smaller amplitudes.

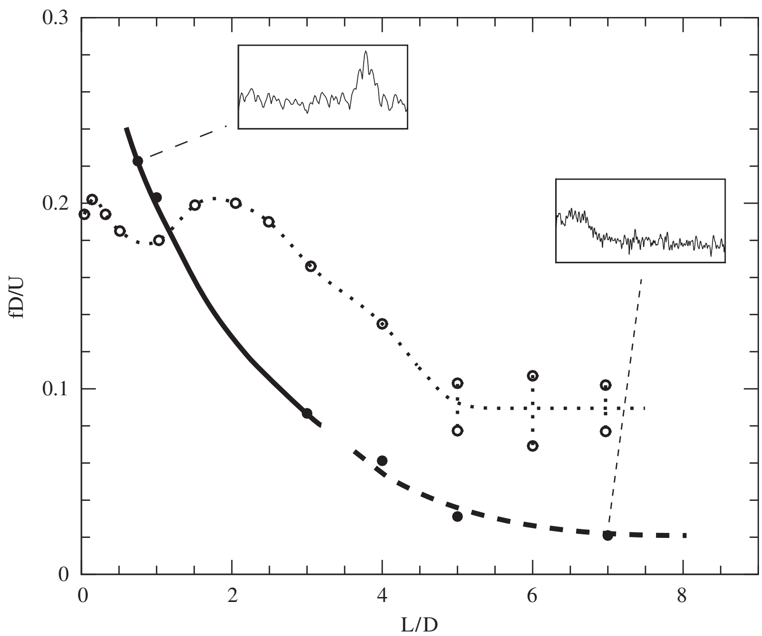

Fig. 8. Overview plot of the frequency response of the splitter plate showing variation of the normalized frequency (at high Re) with splitter plate length (L/D). Between L/D values of 3.0 and 4.0 the nature of the spectra changes suddenly as shown by the insets. In the plot, the solid line indicates the regime of periodic large-amplitude oscillations, while the dashed line indicates the regime where the oscillations are aperiodic with smaller amplitudes. The fixed-splitter plate wake frequency data of Apelt and West (1975) appears to be significantly larger than the present data except at very low splitter plate lengths ($L/D < 1.5$). •, present data; ○, Apelt and West (1975).

sharp transition in amplitude levels is further illustrated in Fig. 7, which shows the saturation amplitude level plotted versus L/D. As the L/D values are increased from low values, the amplitude is found to slowly decrease from a maximum value of about $0.45D$. For L/D values between 3.0 and 4.0, there appears to be a sharp-transition with a sudden drop in the amplitude to about $0.25D$. In the figure, the solid line indicates the regime of periodic-large amplitude oscillations of the splitter plate, while the dashed line shows the regime where aperiodic smaller amplitude oscillations of the splitter plate occur. This overview plot summarizes the effect of splitter plate length on the plate oscillation amplitude.

The variation of the normalized frequency of tip oscillations with Re at different L/D values is shown in Fig. 8. For short splitter plates ($L/D \leqslant 3.0$), the spectra show a sharp peak and the corresponding value of the normalized frequency (fD/U) is shown in the plot. At $L/D = 1$, the normalized frequency is close to 0.2 and is found to drop as the splitter plate length increases. For the larger splitter plate cases ($L/D \geqslant 4.0$), the spectra are very broadband with significantly lower power as suggested by the corresponding time trace shown in Fig. 6 and also shown by the spectra in the inset in Fig. 8. In these cases, there is no dominant frequency, but the centre of the very broad peak can be still picked and the corresponding fD/U value is shown in the plot in Fig. 8 along the dashed line. Between L/D of 3.0 and 4.0, there is a transition in the character of the spectra from sharp peaked to broadband corresponding to the sudden change in the character of the time traces seen earlier. The sudden change in the character of spectra are quite similar to the changes seen in the wake of a fixed-rigid splitter plate by Apelt and West (1975) for $L/D > 5$, where their spectra became broadband, as shown by their data in Fig. 8. It is also clear from the plot that except for very small splitter plate lengths ($L/D < 1.5$), the normalized frequencies in the present case are significantly lower than the corresponding values for the wake frequency in the fixed-splitter plate case. In the present case of the hinged-splitter plate, the sudden transition seen as the splitter plate length (L/D) is increased from 3 to 4 may be attributed to the fact that the wake vortices are no longer synchronized with the plate motions for larger splitter plate lengths. Hence, as observed in other VIV problems, the oscillations become aperiodic and the amplitude reduces dramatically.

5. Conclusions

Previous work on rigid splitter plates in the wake of a cylinder has shown that the primary vortex shedding can be suppressed for sufficiently long splitter plates. In the present work, we study the problem of a hinged-rigid splitter plate in the wake of a circular cylinder. The splitter plate can rotate about the hinge at the base of the cylinder due to the fluid forces acting on it, and hence the communication between the two sides of the wake is not totally disrupted like in the rigid splitter plate case.

The main parameters in this problem are the Reynolds number (Re), splitter plate length to cylinder diameter ratio (L/D), the relative mass of the plate, and the stiffness and internal damping associated with the hinge. In our study, we investigate this problem in the limit where the stiffness and internal damping associated with the hinge are negligible and hence are not parameters of interest. Further, our experiments are conducted at low mass ratios of the plate, where measurements indicate that the response is nearly independent of the precise value of the mass ratio. Hence, we have effectively two nondimensional parameters; L/D and Re.

One of the most basic questions that one can pose about the present problem is: Do sustained oscillations occur for a hinged-rigid splitter plate? Recent experiments by Assi and Bearman (2007) with a slightly different configuration, where the hinge point is at the centre of the cylinder, in fact suggest that oscillations do not occur. However, for the present configuration with the hinge point at the base of the cylinder, our experiments indicate that sustained and nearly periodic large amplitude tip oscillations with peak-to-peak amplitudes of about 1 diameter do occur.

The measurements of tip amplitude show that the splitter plate oscillations increase with Reynolds numbers at low values of Re, and are found to reach a saturation amplitude level at higher Re. This type of saturation amplitude level that appears to continue indefinitely with flow speed appears to be related to the fact that there is no structural restoring force in this case, and has been seen previously for transversely oscillating cylinders with no restoring force. In the present case, the saturation tip amplitude level can be up to $0.45D$.

For the hinged-rigid splitter plate case, it is found that the splitter plate length to cylinder diameter (L/D) ratio is crucial in determining the character and magnitude of the oscillations. For small splitter plate lengths ($L/D \leqslant 3.0$), the oscillations appear to be nearly periodic with tip amplitudes of about $0.45D$ nearly independent of L/D. The nondimensional oscillation frequencies (fD/U) on the other hand are found to continuously vary with L/D from $fD/U \approx 0.2$ at $L/D = 1$ to $fD/U \approx 0.1$ at $L/D = 3$. As the splitter plate length is further increased beyond $L/D \geqslant 4.0$, the character of the splitter plate oscillations suddenly changes: the oscillations become aperiodic with much smaller amplitudes; the spectra of the oscillations become broadband, and are reminiscent of the change in character of the wake oscillations seen in the earlier fixed-rigid splitter plate case for $L/D \geqslant 5.0$.

The sudden transition in the character and magnitude of the splitter plate tip oscillations may be attributed to the fact that the wake is no longer synchronized to the plate motions for larger splitter plate lengths. This type of de-synchronized behaviour leading to smaller amplitudes is usually seen in VIV problems.

Further work to understand the wake vortex dynamics along and downstream of the hinged-rigid splitter plate is presently ongoing using PIV measurements. Forces will also be measured to obtain the mean and unsteady drag and unsteady lift for such a configuration.

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