

2010

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Publication Details

Stappenbelt, B. (2010). Splitter-plate wake stabilisation and low aspect ratio cylinder flow-induced vibration mitigation. *International Journal of Offshore and Polar Engineering*, 20 (3), 1-6.

Splitter-Plate Wake Stabilisation and Low Aspect Ratio Cylinder Flow-induced Vibration Mitigation

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This paper investigates the proposed utility of splitter-plate wake stabilisation as a passive control mechanism for vortex-induced vibration (VIV) mitigation for low aspect ratio cylinders. Stationary cylinder experiments have repeatedly demonstrated the effectiveness of splitter plates in reducing lift and drag coefficients for a cylinder in uniform flow. Rigid attached splitter plates have been shown to be capable of completely eliminating vortex shedding in fixed cylinder investigations. In the limited number of studies that have examined the use of splitter plates in a system which is free to vibrate in the direction transverse to the flow, a galloping-type response has been reported. A range of splitter-plate ratios ($l/D = 0$ to 4) was examined in this study over a reduced velocity interval of $U_r = 3$ to 60. A galloping-type response was observed with the addition of even small splitter plates to the cylinder. At small splitter-plate ratio (l/D), the response of the low aspect ratio cylinders appeared to be strongly influenced by vortex shedding, and key features such as the abrupt decrease in the galloping response at higher reduced velocity aligned well with the bare cylinder VIV response. With increasing splitter-plate ratio, there appears to be a smooth transition from pure VIV (i.e., at $l/D = 0$) to a galloping-type response heavily influenced by the vortex shedding at low reduced velocity and a predominantly galloping response at high reduced velocity. At higher splitter-plate lengths ($l/D \geq 2.8$), no significant VIV or galloping-type response was observed.

INTRODUCTION

Fluid flow past a circular cylindrical object generates vorticity due to the shear present in the boundary layer. This vorticity in the flow field coalesces into regions of concentrated vorticity known as vortices on either side of the cylinder. Flow above a threshold Reynolds number allows perturbations in the flow upstream to cause one of the vortices to grow larger. This vortex, with higher flow velocities and accompanying lower pressures, draws the smaller vortex from the opposing side across the wake centreline. The opposite vorticity from this smaller vortex severs the vorticity supply of the larger vortex, allowing it to convect downstream (Sumer and Fredsoe, 2007). This process is repeated in the reverse sense, leading to alternating vortex shedding from the cylinder.

When the cylinder is elastically restrained and natural frequencies are introduced, a fluid-elastic instability known as vortex-induced vibration (VIV) results. The time varying nonuniform pressure distribution around the cylinder resulting from the vortex shedding causes structural vibrations both inline and transverse to the flow (Hatton, 1999). Near the natural frequency of the structure, the vortex-shedding frequency synchronises with the natural frequency and the vibration frequency. One of the primary mechanisms responsible for this synchronisation is the change in hydrodynamic mass, as demonstrated in the experiments of Vikestad (1998). The range of reduced velocity over which this synchronisation occurs is known as the lock-in range. Mostly, the ensuing vibrations are undesirable, resulting in increased fatigue loading and component design complexity to accommodate these motions. The transverse vibrations also result in higher dynamic relative to static drag coefficients.

In an attempt to mitigate these VIV, the adoption of splitter plates has been proposed (Every, King and Weaver, 1982). A splitter plate is a rigid plate attached to a structure so that it splits the wake. The splitter plate falls within the category of devices termed wake stabilisers. The intention of these devices is to prevent the interaction of the shear developed in the boundary layer flow at either side of the cylinder (Sumer and Fredsoe, 2007). By limiting this interaction, the vortex shedding process is interrupted.

A number of stationary cylinder studies has been conducted to investigate the effectiveness of splitter plates in reducing vortex shedding and the accompanying hydrodynamic forces. (See, for example, Apelt and West, 1975, and Anderson and Szewczyk, 1997.) Roshko's study (1954) reported that at splitter-plate ratios (i.e. the ratio of splitter-plate length to the cylinder diameter) greater than or equal to 5, vortex shedding was completely eliminated. The subcritical stationary cylinder experiments by Anderson and Szewczyk (1997) with splitter-plate ratios of 0.5 and 1 demonstrated significant reduction in vortex interaction and a delay in the formation of vortices by extension of the separated shear layers downstream of the trailing edge. This was also observed in the studies by Roshko (1954) and Bearman (1965).

Gerrard (1966) reported that increasing plate length produced a decrease in the Strouhal number. The investigations by Apelt, West and Szewczyk (1973) and Anderson and Szewczyk (1997) concur, demonstrating that the variation of Strouhal number with splitter-plate ratio is nonlinear. These studies all agreed that even at small splitter-plate lengths (i.e. $0.25 < l/D < 1$) the Strouhal number, drag coefficient and lift forces decreased. Kawai (1990) reported that a drag reduction of up to 36% was attained with the use of splitter plates on stationary cylinders. Studies of stationary cylinders with detached splitter plates have shown similar decreases in lift and drag forces (Hwang, Yang and Sun, 2003; Akilli, Sahin and Tumen, 2005).

There exists a limited number of studies where the effect of splitter plates is investigated when the cylinder is allowed to vibrate (i.e. the cylinder is elastically restrained). The recent

Received July 22, 2009; revised manuscript received by the editors July 8, 2010. The original version was submitted directly to the Journal.

KEY WORDS: Vortex-induced vibration (VIV), galloping, splitter plates, vibration mitigation, wake stabilisation.

studies by Assi, Bearman and Kitney (2009) and Parssinen and Eloranta (2009), and the discrete vortex modelling of Kawai (1990), for example, demonstrated a galloping-type response of a cylinder with splitter plate which was elastically restrained in the transverse direction. The study by Nakamura, Hirata and Kashima (1994) showed that this galloping-type behaviour did not align well with accepted galloping theory. For example, Den Hartog's criteria for galloping instability (i.e. the rate of change of the transverse force coefficient at zero angle of incidence) did not hold true for the case of a circular cylinder with an attached splitter plate. The present study aims to contribute to the systematic experimental examination of the effect of splitter plates on the dynamics and kinematics of a cylinder allowed to vibrate transverse to the flow.

METHODOLOGY

The present experimental investigation examined the single (transverse motion only) degree of freedom VIV response of an elastically mounted rigid cylinder with various splitter-plate ratios under steady, uniform current conditions. The apparatus utilised consisted of a towing carriage and a parallel linkage mechanism capable of translation motion in the transverse direction only; Fig. 1 shows the mechanism. Inline motion was restricted through the use of diagonal cross-braces between linkages. The splitter-plate length range covered was 0 to $4D$. The apparatus for the experiment was lightly damped at around 0.3% of the critical damping. Table 1 lists experimental parameter values adopted in the present investigation.

Throughout the present study, the flow velocities are presented normalised (i.e. as reduced velocities, U_r) by the product of the cylinder diameter and the natural frequency of the bare cylinder in still water. Maximum amplitudes in a time series were defined as the mean of the top 10% half-peak to peak values.

To simulate steady, uniform current conditions, the structure was towed through initially still water. The ratio of cylinder diameter to channel width was 1:25 (representing around 1% of the channel area). No significant variation in local current velocity due to blockage effects was thus experienced. Experimentation was conducted in the Reynolds number range of $1.26 \times 10^4 \sim 8.40 \times 10^4$, which is within the stable subcritical Reynolds number range. Only smooth test-section surfaces were considered.

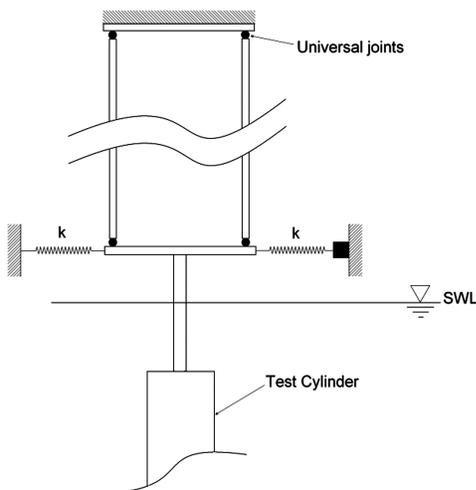


Fig. 1 Elevation view of experimental apparatus

| Parameter | Symbol | Value | Units |
|--|---------------------|--------|-------|
| Cylinder diameter | D | 0.0554 | m |
| Cylinder length | L | 0.4432 | m |
| Cylinder aspect ratio | — | 8.0 | — |
| Cylinder mass ratio | m^* | 2.36 | — |
| System stiffness | k | 53.0 | N/m |
| Damping ratio | ζ | 0.003 | - |
| Natural frequency in air ¹ | ω_v | 9.05 | rad/s |
| Still-water natural frequency ¹ | $\omega_{\omega v}$ | 3.95 | rad/s |
| Splitter-plate ratio range | l/D | 0–4.0 | — |

¹Cylinder without splitter plates attached.

Table 1 Experimental parameters

The cylinder aspect ratio adopted in this study brought the test section closer to commonly employed cylindrical floating structure ratios of 3 to 5. The experiment did not use test section end-plates. The influence of the end-conditions on the cylinder forcing at this small aspect ratio are thus likely to have resulted in lowered excitation frequencies. Strouhal number and vortex shedding frequency data are traditionally collected with very large aspect ratios (i.e. $L/D \gg 100$) and commonly using the tank walls effectively as very large end-plates (maintaining 2D flow at the cylinder ends). A number of studies has shown a decrease in the shedding frequency with decreasing aspect ratio. Examples include the low Reynolds number study of Lee and Budwig (1991) and the higher Reynolds number study of Gowda (1975).

Experimentation and analysis of previous work by Gerich and Eckelman (1982) demonstrated regions near the cylinder ends where the shedding frequency was significantly lower (up to a reported 17% below the Strouhal frequency). Below an aspect ratio of approximately 15, the shedding frequency is dominated by these regions—i.e. the shedding is controlled by the end-conditions). Further examination by Norberg (1994) of the effect of the end-conditions (with Reynolds numbers up to 10^4) on vortex shedding also demonstrated a decreased shedding frequency with reduced end-plate size. In the limit of this trend is of course the present case of a cylinder without end-plates.

In this study, the cylinder was non-surface-piercing and the top cylinder end was at a distance $4D$ below the free surface. No compensating corrections were applied for the surface proximity or to account for the small hydrodynamic forces acting on the rectangular cylinder support structure.

RESULTS AND DISCUSSION

Figs. 2 and 3 illustrate respectively, the amplitude and frequency response curves for the bare cylinder. The initial, upper and lower response branches are visible as is the de-coherence region. Lock-in (where the forcing and vibration frequencies synchronise with the system natural frequency) falls between reduced velocities of approximately 5 and 15. A continual rise in the system natural frequency during lock-in (as a result of the changing hydrodynamic mass) is observed as expected for a low mass ratio system undergoing VIV (Vikestad, 1998). Since galloping motion cannot be excited with an axisymmetric shape such as a circular cylinder, the transverse forcing frequency can reasonably be assumed to be the vortex shedding frequency. The Strouhal number from Fig. 3 is then approximately $St = 0.13$ (with a fit statistic of $R^2 = 0.995$). This value is consistent with previous low mass and aspect ratio experiments by the author (Stappenbelt and Lalji, 2008).

Fig. 4 gives the mean drag coefficient results for the bare cylinder case. The dynamic drag values are observed to increase as a

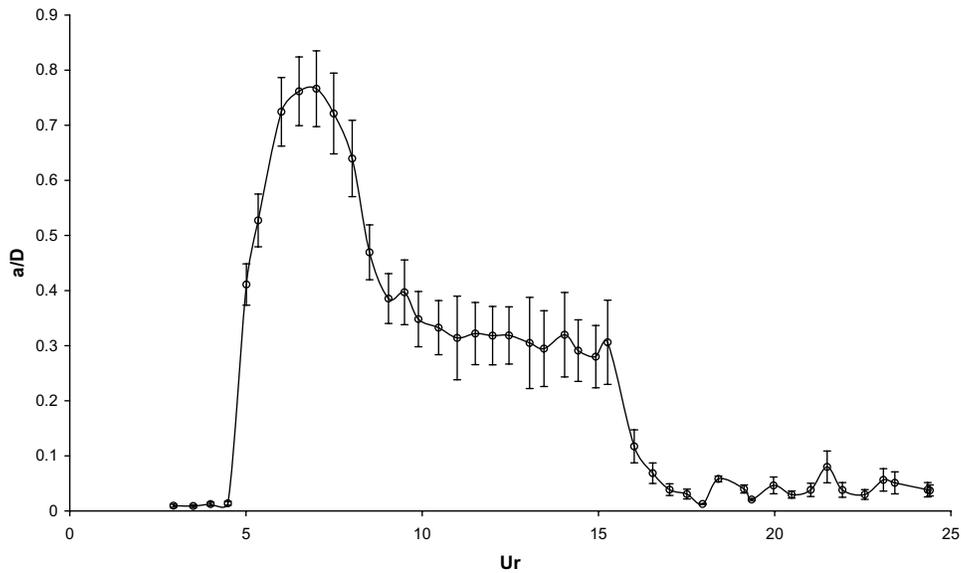


Fig. 2 Amplitude response; bare cylinder case $l/D = 0$

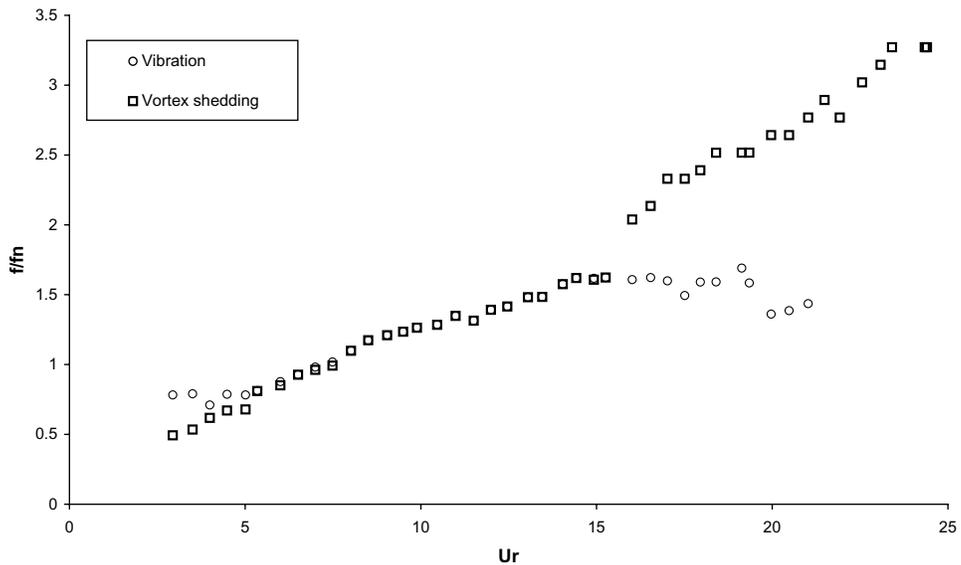


Fig. 3 Frequency response; bare cylinder case $l/D = 0$

function of response amplitude, as described in Det Norske Veritas (2000). The static drag coefficient of the cylinder (estimated from the data outside the lock-in range) is about $C_d = 0.92$.

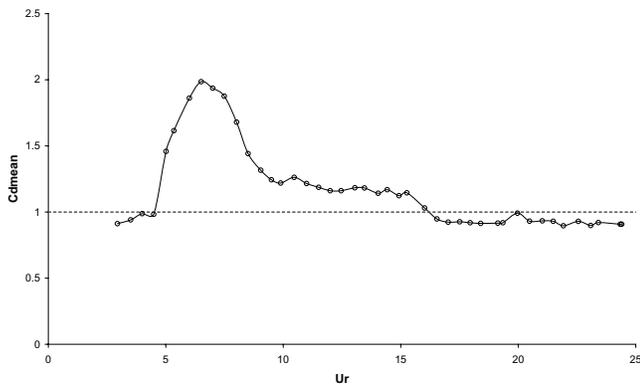


Fig. 4 Mean drag coefficient; bare cylinder case $l/D = 0$

Fig. 5 shows the amplitude response data for all splitter-plate ratios covered. Evident from these plots are the very large vibration amplitudes observed in the splitter-plate cylinder results between $l/D = 0.34$ and 2.4 . The near linear response curve of the cylinder with splitter plates agrees well with the galloping-type response described in Blevins (2001). As reported by Bearman and Luo (1988), the galloping response onset is at the VIV onset point or higher reduced velocity.

In the splitter-plate ratio range of $l/D = 0.34$ to 0.5 , the galloping-type response halts abruptly at higher reduced velocity. When the responses of the various splitter-plate ratio cases are normalised by the true natural frequency (rather than the bare cylinder natural frequency), it is evident that the location of this transition is at the end of the VIV lock-in range. This behaviour may be explained by a system that is only just stable with respect to galloping motions. A system close to a galloping instability may be excited readily by vortex shedding forces and the changing relative free stream velocity due to the induced motions (Nakamura, Hirata and Kashima, 1994). For splitter-plate ratios of

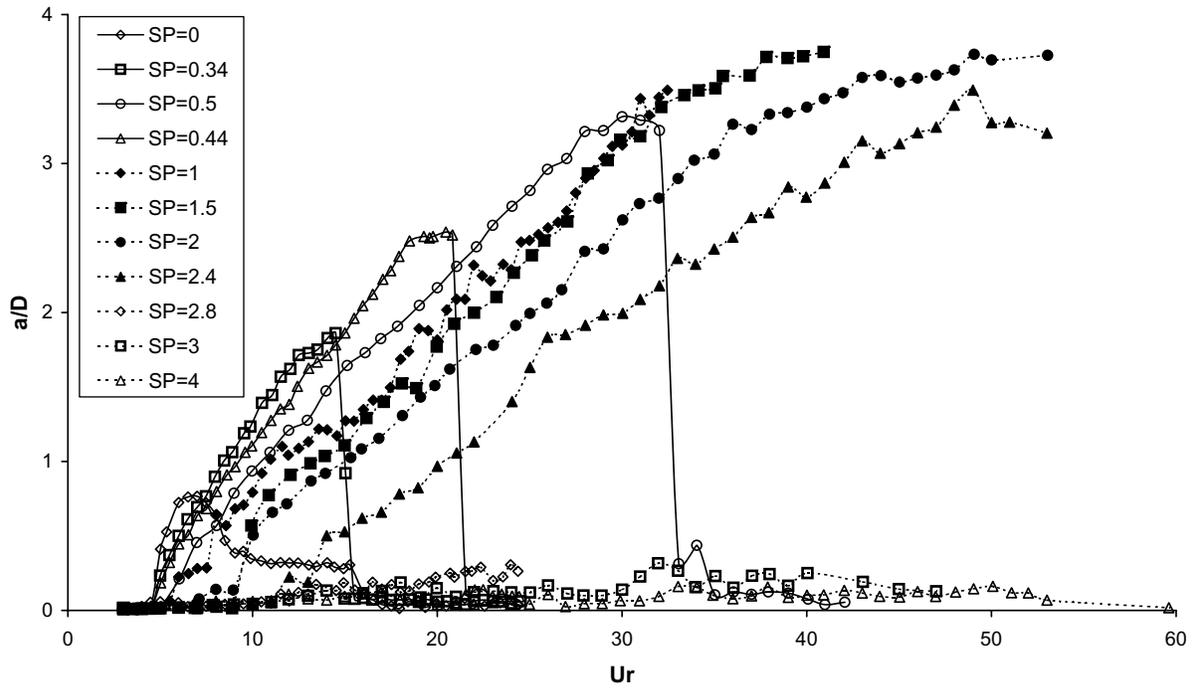


Fig. 5 Amplitude response plots; splitter plate ratios $l/D = 0 \sim 4$

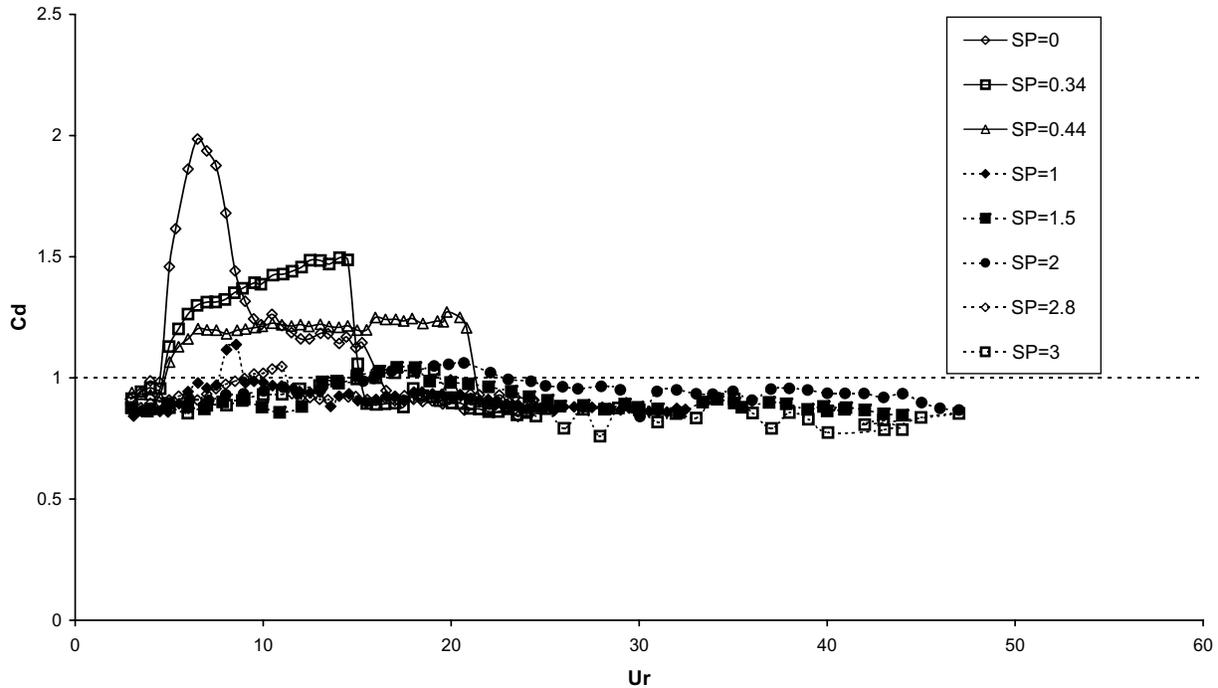


Fig. 6 Mean drag coefficients; splitter plate ratios $l/D = 0 \sim 3$.

$l/D = 2.8$ to 4, no significant vortex-induced or galloping-type vibrations were observed.

The mean drag data presented in Fig. 6 shows the dynamic drag amplification typical of VIV (i.e. as described earlier with reference to Fig. 4) at low splitter-plate ratio ($l/D < 0.5$). This dynamic drag amplification is absent at higher splitter-plate ratios. At $l/D \geq 1$, the drag coefficients measured are equivalent to the static drag coefficient values. These values are consistent with the drag coefficient data from Achenbach (1971), for example. At higher splitter-plate ratio, the mean drag coefficient continues

to drop with increasing splitter-plate length. This is expected, as the form drag is further decreased by improving the streamlining of the structure.

The frequency response of the $l/D = 0.34$ and 0.44 cases (Figs. 7 and 8, respectively) demonstrate the dual presence of galloping and vortex-shedding forces. Within the resonance region, the response is typical of galloping, with the forcing and vibration occurring at the system natural frequency. Outside this region, where there is no appreciable motion and hence no significant galloping forces, the forcing measured is the vortex-shedding

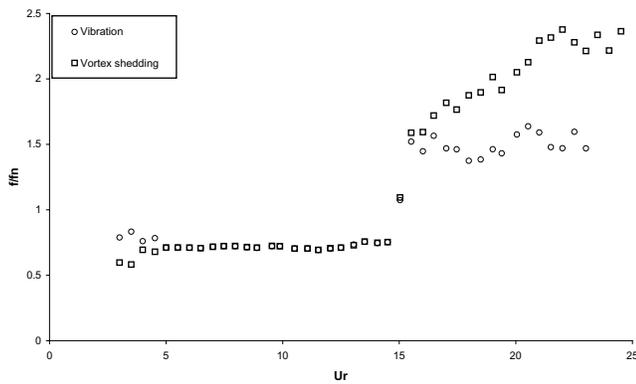


Fig. 7 Frequency response; $l/D = 0.34$

force. The Strouhal number for $l/D = 0.34$ and 0.44 may thus be determined as $St = 0.087$ ($R^2 = 0.9807$) and $St = 0.067$ ($R^2 = 0.9872$), respectively. The observed decrease in Strouhal number with increasing splitter-plate length is consistent with previously reported results (Anderson and Szewczyk, 1997).

Fig. 9 contains the vibration frequency response data for selected splitter-plate ratios where the galloping-type response is evident. The natural frequencies of each case correspond well with the observed galloping frequencies. It may be noted from this figure that there exists a decrease in the system natural frequency with increasing splitter-plate length. This is due to the increased hydrodynamic damping (with the transverse motions) with longer splitter plates.

CONCLUSIONS

The introduction of rigid attached splitter plates to an elastically restrained low aspect ratio cylinder, free to vibrate transverse to the flow, introduces the potential for a galloping-type response. As a result, no vibration mitigation was achieved at splitter-plate ratios less than $l/D = 2.8$. Due to the galloping-type response generated, significantly higher maximum amplitudes were experienced relative to the bare cylinder case. This of course has implications for the passive control of flow-induced vibration using splitter plates.

The galloping-type response for small splitter-plate ratios ($l/D \leq 0.5$) terminates abruptly at the VIV lock-out boundary. The mean drag for these cases has a form similar to that expected for a cylinder undergoing VIV. It is also evident from the frequency response that both vortex shedding and galloping forces are acting on the structure.

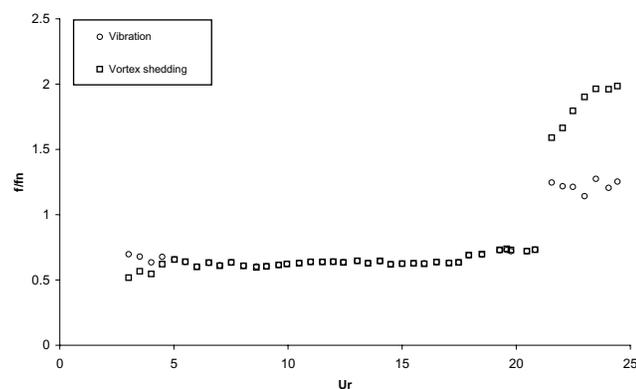


Fig. 8 Frequency response; $l/D = 0.44$

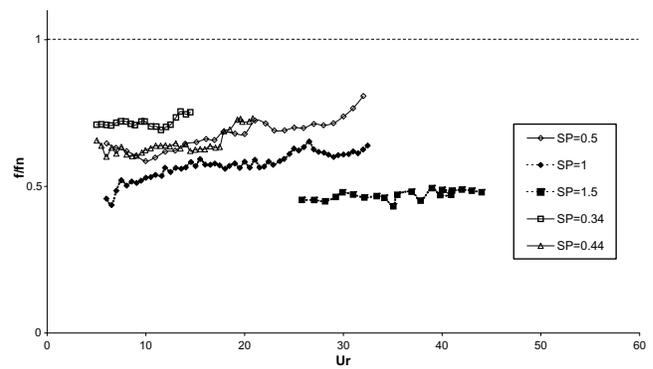


Fig. 9 Vibration frequency response; $l/D = 0.34 \sim 1.5$

It appears that there is a transition, with increasing splitter-plate ratio, from pure VIV (i.e. $l/D = 0$) to a galloping-type response heavily influenced by the vortex shedding at low reduced velocity and a predominantly galloping response at high reduced velocity. This transition, between the region where vortex shedding strongly influences the vibrations and where galloping is dominant, is smooth. This is consistent with the observations made in the square-section galloping experiments by Bearman and Luo (1988).

For splitter-plate ratios of $l/D = 2.8$ to 4 , no significant vortex-induced or galloping-type vibrations were observed for the low aspect ratio cylinder utilised in the present study. It is only within this region that vibration mitigation was realised.

ACKNOWLEDGEMENTS

The contribution of Ibrahim Ayoub, Ji Lu, Brijesh Dutta, Kenneth Elliot and Jie Pan to the experimental work undertaken is gratefully acknowledged.

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