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How should acoustics adapt to meet future demands?

An Experimental Study of the Effect of Splitter Plates on Vortex Induced Vibration

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ABSTRACT

Significant vortex-induced vibration (VIV) occurs when the vortex shedding frequency about a structure coincides with its natural frequency. This is a cause of major problems in the offshore industry that account for large maintenance costs. One method to reduce VIV is by the use of splitter plates to reduce vortex shedding behind bluff bodies such as marine risers. The function of splitter plates was traditionally regarded as prohibiting lift force and amplitude response of VIV by the reduction of vortex interaction from either side of the structure. By allowing the cylindrical structure to vibrate transversely in a towing tank, interesting observations were made as a result of changing splitter plate length. Contrary to existing literature and belief, lock-in region displacement amplitudes of cylinders with splitter plates of lengths 0.5 to 1.5 diameters are up to 4 times larger than bare cylinder displacements. This paper discusses the significance of this experimental result and details on experimental set-up, procedure and vortex induced forces and displacements of cylinders in sub critical flows of reduced velocities ranging from 0 to 32.5 and Reynolds Numbers of $1.0\times10^4 < \mathrm{Re} < 7.5\times10^4$ with splitter plates of lengths 0 to 3 diameters.

INTRODUCTION

Vortex induced vibration (VIV) is the structural vibration resulting from vortex interactions about an elastically restrained structure. As current flows past an object it separates and causes alternate vortex shedding (Fredsoe and Sumer 1997). This shedding is known as a Von Karman Street and creates pressure induced forces in the transverse and longitudinal directions as a result of changing pressure either side of the object and the void preceding it (Hatton 1999).

In sub-critical flow, characterised by a Reynolds number of $300 < Re < 300000$ and a turbulent wake and laminar boundary layer separation, the vortices become unstable and a disturbance in the system causes a wake pressure asymmetry resulting in vortices '*a*' and '*b*' to be severed and convected downstream (Sumer & Fredsoe 1997).

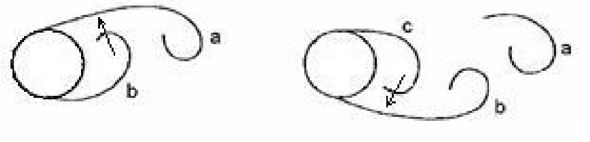

Fig.1 - The Vortex Shedding Mechanism (Adapted from Sumer & Fredsoe 1997)

As the vortex shedding frequency approaches the natural frequency of the cylindrical structure, the elastically restrained structure becomes part of a feedback loop, and interaction occurs between vibration and vortex shedding (Stappenbelt 2006). Large vibration in the structure under VIV may result in cyclic fatigue and failure.

Figure 2 demonstrates a typical normalised amplitude response versus reduced velocity of a bare cylinder in subcritical flow.

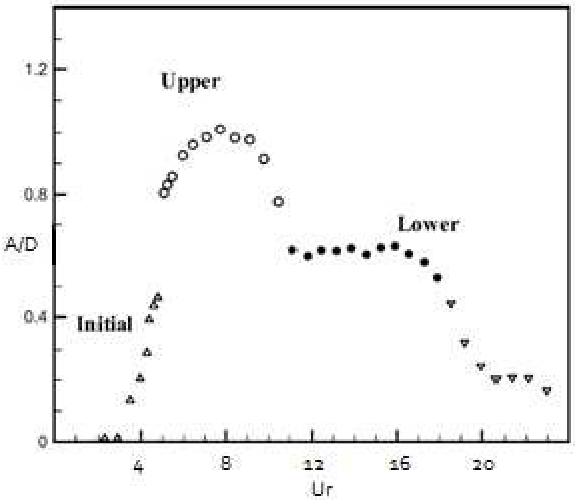

Figure 2 Normalised amplitude versus reduced velocity plot of bare cylinder in sub-critical flow (*Re = 5700*) (Based on data from Govardhan & Williamson 2003)

The reduced velocity is a dimensionless parameter defined as;

$$U_r = U/(f_{nat}D) \qquad (1)$$

For the cylinder's natural frequency, f_{nat}.

In an effort to mitigate VIV, the application of a splitter plate is investigated. A splitter plate is a rigid plate attached perpendicular to a body and mounted parallel to current flow, extending out in the same direction.

With reference to Fig. 1 it can be visualised that introducing a splitter plate will physically reduce or eliminate vortex interaction that causes VIV. Several studies using constrained cylinders with affixed splitter plates have been conducted. It was observed that a splitter plate with a length of 5 cylinder diameters attached to a fixed cylinder was sufficient to completely stop vortex shedding (Roshko 1953). Building on Roshko's research, Gerrard (1966) found that increasing plate length produced a decrease in the Strouhal number which depicts a relationship between flow velocity, U, about a cylinder (with diameter 'D') and the vortex shedding frequency f_{shed} (Stappenbelt 2006);

$$St = f_{shed}D/U \tag{2}$$

This was confirmed by investigations conducted by Apelt et al (1973) and Anderson et al (1997) which showed a non-linear variation in Strouhal number with plate length. These results all showed that even affixing a small splitter plate, of length $0.25< l/d < 1,$ Strouhal number, drag coefficient and base suction all decreased. Research by Kawai (1990) also confirmed that a drag reduction of up to 36% was attained.

Anderson et al's flow visualisation (1997) of a constrained cylinder with splitter plates in sub-critical flow clearly show a massive reduction in vortex interaction and a delay in the formation of vortices by extending the separated shear layers downstream of the trailing edge (Roshko 1953 & Bearman 1965).

The effect of splitter plates of length $0<l/D<1.5$ and mechanisms involved in the formation region can be observed in figure 3.

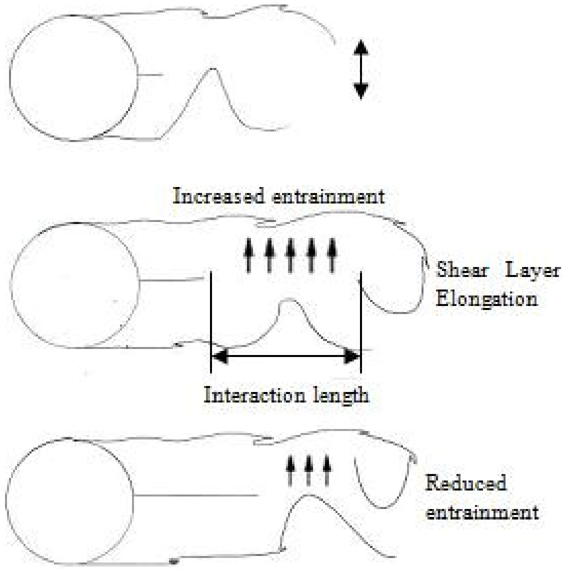

Figure 3 Summary of the effects of the splitter plate on the formation region

The figure summarises accepted knowledge of the effects and mechanism of splitter plates. The first cylinder has a splitter plate of length $l/D < 0.25$ and was found to lessen transverse oscillation of shear layer, decrease momentum thickness and increase Strouhal number. The second cylinder has a splitter plate of length $0.25 < l/D < 0.75$ and possesses an increased entrainment zone and interaction length with decreasing Strouhal number which again was shown to diminish vortex interaction. The final image shows cylinders with plates of length $0.75 < l/D < 1.5$ shows a roughly constant formation length with a decrease in interaction length and increase in Strouhal number.

These existing results and data found for splitter plates in sub-critical flow mounted on constrained cylinders have been extended to encompass general splitter plate behaviour. Splitter plates prevent the interaction between the two shear layers, presumably leading to the complete or partial elimination of vortext shedding and thus suppressing VIV (Sumer and Fredsoe 1997).

By allowing the cylinder to vibrate in the cross flow direction, we have experimentally examined the amplitude of the cylinder's vibration response and analysed VIV with different splitter plate lengths at a range of reduced velocities. Results are contrary to the belief that the existing literature regarding the behaviour of fixed cylinders with attached splitter plates can be extended to the free moving case.

EXPERIMENTAL METHOD

To model an offshore structure with attached splitter plate immersed within a sub-critical flow regime the authors use a testing rig affixed to a towing carriage in a 55m long tank of water. Cylinders with attached splitter plates are suspended via 4 aluminum members attached by universal joints. The Cylinders are supported axially by springs of stiffness of approximately 53N/m.

The cylinder is constrained to move in the transverse flow direction. The rig is equipped with strain gauges and load cells to measure lift and drag forces and transverse displacements.

The Rig is constructed of 20mm RHS steel, front view pictured below;

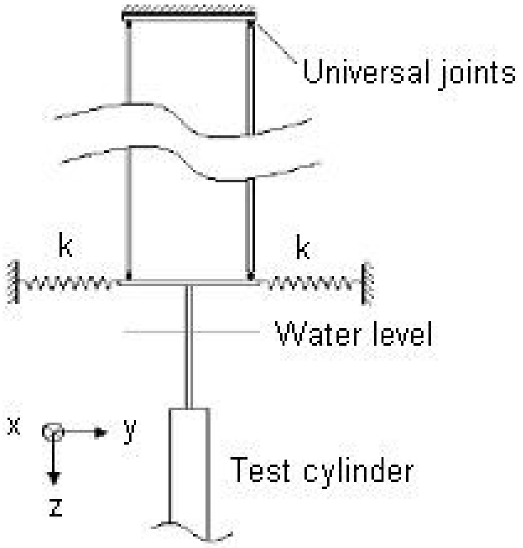

Figure 4 Rig Schematic

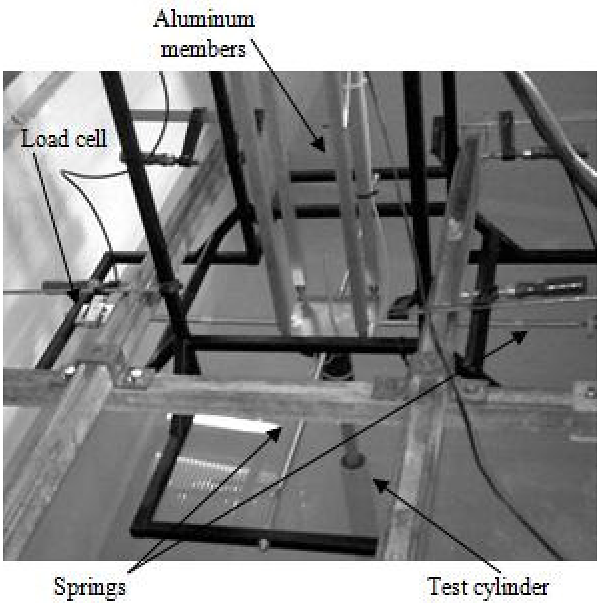

Figure 5 Test rig in the towing tank

Cylinders are constructed of PVC pipe with attached Perspex splitter plates of lengths varying from 0 – 3 cylinder diameter lengths. The natural frequencies of the cylinders and rig are taken in air and still water. The tank carriage tows the rig at speeds varying from 0-1550mm/s, generating a reduced velocity and Reynolds number range of 0-32.5 and 1.0×10^4 to 7.5×10^4 respectively.

System parameters for the test are listed in Table 1.

Table 1 System Parameters

Parameter	Value	Units
Cylinder Diameter	0.0554	m
Cylinder Mass (incl. enclosed fluid)	2.53	kg
Cylinder Aspect Ratio	8	
Damping Ratio (Bare Cylinder)	0.0027	
Natural Frequency in Air (Bare Cylinder)	1.44	Hz
Natural Frequency in Stillwater (Bare Cylinder)	0.628	Hz
Mass Ratio	2.36	
Spring Lengths (un deflected)	210	mm
Spring Lengths (rest position with pre strain)	390	mm
Water Temperature	15	Deg C
Water Viscosity	1.1094 E-6	m^2/s
Tank Width	1.3	m
Tank Water Depth	0.72	m

In analysing the experimental results the authors focused on generating amplitude response plots for the various splitter plate lengths across the reduced velocity range. In deducing deflection amplitudes mean values of amplitudes in the tenth percentile from steady state regions of each run are extracted. The application of a low pass filter removes any components of signal vibration frequencies at least an order of magnitude higher than the system natural frequency.

The steady state duration consists of well over ten full cycles.

RESULTS AND DISCUSSION

The following plots depict the relative amplitude of response of the cylinders, with various splitter plates attached, towed through the tank at increasing reduced velocity.

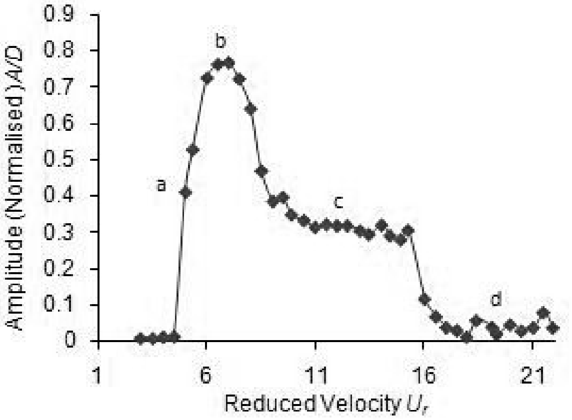

Figure 6 Amplitude of transverse displacement of bare cylinder as a function of reduced velocity

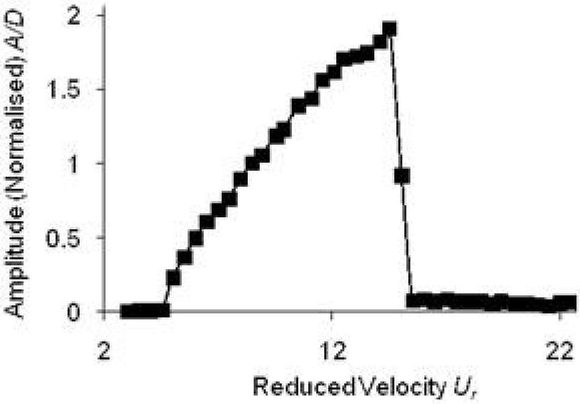

Figure 7 Amplitude of transverse displacement of cylinder with plate of length *l/d = 0.34* as a function of reduced velocity

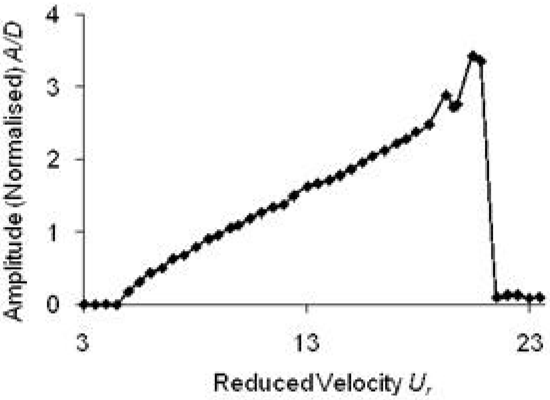

Figure 8 Amplitude of transverse displacement of cylinder with plate of length *l/d = 0.54* as a function of reduced velocity

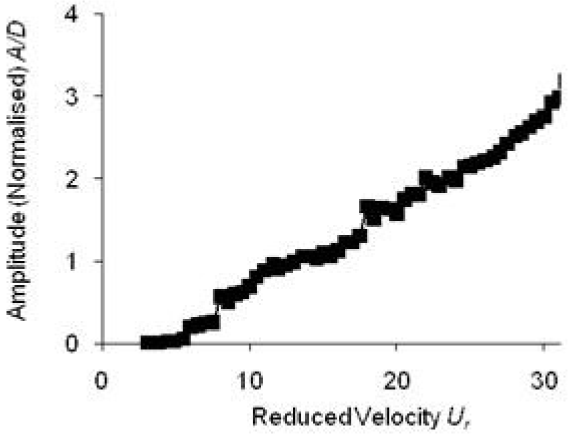

Figure 9 Amplitude of transverse displacement of cylinder with plate of length *l/d = 1* as a function of reduced velocity

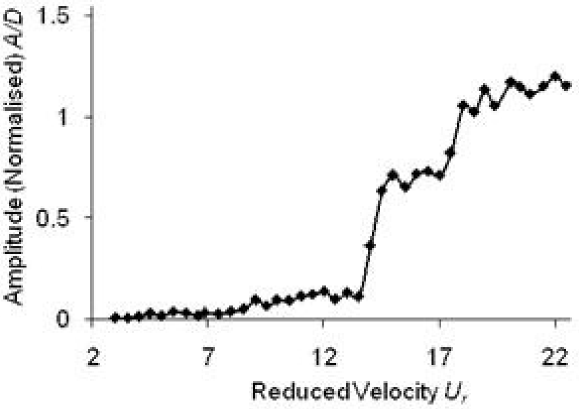

Figure 10 Amplitude of transverse displacement of cylinder with plate of length *l/d = 1.5* as a function of reduced velocity

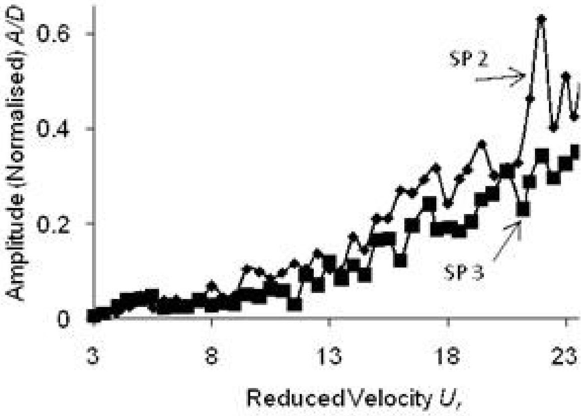

Figure 11 Amplitude of transverse displacement of cylinder with plate of length *l/d = 2, 3* as a function of reduced velocity

The amplitude of response plot of the bare cylinder test case (fig 7) indicates results coinciding with existing literature (T. Sarpkaya 2003 & Govardhan 2003). It is characterised by initial (*a*), upper (*b*) and lower response branches (*c*) and finally a decoherence region (*d*) for reduced velocities *Ur>16*.

According to literature the authors expected an immediate reduction in amplitude with an attached splitter plate but results showed significantly higher amplitudes of response. This is apparent from comparisons of maximum amplitudes and summarised in Table 2.

Table 2 Summary of Results

Splitter Plate Length (normalised)	Maximum Amplitude (normalised)	Reduced Velocity where Amplitude Occurs	Reduced Velocity where Decoherence Occurs
Bare Cylinder	0.77	7.0	16.0
0.34	1.90	14.5	15.0
0.54	3.50	20.5	21.0
1.0	3.50	N/A	N/A
1.5	1.50	N/A	N/A
2.0	0.70	N/A	N/A
3.0	0.44	N/A	N/A

Regardless of splitter plate, the amplitude of response of the cylinders is not realized until a reduced velocity of approximately 5.

It appears that with growing splitter plate length maximum amplitude increases to 3.5 diameters (for cylinders with *l/d = 0.54 & 1.0*) until a splitter plate of *l/d = 1.5* when the maximum amplitude drops to 1.9 diameters, it also appears that with increasing plate length the decoherence region, and thus maximum amplitude, occurs at higher reduced velocities. The experiment was unable to ascertain the decoherence region, and point of maximum amplitude, for splitter plates of lengths 1-3.

A single response branch vortex shedding mode is consistently evolving followed by a sharp transition decoherence, this is most clear for cylinders with plate lengths of *l/d = 0.34, 0.54* (fig's 8 & 9) however the rest of the test cases appear to be following this trend.

CONCLUSION

Experiments have shown without doubt that, contrary to existing knowledge and belief, the amplitude of response increases dramatically with attached splitter plates. This phenomenon, not yet understood, can be observed in comparing maximum amplitude response of the bare cylinder (fig 7) to responses in cylinders with splitter plates, particularly those with plates of lengths 0.54 (fig 8) and 1 (fig 9) diameters where the amplitude response is over 4 times.

This observation has an obvious implication for passive control of vibration in marine risers using splitter plates. Rather than suppressing vibration, attachment of a short splitter plate to the riser may actually amplify the structures vortex induced vibration.

Splitter plates of lengths greater than 2 cylinder diameters can be observed to suppress VIV over the tested range. This coincides with literature and flow field analyses which explain the suppression of VIV as a result of hydrodynamic damping and a reduction of interaction of vortices. There is however a trend of slightly increasing amplitude which is reduced as plate length increases.

The use of splitter plates has transformed the multi region response of the bare cylinder into a single region of linear increase, within it is expected that a solitary vortex shedding pattern occurs, towards a sharp drop in amplitude marking decoherence. This is consistent with all splitter plate lengths.

Further testing is being conducted to capture the lock in range by increasing the reduced velocity range being tested and allowing larger normalised amplitudes. Analysis in conjunction with flow visualisation is also underway to analyse the flow field in an attempt to understand the nature of the phenomenon causing the significant increase in amplitude attaching splitter plates of 0.54 and 1 diameters. This will provide insight into the characteristics of the lift force profile and Strouhal number as functions of reduced velocity and spitter plate length.

ACKNOWLEDGMENTS

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