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Vortex Induced Vibration on Two Equal Diameter Cylinders with Low Mass Ratio in Tandem

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Abstract: Tests have been performed on two equal diameter cylinders with low mass ratio in tandem subjected to uniform flows in a towing tank at subcritical Reynolds numbers. Qualisys video motion capture system was used to measure VIV and spring bars were used instead of commonly used parallel linkage mechanism for this kind of test. Two circular cylinders of 100 mm in diameter and 1.5 m in length were towed vertically at constant speeds through the towing tank to simulate uniform current condition. Some key VIV parameters such as amplitude over diameter, lift and drag coefficients are presented against a non dimensional parameter known as reduced velocity to understand the effect of one riser's motion to another. It was found that the downstream cylinder motion was influenced by the phase difference between upstream and downstream cylinders along with the displacement of upstream cylinder. Results of this study can be used as validation materials for CFD analysis that is very important to design riser system for oil and gas industry, also mentioned experiment procedure can be treated as a guide for future endeavor to perform similar kind of tests.

Key words: Tandem, CFD analysis, Reynolds number, riser model

INTRODUCTION

Vortex-Induced Vibration (VIV) is one of the challenging issues faced by hydrodynamic engineers while designing riser systems used for extracting oil and gas from sea bed due to its potential ability to cause a high level of fatigue damage in a relatively short period of time. Vortex-Induced Vibration (VIV) is a complex hydrodynamic phenomenon that occurs when flow interacts with a certain structure. When a fluid flows past a blunt object, it is excited by forces caused by vortices shed, an unsteady flow that occurs in special flow velocities depending upon the size and shape of the body. Vortices are created at the back of the body and separate periodically from either side of the body causing the time varying non-uniform pressure distribution around the object. These non uniform pressures create a time varying lift force around the object, resulting the structure to vibrate in both inline and transverse to the flow. Lock in occurs when the vibration frequency near the natural frequency of the structure, the change in hydrodynamic mass is the one of main reasons behind this synchronization, as demonstrated in the experiments of Vikestad (1998), this synchronization occurs over a range of reduced velocity that is defined as the lock-in range. Typically the resulting vibrations are detrimental because it increases fatigue loading and component design complexity to accommodate these motions. Numerous experimental and numerical investigations to study Vortex-Induced Vibrations (VIV) of a circular cylinder have been carried out in recent past. Some of the initial studies on flow induced vibrations were summed up by Blevins (1990). A number of experimental evaluation of vortex formation modes were reviewed by Govardhan and Williamson (2000). Willden and Graham (2004) reviewed VIV studies on low mass ratio cylinders. Dong and Karniadakis (2005) reviewed various VIV numerical investigations. Chaplin *et al*. (2005) reviewed and compared some existing CFD codes for riser VIV analysis experimental details for a long riser under a variety of current conditions were presented by Trim *et al*. (2005). Chaplin *et al*. (2005) reviewed some existing CFD codes for analyzing VIV for practical riser. A number of studies on complex modes were reviewed by Lucor *et al*. (2006). Holmes *et al*. (2006) used a fully 3D simulation approach to analyze riser VIV. One of the important parameter that hugely influence VIV of a structure is mass ratio, the behavior of the structure under VIV can be varied in terms of magnitude and frequencies because of mass ratio. For low mass ratio added mass can be very significant. Stappenbelt *et al*. (2007) conducted a series of experiments to understand the mass ratio effect

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on VIV. Normally most of the studies related to the VIV had a tendency to focus single degree of freedom cases, by and large inline vibration was ignored. But when two degrees of freedom were considered, things can be different for low mass ratio structures as revealed by the experimental investigations conducted by Williamson and Jauvtis (2004). They showed the existence of a super-upper response branch when structures have two degrees of freedom. It was found that these vibrations were extremely large and regular at lock in range compared to those observed in the upper response branch in single degree freedom case. Williamson and Jauvtis (2004) also suggested that the offshore design codes should consider this significant deviation from the single degree of freedom VIV data when dealing with structures that have low mass ratios. There are relatively very few experimental and numerical references for oscillating pair of cylinder because of the early assumption that the interference between the two cylinders is weak and thus each of the cylinders may have the same behavior as found in the case of a single cylinder. The upstream cylinder behaves as an isolated single cylinder, while the downstream cylinder experiences larger vibration over a wide range of reduced velocity as reported by King and Johns (1976). Zdravkovich (1985) has observed that in some cases the amplitude of the upstream cylinder could be larger than the downstream one, while in other cases the opposite is true. Allen and Henning (2003) found in some cases where transverse displacement amplitude of upstream cylinder grows beyond 0.5D, downstream cylinder's displacement begins to diminish relative to upstream cylinder's displacement, although they suggested there may be other parameters that also govern the downstream cylinder's displacement beside the high upstream displacement amplitude. A high Reynolds number experiment, in tandem configuration, has been conducted by Allen *et al.* (2005). Effect of VIV on pair of cylinders is very complex subject to be dealt with, this apparent complexity have motivated the present study. In this study some results of the VIV experiments of two circular cylinder with a low mass ratio under two degree of freedom in tandem have been revealed. We used spring bars instead of conventional parallel linkage system.

MATERIALS AND METHODS

Basic setup: The two-degree of freedom VIV responses of two elastically mounted rigid model risers in tandem, with low mass ratio under steady uniform current conditions were experimentally investigated by using spring bars instead of using commonly used parallel linkage system (Fig. 1).

The VIV experiments have been performed in UTM's Marine Technology Centre 2.5×4×120.0 m towing tank, which is equipped with an overhead towing carriage. Two circular test cylinders of 100 mm in diameter and 1.5 m in length were suspended vertically from the carriage with a

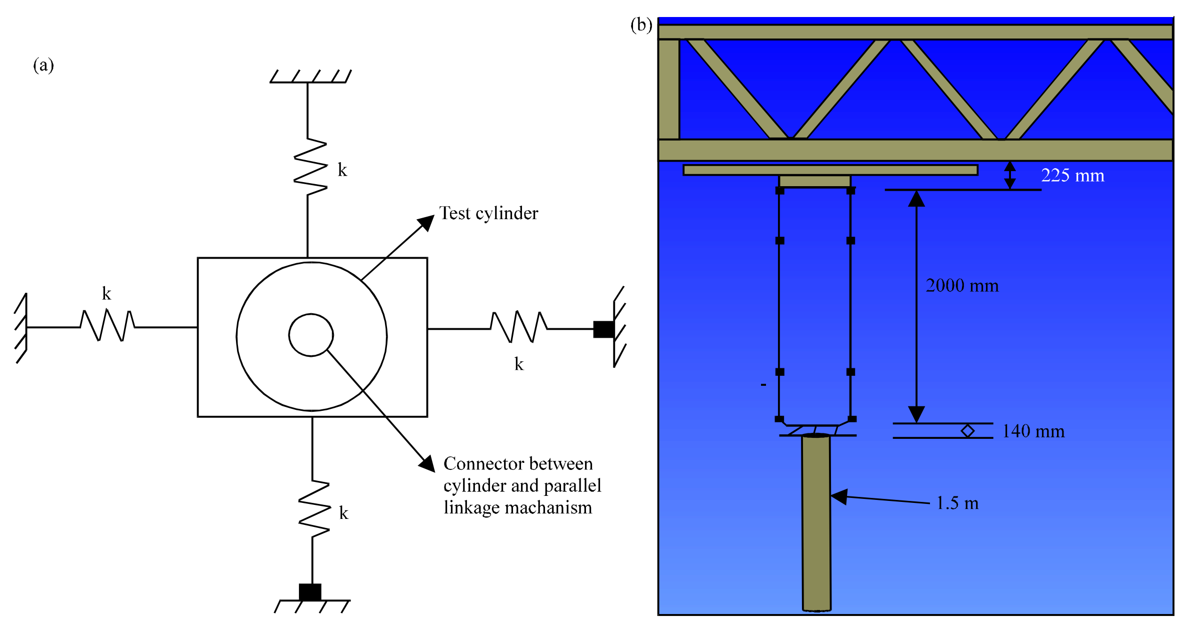

Fig. 1(a-b): Set up for 2DOf VIV response (a) Conventional parallel linkage system and (b) Spring bar system (Vikestad, 1998) certain end spacing. Spring bars were used instead of commonly used parallel linkage mechanism for this kind of test, the system was designed to ensure identical mass ratios and natural frequencies in both inline and cross line directions for each cylinder. Local ventilation of the downstream vortices was avoided by using endplates plate at bottom. Cylinder and coordinate system is shown in Fig. 2. Details of the system design can be seen in Fig. 3. Cylinders were totally submerged by keeping the water depth around 1.5 m. Each system was very lightly damped and was constant over the experimental amplitude response range. Cylinders were towed in still water to simulate the uniform current condition. No significant dissimilarity in local current velocity was found due to

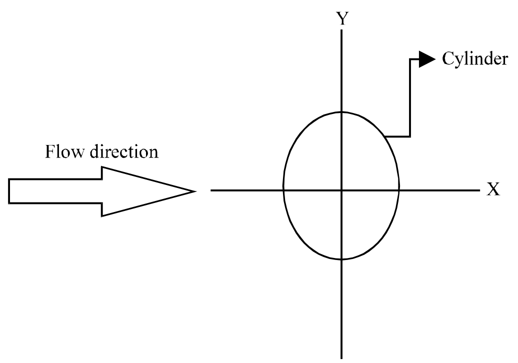

Fig. 2: Cylinder and coordinate system

negligible blockage effect as the ratio of cylinder diameter to channel width was 1:40 which is sufficiently lower.

Riser models were towed at reduced velocity 3-10 m sec^{-1} as higher value of amplitudes or upper branch is normally located at between reduced velocity 4 and 8 m sec^{-1} (Vikestad, 1998). The experimental parameters are shown in Table 1.

Cylinders were towed at Reynolds number up to 7×10^4. Transducers have been used at riser top cap to measure the inline and cross line forces. The cross line and inline vibration amplitudes were measured by using fixed Qualisys video motion capture system, which consists of 2 digital cameras and a data acquisition and analysis software package. These two cameras were strategically placed below the carriage to capture the motion of markers that were located at the top the riser top cap as shown in Fig. 4.

Vortex shedding can be defined as an approximate sinusoidal process, so we can find transverse force (F_Y) responsible for cross flow vibration which is in Y direction and inline force (F_X) in X direction is responsible for inline

Table 1: Experimental parameter for 2 DOF VIV

Parameters	Symbol	Unit	Value
Diameter	D	mm	100
Length	L	m	1.5
Mass ratio	m+		2
Natural frequency	f_n	sec^{-1}	0.70
Aspect ratio	L/D		15
Damping ratio	ζ		0.01

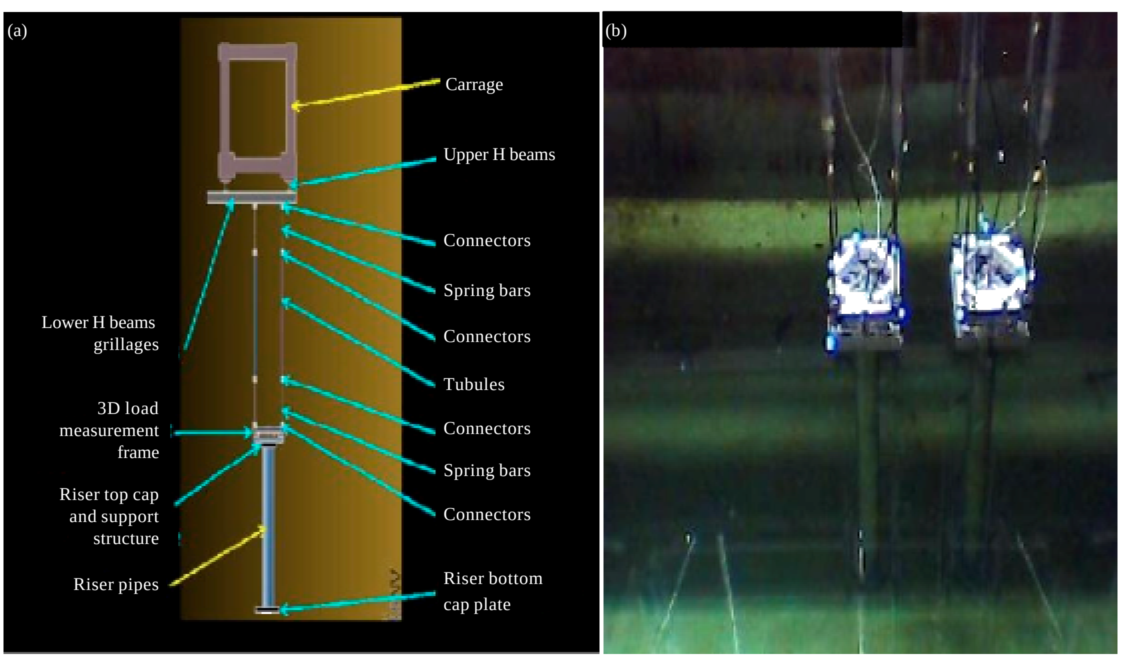

Fig. 3(a-b): (a) Set up for 2DOF VIV response of model riser and (b) Risers at towing tank (In tandem configuration)

Fig. 4: Markers at riser top for Qualisys video motion capture system

vibration. Lift coefficient, drag coefficients, mass ratio, reduced velocity and oscillation frequency are calculated by using following equation:

$$C_L = \frac{F_Y}{0.5\rho LDU^2} \tag{1}$$

$$C_D = \frac{F_X}{0.5\rho LDU^2} \tag{2}$$

$$m^+ = \frac{m}{\rho\pi L\frac{D^2}{4}} \tag{3}$$

$$Ur = \frac{U}{f_n D} \tag{4}$$

$$f_{osc} = \frac{1}{2\pi}\sqrt{\frac{K}{m+m_a}} \tag{5}$$

When the shedding frequency (f_s) becomes equal to the natural frequency (f_n) of the structure the lock-in phenomenon occurs at lock in the vibration amplitude becomes maximum and the correlation between the excitation forces along the span increases dramatically. In other words, when the vortex shedding frequency is controlled by the oscillation frequency lock in occurs. The oscillation frequency (f_{osc}) will be different than natural frequency (f_n) in still water since added mass (m_a) will be varied. for natural frequency we have to use the added mass value in still water (m_{a0}). So, it can be said the synchronisation of the shedding and vibration frequencies largely depends on hydrodynamic mass variation (Vikestad, 1998).

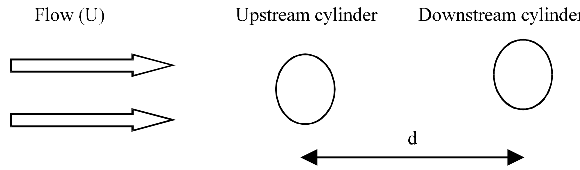

Fig. 5: Inline configuration

Inline configuration: Tests have been performed on two equal-diameter cylinders, one behind the other relative to the stream direction, at two different spacing as shown in Fig. 5, where, d = 4D and 4.5D.

RESULTS AND DISCUSSION

To simplify the problem of VIV analysis some assumptions have to be made, commonly accepted assumptions in today's engineering practices are, in-line and cross-flow vibrations should be analyzed separately; the oscillation amplitude and diameter are presented by using the parameter A/D; the parameter U/fD is used to represent frequency and velocity.

Transverse displacement: Figure 6a and b represent the tranverse displacement over diameter ratio as a function of reduced velocity of two cylinders at different spacing. We found super upper response branch for both cylinder or riser's model which is expected from two degree of freedom sytem with a low mass ratio which is inaccordance with previous study of Williamson and Jauvtis (2004). It was found that the upstream cylinder's transverse displacement is more than that of downstream cylinder at higer reduced velocity this may happens due to the higher VIV amplitude of upstrem cylinder as described by Allen and Henning (2003). It was found that the oscillation frequency of the both cylinders is more or less same. In the present experiment the oscillation or response frequencies varied between 0.9 and 1.05 times the natural frequency during lock in.

Effect of upstream cylinder displacement on downstream cylinder: We found as upstrem cylinder displacement amplitudes attain beyond 0.5D the downstream cylinder's vibration amplitude keep reducing and become less than upstream cylinder displacement amplitudes, which is in agreement with Allen and Henning (2003) (Fig. 7).

Effect of phase difference between upstream cylinder and downstream cylinder motion: The downstream cylinder's vibration amplitude seems to be effected by phase difference between upstream cylinder and downstream

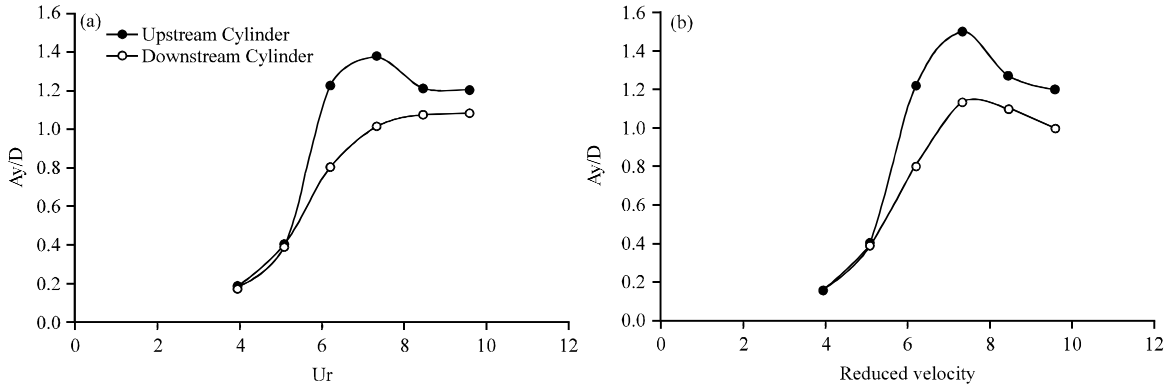

Fig. 6(a-b): Transverse displacement (a) 4D and (b) 4.5D spacing

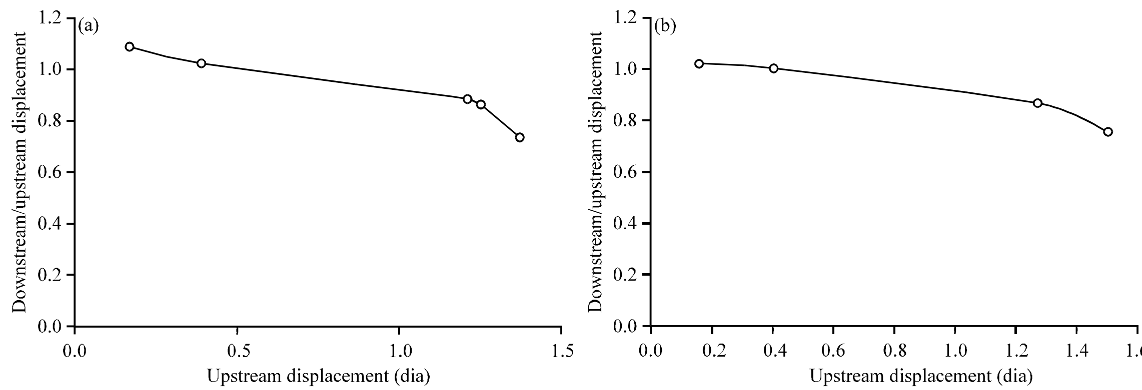

Fig. 7(a-b): Downstream/Upstream cylinder displacement vs. Upstream cylinder displacement transverse at (a) 4D and (b) 4.5D spacing

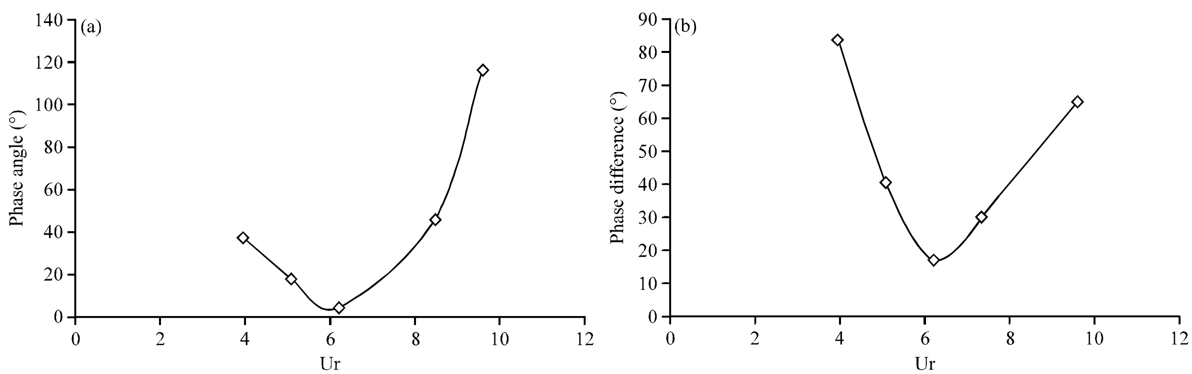

Fig. 8(a-b): Phase difference between downstream cylinder and Upstream cylinder transverse motion (a) 4D and (b) 4.5D spacing

cylinders motion. The phase angle follows V shape pattern, which is evident by Fig. 8a and b. We believe this aspect of VIV (phase difference) of two equal diameter cylinder in tandem has not been studied previously.

We found at Ur = 6 the phase difference become lower, at which point the difference between the magnitudes of the vibration amplitude of upstream and downstream cylinder become maximum. It was found that when the cylinders in phase the upstream cylinder acts as a shield to the downstream cylinder. The effect of phase difference on VIV of downstream cylinder is more prominent at 4D spacing.

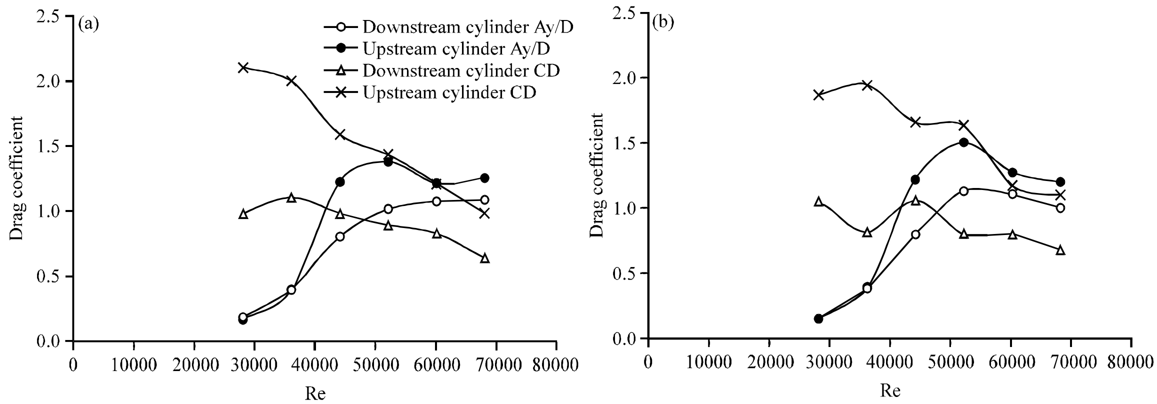

Fig. 9(a-b): Transverse displacement and drag coefficient as a function of Re (a) 4D and (b) 4.5D spacing

Transverse displacement and drag coefficient as a function of Re: The graph of VIV amplitudes and drag coefficients against Reynolds number basically have shown same trends that can be found in the study of Allen *et al*. (2005). It was found that at lower Reynolds number there is little or no effect of end spacing on the displacements but at higher Reynolds number the effect of end spacing is clear and distinct as shown in Fig. 9a and b. On the other hand, the drag coefficient decreases as the Reynolds number increases and is true for both cylinder. Downstream cylinder experiences less drag compare to upstream cylinder.

The VIV characteristics of downstream cylinder depend on several aspects such as mass ratio, degree of freedom, upstream cylinders vibration amplitude, end spacing, phase difference between upstream and downstream cylinders motion.

CONCLUSION

Tests have been performed on two equal diameter cylinders with low mass ratio in tandem subjected to uniform flows in a towing tank at subcritical Reynolds numbers. Following conclusions can be drawn from this study:

- Spring bars were used to conduct the 2DOF VIV interface test, instead of commonly used parallel linkage systems, the details of the test set up are presented
- The super upper response branches were found for both cylinders with low mass ratio. It was found that upstream cylinder with higher vibration amplitude reduces the magnitude of the VIV of downstream cylinder, a finding that is consistent with prior studies
- Both upstream and downstream cylinders seem to have same oscillation frequency. We found a possible correlation between the phase difference between upstream and downstream cylinders and the VIV magnitude of downstream cylinder along with upstream cylinders VIV amplitude. When the phase difference is lower the downstream cylinder vibrates less compare to upstream cylinder, the phase difference is lower at Ur = 6 for both end spacing that were examined

Further researches are needed to be done to understand this complicated hydrodynamics phenomenon.

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REFERENCES

Allen, D.W. and D.L. Henning, 2003. Vortex-induced vibration current tank tests of two equal-diameter cylinders in tandem. J. Fluids Struct., 17: 767-781.

Allen, D.W., D.L. Henning and L. Lee, 2005. Vortex induced vibration tests of smooth and rough flexible cylinders at high reynolds numbers. Proceedings of the ASME Fluids Engineering Division Summer Meeting and Exhibition, June 19-23, 2005, Houston, TX., USA., pp: 475-480.

Blevins, R.D., 1990. Flow-Induced Vibration. 2nd Edn., Van Nostrand Reinhold, New York, USA., ISBN-13: 9780442206512, Pages: 451.

Chaplin, J.R., P.W. Bearman, Y. Cheng, E. Fontaine and J.M.R. Graham *et al*., 2005. Blind predictions of laboratory measurements of vortex-induced vibrations of a tension riser. J. Fluids Struct., 21: 25-40.

Dong, S. and G.E. Karniadakis, 2005. DNS of flow past a stationary and oscillating cylinder at Re = 10000. J. Fluids Struct., 20: 519-531.

Govardhan, R. and C.H.K. Williamson, 2000. Modes of vortex formation and frequency response of a freely vibrating cylinder. J. Fluids Mech., 420: 85-130.

Holmes, S., O.H. Oakley and H. Constantinides, 2006. Simulation of riser VIV using fully three dimensional CFD simulations. Proceedings of the 25th International Conference on Offshore Mechanics and Artic Engineering, June 4-9, 2006, Hamburg, Germany, pp: 563-570.

King, R. and D.J. Johns, 1976. Wake interaction experiments with two flexible circular cylinders in flowing water. J. Sound Vibr., 45: 259-283.

Lucor, D., H. Mukundan and M.S. Triantafyllou, 2006. Riser modal identification in CFD and full-scale experiments. J. Fluids Struct., 22: 905-917.

Stappenbelt, B., F. Lalji and G. Tan, 2007. Low mass ratio vortex-induced motion. Proceedings of the 16th Australasian Fluid Mechanics Conference, December 2-7, 2007, Brisbane, Australia, pp: 1491-1497.

Trim, A.D., H. Braaten, H. Lie and M.A. Tognarelli, 2005. Experimental investigation of vortex-induced vibration of long marine risers. J. Fluids Struct., 21: 335-361.

Vikestad, K., 1998. Multi-frequency response of a cylinder subjected vortex-shedding and supported motions. D.Sc. Thesis, Norwegian University of Science and Technology, Trondheim, Norway.

Willden, R.H.J. and J.M.R. Graham, 2004. Multi-modal vortex-induced vibrations of a vertical riser pipe subject to a uniform current profile. Eur. J. Mech. B/Fluids, 23: 209-218.

Williamson, C.H.K. and N. Jauvtis, 2004. A high-amplitude 2T mode of vortex-induced vibration for a light body in XY motion. Eur. J. Mech.-B/Fluids, 23: 107-114.

Zdravkovich, M.M., 1985. Flow induced oscillations of two interfering circular cylinders. J. Sound Vibr., 101: 511-521.