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# A study on the proximity interference and synchronization between two side-by-side flexible cylinders

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ABSTRACT

In this paper, we present the results of a study of the effects of proximity interference on the hydroelastic responses of two pre-tensioned flexible cylinders in side-by-side arrangement subjected to uniform cross-flow (CF). Two flexible cylinders of the same size, properties, and pretensions were tested with two different vertical separation distances. It was found that at a small center-to-center separation distance (2.75 diameters), the upper cylinder showed no upper branch in the first CF lock-in region. With the increase in the initial vertical separation, both cylinders exhibited amplitude responses similar to the isolated cylinder. At this small separation distance, the upper cylinder showed a CF frequency response (higher values) quite distinct from both the lower cylinder and the single cylinder. For the reduced velocity range of $1.82 \le U_r \le 5.1$, strong phase synchronization was detected. Anti-phase synchronization was even detected within the region of the collapsed classical vortex-induced vibration (VIV) amplitude response. It was also found that even for a separation of 5.5 diameters, the wakes of the cylinders were strongly synchronized within the region of high cylinder vibration amplitudes ($2.91 \le U_r \le 5.1$). From the analysis of the synchronization, no synchronization was built up for very small amplitudes for the large separation case, in contrast to the small separation case. The mean drag and the fluctuating components of the drag and lift forces of both cylinders showed quite different behaviors.



## 1. Introduction

The interference among groups of cylinders is an important factor in the design of marine and civil structures (such as production and drilling risers, Tensioned Leg Platforms (TLP), tendons and moorings, subsea group pipelines, transmission lines, heat exchangers and chimneys, etc.), and has been the subject of some studies in the past. The behavior of a group of cylinders can be very complex because it involves the mutual effects of adjacent cylinders and depends on their different relative positions.

Although the sea risers are generally found in group arrangements, studies on a special arrangement of group cylinders cannot well explain the interference phenomenon. Hence, investigation of the flow around pairs of cylinders can lead to a better understanding of the interference effects for any case involving large numbers of cylinders.

Numerous experimental and computational studies for flow past a single cylinder and stationary pairs of cylinders have been reported in the literature, but information about flow around multiple flexible cylinders is scarce because of the complexities of the responses. The complexities involved in the behavior of multiple pre-tensioned flexible cylinders (compared with stationary cylinders and flexibly-mounted oscillating rigid cylinders that only respond in the first mode of vibration) may arise from this fact: The initial separation distance between flexible cylinders during oscillation cannot remain constant. Most of the earlier studies of the cylinder pairs were conducted for the case where the oscillation of the cylinders was restrained. Hence those studies cannot be truly representative of the real sea applications, e.g., risers and so on. A recent publication by Sumner (2010) demonstrated a complete review and detailed assessment of flow around a pair of stationary cylinders. For the side-by-side arrangement, where both cylinders were arranged transverse to the incoming flow, it was found that if the cylinders are in close proximity, they may behave as a single cylinder. If the separation is significant, they may behave as two independent bodies, although synchronization between the adjacent vortex streets may occur (parallel vortex streets regime (Sumner, 2010)). Complex wake and vortex-street interaction occurred when the cylinders were spaced between these two extremes; in particular an asymmetric, or biased flow pattern, that may be bi-stable in nature (Sumner, 2010).

There are some recent studies by Huera-Huarte and Bearman (2011) and Huera-Huarte and Gharib (2011a, 2011b) for the cases in which the pair of flexible cylinders was free to oscillate. Based on their

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**Nomenclature**

| | |
|---|---|
| $D$ | outside diameter |
| $t$ | wall thicknessr |
| $L$ | length |
| $L/D$ | aspect ratio |
| $m$ | total mass (including internal water) |
| $m_a$ | added mass |
| $m^*$ | mass ratio ($4\,m/\rho\pi D^2$) |
| $T$ | applied pretension |
| EI | bending stiffness |
| $k_s$ | spring stiffness |
| EA/$L$ | cylinder axial stiffness |
| $U$ | flow speed |
| $U_r$ | reduced velocity ($U/f_{nwm}D$) |
| Re | Reynolds number (UD/$\upsilon$) |
| $\upsilon$ | water viscosity |
| $\rho$ | water density |
| $\zeta$ | total damping ratio (structural plus viscous) |
| $A_{std}$ | standard deviation of vibration amplitude |
| $A^*_{std}$ | vibration amplitude ratio ($A_{std}/D$) |
| $f_{nwm}$ | measured in-water natural frequency |
| $f_{nwa}$ | analytical in-water natural frequency |
| $f_{naa}$ | analytical in-air natural frequency |
| $f_y$ | vibration frequency in CF direction |
| $f^*_y$ | non-dimensional frequency in CF direction |
| $F_{Dmean}$ | mean drag force |
| $F_{Dstd}$ | fluctuating drag force |
| $F_{Lstd}$ | fluctuating lift force |
| $CD_{mean}$ | mean drag coefficient |
| $CD_{std}$ | standard deviation of drag coefficient |
| $CL_{std}$ | standard deviation of lift coefficient |

experiments on two flexible circular cylinders with various separations, they re-defined the regions in which the proximity interference (in the side-by-side arrangement) and the wake interference (in the tandem arrangement) occur. Zdravkovich (1988) presented a graph for the interference regions for two stationary circular cylinders of equal diameters. He defined two interference regimes, namely proximity and wake interference. These cited studies on pairs of flexible cylinders focused mainly on analyzing the amplitude response, frequency response, and synchronization between the cylinders.

For the side-by-side arrangement, Huera-Huarte and Gharib (2011a) reported that in the large hydro-elastic response region, with a reduced velocity between 4 and 8, and the center-to-center separations smaller than 3.5D, strong proximity interference exists. They found that in this region, the cross-flow motion of the cylinders was either out-of-phase for reduced velocities smaller than 6, or in-phase for reduced velocities between 6 and 8. This behavior has been previously reported by Zdravkovich (1988) as a biased flow regime. For the center-to-center separations larger than 3.5 diameters, they reported that the cylinders show no synchronized motions, suggesting that the coupling between the two models through the wake is very weak and showing independent vortex-induced vibration (VIV). As we shall show in later sections, for a separation distance of 5.5 diameters, out-of-phase synchronization was detected in our experiments during high amplitude vibration. Sumner (2010) cited studies on stationary side-by-side cylinders with a separation distance of 4.5 diameters that experienced anti-phase synchronization in the parallel vortex street regime.

An interesting feature of flow around side-by-side cylinders was presented by Bearman and Wadcock (1973) for a pair of stationary cylinders. They found that for small separations (1.1D ~ 2.2D), the flow was intermittently biased towards the near wake of one cylinder or the other. The deflection of the biased gap flow varied with separation distance. The trend was toward a smaller degree of deflection with increasing separation and similar to the difference between the high and low vortex shedding frequencies (Sumner, 2010).

The cylinder towards which the flow was biased had narrower near-wake, higher-frequency vortex shedding, and higher mean drag coefficients, while the other cylinder had wider near-wake, lower-frequency vortex shedding and lower mean drag coefficients. Beyond the biased flow regime, the mean drag coefficient approached the value for a single cylinder (Bearman and Wadcock, 1973; Alam et al., 2003 and Sumner, 2010).

We set up numerous experiments to investigate the hydro-elasticity of groups of flexible pre-tensioned cylinders arranged separately in: pairs (tandem, staggered and side-by-side), triplets (three cylinders) and quadruplets (four cylinders). In this paper, we present the results of two flexible cylinders in side-by-side arrangement subjected to uniform CF. Two cylinders of the same size, property, and pretension (tension-dominated structure) were tested with two different center-to-center vertical separation distances. The purpose of this study was to investigate the effects of various separation distances on the hydro-elastic responses of flexible cylinders compared to an isolated flexible cylinder.

The CF vibration amplitude and its frequency response, force coefficients including mean and fluctuating components of the drag and lift forces, and synchronization between cylinders were analyzed.

In the following sections, the experimental setup, test model characteristics, and measurement system are described. Then, the results are presented and discussed, followed by the conclusions.

## 2. Experimental setup

For a more realistic modeling of the VIV phenomenon in ocean field applications (risers, moorings and so on), we set up our experimental model with tri-directional vibrations, i.e., free to vibrate in inline (IL), CF and axial directions.

### *2.1. Test parameters and characteristics*

Polyvinyl chloride (PVC) pipes were used to provide a flexible model with low bending dependence. The characteristics and parameters of the experimental model are listed in Table 1. The pipes were submerged horizontally 0.45 m below the still-water

**Table 1**
The test model characteristics and the experiment parameters.

| | |
|---|---|
| Outside diameter ($D$) | 18 mm |
| Wall thickness($t$) | 2.5 mm |
| Length ($L$) | 2.92 m |
| Aspect ratio ($L/D$) | 162 |
| Cylinder air weight | 1.64 N/m |
| Total weight-including internal water (mg) | 2.97 N/m |
| Gravitational acceleration ($g$) | 9.81 m/s$^2$ |
| Applied pretensions ($T$) | 147 N |
| Mass ratio ($m^*$) | 1.17 |
| (Structural plus viscous) Damping ratio ($\zeta$) | 0.024 |
| Bending stiffness (EI) | 9.0 Nm$^2$ |
| Spring stiffness ($k_s$) | 6.5 N/mm |
| Cylinder axial stiffness (EA/$L$) | 100 N/mm |
| Flow speed ($U$) | 0.07–1.00 m/s |
| Subcritical Reynolds number range (Re) | 1400–20,000 |