Effect of the Inlet Flow Angle on the Vortex Induced Vibration of a Collinear Array of Flexible Cylinders

F. Oviedo-Tolentino, R. Romero-Méndez, F. G. Pérez-Gutiérrez, G. Gutiérrez-Urueta and H. Méndez-Azúa

Abstract In this work an experimental study of vortex-induced vibration (VIV) was carried out in an collinear array of ten identical cylinders. This investigation was conducted with a mass ratio ($m^*\xi = 0.13$) and a blockage ratio ($W/D < 1\%$). The inlet flow angle was fixed to 30° and the leading cylinder vibration amplitude was compared under the condition of 0° inlet flow angle. The free-end cylinders had two degrees of freedom with identical in-line and cross-flow natural frequencies in still fluid medium. The experimental essays were performed in a water tunnel in the lock-in region ($90 < Re < 450$). The results show that the cross-flow vibration amplitude is 68 % reduced when the inlet flow angle increases to 30°.

1 Introduction

In some industrial applications, such as marine risers, tall buildings, large suspension bridges, high voltage lines, tube and shell heat exchangers, smokestacks, etc., vortex induced vibration may occur. The particular importance of VIV on circular cylinders is partly due to industrial problems logged on this subject. The practical importance of VIV has led a number of fundamental studies, most of them on elastic cylinders with one degree of freedom. The physics involved in the VIV phenomenon is extensive, and some discussions on this topic are in the reviews of (Bearman 1984 and Gabbai and Benaroya 2005).

The fundamental studies on VIV involved the study of the mass-damping ratio, the cylinder natural frequency, vortex shedding modes and added mass on the lock-in region. The lock-in region is frequently represented by three distinguishable

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responses: initial, upper and lower branches. High mass-damping cases are associated to lock-in regions with only two response branches, initial and lower. However, for low mass-damping cases the lock-in region consists of three branches: initial, upper and lower. This type of response is frequently referred as the Feng-type response, Feng (1968). On the other hand (Khalak and Williamson 1996, 1997a,b, 1999) conducted experimental studies for a very low mass damping ratio ($m^*\zeta = 0.013$). They concluded that the peak vibration amplitude is principally governed by the mass-damping ratio, whereas the mass ratio controls the lock-in range. Vikestad et al. (2000) found a mass ratio dependence on the Reynolds number. This dependence modifies the natural frequency of the cylinder in the lock-in region. The lock-in region has shown hysteretic behavior in the initial and lower branches. However for blockages of 1 % or less, the hysteretic behavior is completely eliminated in the initial branch.

There is evidence of the destructive nature of the vortex-induced vibration in cylinder arrays. Paidoussis (1980) cited various industrial problems registered in heat exchangers and nuclear reactors due to the VIV phenomenon. A good starting point in the study of cylinder arrays is a tandem configuration. The results on this configuration have shown a dependence of the vibration amplitude on the distance between cylinders. The important parameter in these studies was the ratio between the cylinder separation P to cylinder diameter D, P/D. Papaioannou et al. (2008) showed that for $P/D < 3.5$, the vibration amplitude is very similar to that of an isolated cylinder. However for $P/D > 3.5$ the vibration amplitude is significantly increased. This result confirmed the hypothesis made by Tanaka and Takahara (1981), who suggested that cylinder vibration is induced by the forces originated due to the fluid dynamics around both the neighbor cylinders and the cylinder itself. For the VIV in cylinder arrays, various excitation mechanisms are involved. Weaver and Fitzpatrick (1988) discussed the excitation mechanisms in typical tube array patterns in tube and shell heat exchangers. They pointed out the destructive nature of the fluid-elastic instability excitation mechanism in a heat exchanger. Recently, Zhao and Cheng (2012) investigated the effect of the inlet flow angle on the lock-in range in a square cylinder array configuration. They showed that as the flow inlet angle increases up to 30°, the lock-in range is also increased; after this flow inlet angle the lock-in range is reduced.

This investigation presents experimental results of VIV of ten identical flexible cylinders positioned in a collinear array at 30° angle with respect to the inlet flow direction. The experiments were conducted at a low mass-damping ratio $m^*\zeta = 0.13$ and blockage ratio $W/D < 1\%$. The natural cylinder frequency as well as the cross-flow and in-line vibrational response were determined in the lock-in region. The vibrational response of the leading cylinder in the array is compared with the case when the array is aligned with the free stream direction previously studied in Oviedo-Tolentino et al. (2013). The results show that the cross-flow vibrational response is reduced by 68 % at 30° inlet flow angle. This behavior is manly due to the low synchronization between cylinders in the lock-in region. On the other hand the lock-in range is slightly larger in the 30° inlet flow case.

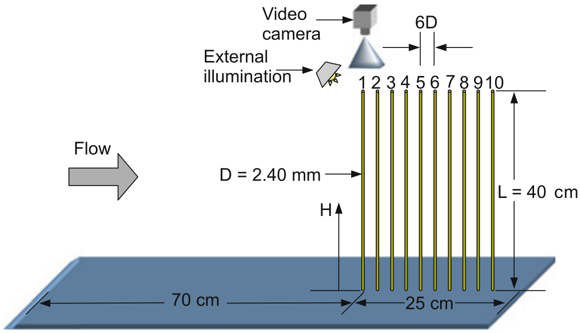

Fig. 1 Experimental model at 0° inlet flow angle

2 Experimental Procedure

2.1 Experimental Setup

Figure 1 shows a sketch of the experimental model. The model consisted of a 9 mm thick, 95 cm long and 37.5 cm wide acrylic flat plate. The ten identical circular cylinders were inserted into a drilled hole in a collinear arrangement. The cylinder array can be rotated with respect to the inlet flow angle. The cylinders were 2.40 mm in diameter and 40 cm in height with an elastic modulus of 10.5×10^{10} Pa. The experiments were carried out in a water tunnel with a test section 38.1 cm wide, 50.8 cm high and 1.5 m long. The water velocity can be varied from 0.01 to 0.3 m/s. A flow conditioning system maintains the turbulence levels at less than 1 % RMS at the inlet test section.

The vibration amplitude was obtained using a fast recording camera. This camera has an internal memory (2 GB) in which images can be stored digitally at 506 frames per second with full resolution, 1280×1024 px. For lower resolutions the frame rate can be increased up to 112,000 frames per second. The shutter time can be adjusted in the interval of 2 μs to 1 s. With these features, the free-end cylinder displacements could be measured up to an accuracy of the order of 11 μm.

2.2 Experimental Methodology

With the experimental setup described above, the cylinder free-end was recorded during 20 s at a rate of 240 frames per second using 100 μs as exposure time. Under this recording conditions, an external illumination was needed. The dynamic vibration amplitude was obtained using a particle tracking velocimetry technique on the recorded fotograme. Therefore, plots of the cylinder free-end position as a function of time were obtained. The cylinder frequency was determined through spectral analysis of the cylinder free-end time trace.

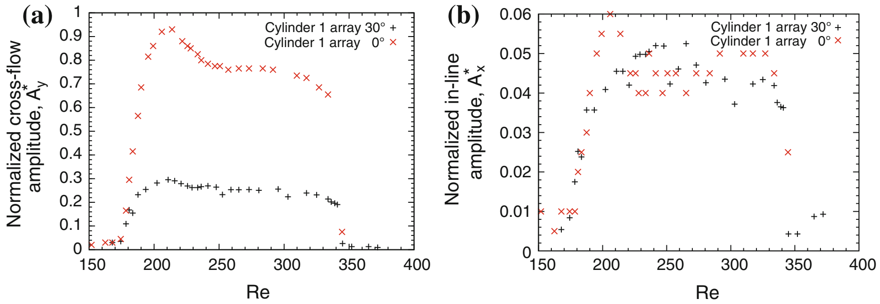

Fig. 2 Inlet flow angle effect on the vibrational response, **a** Cross-flow lock-in and **b** In-line lock-in

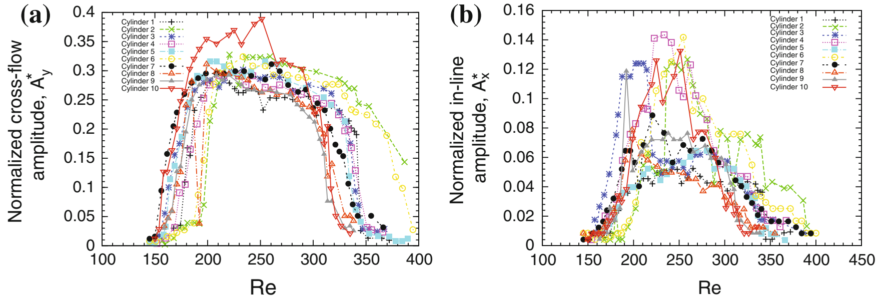

Fig. 3 Vibrational response in the array, **a** Cross-flow and **b** In-line

3 Results

Figure 2 shows the maximum cross-flow and the in-line vibrational responses for cylinder 1 as a function of the Reynolds number. In the cross-flow vibrational response (Fig. 3a), three branches are identified. This behavior confirms the mass-damping and the vibration amplitude branches relationship made by Feng (1968) who suggested that for low mass-damping ratio three response branches are associated. (Khalak and Williamson 1996, 1997a,b, 1999) related the peak amplitude with the mass-damping ratio in an isolated cylinder. The results in the collinear array reveal that the peak response is highly related to the inlet flow angle. On the other hand, the mass ratio has been associated with the lock-in range. The results in the collinear array show almost no influence of the inlet flow angle on the lock-in range.

The lock-in region for the ten cylinders in the collinear array is shown in Fig. 3. The peak vibrational response of cylinders 1 to 9 is, in general, of the same order of magnitude. However, cylinder 10 registers the maximum peak cross-flow vibrational response. This results suggest that the inlet flow angle prevents synchronization between cylinders. Figure 4 shows the non-dimensional frequency for the ten cylinders in the array. In order to show the preferred frequency at which the cylinders in

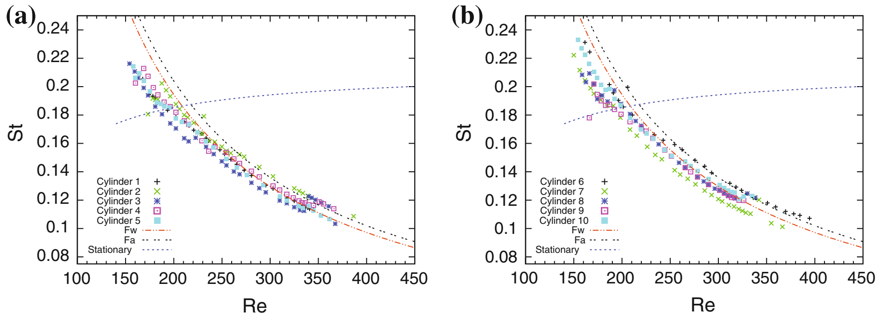

Fig. 4 Dimensionless frequency, **a** Cylinders from 1 to 5 **b** Cylinders from 6 to 10. The frequency was normalized using the Strouhal number

the array vibrate in the lock-in region, the cylinder frequency in still water (F_w), still air (F_a) and the vortex shedding frequency of an stationary cylinder were included in Fig. 4 as a reference. The non-dimensional cylinder frequency shows no synchronization between cylinders in the lock-in range. The low cylinder synchronization is partly due to the inlet flow angle. These experiments suggest that the inlet flow angle should be taken into account in the study of the synchronization between cylinders. The cylinder frequency in the lock-in region has, as a maximum value, the natural frequency in still air. In accordance with the results of (Vikestad et al. 2000), the added mass has a Reynolds numbers dependence in the lock-in region. The added mass changes leaded to natural cylinder frequency changes. The frequency and the added mass changes can be observed in Fig. 4. From this observation, it can be concluded that the results show low and high added mass dependence on the Reynolds number in the lock-in region.

4 Conclusions

An experimental study of vortex induced vibration in a collinear array was conducted. The inlet flow angle shows high influence on the peak cross-flow vibration. The cross-flow vibration amplitude is reduced by 68 % in the case of a 30° inlet flow angle. The reduction in the cross-flow vibration amplitude is due to a low cylinder synchronization in the lock-in. On the other hand, the inlet flow angle has almost no influence on the lock-in range. The cylinders response shows agreement with previous results, where three response branches were identified for the study mass-ratio case. The non-dimensional frequency results show low and high added mass dependence on the Reynolds number in the lock-in region.

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