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The influence of higher harmonic flow forces on the response of a curved circular cylinder undergoing vortex-induced vibration

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ABSTRACT

Vortex-induced vibration (VIV) of a curved circular cylinder (a quarter of a ring, with no extension added to either end) free to oscillate in the crossflow direction was studied experimentally. Both the concave and the convex orientations (with respect to the oncoming flow direction) were considered. As expected, the amplitude of oscillations in both configurations was decreased compared to a vertical cylinder with the same mass ratio. Flow visualizations showed that the vortices were shed in parallel to the curved cylinder, when the cylinder was free to oscillate. The sudden jump in the phase difference between the flow forces and the cylinder displacement observed in the VIV of vertical cylinders was not observed in the curved cylinders. Higher harmonic force components at frequencies twice and three times the frequency of oscillations were observed in flow forces acting on the vertical cylinder, as well as the curved cylinder. Asymmetry in the wake was responsible for the 2nd harmonic force component and the relative velocity of the structure with respect to the oncoming flow was responsible for the 3rd harmonic force component. The lock-in occurred over the same range of reduced velocities for the curved cylinder in the convex orientation as for a vertical cylinder, but it was extended to higher reduced velocities for a curved cylinder in the concave orientation. Higher harmonic force components were found to be responsible for the extended lock-in range in the concave orientation. Within this range, the higher harmonic forces were even larger than the first harmonic force and the structure was being excited mainly by these higher harmonic forces.

1. Introduction

Vortex-induced vibration of a cylinder placed normal to the flow has been studied extensively, both for a flexibly-mounted rigid cylinder [1–4] and a flexible cylinder [5–8]. In many real world applications, however, the cylinder is not placed perfectly perpendicular to the direction of the oncoming flow. In some cases, the cylinder makes a fixed angle with respect to the oncoming flow (an inclined cylinder) and in some other cases, the angle that the cylinder makes with the oncoming flow varies continuously along its length (a curved cylinder). There are several studies on a fixed (e.g., [9–12]) or a free-to-oscillate (e.g., [13–15]) inclined cylinder placed in flow.

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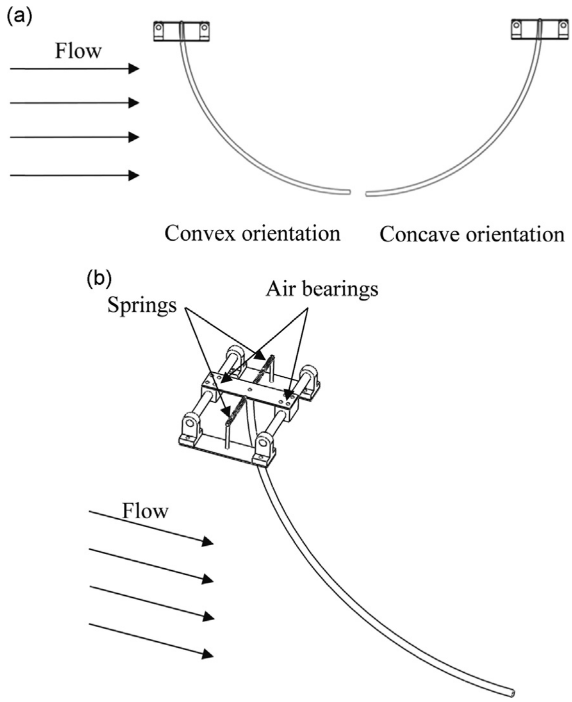

Fig. 1. Schematics of the experimental set-up.

In a curved cylinder, the angle of inclination varies continuously along the length of the cylinder. The work by Takamoto and Izumi [16] is among the first experimental studies in which flow passing a curved structure was considered. Stable vortex rings were observed downstream of a fixed axisymmetric circular ring. Ahmed [17] studied the wake dynamics of a cylinder with a mid-span curvature, experimentally. His observations showed that depending on the orientation of the structure with respect to the oncoming flow direction, varying vortex shedding patterns could be observed. A symmetric vortex shedding pattern was observed when the flow direction was toward the inner part of the curved structure (saddle attachment). Also, wake velocity profiles showed that the drag forces acting on the curved structure were highly dependent on the configuration of the curved section. For the saddle attachment, the drag forces were maximum and for nodal attachment, in which the flow first saw the outer part of the curved cylinder, the drag forces were minimum.

A curved cylinder (a quarter of a ring) can be considered in two different orientations: the convex orientation in which the upper end of the cylinder sees the flow first and the concave orientation in which the lower end of the cylinder sees the flow first (Fig. 1(a)). Miliou et al. [18], in their numerical study based on a spectral/*hp*-element Navier Stokes solver, investigated the dynamics of the flow past a quarter of a ring fixed in flow. Their results matched well the empirical findings of Takamoto and Izumi [16] in terms of the vortex shedding patterns. Fully three-dimensional wake dynamics were observed for both the concave and the convex configurations. de Vecchi et al. [19] performed a three-dimensional simulation for a curved cylinder in the convex orientation, forced to oscillate in the crossflow direction at a Reynolds number of $Re = 100$. They showed that the flow was highly three dimensional as a result of the curvature of the structure. The cylinder used in their simulations featured a long horizontal extension attached to the lower part of the cylinder. This part of the cylinder was parallel to the flow and acted as a slender body, rather than a bluff body, and therefore experienced drag-type forces. The component of the lift coefficient in phase with velocity, C_{Lv}, was negative for the entire length of the cylinder. They concluded that the horizontal extension acted as a hydrodynamic damper, ultimately resulting in a negative energy transfer, and therefore suppressing VIV. When they applied a rotating motion to the horizontal extension, the hydrodynamic damping was greatly reduced and the net energy transfer from the flow to the structure became positive ($C_{Lv} > 0$), indicating that the flow could excite the structure. In the wake of the cylinder, the vortex columns were bent according to the curvature of the cylinder contrary to the case of the stationary cylinder in which the vortex columns remained straight [20]. Vortex dislocations were observed for the convex orientation at mid-span of the curved cylinder as a consequence of different shedding frequencies at the lower and upper parts of the cylinder. Assi et al. [21] conducted a series of tests on a curved cylinder, placed in flow and free to oscillate in two perpendicular directions. Their set-up had a horizontal extension attached to the lower end of the curved cylinder, similar to the cylinder used by de Vecchi et al. [19]. They observed a reduction in the amplitude of oscillations both for the convex and the concave orientations, while the resulting amplitudes in the convex orientation were smaller than the amplitudes in the concave direction. They also conducted a series of flow visualizations on a fixed curved cylinder and observed that the flow around the horizontal extension highly affects the response of the system.