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On the origin of wake-induced vibration in two tandem circular cylinders at low Reynolds number

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ABSTRACT

We numerically investigate flow-induced vibrations of circular cylinders arranged in a tandem configuration at low Reynolds number. Results on the coupled force dynamics are presented for an isolated cylinder and a pair of rigid cylinders in a tandem configuration where the downstream cylinder is elastically mounted and free to vibrate transversely. Contrary to turbulent flows at high Reynolds number, low frequency component with respect to shedding frequency is absent in laminar flows. Appearance and disappearance of the vorticity regions due to reverse flow on the aft part of the vibrating cylinder is characterized by a higher harmonic in transverse load, which is nearly three times of the shedding frequency. We next analyze the significance of pressure and viscous forces in the composition of lift and their phase relations with respect to the structural velocity. For both the isolated and tandem vibrating cylinders, the pressure force supplies energy to the moving cylinder, whereas the viscous force dissipates the energy. Close to the excitation frequency ratio of one, the ratio of transverse viscous force to pressure force is found to be maximum. In addition, movement of stagnation point plays a major role on the force dynamics of both configurations. In the case of isolated cylinder, displacement of the stagnation point is nearly in-phase with the velocity. During vortex-body interaction, the phase difference between the transverse pressure force and velocity and the location of stagnation point determines the loads acting on the cylinder. When the transverse pressure force is in-phase with velocity, the stagnation point moves to higher suction region of the cylinder. In the case of the tandem cylinder arrangement, upstream vortex shifts the stagnation point on the downstream cylinder to the low suction region. Thus a larger lift force is observed for the downstream cylinder as compared to the vibrating isolated cylinder. Phase difference between the transverse load and the velocity of the downstream cylinder determines the extent of upstream wake interaction with the downstream cylinder. When the cylinder velocity is in-phase with the transverse pressure load component, interaction of wake vortex with the downstream cylinder is lower compared to other cases considered in this study. We extend our parametric study of tandem cylinders for the longitudinal center-to-center spacing ranging from 4 to 10 diameter.

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1. Introduction

When a rigid cylinder is free to vibrate in a cross-flow direction, there is a strong nonlinear coupling between the motion and the flow dynamics. This results in a complex evolution of shedding frequency which does not follow the Strouhal law as the natural frequency of the cylinder is approached, which is referred to as a lock-in or synchronization of the wake frequency to the cylinder frequency. In the lock-in range, the frequency of perturbed wake system and the natural frequency of the cylinder are close to each other, which results in an increased amplitude of motion (Paidoussis et al., 2010; Sarpkaya, 2004). In such self-excited cylinders in fluid flows, the amplitude of vibration grows until it becomes so large that nonlinear dynamical effects become relevant and achieve a self-limiting amplitude. The oscillatory nature of the forces arise from the vortex shedding and wake instabilities around cylinders. However, there is a considerable difference between the fluid-structure coupled response of an isolated cylinder arrangement and a tandem cylinder arrangement (Bokaian and Geola, 1984; Hover and Triantafyllou, 2001; Assi et al., 2010, 2013).

The phenomena of vortex and wake-induced vibration have applications in offshore industry, aerospace, power transmission, energy extraction, and many more. In particular, the majority of the risers of offshore industry and power transmission wires typically operate in bundles and the oncoming flow interacts in a complex way. Flow-induced vibrations due to vortex and wake excitations significantly affect the performance and fatigue life of the structures undergoing complex motions with nonlinear dynamics such as traveling waves (Jaiman et al., 2009; Marcollo et al., 2011) and chaotic motions. Due to the complex nature of flow-induced vibrations, the design of riser arrays has been an area of great uncertainty in the recent years. The wake dynamics of the upstream riser influences the loads and the structural response of the downstream riser. Through experiments Allen and Henning, 2003 and numerical simulations Springer et al., 2009, it was shown that the case with the straked upstream riser has suppressed motion whereas the downstream riser experienced low frequency oscillations with amplitude higher than the upstream due to continuous impingement of vorticity with the downstream structure. This suggested that when a straked riser resides in the wake of another riser, the strakes lose their ability to suppress flow-induced vibrations. To understand the wake interactions with flexible structure, the flow around two cylinders mounted elastically can be considered as an idealized model.

Many researchers have attempted to characterize coupled response of stationary and vibrating cylinders in a tandem arrangement. When an additional cylinder is placed downstream of the first, the flow phenomena become intricate due to vortex-body interactions and are governed by the relative positioning of the two bluff bodies. In the present study, this parameter has been defined in terms of the distance separating the centers of the two cylinders x_0 as shown in Fig. 1. Three flow interference regimes (Zdravkovich., 1987; Igarashi, 1984): proximity interference, wake interference and no interference, are identified for the tandem cylinder configuration based on the ratio of spacing x_0 to cylinder diameter D. In the proximity interference regime for $1 \le x_0/D \le 1.2$ to 1.8, negative drag is produced on the downstream cylinder and vortex shedding from the upstream cylinder is suppressed. The tandem bodies behave like a single bluff body and vortex shedding occurs behind the rear cylinder. In the wake interference or reattachment regime for 1.2 to $1.8 \le x_0/D \le 3.4$ to 3.8, a number of different phenomena such as shear layer reattachment, intermittent vortex shedding, etc. are observed as the separation distance is gradually increased. In the regime of large spacing $x_0/D \ge 3.8$, the so-called co-shedding regime, vortex shedding occurs from both the cylinders and there is no significant interference effect.

The critical separation distance x_{cr} for the onset of the co-shedding regime has been indicated by several researchers (Xu and Zhou, 2004; Zhou and Yiu, 2005; Mussa et al., 2009) both numerically and experimentally to be between $3.5D$ to $5D$ for a wide range of Reynolds numbers. The study of stationary setup of tandem cylinders was attempted by researchers in Alam et al. (2003); Sharman et al. (2005) to understand the forces developed on the downstream cylinder. The loads on the cylinders in tandem arrangement were experimentally investigated in Alam et al., 2003. The authors reported that if the phase of flow pattern between upstream and downstream cylinders coincides, then the lift forces become maximum. The authors in Sharman et al., 2005 numerically studied the laminar flow over two tandem cylinder at Reynolds number of 100.

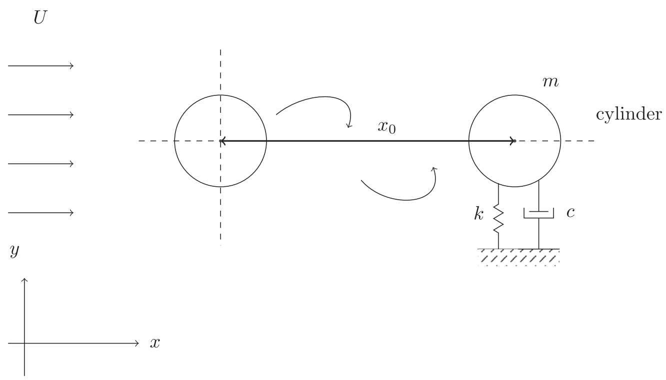

Fig. 1. Schematic of tandem cylinder arrangment for wake-induced vibration. Here U is freestream velocity, x_0 denotes streamwise distance, and m, c, k are mass, damping and stiffness parameters of the elastically mounted downstream cylinder.