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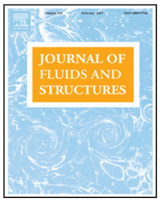

Interaction dynamics of upstream vortex with vibrating tandem circular cylinder at subcritical Reynolds number

R.C. Mysa, Y.Z. Law, R.K. Jaiman [*]

Department of Mechanical Engineering, National University of Singapore, Singapore 119077, Singapore

HIGHLIGHTS

- Interaction dynamics of vortex with vibrating downstream tandem cylinder.
- Role of stagnation point and boundary layer movement on wake excitation.
- Movement of boundary layer causes low frequency wake excitation.
- Analogous forced vibration results to deduce stagnation point dynamics.
- Validation of fluid–structure solver with dynamic subgrid LES.

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ABSTRACT

This numerical study investigates the local unsteady characteristics of transverse wake-induced vibration (WIV) of an elastically mounted downstream circular cylinder in a tandem arrangement at subcritical Reynolds number regime of $5000 \leq Re \leq 10000$. The upstream cylinder with an equal diameter is kept fixed and the downstream one is free to vibrate in a direction perpendicular to the freestream flow with a low mass damping parameter $m^*\zeta = 0.018$, where m^* is mass ratio and ζ is damping. Similar to the recent experiment study, we consider a longitudinal separation $L_x/D = 4.0$ in the co-shedding regime, where L_x denotes the center-to-center distance and D is the diameter of cylinder. In the present study, we perform three-dimensional simulations to further shed light on the sustained low frequency motion and the larger amplitude of downstream cylinder interacting with a turbulent vortical wake. We employ a nonlinear partitioned iterative scheme and a dynamic subgrid-scale model based on variational formulation for simulating the fluid–structure interaction in a turbulent wake. We assess the transverse amplitude and the frequency response against the experimental measurements for the reduced velocity $U_r \in [4, 14]$, whereby the reduced velocity is adjusted by changing the freestream Reynolds number. Of particular interest is to study the interaction of freely vibrating downstream cylinder with upstream vortices and the role of stagnation point movement in the transverse load generation over the downstream cylinder. We examine instantaneous energy transfer from the fluid flow to the vibrating downstream cylinder with respect to the movement of stagnation point and the vortex–structure interaction. We compare the WIV response of downstream cylinder against the isolated cylinder with prescribed periodic motion in a freestream flow. Through the vorticity contours and pressure distribution, we finally investigate the upstream vortex interaction with the vibrating downstream cylinder during the oscillation cycle of wake excitation.

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* Correspondence to: Block EA, 9 Engineering Drive 1, Singapore 117576, Singapore.
E-mail address: mperkj@nus.edu.sg (R.K. Jaiman).

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1. Introduction

Riser pipelines, heat exchangers, and transmission lines generally operate in groups, which can result into nonlinear dynamical motions due to unsteady flow interaction with the structures. These complex motions significantly affect the system performance and fatigue life of the constituent structure. In particular when riser pipelines are exposed to high speed flow current, they interact in a very complex manner due to vortex-induced vibration (VIV), wake-induced vibration (WIV), jet switching, turbulent buffeting and fluid-elastic instability. Apart from the significance in various engineering applications, such flow interference phenomena and associated flow-induced vibrations are of fundamental importance in fluid mechanics. Due to complex wake–body interactions, there is a considerable difference between the fluid–structure interaction of an isolated cylinder arrangement and multiple cylinder arrangements. Although in the last few decades, a vast body of works on flow-induced vibrations is reviewed by many authors (Bearman, 2011; Sarpkaya, 2004; Williamson and Govardhan, 2004; Paidoussis, 1981; Weaver and Fitzpatrick, 1988), it is still challenging for engineers to determine a range of optimal parameters and conditions to avoid flow-induced vibrations and collisions, owing to the complexities pertaining to fluid–structure interaction and operating flow environment.

To understand the flow-induced vibration of an array of flexible bluff bodies, the flow around multiple elastically mounted cylinders can be considered as an idealized model, which serves as a generic problem to analyze the interactions of bluff bodies. More specifically, we consider a pair of two cylinders in a tandem arrangement to understand the upstream vortical wake excitation mechanism from a fundamental viewpoint (Assi et al., 2010). It is well known that the dynamic response of an isolated cylinder due to vortex-induced excitation is characterized by a vortex shedding frequency via a resonant phenomenon (Williamson and Govardhan, 2004), whereas the downstream tandem cylinder exhibits a low frequency and high amplitude vibration during the interaction with vortices coming from the upstream cylinder (Bokaian and Geola, 1984; Hover and Triantafyllou, 2001; Assi et al., 2010, 2013). This subharmonic low frequency dominant motion is an intrinsic action of turbulent von Kármán vortex street for the Reynolds number approximately greater than 2000 (Bokaian and Geola, 1984; Assi et al., 2010, 2013; Mysa et al., 2016). At higher reduced velocity, such subharmonic frequency appears due to the self-excited nonlinear behavior of elastically mounted downstream cylinder. The physical complexity of WIV excitation lies in the nonlinear interaction dynamics of the convecting upstream von Kármán vortex with the downstream cylinder surface undergoing complex motion. Asymmetric oncoming wake vortices generate unbalance loads, which can trigger the self-induced instability of elastically mounted downstream cylinder in the post-lock-in region.

In the past literature, there has been considerable experimental works reported about the vortical wake interfering motion of downstream cylinder for a prototypical tandem arrangement of two identical circular cylinders. In the majority of studies, the upstream cylinder is kept stationary and the downstream cylinder is mounted on a linear spring and is allowed to move in transverse direction only, as shown in Fig. 1. One of the pioneering experimental study by Bokaian and Geola (1984) reported the response of the downstream cylinder for a streamwise gap of $L_x \leq 3D$. The downstream cylinder was found to experience a relatively large dynamic response in the post-lock-in region (i.e., high reduced velocities), as compared to the isolated cylinder arrangement. Due to similarity with the galloping response of a sharp cornered square cylinder, this peculiar behavior of downstream tandem cylinder was termed as wake-induced galloping by Bokaian and Geola (1984). The critical streamwise gap L_{xcr}, where the onset of co-shedding regime for stationary tandem cylinders, occurs somewhere between $3.5D$ to $5D$ for a wide range of Reynolds numbers as reported both numerically and experimentally (Xu and Zhou, 2004; Zhou and Yiu, 2005; Mussa et al., 2009; Gopalan and Jaiman, 2015). For a streamwise gap of $L_x = 4.7D$ in the co-shedding regime, the vibrational characteristics of downstream cylinder response were investigated experimentally by Hover and Triantafyllou (2001). At higher reduced velocities in the post-lock-in region, the response of the downstream cylinder was characterized by the combination of vortex shedding frequency and a lower frequency, whereby the lower frequency became closer to the natural frequency of the downstream cylinder.

Through a series of physical experiments for a pair of cylinders in a tandem arrangement, Assi et al. (2010) provided a detailed mechanism of vortical wake-induced excitation of the downstream cylinder at subcritical Reynolds number flow. The authors suggested that a build of amplitude of downstream cylinder for high reduced velocities is due to the unsteady vortex–structure interaction between the body and the vortical wake. In the absence of unsteady vortices, the authors demonstrated that the steady shear flow has a similar effect to that of uniform flow inducing vortex-induced vibration for an isolated cylinder case. Specifically, the upstream von Kármán vortex, which has rotational velocity and induces the high speed velocity in the gap region is the key for the sustained wake-induced vibration of downstream cylinder. Recently, Assi et al. (2013) proposed a concept of wake stiffness based on the experimental results of tandem cylinder arrangement for $L_x \geq 4D$ and for $Re \gtrsim 2000$. The characteristic wake stiffness concept has been deduced based on the response of the downstream cylinder with and without elastically mounted spring, where the restoration force was extracted from the stiffness-like behavior of wake region. In another recent study of Assi (2014), the wake effect on the downstream cylinder was found to decrease with an increase in the lateral distance between a pair of two cylinders. Similar numerical and experimental studies were conducted on two flexible riser sections in a tandem arrangement (Springer et al., 2009; Huera-Huarte and Bearman, 2011).

While the importance of stagnation point on the coupled dynamics of tandem cylinders has been suggested by Carmo et al. (2011), the origin of WIV response of the downstream cylinder for various streamwise gaps in a laminar flow has been systematically investigated by Mysa et al. (2016). The numerical study of Mysa et al. (2016) attempted to provide a detailed local behavior of vortical wake-induced vibration and the interaction dynamics of upstream von Kármán vortex with the