Journal of Fluids and Structures 78 (2018) 215–238

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Vortex-induced vibrations of three tandem cylinders in laminar cross-flow: Vibration response and galloping mechanism

Weilin Chen [a], Chunning Ji [a], John Williams [b,c,*], Dong Xu [a], Lihong Yang [a], Yuting Cui [a]

[a] *State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China*
[b] *School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom*
[c] *State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China*

HIGHLIGHTS

- Wake-induced galloping (WG) appears in low-Re VIV of 3 tandem cylinders with $L/D = 1.2$.
- T+S wake pattern is caused by asymmetric vibration and transverse dislocation.
- WG lies in the 'perfect' timing between vortex-shedding and cylinder motion.

ARTICLE INFO

Article history:
Received 14 July 2017
Received in revised form 5 November 2017
Accepted 20 December 2017

Keywords:
Three tandem cylinders
Wake-induced vibration
Wake-induced galloping
Laminar flow

ABSTRACT

Vortex-induced vibrations (VIV) of three tandem cylinders are numerically studied using the immersed boundary method. Cylinders are free to vibrate in the cross-flow direction. The Reynolds number is $Re = 100$ and the reduced velocity is $U_r = 3 \sim 80$. Six spacing ratios are selected in the range $L/D = 1.2 \sim 5.0$. The mass ratio is $m^* = 2.0$, while the damping ratio is set as zero for achieving large vibration amplitudes. The characteristics of the vibration amplitude, drag and lift forces, lift frequency, phase difference between displacement and lift, and the wake patterns are discussed. It is found that, in the case with small L/D, large-amplitude vibrations of the cylinders are excited due to strong wake-cylinder interference. However, in the cases with large L/D, the vibration responses of the upstream cylinder resemble those of an isolated cylinder indicating vanishing interference from the downstream cylinders. While, the two downstream cylinders attain large vibration amplitudes even at high reduced velocities. A wake pattern, T+S, i.e. the cylinders alternately shed triple vortices and a single vortex in a vibration cycle, is observed. This wake pattern is caused by the asymmetric vibration of the cylinders and transverse dislocation of the equilibrium positions. With increasing L/D, two different vibration patterns are observed: wake-induced galloping (WG) for the small-L/D case ($L/D = 1.2$) and vortex-induced vibration (VIV) for the moderate- to large-L/D cases ($L/D = 1.5 \sim 5.0$). The major characteristic feature of WG, distinct to VIV, are the divergent vibrations of the cylinders with the increasing reduced velocity. The mechanism of WG is elucidated by analyzing the complex but stable interactions between vortices and cylinders. Three pivotal factors are identified: the 'perfect' timing between vortex-shedding and cylinder

* Corresponding author at: School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom.
E-mail address: j.j.r.williams@qmul.ac.uk (J. Williams).

https://doi.org/10.1016/j.jfluidstructs.2017.12.017

motion, the transverse dislocation of the equilibrium positions, and the low and decreasing vibration frequency.

1. Introduction

Vortex-induced vibrations (VIV) of an isolated elastically-supported cylinder in cross-flow has been studied extensively (Sarpkaya, 2004; Williamson and Govardhan, 2004; Williamson and Govardhan, 2008; Bearman, 2011). However, a deep understanding of the mechanism of vortex-induced vibration (VIV) of multiple cylinders in the tandem arrangement is still lacking due to the complexity of the nonlinear wake-cylinder interferences.

Generally, the flow patterns around two stationary cylinders in the tandem arrangement can be classified into three regimes. With the increasing streamwise spacing ratio L/D, they are the extended bluff-body regime ($L/D < 1.2 \sim 1.8$), the reattached regime ($1.2 \sim 1.8 < L/D < 3.4 \sim 3.8$) and the co-shedding vortex regime ($L/D > 3.4 \sim 3.8$) (Sumner, 2010). In above, L is the streamwise center-to-center spacing between the cylinders and D is the diameter of the cylinders. In the extended bluff-body regime, the shear layers separated from the upstream cylinder embrace the downstream cylinder, resulting in an extended bluff body. In the reattached regime, the shear layers reattach to the surface of the downstream cylinder. This regime can be further divided into two sub-regimes, according to the different positions of the reattachment points (Zhou and Yiu, 2006). In the co-shedding vortex regime, the gap between the cylinders is large enough for the separated shear layers to roll up and form vortices. These vortices alternately impinge on the downstream cylinder and interact with the vortices shed from the downstream cylinder. The critical L/D between different regimes is affected by the Reynolds number, the aspect ratio (cylinder length to cylinder diameter), the cylinder's end support conditions, and etc. (Xu and Zhou, 2004). A recent review of related research progress can be found in Sumner (2010).

When the cylinders are free to vibrate, the alternately shed vortices from the cylinders will lead to cross-flow (CF) and in-line (IL) vibrations. Compared to the vibration of an isolated cylinder undergoing VIV (referred to as ICVIV hereafter), the vibration of two tandem cylinders is far more complicated. When L/D is small, the existence of the downstream cylinder significantly affects the wake of the upstream cylinder, and thus, in some cases, may result in a galloping-like vibration, named as wake-induced galloping (WG), of the cylinders. The vibration amplitude monotonously increases with the increasing reduced velocity $U_r = U/f_N D$, where f_N is the natural frequency of the cylinder and U is the unaffected incoming flow velocity. This is obviously distinct from ICVIV in which large amplitude vibrations only occur in the 'lock-in' region. With increasing L/D, the vibration of the upstream cylinder gradually approaches that of a typical ICVIV. However, the vibration of the downstream cylinder can be affected by the wake of a cylinder far upstream even when L/D is as large as 5.0 (Papaioannou et al., 2008). Depending on L/D, the downstream cylinder shows three vibration patterns, i.e. the combined VIV and WG, the separated VIV and WG, or VIV.

For moderate- and high-Re VIV of two tandem cylinders, Bokaian and Geoola (1984) ($700 < Re < 2 \times 10^3$) carried out a series of experiments in which a stationary circular cylinder was placed downstream or upstream of an elastically mounted rigid circular cylinder with an identical diameter. It was found that, for the case with a stationary downstream cylinder, the upstream cylinder underwent WG only when the downstream cylinder was well submerged in the near-wake of the upstream one. On the other hand, for the case with a stationary upstream cylinder, the downstream cylinder experienced combined VIV and WG, separated VIV and WG, or VIV with increasing spacing ratio.

Zdravkovich (1985) investigated the fluid-elastic instability of two cantilever-supported rigid circular cylinders in a wind tunnel with flows in the range of $1.5 \times 10^4 < Re < 9.5 \times 10^4$. It was reported that the dimensionless transverse displacement amplitude of the downstream cylinder gradually built up to 1.7D when the reduced velocity reached 80, while the amplitude of the upstream cylinder was small. Zdravkovich and Medeiros (1991) ($5 \times 10^3 < Re < 1.4 \times 10^5$) further investigated the damping effects on the vibration response of two cylinders and found that WG is observed on both cylinders when the damping was low and L/D was small. However, when L/D was large, WG occurred only on the downstream cylinder.

Brika and Laneville (1999) ($5 \times 10^3 < Re < 2.7 \times 10^4$) experimentally investigated the dynamic responses of a flexible cylinder in the wake of a stationary geometrically identical cylinder. A combination of VIV and WG was observed for streamwise separations from 7D to 8.5D. The 'lock-in' region of the downstream cylinder began at a larger U_r, compared to that of ICVIV, due to the shielding effects of the upstream cylinder. Laneville and Brika (1999) further investigated the VIV of two tandem flexible cylinders with a large spacing ratio range of $L/D = 7.0 \sim 25.0$. Compared to the stationary upstream cylinder case, the downstream cylinder entered the synchronization region at a lower reduced velocity because the synchronized vortices of the upstream cylinder initiated the downstream cylinder's vibration at the same velocity as that of the upstream cylinder.

Hover and Triantafyllou (2001) ($Re = 3.05 \times 10^4$, $m^* = 3.0$, $L/D = 4.75$) studied the displacement and force responses of an elastically mounted cylinder behind a stationary leading cylinder in a towing tank. Large-amplitude WG responses sustained to the reduced velocity of at least $U_r = 17$. The largest displacement amplitude achieved was 1.9D.

Assi et al. (2006) ($3 \times 10^3 < Re < 1.3 \times 10^4$) carried out flume experiments on VIV of an elastically mounted rigid cylinder in the near-wake of an upstream stationary cylinder. Wake-induced galloping was observed in the range of $2.0 \leq L/D \leq 5.6$. Assi et al. (2010, 2013) ($2 \times 10^3 < Re < 3 \times 10^4$) reported that a combined VIV and WG response was observed on the