Journal of Fluids and Structures 66 (2016) 571–588

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Multi-mode vortex and wake-induced vibrations of a flexible cylinder in tandem arrangement

F.J. Huera-Huarte[a,*], Z.A. Bangash[a], L.M. González[b]

[a] Department of Mechanical Engineering, Universitat Rovira i Virgili (URV), 43007 Tarragona, Spain
[b] Naval Architecture Department, Technical University of Madrid (UPM), 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form
22 June 2016
Accepted 29 July 2016

Keywords:
Vortex-induced vibration
Wake-interference
Wake-induced vibration
Long flexible circular cylinders
Tandem cylinders
Vortex shedding
Multi-mode VIV
Marine risers

ABSTRACT

Experiments with a flexible cylinder of circular cross-section towed behind a stationary circular cylinder at various distances are described in this paper. The dynamics of the model immersed in the wake of the leading one are fully characterised after data processing and computation of amplitude and frequency responses, as well as modal content as a function of reduced velocity. Reduced velocity was controlled by changing the towing speed of the system and by adjusting different pre-tensions on the model.

The amplitude response of the model has been found to be dominated by resonance or lock-in regions in the reduced velocity axis at the different structural modes of the cylinder model. Separation distance does not produce significant qualitative changes in the response amplitudes and frequencies observed when compared to the response of the same cylinder without wake interference. However, there is a clear effect of the incoming wake, because amplitude responses are considerably higher than those expected in isolated cylinders at the same reduced velocities. Also, the response has been found to be more multi-modal with responses made of large amplitude contributions of several adjacent modes.

1. Introduction

The flow around a cylinder, and its effect on the structural dynamics of the body is a classical multidisciplinary problem involving fluid dynamics, structural dynamics and vibrations. Since the beginning of the 20th century the research related to that topic has been driven by classical engineering problems such as flow induced vibrations of civil engineering structures, as well as aerospace related applications. With development of ambitious engineering projects for energy extraction and generation like marine risers for deep sea oil exploration, mooring lines for floating wind turbines and other offshore structures, heat exchangers, cooling systems for nuclear power generation, power lines and grids and submarine data cables, there has been an unprecedented surge for understanding of fluid–structure interaction problem, specifically towards systems based on single and multiple flexible cylindrical structures. The advent of faster computers, data acquisition systems and processing power has resulted in a large amount of research work on this subject in the last few decades. Often, practical applications involve structures that have two or more cylindrical elements that are arranged in tandem, side by side or staggered configuration. In the majority of these applications vortex shedding is responsible for flow induced vibrations and noise.

---

* Corresponding author.
E-mail address: francisco.huera@urv.cat (F.J. Huera-Huarte).

http://dx.doi.org/10.1016/j.jfluidstructs.2016.07.019
0889-9746/

There is a significant amount of literature focusing on flow around single rigid cylinder undergoing vortex-induced vibrations (VIV). Some excellent reviews by Bearman (1984), Williamson (1997), Sarpkaya (2004), and Williamson and Govardhan (2004, 2008) present the state of the art on the subject. Most of the mentioned research focuses on response regimes, amplitudes of oscillation and associated drag for flexibly mounted rigid cylinders. In case of flexible slender cylinders there are many natural frequencies associated to their structural modes, and the response can be built up of combinations of several high mode numbers. Lock-in in these cases can be understood at different modes, but in general one mode of oscillation has significantly higher energy than the competing modes (Vandiver et al., 1996; Chaplin et al., 2005a,b). This type of response is associated to large amplitudes of vibrations and large mean drag coefficients (Vandiver, 1993; Chaplin et al., 2005a,b; Huera-Huarte et al., 2014). A brief review of VIV of flexible cylinders was compiled by Wu et al. (2012).

Moreover, it is well known from works such as Chaplin et al. (2005b) and Trim et al. (2005), and more recently observed too by Huera-Huarte et al. (2014), that the main characteristic in the response of flexible cylinders is the arrangement of its response according to lock-in branches in the reduced velocity (U^*) axis. In such systems, the response is driven by the resonant excitation of each structural mode, with amplitudes growing with reduced velocity until they discontinuously fall, to start growing again in the buildup of the next structural mode and so on. This phenomenon is especially dominant when the excitation is caused by uniform flows and when the cylinders are characterised by a high density of natural frequencies or a large mode count. As soon as one mode is excited, if the reduced velocity is changed, another mode with a frequency closest in value enters in competition and so on. On the other hand, it is also well known that even if the cylinder is flexible, if it has largely spaced natural frequencies or what is the same low modal density, the successive lock-in phenomenon would not take place. In such cases, if reduced velocity is augmented, the cylinder undergoes lock-in in a certain structural mode with large amplitude, then the amplitudes decrease slowly desynchronising, because the next mode frequency is still far away with respect to the excitation one until they disappear. Amplitudes will not appear again until the conditions to excite the next mode are met. These are flexible cylinders that mostly behave as elastically mounted rigid ones at each structural mode. Experiments with isolated cylinders showing that behaviour are for example those by Brika and Laneville (1993), Huera-Huarte and Bearman (2009a,b), Sanaati and Kato (2013), and Gu et al. (2013).

Just like the case of isolated cylinders where there are significant studies of VIV of flexibly mounted rigid cylinders the study of rigid cylinder in vicinity of another rigid cylinder has also received considerable attention. A comprehensive review on the subject was produced by Sumner (2010). The focus of most multiple cylinder studies has been on the flow patterns and regimes based on the distance between cylinders. The response regimes, i.e. the amplitudes of oscillation for rigid cylinders in tandem have received lesser attention. Some numerical analysis carried out by Prasanth and Mittal (2009) and Borazjani and Sotiropoulos (2009) have shown the relationship between the response regimes of rigid cylinders in tandem arrangement and those of isolated rigid cylinders for various gap distances. Experimental analysis by Kim et al. (2009) for cross-flow and Okajima et al. (2007) for stream-wise oscillation show the response regimes for a range of in-line distances. Assi et al. (2013) show that, for a rigid cylinder in tandem arrangement, the response regime consists of a single branch of consistently increasing amplitude of oscillation for medium to high gap spacing. For low gap spacing they show a peak at the resonant case, followed by a decreasing trend, that is followed by an increase in amplitude similar to larger gaps. Bokaian and Geoola (1984) suggested that it was due to a form of galloping and Assi et al. (2010, 2013) introduced the concept of wake stiffness to explain their frequency response observations. Therefore, one of the main points to look at in all that studies was to investigate the origin of the very large amplitudes observed outside the resonance region.

The work with a flexible cylinder in the wake of another stationary one, reported by Brika and Laneville (1999), is based on one of these flexible models with low modal density and it behaves as an elastically mounted rigid model. In previous experiments by Huera-Huarte and Bearman (2011), interference effects between two cylinders in tandem, both free to oscillate, were investigated. Very rich dynamics and synchronisation processes were observed between the models with some cases showing larger excursions in the leading cylinder. It was verified in that experiments, by using particle image velocimetry (PIV), that there were several flow regimes depending on the existence or not of vortex shedding between the models. At the smallest centre to centre separations a wake between the models was not formed and the motions of the trailing cylinder were very limited in amplitude. The amplitudes grew up in value in any of the two other regimes observed at larger centre to centre separations. For intermediate separations, a bi-stable regime was observed, with shedding that intermittently appeared and disappeared, generating disorganised oscillations. Finally, at the largest distances, the wake was stable and vortices emanating from the leading cylinder hit the trailing one generating large oscillations. In those experiments the natural frequencies of the model were well separated because of the dimension limitations imposed by the facility so the second mode was not fully excited and oscillations disappeared as the reduced velocity reached values over 16. This was in contrast to that observed by Assi et al. (2010, 2013). In those, the authors studied the wake-induced vibration (WIV) phenomena of a tandem arrangement of an elastically mounted rigid cylinder immersed in the wake of a stationary one. Their data shows a very strong WIV amplitude dependence on the centre to centre separation imposed in their experiments. It also shows how the amplitude response is practically the same for all separations tested (up to 20D) for reduced velocities less than 6, fact attributed to resonance. For higher U^* the amplitudes monotonically increased as the distance decreased. Their frequency data shows that the frequencies remained at expected shedding values up to the resonance peak and departed from the expected slope to keep at lower values for higher reduced velocities. After these observations the authors argued that the large amplitude oscillations observed at the largest reduced velocities were not