Journal of Fluids and Structures 74 (2017) 53–63

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Experimental sensitivity of vortex-induced vibrations to localized wake perturbations

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ARTICLE INFO

Article history:
Received 20 January 2017
Received in revised form 29 May 2017
Accepted 10 July 2017

Keywords:
Sensitivity analysis
Vortex-induced vibrations
Bluff body wakes
Localized perturbations

ABSTRACT

We present the experimental sensitivity of vortex-induced vibration (VIV) to localized perturbations, in the wake of a low mass-damping one-degree-of-freedom circular cylinder subject to uniform cross-flow. Regions of VIV sensitivity have been identified, clearly indicating positions in the wake where control systems should be placed in order to attenuate VIV amplitudes.

As a validation of the sensitivity maps, we demonstrate how by using control cylinders with diameters of only 12% of the main cylinder diameter, reductions of VIV response of more than 65%, can be reached. The use of Digital Particle Image Velocimetry (DPIV) has allowed us to identify the physical mechanisms underlying the VIV response modifications induced by the control cylinders.

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1. Introduction

The flow around circular cylinders and the existence of vortex-induced vibrations (VIV) under particular flow and structural conditions, constitutes a widespread problem which is encountered in many engineering applications. In particular, in ocean and offshore engineering systems (e.g. riser pipes, undersea cables or other slender structural components), the amplitude of vibrations can be large. There has been a wide scientific interest that has given rise to a large amount of work devoted to VIV characterization and control (see e.g. Zdravkovich, 1981; Bearman, 1984; Williamson and Roshko, 1988; Sarpkaya, 2004; Williamson and Govardhan, 2004; Bearman, 2011). In that sense, to reduce or completely suppress cylinder vibrations, different approaches have been proposed, which can be generally classified into passive, active open-loop and active closed-loop methods (Choi et al., 2008). Passive methods offer generally simple and efficient solutions for vibration attenuation in real configurations, and have traditionally received more attention (Zdravkovich, 1981). These strategies are mainly based on geometry modifications of the body (e.g. Bearman and Brankovic, 2004; Sánchez-Sanz and Velazquez, 2009; Zhou et al., 2011; Lee et al., 2014) and perturbations of the flow around it, using, for instance, splitter plates (Assi et al., 2009) or smaller control cylinders (Korkischko and Meneghini, 2012; Zhu et al., 2015; Zhu and Yao, 2015), whose aim is to alter the vortex shedding process. The performance of such control devices might be improved by previously identifying the wake regions that contribute most to VIV reduction, when the flow is perturbed locally by means of infinitesimal forcing. This approach stems from the concept of sensitivity to localized perturbations, which, to the best of our knowledge, has not been yet applied to VIV.

The use of sensitivity to localized perturbations in the wake has been widely investigated in the recent years for rigid stationary cylinders and other two-dimensional bodies. The seminal experimental study from Strykowski and Sreenivasan

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http://dx.doi.org/10.1016/j.jfluidstructs.2017.07.010
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(1990) demonstrated that the vortex-shedding behind a cylinder can be effectively suppressed at low values of Reynolds numbers, through the placement of a small cylinder in a particular region of the wake, leading to a shift on the onset of the instability, towards a higher critical value of Reynolds number well above the value of $Re = 46$. These observations on the wake sensitivity were later reproduced using adjoint linear stability formalisms (Hill, 1992; Giannetti and Luchini, 2007; Marquet et al., 2008), identifying similar regions in the flow where an infinitesimal localized perturbation, e.g. control cylinders, might be able to reduce the growth rate and amplitude of the unstable global mode. The effect of such localized perturbations is related to wake stabilization mechanisms that reduce the shear or the flow recirculation, which are known to be a source of global instability. More interestingly, the presence of these perturbations in the wake affects also the frequency of shedding and the pressure distribution, and therefore, alters the forcing acting on the body. For instance, Sakamoto and Haniu (1994) showed experimentally that mean and fluctuating values of force coefficients acting on a cylinder can be considerably reduced by placing a small perturbing cylinder either along the boundary layer or within the separation region. Moreover, Parezanović and Cadot (2012) performed experiments in the wake of a D-shaped cylinder at turbulent regimes, showing that important variations of shedding frequency can be achieved when the cylinder is placed along the shear layers, modifying the interaction between them and therefore, vortex formation. The effects of localized perturbations on the global frequency have also been characterized by means of adjoint sensitivity analyses in recent works by (Meliga et al., 2012; Mettot et al., 2014). Similarly, important variations of drag and lift magnitudes can also be obtained when the disturbing cylinders are spatially arranged according to the areas with the largest sensitivity (Meliga et al., 2014, 2016).

In view of such results on wakes behind rigid stationary bluff bodies, it seems evident that sensitivity analyses may provide valuable information on the optimal placement of wake perturbing devices in elastically mounted rigid cylinders. In that sense, a first theoretical step to understand and derive the flow sensitivity are the works from Meliga and Chomaz (2011) and Meliga et al. (2011), where the main features of VIV, at low Reynolds numbers, were investigated using adjoint-based formulation and asymptotic expansions, identifying fluid and structure modes and its role on lock-in and hysteretic phenomena. However, the lack of results at high Reynolds numbers and the complex system behaviour, makes the experimental analysis an interesting approach. Consequently, in order to set a base for improved devices, we will apply the concept of sensitivity maps to chose appropriate locations of perturbing cylinders, prior experimental determination of VIV response sensitivity.

We aim at obtaining sensitivity maps of VIV amplitude and frequency to localized perturbations in the flow around the cylinder. A symmetric pair of tinny perturbation cylinders will be placed at different wake positions, covering a fine grid of wide radial and azimuthal ranges, relative to the origin of the vibrating cylinder. Note that, unlike other previous works on rigid bodies, symmetric configurations for perturbations cylinders will be employed to obtain dynamic responses without any mean lift component, which is known to appear if an asymmetric scheme is adopted (see e.g. Assi et al., 2009), and might be undesirable in terms of control for practical applications. These tests will be conducted for selected values of Reynolds numbers or reduced velocities. The usefulness of the obtained sensitivity maps will be validated by placing, only in several locations with the highest sensitivity, pairs of control cylinders with diameters larger that those of the previous perturbation ones. The VIV response of the new controlled system will be studied in depth using Digital Particle Image Velocimetry (DPIV).

2. Experimental set-up

The experiments were performed in the free surface water channel (FSWC) of the Department of Mechanical Engineering at Universitat Rovira i Virgili (URV) in Tarragona. The experimental set-up and the layout of the experiment appear in Fig. 1. The water channel has a cross-section of 1×1.1 m^2, and with a water height of 1 m it can reach flow velocities well over to 0.5 m/s. The flow profile is characterized by a very low flow velocity variability, with a maximum deviation of axial velocity of 1.58% at the working section.

The circular cylinder model consisted of a rigid acrylic tube of immersed length $L = 0.55$ m and diameter $D = 0.05$ m, i.e. of aspect ratio $L/D = 11$, and had an end-plate attached to his bottom base, with the aim at suppressing three-dimensional effect close to the cylinder end. The system, elastically connected to a fixed supporting structure by means of a pair of springs, was hung from a one-degree-of-freedom air bearing rig, which allowed the cylindrical model to oscillate in the cross-flow, y-direction (see Fig. 1(a)) with very low damping.

The VIV sensitivity study was performed by placing in the wake a symmetric pair of perturbation cylinders, whose centres are located at positions $(r, \pm\theta)$, relative to the coordinate system defined by the oscillating cylinder, as shown in Fig. 1(b). Perturbation cylinders consisted of stainless steel rods with a diameter $d = 0.032D$.

The dynamic response validation carried out at the points in which sensitivity was found to be the maximum, was performed with larger cylinders, consisting of aluminium tubing with an external diameter $d = 0.12D$. Holding devices were made of slim, streamlined, 3D printed parts of polylactic acid (PLA), that allowed precise placement of cylinders at any radius r and angle θ of interest.

For the sensitivity analysis, a discrete fine grid of points was designed, covering the ranges $0.6D \le r \le 1.54D$ and $-90^\circ \le \theta \le 90^\circ$, with $\Delta r = 0.06D$ and $\Delta\theta = 10^\circ$, configuring a grid of 13×19 (247) nodes. At the second stage of the work, several specific control locations were picked for the control cylinders, based on the areas of highest sensitivity identified in the previous analysis.

The structural damping coefficient in air after decay tests, was found to be $\xi = 0.0117$. The mass ratio was $m^* = 4m/(\pi\rho LD^2) = 1.94$, with m being the structural mass of the system including the mass of the perturbation cylinders

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