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Two-degree-of-freedom vortex-induced vibrations of a circular cylinder at Re=3900

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ABSTRACT

The vortex-induced vibrations of an elastically mounted circular cylinder are investigated on the basis of direct numerical simulations. The body is free to move in the in-line and cross-flow directions. The natural frequencies of the oscillator are the same in both directions. The Reynolds number, based on the free stream velocity and cylinder diameter, is set to 3900 and kept constant in all simulations. The behavior of the coupled flow-structure system is analyzed over a wide range of the reduced velocity (inverse of the natural frequency) encompassing the lock-in range, i.e. where body motion and flow unsteadiness are synchronized. The statistics of the structural responses and forces are in agreement with prior experimental results. Large-amplitude vibrations develop in both directions. The in-line and cross-flow oscillations are close to harmonic; they exhibit a frequency ratio of 2 and a variable phase difference across the lock-in range. Distinct trends are noted in the force-displacement phasing mechanisms in the two directions: a phase difference jump associated with a sign change of the effective added mass and a vibration frequency crossing the natural frequency is observed in the cross-flow direction, while no phase difference jump occurs in the in-line direction. Higher harmonic components arise in the force spectra; their contributions become predominant when the cylinder oscillates close to the natural frequency. The force higher harmonics are found to impact the transfer of energy between the flow and the moving body, in particular, by causing the emergence of new harmonics in the energy transfer spectrum.

1. Introduction

Vortex shedding from a bluff body immersed in a flow is accompanied by unsteady forces exerted by the fluid on the body. In the case of flexible bodies with bluff cross-section, these unsteady forces may lead to structural vibrations. Vortex-induced vibrations (VIV) occur when the body oscillation and the unsteady wake synchronize, a mechanism referred to as lock-in. VIV are encountered in a variety of natural and industrial systems. In civil and offshore engineering, these vibrations lead to fatigue or even failure of the structures and their prediction is thus crucial. On the other hand, VIV can also be used as mechanical energy converter in the context of flow energy harvesting (e.g. Grouthier et al., 2014). The physical analysis and the prediction of VIV have motivated a number of studies, as reviewed by Bearman (1984), Sarpkaya (2004), Williamson and Govardhan (2004), and Païdoussis et al. (2010).

During the last decades, VIV have been extensively studied through the canonical problem of a rigid circular cylinder elastically mounted or forced to oscillate in the cross-flow direction, as a paradigm of more complex configurations (e.g. Feng, 1968; Mittal and Tezduyar, 1992; Hover et al., 1998; Khalak and Williamson, 1999; Govardhan and Williamson, 2000; Carberry et al., 2001;

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Blackburn et al., 2001; Shiels et al., 2001; Leontini et al., 2006). Significant body vibrations occur on a well-defined range of the reduced velocity, which is defined as the inverse of the oscillator natural frequency non-dimensionalized by the inflow velocity and the body diameter. In this range called lock-in range, the body oscillation frequency is the same as the unsteady wake frequency. The body response amplitude exhibits a bell-shaped evolution as a function of the reduced velocity. For large mass ratio between the body and the fluid, and large damping, two branches of response are observed, the initial and lower branches (following the terminology of Khalak and Williamson, 1996). Decreasing the mass ratio and damping results in the appearance of an upper branch, between the initial and lower branches (Khalak and Williamson, 1997a, 1999). The vibration amplitudes are larger in the upper branch and may reach one cylinder diameter. When the mass ratio is large, the lock-in frequency significantly departs from the Strouhal frequency (i.e. the shedding frequency downstream of a stationary body) but it remains close to the natural frequency of the oscillator, as observed in the experiments of Feng (1968). At lower mass ratios, the lock-in frequency can shift away from the natural frequency of the oscillator; such deviation may be connected to the variability of the effective added mass related to the unsteady fluid forces (Moe and Wu, 1990; Khalak and Williamson, 1997a).

Previous studies have shown that adding a degree of freedom in the in-line direction, viz. the direction aligned with the current, can considerably alter the cross-flow response. In their experiments, Jauvtis and Williamson (2004) (referred to as J & W in this paper) identified an amplification of the cross-flow vibration in the upper branch, called super-upper branch, with amplitudes up to 1.5 diameters. In the in-line direction, the maximum amplitudes are close to 0.3 diameters. Dahl et al. (2010) pointed out the effect of the ratio between the in-line and cross-flow natural frequencies on the system responses.

Numerical simulation is a useful tool to study VIV: it provides a simultaneous vision of the wake patterns, fluid forcing and body responses, which allows a coupled analysis of the flow-structure system. However, the numerical simulation of VIV in conditions close to those encountered in nature or in the experimental works remains challenging. In particular, the simulation of flows at high Reynolds number (*Re*, based on the inflow velocity and the cylinder diameter) requires massive computational resources and often, additional modeling (e.g. turbulence closure). This explains why most of the numerical works concerning VIV have been dedicated to low Reynolds number configurations, even though the Reynolds number is known to have a significant impact on the system behavior (Govardhan and Williamson, 2006; Raghavan and Bernitsas, 2011; Bearman, 2011). Recent studies have shown that with the improvement of numerical methods and the development of computational resources, the investigation of VIV in the turbulent regime via numerical simulation becomes possible (e.g. Al-Jamal and Dalton, 2004; Lucor et al., 2005; Sarkar and Schlüter, 2013; Navrose, 2013; Lee et al., 2014; Zhao et al., 2014). The present work aims at contributing to this effort.

In the present study, the response of an elastically mounted circular cylinder free to move in the in-line and cross-flow directions is investigated on the basis of direct numerical simulation (DNS) results, at $Re=3900$. This value of the Reynolds number was often selected in prior studies concerning flows past fixed cylinders as a typical case of the early turbulent regime (e.g. Beaudan and Moin, 1994). The fluid–structure system behavior is computed over a wide range of reduced velocities encompassing the lock-in range. The Reynolds number is kept constant in all simulations so that the reduced velocity is the only varying parameter. The DNS approach involves the prediction of the three-dimensional flow around the cylinder, as illustrated in Fig. 1, which represents an instantaneous iso-surface of the Q criterion (Hunt et al., 1988) colored by iso-contours of the spanwise vorticity around a cylinder subjected to VIV. However, this paper does not aim at providing a detailed analysis of the three-dimensional wake patterns; instead, the objective here is to focus on the interaction between the moving body and the flow through the span-averaged fluid forces, with a particular

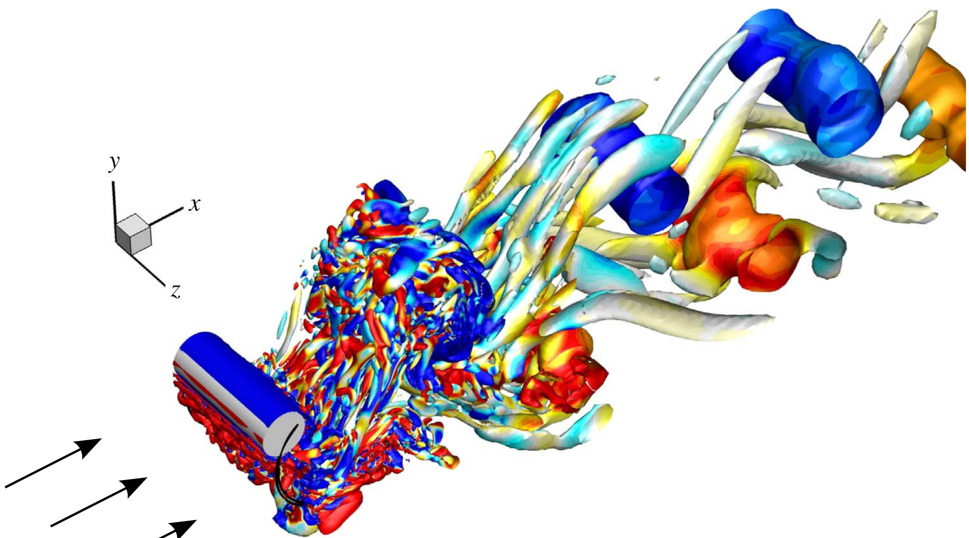

Fig. 1. Three-dimensional wake downstream of a freely vibrating cylinder: instantaneous iso-surface of the Q criterion ($Q=0.1$) colored by iso-contours of the spanwise vorticity ($\omega_z \in [-0.85, 0.85]$) in the region of maximum vibration amplitudes ($U^* = 6$). The trajectory of the cylinder is represented by a line at the end of the body and arrows indicate the direction of the oncoming flow. Part of the computational domain is shown.