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Mode excitation hysteresis of a flexible cylinder undergoing vortex-induced vibrations

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ABSTRACT

A series of experiments was performed to investigate the modal excitation of a tensioned flexible cylinder in a uniform flow due to flow-induced vibrations. Experiments were conducted in a recirculating flow channel using a flexible cylinder with relatively low aspect ratio such that low structural mode numbers were excited. The spanwise motion of the cylinder was measured using standard motion tracking techniques with high-speed cameras. Hysteresis is observed in the response of the cylinder dependent on whether the flow speed is increased or decreased from the previous experiment. This observation differs from predictions in the literature regarding hysteresis and is attributed to hysteresis in the transition between excited structural modes coupled with the cylinder wake. It is also found that the flexible cylinder is unable to sustain excitation of asymmetric modes in the in-line direction unless the fluid-structure interaction excites a 1:1 frequency response between the in-line (IL) and cross-flow (CF) directions, resulting in a pedaling mode response. The inability to excite asymmetric modes is consistent with the response of linear systems undergoing a symmetric drag load and is consistent with the cylinder undergoing a preferred figure eight shape motion when excited. Distributed fluid forces are derived from the structural characteristics and body motions illustrating the transition of the distribution of added mass and excitation forces on the body.

1. Introduction

Vortex-induced vibrations (VIV) are a fundamental fluid-structure interaction problem in many engineered systems (e.g. offshore structures, mooring systems, heat exchangers, etc.). The non-linear interaction between a circular cylinder in a uniform current and the vortex shedding in the wake of the cylinder is dependent on a large number of variables (Sarpkaya, 2004). In order to study the phenomenon of VIV, simplifications are often made when conducting experiments in order to limit the number of variables that may affect the observed response. This often leads to observed differences between the responses of different systems undergoing VIV. For example, an elastically mounted, rigid cylinder undergoing VIV in an experimental water channel (Williamson and Govardhan, 2004) will inherently display different response features than the multi-mode excitation of a flexible pipe in a sheared current in the ocean (Vandiver et al., 2009; Vandiver and Jong, 1987). Differences may simply occur based on the experimental setup due to differences in surface roughness, free stream turbulence, or blockage effects. One of the observed non-linear behaviors of VIV, particularly for experiments conducted in confined channels, is hysteresis.

In the context of vortex-induced vibrations, hysteresis is typically associated with the amplitude response of the structure as a function of reduced velocity. For example, if one conducts an experiment with an elastically mounted circular cylinder in a water

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channel with a uniform current, one may observe different responses of the structure by varying the flow speed. The variation in flow speed is related to a change in both the reduced velocity of the system and a change in the Reynolds number. As one increases the flow speed, one may observe a transition from a large amplitude response to a lower amplitude response. In contrast, if the flow speed is reduced, one may observe a transition from low amplitude response to high amplitude response, however this transition may not occur at the same reduced velocity, hence a hysteretic response. This type of response is common in non-linear systems and has been observed in vortex-induced vibrations under a variety of experimental and simulation conditions.

Hysteresis in vortex-induced vibrations is known to be related to blockage and Reynolds number effects, often being observed in experiments and simulations with high blockage ratios and low Reynolds numbers. It has been observed in both free vibration conditions and forced vibration conditions, where transitions between wake modes become dependent on whether flow speed is increased or decreased from the previous experimental condition. Bishop and Hassan (1964) observed hysteresis in a series of forced vibration experiments, where the cylinder was forced to oscillate in the cross-flow direction with a prescribed frequency. In these experiments, Reynolds numbers ranged from 4×10^3 to 11×10^4 and the blockage ratio was 8.3. In order to understand the parameters which affect hysteresis in VIV, Stansby (1976) conducted a systematic series of forced cylinder experiments in air in which blockage ratio was varied, demonstrating hysteresis for higher blockage ratios. Khalak and Williamson (1999) reported hysteresis in freely-vibrating rigid cylinder experiments where the cylinder was allowed to oscillate only in the cross-flow direction for low mass ratio and damping and relatively low Reynolds numbers between 2×10^3–13×10^3. Klamo et al. (2006) conducted a systematic set of rigid cylinder experiments in order to examine the effects of damping on the response of the cylinder, where the cylinder was only allowed to oscillate in the cross-flow direction. In these experiments, a hysteretic region was observed for low Reynolds numbers between 525 and 2600.

Prasanth et al. (2011) developed a general characterization map for hysteresis, defining a critical blockage ratio region as a function of mass ratio. The map, based on a comprehensive set of low Reynolds number simulations with varying blockage ratio and mass ratio, shows that for a freely vibrating rigid circular cylinder, at low mass ratios and low blockage ratios, a region exists where hysteresis will not be observed. The map is compared with a number of experiments and simulations to demonstrate that it holds for a variety of conditions. Although the simulations are performed at very low Reynolds number, in the laminar boundary layer and laminar wake region, the map still compares well with experiments performed at Reynolds numbers with turbulent wakes. In addition, Prasanth et al. (2011) shows good prediction of hysteresis conditions for rigid cylinder experiments (Khalak and Williamson, 1999; Klamo et al., 2006) and flexible cylinder experiments (Brika and Laneville, 1993; Triantafyllou et al., 2003).

Although the experiments of Brika and Laneville (1993) and Triantafyllou et al. (2003) were performed with flexible cylinders in a wind tunnel and water tunnel respectively, these experiments still demonstrate many response features similar to the vibration of an elastically mounted rigid cylinder, since neither experiment observed a multi-modal response of the cylinder. For example, the pinned locations of the flexible cylinder in Brika and Laneville (1993) required a characterization of the excited structural mode such that the peak response at the center of the test section could be reconstructed from measurements of vibrations of the flexible cylinder outside of the wind tunnel. This center point measurement only gives information about the response of the cylinder at a single point and the resulting hysteresis of the response at that single point. Similarly, the response of the flexible cylinder in Triantafyllou et al. (2003) is only measured at the center point and the cylinder only displays a first mode response at the center point.

A significant number of experiments have been performed to characterize the multi-mode responses of long, flexible cylinders, particularly with interest in modeling the characteristics of ocean structures. Often, these experiments are performed in the field to capture characteristics typical of operating conditions for offshore structures (Vandiver and Jong, 1987; Lie and Kaasen, 2006; Vandiver et al., 2005, 2009), however field experiments introduce many additional experimental parameters that are difficult to control. This introduces a need for conducting controlled laboratory experiments to help limit variables in the experiment. Recent controlled laboratory experiments have characterized the response of flexible structures undergoing VIV with low mode number and high mode number excitations (Gedikli and Dahl, 2014; Huera-Huarte and Bearman, 2009; Passano et al., 2010; Trim et al., 2005), where the response of the structure follows excitation of distinct modes or combinations of modes. However, conducting laboratory experiments with flexible structures introduces questions about hysteresis, as laboratory experiments are typically conducted in confined water channels or towing tanks. In the above mentioned flexible cylinder experiments, hysteresis was not observed.

In this paper, results are reported for the observed vortex-induced vibration of a low mode number, tensioned flexible cylinder. In contrast to previous studies, a hysteretic effect on the dynamic response of the body is observed. In contrast to rigid cylinder experiments, this hysteretic effect is observed to be related to the transition between mode excitation, rather than a transition between upper and lower branch responses. When compared with the critical blockage map predicted by Prasanth et al. (2011), the structural characteristics and blockage characteristics place the cylinder directly in the middle of the “no hysteresis” region. The fundamental difference in the present experiment from the requirements of the critical blockage map in Prasanth et al. (2011) is the possibility of multi-mode excitation of the structure.

2. Experimental description

Experiments were conducted in a uniform recirculating water channel located on the Narragansett Bay Campus of the University of Rhode Island. The flow channel has a test section with dimensions 38 cm wide by 48 cm tall. The test section of the flow channel consists of three glass walls on the sides and bottom, with the top of the channel open. The flow channel can be operated at speeds between 0.1–1.3 m/s, although the present experiments were limited to speeds between 0.1 and 0.6 m/s. Fig. 1 shows a schematic drawing of the experimental set-up inside the flow channel. A flexible cylinder made of rubber was stretched horizontally across the