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Observed mode shape effects on the vortex-induced vibration of bending dominated flexible cylinders simply supported at both ends

Ersegun D. Gedikli [a,b,*], David Chelidze [c], Jason M. Dahl [a]

[a] *Ocean Engineering, University of Rhode Island, Narragansett, RI, 02882, USA*
[b] *Sustainable Arctic Marine and Coastal Technology (SAMCoT), Centre for Research-based Innovation (CRI), Norwegian University of Science and Technology (NTNU), Trondheim, Norway*
[c] *Mechanical, Industrial and Systems Engineering, University of Rhode Island, Kingston, RI, 02881, USA*

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The effect of varying the structural mode excitation on bending-dominated flexible cylinders undergoing vortex-induced vibrations was investigated. The response of the bending-dominated cylinders was compared with the response of a tension-dominated cylinder using multivariate analysis techniques. Experiments were conducted in a recirculating flow channel with a uniform free stream with Reynolds numbers between 650 and 5500. Three bending-dominated cylinders were tested with varying stiffness in the cross-flow and in-line directions of the cylinder in order to produce varying structural mode shapes associated with a fixed 2:1 (in-line:cross-flow) natural frequency ratio. A fourth cylinder with natural frequency characteristics determined through applied axial tension was also tested for comparison. The spanwise in-line and cross-flow responses of the flexible cylinders were measured through motion tracking with high-speed cameras. Global smooth-orthogonal decomposition was applied to the spatio-temporal response for empirical mode identification. The experimental observations show that for excitation of low mode numbers, the cylinder is unlikely to oscillate with an even mode shape in the in-line direction due to symmetric drag loading, even when the system is tuned to have an even mode at the expected frequency of vortex shedding. In addition, no mode shape changes were observed in the in-line direction unless a mode change occurs in the cross-flow direction, implying that the in-line response is a forced response dependent on the cross-flow response. The results confirm observations from previous field and laboratory experiments, while demonstrating how structural mode shape can affect vortex-induced vibrations.

1. Introduction

The vortex-induced vibration (VIV) of long, flexible structures is a complex problem due to the large number of variables that can contribute to the coupled response of the structure with the surrounding fluid (Sarpkaya, 2004). While a significant number of experimental studies have been devoted to characterizing the fundamental fluid–structure interaction

* Corresponding author at: Sustainable Arctic Marine and Coastal Technology (SAMCoT), Centre for Research-based Innovation (CRI), Norwegian University of Science and Technology (NTNU), Trondheim, Norway.
E-mail address: deniz.gedikli@ntnu.no (E.D. Gedikli).
URL: https://www.ntnu.edu/employees/deniz.gedikli (E.D. Gedikli).

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for an elastically mounted rigid circular cylinder undergoing vortex-induced vibrations (Bearman, 1984; Sarpkaya, 2004; Williamson and Govardhan, 2004; Bearman, 2011), the spanwise effects of flexible structures have been more difficult to quantify due to the complexity of additional variables associated with flexible, continuous systems that are capable of multi-modal responses.

In the single degree of freedom spring–mass–dashpot model for vortex-induced vibrations, the forcing function resulting from vortex shedding may be represented as a phase shifted harmonic function to the first order approximation (Sarpkaya, 2004). Assuming a sinusoidal response to the system, one can show that the amplitude and frequency of a cylinder undergoing vortex-induced vibrations in purely cross-flow excitation are functions of the motion of the cylinder and the resulting forces acting on the cylinder in phase with the acceleration and velocity of the body. The force in phase with acceleration alters the effective mass of the system, while the fluid force in phase with velocity alters the effective damping of the system. Since these fluid force terms are functions of the motion of the body, the frequency at which the body oscillates may constantly change in time, however this frequency is often fairly constant when observed in laboratory experiments. Using integral quantities of the forces in phase with velocity and acceleration, one can consider the system to have an effective natural frequency that is dependent on the fluid force in phase with acceleration.

In contrast to a single degree of freedom system, the natural frequencies of a continuous system are not only related to the stiffness and mass of the physical structure, but also are dependent on the particular spanwise shape of the oscillating structure. For example, an infinite string contains an infinite number of natural frequencies with each frequency corresponding to a particular spanwise shape. In VIV, the relative motion of vortices shed from the structure in relation to the motion of the body determines the phasing and magnitude of forces exerted on the body, hence for a continuous structure, the particular shape of the structure oscillation must have an effect on the resulting forces exerted on the structure. If we model a continuous system undergoing VIV similar to the 1-DOF system undergoing VIV, this would imply that the mode shapes corresponding to particular natural frequencies of the structure must be excited when that natural frequency is excited (or slightly modified by the added mass). The problem with this assumption is that since the fluid forces are dependent on the body oscillation and vice versa, there is no guarantee that the resulting fluid forces will drive a motion that is consistent with the analytic structural mode shape in a vacuum, particularly since the distribution of forcing must also be considered.

The complexity of the flow-induced vibration of flexible cylinders is evident in the variety in the types of responses that are observed for these types of structures. For instance, the flow-induced vibration of flexible structures may undergo complex three-dimensional vibrations, experiencing traveling waves (Marcollo et al., 2011) and chaotic motions (Modarres-Sadeghi et al., 2011). Sarpkaya (2010) discusses such complexities and effects of additional VIV parameters on the dynamic response. A variety of studies on marine risers (Lie and Kaasen, 2006; Chaplin et al., 2005; Trim et al., 2005; Vandiver et al., 2005) have shown that long, flexible structures exhibit similar forcing from vortex shedding as that observed for rigid cylinders, where vortex shedding leads to an oscillating drag force with a dominant frequency that is twice the oscillating lift force frequency. The laboratory experiments conducted by Passano et al. (2010), Huera-Huarte et al. (2014) and field experiments conducted by Vandiver et al. (2005) and Vandiver and Jong (1987) showed that for long flexible structures subjected to vortex-induced vibrations, it is possible to excite different modes in in-line and cross-flow directions separately, as observed from the frequency of the response and reconstructions of the spatial shape of the structure. In particular, Huera-Huarte et al. (2014) examined very low mass ratios ~ 1, where the response frequency can vary significantly due to forcing in phase with the acceleration of the body.

Previously, Fujarra et al. (2001) investigated the behavior of a flexible cantilever in VIV where flexible cantilever had 4:1 (in-line to cross-flow) frequency ratio and they showed that cross-flow stable response branch is caused by the in-line oscillations. Later, in an effort to model the effects of different modal excitations in flexible cylinders, Dahl et al. (2006) investigated the effect of differing natural frequency ratios (in-line to cross-flow) on an elastically mounted rigid cylinder. The cylinder was allowed to oscillate both in cross-flow and in-line directions while the natural frequency in each direction was tuned with different values to model a long structure excited with different structural modes in each direction. These experiments demonstrated response behaviors that consisted of preferred figure-eight type motions where the cylinder moves upstream at the top and bottom of its orbital motion, which can contribute to large third harmonic forcing of the structure in the lift direction (Dahl et al., 2007). Similar studies by Srinil et al. (2013) and Kang and Jia (2013) have demonstrated similar behaviors and expanded understanding of frequency ratio effects on a rigid cylinder response for frequency ratios less than one, where tear drop shape motions may be observed with multifrequency excitation of the structure in the in-line direction. Dahl et al. (2010) observed similar behaviors for rigid cylinders at supercritical Reynolds numbers. While these previous studies demonstrate the effect on the response of a rigid cylinder of varying the ratio between in-line and cross-flow natural frequencies, they do not consider effects of the spanwise mode shape on the response of the system, which is only realized in the response of a spanwise flexible structure.

This paper attempts to systematically test the effects of vortex-induced vibrations on the expected modal response of a flexible body by tuning several beams to have specific frequency properties for specific structural mode shapes. The purpose of these experiments is to illustrate differences in the response of a flexible structure from an elastically-mounted rigid structure due to the spanwise excitation of the flexible structure. Comparisons are made between a bending-dominated structure and tension dominated structure, with the modal response analyzed empirically through multivariate analysis. In the experiments, four flexible cylinders were designed and tested to understand the dynamic relationship between the cylinder's structural characteristics and the modal response. Assuming that one can control the modal response of a flexible