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Empirical Mode Analysis Identifying Hysteresis in Vortex-Induced Vibrations of a Bending-Dominated Flexible Cylinder

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In this paper, we experimentally investigate flexible cylinder multimodal responses and their corresponding frequency variations in vortex-induced vibrations. In the experiments, we test the response of a bending-dominated flexible cylinder under uniform flow conditions between the Reynolds numbers of 1600 and 4700 and examine the response for potential hysteretic effects. We study the nonlinear modal interactions by means of analyzing the spatial response using a multivariate analysis technique called generalized smooth orthogonal decomposition (GSOD). Results of this study show that 1:1 (in-line to cross-flow) frequency ratios appear in one branch of a hysteresis region and 2:1 frequency ratios appear along a different branch and outside of the hysteresis regime. In addition, GSOD-based modal frequency response curves identify a subcritical Hopf bifurcation in the first two modal oscillations.

INTRODUCTION

Technology, law, and the world's appetite for more energy have pushed oil and gas exploration farther from the shores. This need—moving into deeper waters—has brought extra challenges with it. For example, offshore structures inherently have become more prone to environmental loads that may easily lead to nonlinear responses. Understanding the nonlinear behavior of such structures is therefore critically important to the design and operation of these structures.

Vortex-induced vibration (VIV) is an inherent problem seen in offshore structures where coupled fluid–structure interaction may lead to large structural motions that can have a significant effect on structural fatigue and offshore operations. Much previous research has focused on understanding the response of a flexibly mounted rigid cylinder that is allowed to move only in the cross-flow (CF) direction (also known as one-degree-of-freedom (1-DOF) response) as a canonical representation of this problem, and later work has concentrated on understanding combined in-line (IL) and CF responses (also known as two-degrees-of-freedom (2-DOF) response), which is analogous to the response of long, flexible structures. The previous reviews by Bearman (1984), Sarpkaya (2004), and Williamson and Govardhan (2004) give insights into 1-DOF cylinder dynamics, and work by Jauvtis and Williamson (2004) and Dahl et al. (2006) illustrates how a rigid cylinder behaves in a 2-DOF VIV system.

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Dahl et al. (2006) investigated the effect of different IL:CF frequency ratio combinations on the dynamics of the body. They showed that, when this frequency ratio approaches 2, the cylinder oscillates with a figure-eight type of response and inherently oscillates, with the cylinder moving upstream at the top and bottom of the figure eight when undergoing a free vibration (Dahl et al., 2007). Although these studies provide insights into 2-DOF rigid cylinder experiments, it is not clear if a flexible structure undergoing multimodal excitations could lead to similar results along the length of the body.

Since real offshore structures behave similarly to long, flexible cylinders with the same mass, damping, and mechanical characteristics in both IL and CF, they can undergo complex multimodal type motions. Such responses have been observed both in the field (Vandiver and Jong, 1987; Vandiver et al., 2005, 2009; Lie and Kaasen, 2006; Marcollo et al., 2011) and in controlled laboratory experiments (Trim et al., 2005; Huera-Huarte and Bearman, 2009; Passano et al., 2010; Huera-Huarte et al., 2014; Gedikli and Dahl, 2014; Gedikli et al., 2017; Seyed-Aghazadeh et al., 2019). Among those complex responses, Gedikli and Dahl (2017) and Gedikli et al. (2017) identified a hysteresis region in VIV for a tensioned flexible cylinder. They observed mode hysteresis in addition to amplitude response hysteresis, where the cylinder sustained its mode shape (second mode) for several reduced velocities as the flow speed was decreased, whereas it was excited with a first mode shape at the same reduced velocities for increasing flow speeds. They also observed a 1:1 (IL:CF) frequency ratio response in the hysteresis region that resulted in the cylinder oscillating with an asymmetric "pedaling" type of motion.

Subsequently, Gedikli et al. (2018) studied the response of three bending-dominated flexible cylinders for increased flow speeds where the mass ratio of the cylinders was approximately 1 and the IL:CF frequency ratio was constant at 2. They showed that the cylinder that was designed to oscillate with the first mode in CF