Physics-based Data-informed Prediction of Vertical, Catenary, and Stepped Riser Vortex-induced Vibrations

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Semi-empirical models serve as current state-of-the-art prediction technologies for vortex-induced vibrations (VIV). Accurate prediction of the flexible body’s structural response relies heavily on the accuracy of the acquired hydrodynamic coefficient database. The construction of systematic databases from rigid cylinder forced vibration experiments not only requires an extensive amount of time and resources but also is a virtually impossible task, given the wide multidimensional space the databases span. In this work, we improve the flexible cylinder VIV prediction by machine learning the hydrodynamic databases using measurements along the structure; such a methodology has been proven effective for vertical flexible risers in uniform and sheared flows using vibration amplitude and frequency data. This work demonstrates the effectiveness of the framework on flexible vertical risers in a stepped current and flexible catenary risers (with the catenary plane parallel or at an oblique angle with respect to the incoming flow). Moreover, the framework is applied to stepped (two-diameter) risers undergoing dual-frequency vibrations. Last, but not least, the framework is extended to using only sparse strain sensing. The predicted VIV responses using the learned hydrodynamic coefficient databases are compared with experimental observations.

INTRODUCTION

Observations of vortex-induced vibrations (VIV) date back thousands of years, first noticed by the ancient Greeks as "Aeolian tones"—sounds created by vortex-induced pressure fluctuations created by the wind passing around slender obstacles with a bluff cross section. Later, such vortices were sketched by Leonardo da Vinci. In recent years, following the development of bluff-shaped underwater equipment such as risers and cables, extensive studies have been conducted (Williamson et al., 2004, 2008; Bearman, 2011; Wu et al., 2012; Wang et al., 2020) on the subject, mainly to suppress VIV because of their destructive capabilities (Bernitsas et al., 2008; Baek and Karniadakis, 2009; Park et al., 2016). VIV affect bluff bodies in the presence of currents as a result of periodic shedding vortices developed in the wake aft bodies. The vortices lead to an alternating pressure variation that synchronizes with body motion, creating consistent vibrations that can cause extensive fatigue damage; however, they may also be exploited to harness clean and sustainable marine renewable energy (Bernitsas et al., 2019; N Li et al., 2022). Given the bluff nature of many modern offshore engineering equipment, such as cables, mooring lines, and marine risers (Fan and Triantafyllou, 2017; Wu et al., 2017; Fan, Wu, et al., 2019), a thorough understanding of the underlying physics of VIV is essential in controlling their effects, be they fatigue damage to offshore equipment or energy harnessed from flows (Bernitsas et al., 2008; Ma, Resvans, and Vandiver, 2022).

VIV occur across a wide range of oscillating frequencies (Govardhan et al., 2002) known as the "lock-in" range, in which synchronization between vortex shedding and body motion takes place (Williamson and Govardhan, 2004; Wang et al., 2020). During lock-in, vibrations are typically self-limited to about one diameter. In addition, the vortex shedding frequency can differ from the Strouhal frequency of a fixed cylinder because the relative motion between the vibrating cylinder and the shed vortices significantly alters the effective fluid added mass (Wang, Fan, and Triantafyllou, 2021), resulting in a variable natural frequency as a function of stream velocity (Williamson, 1996).

Both experimental (Hover et al., 2001; Raghavan and Bernitsas, 2011; Xu et al., 2013; Resvans et al., 2015; Resvans and Vandiver, 2017, 2022) and numerical (Evangelinos et al., 2000; Wu et al., 2014, 2020; Kharazmi, Fan, et al., 2021; Meng et al., 2021; Wang, Fan, et al., 2021; Ma, 2022; Mentzelopoulos et al., 2022) studies demonstrate that significant variations of the fluid forces occur on an oscillating rigid cylinder as the incoming flow stream velocity and the cylinder motions change. Moreover, literature suggests that these variations are caused by changes in the vortex shedding pattern (Gopalkrishnan, 1993; Sarpkaya, 1995; Fan, Wang, et al., 2019). However, not only do the fluid forces depend heavily on the vortex shedding pattern; so do the hydrodynamic coefficients. Specifically, the added mass and lift coefficients may vary significantly as the vortex shedding pattern changes with both coefficients assuming positive and negative values.

Rigid cylinder-forced vibration experiments were the first attempts to estimate the hydrodynamic coefficients of oscillating cylinders undergoing VIV. The obtained coefficients were later...