International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 18, No. 2, June 2008, pp. 99–105

Vortex-induced Vibration Super-Upper Response Branch Boundaries

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The purpose of this study was to experimentally investigate the vortex-induced vibration response of cylindrical structures with low mass ratio. Much of our understanding of vortex-induced vibration has been established through single degree of freedom and/or higher mass ratio experiments. The empirical relationships based on these data capture only the characteristics of the upper vortex-induced vibration response branch. The corresponding super-upper response branch observed in 2 degree of freedom systems at low mass ratio is shown to present significantly larger amplitudes and more regular oscillations. Understanding the boundaries of this super-upper response has implications for offshore structure design. This study revealed that damping in addition to the mass ratio appears to be one of the governing parameters in establishing super-upper response branch vibrations. Based on the experimental evidence available, super-upper response boundaries are suggested, and the potential bearing of these on empirical design formulations not considering the super-upper response are discussed.

INTRODUCTION

Fluid flow past a circular cylindrical object generates vorticity due to the shear present in the boundary layer. This vorticity in the flow field coalesces into regions of concentrated vorticity, known as vortices, on either side of the cylinder. Flow above a threshold Reynolds number allows perturbations in the flow upstream to cause one of the vortices to grow larger. This vortex, with higher flow velocities and accompanying lower pressures, draws the smaller vortex from the opposing side across the wake centreline. The opposite vorticity from this smaller vortex severs the vorticity supply of the larger vortex, allowing it to convect downstream (Sumer and Fredsoe, 2007). This process is repeated in the reverse sense, leading to alternating vortex shedding from the cylinder.

When the cylinder is elastically restrained and natural frequencies are introduced, a fluid-elastic instability known as vortex-induced vibration (VIV) results. The time-varying nonuniform pressure distribution around the cylinder resulting from the vortex shedding causes structural vibrations both inline and transverse to the flow. Near the natural frequency of the structure, the vortex-shedding frequency synchronises with the natural frequency and the vibration frequency. One of the primary mechanisms responsible for this synchronisation is the change in hydrodynamic mass, as demonstrated in the experiments of Vikestad (1998). The range of reduced velocity over which this synchronisation occurs is known as the lock-in range. Mostly, the ensuing vibrations are undesirable, resulting in increased fatigue loading and component design complexity to accommodate these motions. The transverse vibrations also result in higher dynamic relative to static drag coefficients.

With decreasing mass ratio, an increase in the amplitude response is generally evident (Sumer and Fredsoe, 2007). Also, the smaller the mass ratio, the larger the relative influence of the hydrodynamic mass on the vibration response of the structure. Since the hydrodynamic mass variation is largely responsible for synchronisation of the shedding and vibration frequencies, typically much wider lock-in regions are experienced at low mass ratio (Vikestad, 1998). The limit of this trend is found at the critical mass ratio of around 0.54 (Govardhan and Williamson, 2004), below which there exists no de-coherence region and VIV occurs at all velocities above the initial lock-in.

Various definitions for the mass ratio are widely employed. In this work, the mass ratio is defined by the relationship:

$$m^* = \frac{m}{m_f}. \tag{1}$$

The denominator in Eq. 1 is the displaced fluid mass:

$$m_f = \rho L \pi \left(\frac{D^2}{4}\right). \tag{2}$$

The structural mass, m, includes enclosed fluid, but excludes the hydrodynamic mass. The term L is the submerged length of the cylinder. The mass ratio parameter is then the ratio of the oscillating structural mass to the displaced fluid mass. In this study, the term low mass ratio refers to mass ratios of the order of one. This mass ratio magnitude is common for marine structures.

The mass ratio parameter influences both the amplitude and frequency response of the cylinder. With higher mass ratios (e.g. a cylinder vibrating in air, with a mass ratio O(100)), changes in added mass are relatively insignificant due to the low density of the fluid. The natural frequency then remains relatively unchanged throughout the lock-in range. When the fluid medium under consideration is much denser (e.g. a cylinder vibrating in water), distinct changes in the natural frequency are observed. The increasing natural frequency observed with increasing reduced velocity is directly attributable to the decreasing added mass throughout the lock-in range (Stappenbelt, 2006; Vikestad, 1998).

The shedding of vortices from cylindrical bluff objects and the resulting vibrations are well documented for single degree of freedom cases; see for example the review by Griffin (1985). Investigations tended to focus on the larger transverse vibrations, and any interaction with the inline oscillations, which occur at twice the transverse vibration frequency, was ignored. Experimental investigations conducted by Williamson and Jauvtis (2004) revealed

Received January 17, 2008; revised manuscript received by the editors March 17, 2008. The original version was submitted directly to the Journal.
KEY WORDS: Vortex-induced vibration, low mass ratio, super-upper response branch, upper response branch.