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The Critical Point in Vortex-Induced Vibration of Pivoted Cylinder

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It has been well established that a critical mass ratio for cylinders undergoing vortex-induced vibration (VIV) in a translational system exists. Below this critical point, there exists no de-coherence region and VIV occurs at all velocities above the initial lock-in. While it has been surmised that a corresponding mass moment of inertia ratio must exist for a pivoted cylinder arrangement, there are limited studies published investigating this premise. The aim of this present study then was to examine the VIV critical point for cylinders in a rotational system. The approach adopted involved measuring the VIV amplitude response of a positively buoyant pivoted cylinder at very high reduced velocity. The results of 2 experiments regarding the critical point of a cylinder in a rotational system are presented in this paper. The key finding of this study is the presence of a critical point with a value similar to that of the critical mass ratio in translational systems. This critical point does not however appear to be governed by the mass moment of inertia ratio, but rather by the force moment ratio.

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 (Stappenbelt and O'Neill, 2007). Also, the smaller the mass ratio, the larger the relative influence of the hydrodynamic mass on the vibration response of the structure.

Various definitions for the mass ratio are widely employed. In this work, the mass ratio is defined as the ratio of the oscillating structural mass, m, to the displaced fluid mass, m_d, as:

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

The structural mass, m, includes any enclosed fluid, but excludes the hydrodynamic mass. Note that the mass ratio is equivalent to the magnitude of the ratio of the weight, W, and buoyancy, B, forces since:

$$m^* = \frac{W}{B} = \frac{mg}{m_d g}. \tag{2}$$

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, 2010; Vikestad, 1998). An overview of the characteristics of low mass damping VIV is given in the review paper by Gabbai and Benaroya (2005).

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; Stappenbelt and O'Neill, 2007). 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. In fact, at mass ratios below the critical point, the lower response branch can never be reached.

The initial discovery of the critical mass ratio resulted from the examination of elastically constrained cylinder experimental data (Govardhan and Williamson, 2000). Subsequent transverse amplitude tests on translational cylindrical systems where restoring forces have been removed (i.e. with the reduced velocity, $U_r \to \infty$) have been conducted with results as illustrated in Fig. 1

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