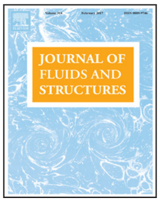
Journal of Fluids and Structures 83 (2018) 218–237

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs



Two degrees of freedom vortex-induced vibration responses with zero mass and damping at low Reynolds number

Kintak Raymond Yu, Alexander Hay, Dominique Pelletier, Stéphane Étienne*

Département de Génie Mécanique, École Polytechnique de Montréal, Montréal, Québec, H3C3A7, Canada

ARTICLE INFO

Article history:
Received 10 February 2018
Received in revised form 5 June 2018
Accepted 30 August 2018
Available online xxxx

ABSTRACT

This work aims to characterize the two degrees of freedom (transverse and streamwise) responses of vortex-induced vibrations (VIV) of a cylinder at low Reynolds number for the limiting case of zero mass ratio and zero damping. The main focus is on determining the maximum peak amplitude value as a function of the Reynolds number. We believe it occurs for zero mass ratio and damping. We numerically investigate the responses in the following parameter space: Reynolds number ($75 \leqslant Re \leqslant 175$), reduced velocity ($5.0 \leqslant U_r \leqslant 11.0$) and mass ratio ($m^* = 0$). For comparison, we also investigate one and two degrees of freedom VIV for $m^* = 1$. The effect of Re and m^* onto the oscillation responses are examined. Overall maximum transverse peak amplitude (A_Y) of $0.9D$ is obtained for the two dof VIV with $m^* = 0$ at $Re = 175$, a significant 50% increase from $0.6D$ for single dof VIV. The peak A_Y occurs at different U_r with respect to the Reynolds number. Furthermore, the maximum A_Y continuously increases with Re in contrast with the plateau observed for single dof VIV. This is most evident for the XY oscillation for $m^* = 0$. Critical mass ratios of 0.106 for XY oscillation and 0.117 for transverse only oscillation have been obtained at $Re = 100$.

1. Introduction

Vortex-induced vibration (VIV) is an important flow–structure interaction phenomenon in offshore engineering. When flow passes over a bluff body (e.g. a cylinder), the flow field is disturbed and vortices can form behind the body. The shedded vortices can impose forces back onto the bluff body and become a source of excitation forces for the structures. The motion of the structure will affect the patterns of vortices generated, which in turn alter the characteristics of the excitation forces. However, under the right conditions, the induced vibrations can become so significant that they pose concern in terms of engineering design safety.

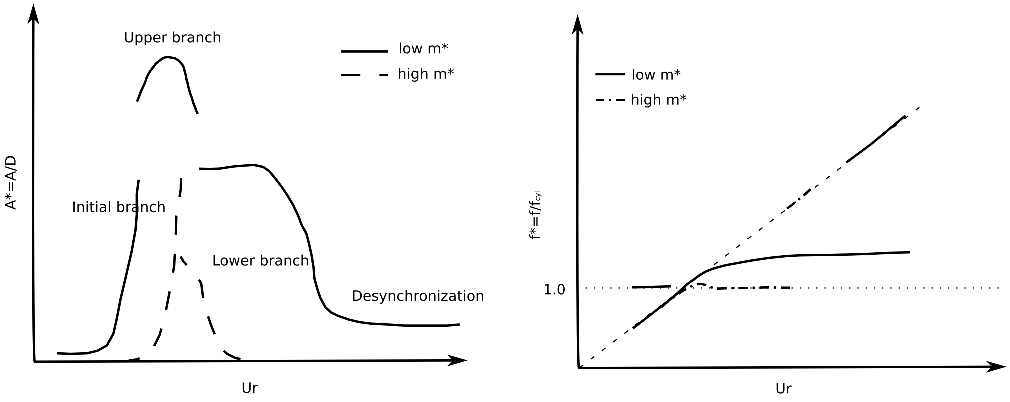
There have been extensive studies in vortex-induced vibrations in the past four decades (Sarpkaya, 2010). A set of important non-dimensional parameters, e.g. amplitude ratio A^*, Reynolds number Re, reduced velocity U_r, mass ratio m^*, etc., are identified (Sarpkaya, 2010). Generally, investigations attempt to examine the characteristics of the vibration responses (e.g. maximum amplitude, lift and drag forces, etc.) and flow patterns, and their changes when the non-dimensional parameters are varied. It is noted that the importance of the non-dimensional parameters change throughout the parameter space (Sarpkaya, 2010).

Many different aspects of the vortex-induced vibration have been investigated. Most studies focus on the fundamental behaviour of the transverse vibrations (one degree of freedom) of an isolated cylinder in a uniform flow (Williamson and

---

* Corresponding author.
E-mail address: stephane.etienne@polymtl.ca (S. Étienne).

https://doi.org/10.1016/j.jfluidstructs.2018.08.017
0889-9746/



(a) Max amplitude. (b) Frequency.

Fig. 1. Illustrations of typical Vortex-Induced Vibrations amplitudes and frequencies.

Govardhan, 2004; Sarpkaya, 2004). One key characteristic is the "lock-in" effect, for which, there is a range of reduced velocity such that the frequencies of the vortex-shedding and vibrations are synchronized, and vibrations of large amplitudes are observed (Sarpkaya, 2004). Another key characteristic is that when the reduced velocity is varied in the "lock-in" range, the response is not smooth but exhibits "branches" (Sarpkaya, 2004). Hysteresis is observed at the transitions between branches (Sarpkaya, 2004). The shapes and appearances of the branches change with mass-damping factor $m^*\zeta$. The damping ratio is often very small. Hence, we can practically consider that the influence is principally due to the mass ratio m^*. For a large value of m^*, one can observe two branches: the initial and lower branches. Decreasing m^* to small values, the upper branch now appears between the initial and the lower branches. A smaller m^* also leads to a wider interval of lock-in reduced velocities and a larger maximum amplitude value. The typical characteristic of the maximum transverse amplitude with respect to the mass ratio is illustrated in Fig. 1(a). If we further decrease the mass ratio below a certain "critical" value, the lower branch eventually disappears and merges with the upper branch. Govardhan and Williamson (2002) showed experimentally that a vibration amplitude of 0.8D can still be attained even at "infinite" reduced velocity. In other words, when the mass ratio is smaller than the critical value, there is no desynchronization. Note that for the hysteresis responses, Prasanth et al. (2011) demonstrated numerically that the blockage and the mass ratios are two important factors for the hysteresis behaviour between the initial and the lower branches in the laminar shedding regime. In particular, for certain combination of the two factors, the hysteresis between the initial and the lower branches may be completely suppressed.

Inside the "lock-in" range, the frequency of oscillation varies rather smoothly. However, a jump in frequency can be observed when we shift from one branch to another (Khalak and Williamson, 1999). The typical frequency response is illustrated in Fig. 1(b). If the mass ratio is large, the frequency of oscillation will be close to the natural frequency of the cylinder. With low mass ratio, the frequency of oscillation is generally larger than the natural frequency of the cylinder but smaller than the vortex-shedding frequency of a fixed cylinder (Williamson and Govardhan, 2004). However, with very low mass ratio, the oscillation frequency can even be above the vortex-shedding frequency in some reduced velocity ranges (Govardhan and Williamson, 2002; Khalak and Williamson, 1999).

The corresponding flow field is generally described in terms of the observed vortex shedding pattern. The changes of vortex patterns are associated with a change of branches. The major vortex patterns identified include 2P, 2S, 2C, 2T (Williamson and Govardhan, 2004).

For further details regarding the phenomena of vortex-induced vibrations, we refer the readers to the excellent reviews by Williamson and Govardhan (2004) and by Sarpkaya (2004).

More recently, the importance of the streamwise vibration and its interactions with the transverse vibrations have been recognized (Aglen and Larsen, 2011). Streamwise vibrations generally have smaller amplitude than transverse vibrations, and their lock-in range usually occurs at a frequency twice that of the transverse vibration. However, streamwise vibration can occur at very low ambient velocity. Thus, streamwise vibration can occur more often than the transverse vibration and hence, can have major impacts on equipment fatigue (Aglen and Larsen, 2011). Jauvtis and Williamson (2004) investigated the fundamental two degrees of freedom responses for vortex-induced vibrations for moderate values of the Reynolds number in the range of 1000 to 15 000. For mass ratios above 5 or 6, the envelope of the transverse vibration amplitude for such cylinder resembles that of a cylinder that vibrates transversely only. When the mass ratio is reduced below 5, the maximum transverse amplitude can be significantly larger than those (the upper branch) found in vortex-induced vibration response of transverse only oscillations. This latest branch of response was named the super-upper branch. The vortex pattern (2T) is identified when the system is on the super-upper branch (Jauvtis and Williamson, 2004).

Williamson and Govardhan (2006) observed that the Reynolds number can affect the maximum amplitude. At Reynolds number higher than 500, a larger *Re* results in a larger maximum amplitude for the initial and upper branches of single dof