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# Numerical simulation of vortex-induced vibration of a circular cylinder at low mass-damping using RANS code

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## Abstract

Fundamental research on vortex-induced vibration (VIV) of a circular cylinder is still needed to build more rational VIV analysis tools for slender marine structures. Numerical results are presented for the response of an elastically mounted rigid cylinder at low mass damping constrained to oscillate transversely to a free stream. A two-dimensional Reynolds-averaged Navier–Stokes (RANS) code equipped with the SST $k-\omega$ turbulence model is applied for the numerical calculations. The numerical results are compared in detail with recent experimental and computational work. The Reynolds-averaging procedure erases the random disturbances in the vortex shedding process, so that the comparison between experimental data and the numerical results obtained by RANS codes may reveal some random characteristics of the VIV response. How random disturbance affects the observation in the experiments is discussed in this paper and the issues influencing the appearance of the upper branch in experiments are especially investigated. The absence of the upper branch in RANS simulations is explained in depth on account of discrepancies, which exist between experiments and RANS simulations. In addition, the formation of the 2P vortex shedding mode and its transition through the lock-in region are well reproduced in this investigation.


*Keywords:* Vortex-induced vibration (VIV); Circular cylinder; RANS; Vortex shedding mode

## 1. Introduction

Vortex-induced vibration (VIV) arises in many engineering areas, especially in coastal and marine applications such as marine cables, subsea pipelines and flexible risers. The increased interest in worldwide deep-water petroleum production draws renewed attention to research activities on VIV of slender marine risers; see recent overviews on VIV by Sarpkaya (2004) and Williamson and Govardhan (2004).

Analyses of VIVs of marine risers are performed either by empirical prediction tools which depend on experimental data, or by computational fluid dynamics (CFD) techniques in which the viscous Navier–Stokes equations are numerically solved to obtain the hydrodynamic forces directly. In empirical models, slender risers are usually divided into elements, so that one can use the data from measurements on rigid cylinders undergoing vortex-induced or forced vibrations. Correspondingly, CFD methods often cooperate with the strategy known as the "strip theory approach" in

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which computations by 2-D CFD codes are carried out for a number of strips along the riser and loads are then applied to the structure for the dynamic analysis. Currently, large discrepancies exist between the results obtained by different prediction schemes due to different assumptions and experimental data-bases employed in empirical methods; on the other hand, due to uncertainties in CFD techniques over the modeling of the vortex-shedding interacting with dynamic response of the structure [see Larsen and Halse (1997) and Chaplin et al. (2005)]. Therefore, more fundamental research work on rigid cylinder sections, both experimental and computational, is still necessary in order to deepen our understanding on VIV of slender marine structures.

Recently, there have been many publications on VIV of an elastically mounted cylinder at low mass damping constrained to move transversely in a uniform incoming flow. Much progress has been made by Prof. Williamson's group with a series of physical experiments (Khalak and Williamson, 1996; Khalak and Williamson, 1999; Govardhan and Williamson, 2000). The main results can be summarized as follows. For a cylinder (of diameter $D$) with low mass ratio $m^*$ (structure mass/displaced fluid mass) and damping ratio $\zeta$, as the flow velocity $U$ is varied ($U$ is normalized by different researchers with the natural frequency of the structure in vacuum $U_r = U/f_nD$ or in water $U^* = U/f_{wtr}D$), three distinct response branches are observed with different response amplitude $A$; namely the *initial branch*, the *upper branch* and the *lower branch*. The upper branch is absent in the classical high mass-damping cases (Feng, 1968). The transition between the initial and upper branches is found to be hysteretic, while the transition from the upper to lower branch is assumed to be involved in an intermittent switching in response with a jump in phase $\phi$ (between the lift force and cylinder response) by about 180°. Amplitude modulation is observed in the initial branch, indicating a combination of two frequencies. In the upper and lower branches, the vortex-shedding frequency is locked on to the response frequency of the cylinder. The extent of such a synchronization region (measured by the range of $U^*$) is determined primarily by $m^*$. Moreover, it has been found in experimental work that there is a correspondence of the 2S mode (two single vortices shed per cycle) with the initial branch, and the 2P mode (two pair vortices shed per cycle) with the lower branch. The 2P mode is also observed in the upper branch, but the second vortex of each pair is much weaker than the first one.

However, the departure of the upper branch from the lower branch and the random characteristics of the response are not well understood. Moreover, few numerical studies have reported the 2P mode (Blackburn et al., 2001; Lucor et al., 2005), much less on the vortex-shedding mode transition through the lock-in region. The debate remains on the existence of the 2P mode as a steady-state pattern. Al Jamal and Dalton (2005) reviewed recent numerical studies on VIV of a circular cylinder and investigated the irregular behavior of the phase angle. Apparently, all vortex-shedding-related problems appear irregular in the vortex shedding mode, fluid forces and body response. Such an irregular phenomenon complicates the physical problem and handicaps our observations.

The span-wise correlation of the wake and then that of the fluid force remain hot issues. It is known that the structural vibration produces a high degree of span-wise correlation, giving rise to nearly 2-D flow for an elastically mounted cylinder subjected to flow, so that 2-D numerical simulations are of more value under this condition than for fixed body problems. In the earlier studies, a longer correlation length was considered to be associated with larger response (Pantazopoulos, 1994). In fact, a high correlation does not necessarily correspond to large amplitude response. Hover et al. (2004) "surprisingly" found in physical experiments that the span-wise correlation undergoes a sharp reduction near the region with maximum amplitude where the phase angle $\phi$ is undergoing transition. These findings were confirmed by Lucor et al. (2005) with 3-D numerical simulations. In addition, Hover et al. (2004) concluded that high mass and damping reinforce correlation during such transition, whereas low values admit a correlation loss; their study may help our understanding on the response characteristics in the upper branch and the transition between the upper and lower branches. One may note that the region with poor correlation overlaps well with the upper branch. The upper boundary of this region might correspond to the beginning of the lower branch with the recovery of higher correlation.

The time-dependent series of the fluid forces and the structural response, associated with vortex shedding, should be treated as random processes. The span-wise correlation is an indicator to the degree of three-dimensionality of the wake and might relate to the statistical characteristics of the fluid forces and the cylinder displacement. A high level of correlation might restrain the randomness of the vortex shedding and bring on a periodic response, whereas poor correlation might result in the variation in response amplitudes. Experimental results show that the response in the upper branch is less periodic and is subjected to more random disturbance than that in the lower branch. Such distinctions are more remarkable with smaller $m^*$ and $\zeta$ (Khalak and Williamson, 1999; Govardhan and Williamson, 2000).

It is difficult to formulate the random characteristics of the fluid forces and the cylinder response. Therefore, the following linearized representation for the self-excited motion of a cylinder and the corresponding unsteady force still prevail in the relevant literature:

$$y = A \sin(\omega_{ex} t), \tag{1}$$