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Hydrodynamic force investigation of a rigid cylinder under the coupling CF and IL motion

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ABSTRACT

Extensive researches have been conducted to simulate the two-degree-of-freedom (2DOF) vortex induced vibration (VIV) of a cylinder during the past few decades. However, there are still very few publications in terms of the hydrodynamic force of a cylinder with 2DOF motion in cross-flow (CF) and in-line (IL) directions. This study employs the Reynolds-Average-Navier–Stokes (RANS) equations and shear stress transport (SST) k-ω turbulence model to investigate the hydrodynamic force characteristics. The numerical model is firstly validated based on the 2DOF VIV experiment of an elastically supported cylinder in the literature. The results indicate that the predicted displacement and hydrodynamic force are approximately harmonic, and are in reasonable agreement with the experimental data. By imposing harmonic motion on the cylinder in CF and IL directions with period ratio of 2, parametric analyses are carried out to simply broaden the understanding of the sensitivity of the hydrodynamic coefficients including force coefficient, excitation coefficient and added mass coefficient, to the motion-related parameters, such as the motion phase angle, non-dimensional amplitude and frequency. There would be a sudden change for the excitation coefficient and added mass coefficient at a certain motion phase angle approximately corresponding to the peak of the force coefficient. The varying trend of the hydrodynamic coefficient with non-dimensional amplitude is different from that obtained from one-degree-of-freedom (1DOF) forced vibration test in literatures, and is significantly related with the motion phase angle and non-dimensional frequency. The non-dimensional frequency seems to mainly affect the excitation coefficient, added mass coefficient and mean drag coefficient in the lock-in range.

Nomenclature

U_i	Instantaneous velocity of the conservative flow in i direction
p	Pressure
ρ	Fluid density
t	Time
x and y	Displacements in IL and CF directions
A_x and A_y	Response amplitudes in IL and CF directions
f_{ex}	Response frequency in CF direction

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T	Response period in CF direction
θ	Motion phase angle between CF and IL responses
F_x and F_y	Hydrodynamic force in the IL and CF directions
C_x and C_y	Hydrodynamic force coefficient in the IL and CF directions
C_D and $\widetilde{C}_x$	Mean drag coefficient and fluctuating force coefficient in IL direction
$C_{x,rms}$ and $C_{y,rms}$	Root mean square of C_x and C_y
U_∞	Freestream velocity
D and L	Cylinder diameter and length
$C_{e,x}$ and $C_{a,x}$	Excitation coefficient and added mass coefficient in IL direction
$C_{e,y}$ and $C_{a,y}$	Excitation coefficient and added mass coefficient in CF direction
f_r	Non-dimensional frequency
A_x^* and A_y^*	Non-dimensional amplitude
U_r	Reduced velocity
f_N	Natural frequency in still water
ω_0	Natural circular frequency in vacuum
m	Cylinder mass
ζ	Damping ratio

1. Introduction

Flow past a bluff body is often accompanied with vortex shedding leading to the vibration of the body, called vortex induced vibration (VIV). VIV is a common phenomenon for the slender structures in the offshore engineering, such as the risers, umbilicals and pipelines. When the vortex shedding frequency is close to the vibration frequency, the synchronization of the vortex shedding and structure vibration, i.e. lock-in, may occur, which would amplify the response amplitude, thus aggravating the fatigue damage and even result in fatigue failure. Therefore, lots of researches have been dedicated to the VIV investigation, as reviewed by Sarpkaya (1979), Bearman (1984), Sarpkaya (2004), Williamson and Govardhan (2004), and Wu et al. (2012).

The rigid cylinder mounted with springs is a common system employed to study the VIV characteristics, and is initially limited to the response transverse to flow, i.e. cross-flow (CF) VIV (Khalak and Williamson, 1996; 1999; Govardhan and Williamson, 2000). Jauvtis and Williamson (2004) firstly reported the VIV experiment of a cylinder with equally natural frequency in the CF and in-line (IL) directions, and demonstrated the coupling effect of the CF and IL VIV. Due to the coupling effect, the CF VIV amplitude can reach up to 1.5 times diameter of the cylinder with small mass ratio at the upper branch of response, which is renamed as super-upper branch (Jauvtis and Williamson, 2004). Meanwhile, the IL VIV amplitude can be amplified to 0.3 times diameters. Except for the 2S and 2P vortex shedding modes, a new mode, named 2T, can be observed at the super-upper branch, which may be the reason of large response amplitude since the hydrodynamic force is directly related with the vortex shedding. In the following years, some researchers have designed different experimental apparatus for the two-degree-of-freedom (2DOF) VIV (Flemming and Williamson 2005; Stappenbelt et al., 2007; Blevins and Coughran, 2009; Gonçalves et al., 2012), and further studied the sensitivity of the coupling effect to different parameters, such as mass-damping ratio and aspect ratio.

Hydrodynamic force associated with VIV has been paid much attention to in the past decades. The reason is that a comprehensive understanding of hydrodynamic force is the premise of the VIV prediction of slender structures in offshore engineering. Since the VIV of each segment of the slender structure can be considered as forced vibration, the hydrodynamic force can be investigated based on a rigid cylinder under forced vibration. Gopalkrishnan (1993) and Aronsen (2007) carried out 1DOF forced vibration test of a cylinder, and in detail reported the obtained hydrodynamic coefficients of CF and IL VIV, respectively. Blevins (1990) studied the drag amplification due to the CF VIV. The publication of these data greatly promoted the development of the VIV prediction model of slender structures. However, existing investigations for hydrodynamic force just focused on the 1DOF VIV, neglecting the coupling effect of CF and IL VIV. Wu et al. (2016) indicated that the motion phase angles between CF and IL VIV can significantly affect the hydrodynamic force. Therefore, it is necessary to have a better understanding on the hydrodynamic force under coupling CF and IL VIV.

Numerical simulation is an effective approach to predict the cylinder VIV, hydrodynamic force and vortices in the wake, thus it has been widely utilized with the development of numerical methods and computational resources in recent years. The vortex shedding around a cylinder is generally simulated by using Reynolds-Averaged-Navier-Stokes (RANS) equations combined with different turbulence models. Guilmineau and Queutey (2004) compared the numerically and experimentally obtained CF VIV response of a circular cylinder, and presented satisfying results although the upper branch was not well captured. This encouraged many researchers to follow the fundamental investigation of the cylinder's CF VIV using numerical method (Pan et al., 2007; Wanderley et al., 2008; Li et al., 2011; Stringer et al., 2014; Zhao et al., 2014). With the coupling response of CF and IL VIV attracting more and more attention, 2DOF simulation are often conducted for the cylinder VIV, and the super-upper branch and high harmonic component were well numerically captured (Lucor and Triantafyllou,