International Journal of Mechanical Sciences 148 (2018) 352–365

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Hydrodynamic characteristics of an inclined slender flexible cylinder subjected to vortex-induced vibration

Qinghua Han[a,b,c], Yexuan Ma[a,c], Wanhai Xu[a,b,*], Dixia Fan[d], Enhao Wang[a]

[a] *State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China*
[b] *Collaborative Innovation Centre for Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China*
[c] *School of Civil Engineering, Tianjin University, Tianjin 300072, China*
[d] *Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge MA02139, USA*

ARTICLE INFO

Keywords:
Inclined flexible cylinder
Vortex-induced vibration (VIV)
Lift coefficient
Drag coefficient
Added mass coefficient

ABSTRACT

The hydrodynamic coefficients (e.g., lift coefficients, drag coefficients and added mass coefficients) are key parameters for predicting the vortex-induced vibration (VIV) of flexible cylinders. It is an experimental challenge to directly measure the forces/coefficients along a flexible cylinder during model tests without disturbing the flow field. However, such hydrodynamic features can be successfully obtained via an inverse analysis of the displacement responses based on the structural dynamics. In this paper, the hydrodynamic coefficients were calculated using the towing tank experimental results of an inclined flexible cylinder undergoing VIV at five different inclination angles ($a = 0^\circ$, 15°, 30°, 45° and 60°, where a denotes the inclination angle defined as the angle between the cylinder axis and the plane orthogonal to the oncoming fluid flow). It is found that the influence of the inclination angle on the hydrodynamic coefficients is generally insignificant when the inclination angle is varied from 0° to 15°. In contrast, the hydrodynamic characteristics of the inclined cylinder with large inclination angles ($a = 45^\circ$ and 60°) are distinct from those of the vertical flexible cylinder ($a = 0^\circ$) and this difference becomes more evident as the inclination angle is increased. The RMS of the fluctuating force coefficients in the cross-flow (CF) and in-line (IL) directions, mean drag coefficients, axial mean lift and varying drag coefficients in the case of $a = 60^\circ$ are much larger than those in the normal case($a = 0^\circ$). Meanwhile, the axial mean IL added mass coefficients in the cases of $a = 45^\circ$ and 60° demonstrate higher values compared to those in the normal case at certain reduced velocities. It can be speculated that different wake behaviors are associated with the distinct hydrodynamic behaviors of the inclined flexible cylinder at different inclination angles. Within the same mode synchronized region, the axial distributions of the hydrodynamic coefficients in the cases of $a = 15^\circ$ and 30° resemble that of the vertical flexible cylinder, while the spanwise variations of the hydrodynamic coefficients for $a = 45^\circ$ and 60° agree well with each other.

1. Introduction

Alternating vortex shedding behind a bluff body could lead to vortex-induced vibration (VIV) if the structure is free to oscillate in cross-flow (CF) direction only or in both CF and in-line (IL) directions. VIV is a ubiquitous natural phenomenon, especially for slender cylindrical objects. It may result in severe fatigue damage if not dealt with properly. Hence, it has become one of the most challenging issues in many fields of engineering. A large number of research works have been devoted to this complex fluid-structure interaction (FSI) problem from many perspectives, including wake flow behaviors, FSI mechanisms, structural responses and hydrodynamic features [1–5].

The fluctuating forces in the CF and IL directions, which give rise to VIV, are caused by the alternatively shed vortices around the cylinder. If the cylinder is fixed in the flow, the fluctuating forces do not contain the added mass forces and are named as lift and drag in the CF and IL directions, respectively. The drag can be further divided into the varying drag and the mean drag [6]. In order to enhance our understanding of VIV, the hydrodynamic characteristics of the flow around a fixed cylinder have been studied extensively over the past several decades [7]. If the cylinder is allowed to vibrate in the flow, the CF fluctuating forces can be decomposed into one part in phase with the velocity, and the other in phase with the acceleration, namely the lift and CF added mass force [8]. Similarly, the IL fluctuating forces consist of the varying drag and IL added mass force [9].

There have been many publications on the hydrodynamics of an elastically-mounted rigid cylinder subjected to forced or free vibrations

---

[*] Corresponding author at: State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China.
E-mail address: xuwanhai@tju.edu.cn (W. Xu).

https://doi.org/10.1016/j.ijmecsci.2018.09.010
Received 17 March 2018; Received in revised form 5 September 2018; Accepted 6 September 2018

in fluid flow [8–13]. The mean drag coefficients increase with increasing CF displacements and reach the highest point as "lock-in" occurs. Moreover, the CF fluctuating force coefficients soar to the maximum value within the "lock-in" region and are followed by a slump. The drop is closely related to the jump of the phase between the lift coefficients and CF displacements, attributed to the switch of near wake patterns [10]. The lift coefficients show a significant dependence on the response amplitudes and frequencies of the structure and would peak when the vortex shedding frequency synchronizes with the natural frequency [8,13]. The magnitudes of the varying drag coefficients are small at low amplitudes and frequencies, whereas they rocket to prominent values when the amplitudes and frequencies reach high values [9]. The added mass coefficients are proved to be more relevant to the response frequency than the response amplitude within "lock-in" region [11,12].

The hydrodynamic coefficients of elastically-mounted rigid cylinders undergoing forced vibrations have been employed in the empirical models for predicting the VIV responses of flexible cylinders, such as VIVA, VIVANA, VICoMo, SHEAR7 and ABAVIV. However, there exist considerable discrepancies between the VIV prediction results and experimental results [14]. Utilizing VIV hydrodynamic coefficients of long flexible cylinders could further improve the prediction accuracy. Unfortunately, it is difficult to measure the hydrodynamic forces acting along the flexible cylinders directly during model tests without affecting the ambient flow field. Previous researchers applied indirect methods to identify the fluid forces [15–18]. Huera-Huarte [15] proposed a finite element method (FEM) to calculate the fluid forces of a flexible cylinder undergoing VIV based on the displacement responses. It was found that the axial distributions of the fluctuating forces and displacements in the CF direction followed an analogous trend. Tang et al. [16] employed the master-slaved technique to reduce all the rotational degrees of freedom and input the VIV displacements into a finite element model to obtain the fluid forces. It was pointed out that the lift and varying drag coefficients were associated with the energy transfer. Song et al. [17] acquired the hydrodynamic forces on a flexible cylinder by an inverse analysis method. It was found that the hydrodynamic coefficients of a flexible cylinder undergoing VIV disagreed with those obtained from forced oscillation tests of rigid cylinders and the added mass coefficients were dependent on the response frequencies and the response amplitudes. Wu et al. [18] investigated the effect of the phase angles between IL and CF displacements on the lift coefficients. It was concluded that the lift coefficients were associated with the motion phase angles and tended to have a strong spatial variation as the response have a significant contribution of standing waves.

It is well known that cylindrical structures are often inclined with respect to the direction of the oncoming flow in practical engineering applications. The inclination angle α is defined as the angle between the cylinder axis and the plane perpendicular to the oncoming flow. Hence, $\alpha = 0^\circ$ is corresponding to the normal flow configuration. In order to estimate the vortex shedding characteristics of inclined rigid cylinders, Hanson [19] and Van Atta [20] introduced the Independence Principle (IP) which assumes that the wake flow of the inclined cylinders are essentially driven by the inflow normal component and the axial component has a negligible impact. In recent years, the validity of the Independence Principle has been verified by examining the fluid-structure interaction characteristics (e.g. the vortex shedding behaviors, hydrodynamic features and structural responses) of fixed or elastically supported rigid cylinders inclined to the oncoming flow [21–26]. However, the performance of the Independence Principle in predicting VIV hydrodynamic coefficients of the inclined flexible cylinders has been scarcely reported.

The hydrodynamic characteristics of an inclined stationary cylinder are obviously different from those of a cylinder normal to the flow as a result of the three-dimensional flow features [21]. Some experimental and numerical studies on the hydrodynamic behaviors of a fixed cylinder inclined at different inclination angles have been conducted by Ramberg [21] and Zhao et al. [22,23]. The three-dimensional wake vortex flow was observed in the case of flow past an inclined stationary cylinder with finite length. The values of the mean drag coefficients and lift coefficients are much higher than that predicted by the Independence Principle, especially in the case of large inclination angles owing to the strong influence of the axial flow on the vortex shedding. The hydrodynamic force coefficients show strong spanwise dependence due to the significant effect of the three-dimensional phenomenon.

The hydrodynamic mechanisms become more complicated if the inclined cylinder can oscillate in the flow. Several researchers have considered the VIV hydrodynamics of inclined elastically supported rigid cylinders. Lucor and Kamiadakis [24] numerically studied the hydrodynamics of an inclined elastically supported cylinder undergoing VIV with $\alpha = 0^\circ$, $-60^\circ$and -70°. It was found that the base pressures on the inclined cylinder were lower than the results predicted by the Independence Principle, which produced significantly greater drag coefficients than those estimated by the Independence Principle. Franzini et al. [25] conducted model tests to explore the hydrodynamics of an inclined elastically supported rigid cylinder with the CF oscillation only. The inclination angles were set to 0°, $-20^\circ$and -45°, respectively. It was found that the CF fluctuating force coefficients did not decrease significantly as the inclination angle was increased, and the added mass coefficients gradually dropped in "lock-in" region. Franzini et al. [26] carried out experiments on VIV of an inclined rigid cylinder elastically supported in both the CF and IL directions with $\alpha = 0^\circ$, $\pm 15^\circ$, $\pm 30^\circ$ and $\pm 45^\circ$. It was observed that the mean drag coefficients and the CF fluctuating force coefficients reduced at larger inclination angles. However, the mean drag coefficients were positively related to the displacement in the CF direction.

Nevertheless, little attention has been paid to the VIV hydrodynamics of inclined flexible cylinders. Recently, Bourguet et al. [27] and Bourguet and Triantafyllou [28] studied VIV of inclined flexible cylinders at $\alpha = 60^\circ$ and 80° by means of direct numerical simulation (DNS). It was found that the part of the inflow axial component perpendicular to the cylinders could result in distinct responses of the fluid-structure system and affected the hydrodynamic characteristics. The mean drag coefficients and lift coefficients of the inclined cylinder were much higher than those of the vertical cylinder. In addition, there was an obvious discrepancy in the axial distribution of the hydrodynamic coefficients between the inclined cylinder and the vertical one. Han et al. [29] performed experimental investigations of the VIV responses and the mean drag features of an inclined flexible cylinder with $\alpha = 45^\circ$ in uniform flow. The mean drag coefficients were obtained using the FEM technique put forward by Huera-Huarte [15]. It was found that the mean drag coefficients of the inclined flexible cylinder at $\alpha = 45^\circ$ agreed well with those of the vertical cylinder. In addition, the mean drag coefficients of the inclined flexible cylinder did not show a sharp decrease, which was inconsistent with the trend of an inclined rigid cylinder.

According to the aforementioned literature review, the VIV hydrodynamic characteristics of an inclined flexible cylinder differ from those of an inclined rigid cylinder. Hence, the VIV hydrodynamic features of the inclined cylinder urgently need to be further investigated. There are two main objectives of our current research. The first one is to study the effects of the inclination angle on the hydrodynamic characteristics of an inclined flexible cylinder undergoing VIV. The second one is to improve the database of VIV hydrodynamic coefficients to a certain extent. In this paper, the hydrodynamic coefficients are obtained indirectly from the displacement responses from our previous towing tank experimental campaigns on VIV of an inclined flexible cylinder with five inclination angles ($\alpha = 0^\circ$, 15°, 30°,45° and 60°) [30].

The outline of the rest of the paper is as follows. Section 2 introduces the method for force calculations and a brief description of the experimental arrangement and data processing is provided in Section 3. In Section 4, the results of the hydrodynamic coefficients and in-depth discussions about their characteristics varying with the inclination angle are presented. Finally, the conclusions of this paper are summarized in Section 5.