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Theoretical and experimental study on dynamic characteristics of V-shaped beams immersed in viscous fluids: From small to finite amplitude

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ABSTRACT

In this paper, an underwater vibration model is developed to depict the dynamic characteristic of V-shaped beams for both small and finite amplitude vibrations by considering the fluid–structure interactions between the complicated geometry and viscous fluids. The gap to width ratio in beam's cross-section is introduced to describe the geometry of the V-shaped beam. For small amplitude vibrations, a complex hydrodynamic function in terms of the gap to width ratio and the frequency parameter is presented to characterize the fluid–structure interactions according to the 2-D fluid dynamics simulations. Besides, a 3-D numerical simulation is performed to verify the proposed computational approach and hydrodynamic function in the 2-D analysis. As the vibration amplitude increases, the 2-D fluid dynamics simulations are further conducted to investigate the effects of amplitude parameter on the flow physics. Therefore, a revised hydrodynamic function governed by the interplay of the frequency parameter, the gap to width ratio and the amplitude parameter is presented to model the hydrodynamic force for finite vibration amplitude accounting for nonlinear damping effects. Moreover, the experimental verifications on both small and finite amplitude vibrations of several V-shaped beams with different geometrical sizes are carried out. It illustrates that the presented model is capable of capturing the nonlinear damping phenomenon occurred at finite oscillation amplitudes and is generally able to predict the underwater vibrations of V-shaped beams with both small and finite amplitude.

1. Introduction

As a significant flexible structure, V-shaped beams have been widely used in many research fields, such as atomic force microscopy (Stark et al., 2001; Korayem and Zakeri, 2011; Slattery et al., 2014; Korayem et al., 2015; Ansari et al., 2015; Sader et al., 2016; Namvar et al., 2017), energy harvester devices (Hosseini and Hamedi, 2016; Litak et al., 2017) and quality sensors (Lee et al., 2002; Steiner et al., 2015; Wu et al., 2016). V-shaped beams are less prone to lateral twisting and rolling once the beams jump into and out of contact with the surface, thus improving the performance of the applications with V-shaped beams and making the use of V-shaped beams currently popular (Jericho and Jericho, 2002). On the other hand,

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the cross-section and bending stiffness of the V-shaped beam are variable so that the dynamic response of the V-shaped beam is difficult to analyze due to its complicated geometries (Cleveland et al., 1993).

Lots of works in studying the physical design, universal characterization and dynamic behavior of V-shaped beams have been proposed over the past few years. Sader et al. (1995) proposed a method for the calibration of V-shaped cantilevers and the physical basis for the method was elucidated and its extension to small elastic bodies of arbitrary shape presented in Sader et al. (2005). Moreover, the method was also applied to a series of commercially available V-shaped cantilevers (Sader et al., 2012) recently. Lee et al. (2005), Lee and Chang (2011) and Lee and Chang (2016) investigated the sensitivity of V-shaped cantilevers of an atomic force microscopy based on the classical beam theory and the modified couple stress theory. The results show that the sensitivity of the V-shaped cantilever using the modified couple stress theory is smaller than that using the classical beam theory for the lower contact stiffness. Korayem et al. (2011, 2016a, b) and Korayem and Nahavandi (2017) proposed a comprehensive model for stiffness coefficients in V-shaped cantilevers and dealt with the mechanical and dynamic analysis of tapping-mode AFM and non-contact mode AFM. Moreover, Korayem et al. (2012) developed a concurrent multiscale methodology for modeling of single and multi-body solid structures and it could be used to perform the mechanical analysis of V-shaped beams at the finite temperatures.

While a series of efforts have been proposed to study the vibration behavior of V-shaped beams in vacuum or in air, the analysis of flexural vibration of V-shaped beams immersed in viscous fluids remains an analytically intractable problem. In fact, V-shaped beams are more commonly used in liquid environments (Berthold et al., 2017), such as the application in molecular and cell biology (Dufrãane et al., 2017), the measurement of the carbon chain length in nutrient solution (Wu et al., 2013) and the detection of the antibody concentration (Wu et al., 2014). Therefore, it is of fundamental importance to investigate the dynamic behavior of V-shaped beams submerged in viscous fluids. And the major task of flexural vibration in viscous fluid is to estimate the hydrodynamic force exerted on the submerged structure by the encompassing fluid (Yuan et al., 2017; Qin et al., 2017; Yuan et al., 2018b). Traditionally, such hydrodynamic force can be decomposed into an in-phase component with the oscillation of the solid body, called added mass, and out-phase component, termed hydrodynamic damping (Hasheminejad et al., 2014b, a; Hasheminejad and Mohammadi, 2016; Chen and Christensen, 2018).

For a low Keulegan–Carpenter (KC) number, which represents the vibration amplitude, the hydrodynamic loading distributed on the cylinder of sharp-edged cross sections is estimated from the 2-D unsteady Stokes flow described by linearized Navier–Stokes equations and the convective terms are neglected, as reported by Tuck (1969). Therefore, the loading acting on the structure depends on the sole Reynolds number. Subsequently, Sader (1998) presented that such hydrodynamic loading such loading can be described through a hydrodynamic function in which the real and imaginary parts are related to the added mass and viscous damping produced by the encompassing fluid, respectively. Moreover, Aureli et al. (2012) proposed a manageable expression of the complex hydrodynamic function for infinitely small vibration amplitude of sharp-edged beams by introducing a non-dimensional frequency parameter in which the hydrodynamic function is only in terms of the frequency parameter. Different from sharp-edged beams, V-shaped beams have more complicated geometries, the prediction of the loading exerted on the oscillating V-shaped structure for infinitely small vibration amplitude by the encompassing fluid is still scarce due to the complexity of the fluid–structure interactions. Considering the structural property of V-shaped beams, the hydrodynamic function of V-shaped beams vibrating with small amplitude depends not only on the oscillatory Reynolds number, or a frequency parameter, but also on the gap to width ratio in beam's cross-section. In order to analyze and predict the small amplitude vibration of the V-shaped beams vibrating under harmonic base excitation within an encompassing fluid, a computationally tractable model is proposed and the experimental verifications on the model are carried out for small amplitude.

Indeed, as the amplitude increase, that is, the KC number increases, advection phenomena and vortex shedding become important and dominate the evolution of the flow (Fu et al., 2018; Yuan et al., 2018a; Pigazzini et al., 2018). Therefore, the solution based on the small amplitude vibration is no longer suitable in estimating the hydrodynamic loading exerted on the submerged structure (Bidkar et al., 2009). On account of the effect of finite amplitude vibrations on the hydrodynamic loading, the complex hydrodynamic function for infinitely small vibration amplitude of sharp-edged beams was revised by introducing an amplitude parameter to the function in Aureli et al. (2012). The effect of the KC number on the fluid–structure interaction is also demonstrated in the closely related literature on rigid structure immersed in oscillating flows (Guilmineau and Queutey, 2002; Duclercq et al., 2011; Lee et al., 2013). In this work, as the oscillation amplitude of V-shaped beams increases, it needs to be paid more attention on the effect of the KC number, or the amplitude parameter on hydrodynamic loading. The hydrodynamic function proposed in the condition of small vibration amplitude is corrected due to the effect of finite vibration amplitude. As a result, the hydrodynamic function of V-shaped beams for finite vibration amplitude is governed by the interplay of three non-dimensional parameters that control the flow physics, that is, the frequency parameter, the gap to width ratio and the amplitude parameter.

The rest of this work is organized as follows. In Section 2, the problem under investigation is stated and the analysis of the motion is presented. In Section 3, the small amplitude vibrations of V-shaped beams are investigated. A two-dimensional problem is studied and a manageable formula for the hydrodynamic function which is in terms of the frequency parameter and the gap to width ratio is established. A three-dimensional simulation is performed and results are compared with the two-dimensional analysis. A validation of the proposed model against experimental results on flexural small amplitude vibrations of several V-shaped beams is reported. Moreover, a remark of the proposed hydrodynamic function is presented to highlight the importance and innovation of this work. In Section 4, the finite amplitude vibrations of V-shaped beams are discussed. The two-dimensional fluid problem and the identification of the hydrodynamic function accounting for