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Experimental investigation on the flow induced vibration of an equilateral triangle prism in water

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ABSTRACT

A series of flow induced vibration (FIV) experiments for an equilateral triangle prism elastically mounted in a water channel are performed with different system stiffness at constant damping and mass. An amplitude variation coefficient is proposed to describe FIV stationarity in the present study. The FIV of the prism can be divided into three primary regions based on the amplitude and frequency responses, which are the vortex induced vibration (VIV) branch, the transition branch from VIV to galloping, and the galloping branch. The transition branch occurs at the reduced velocity in the range of $7.8 < U_r = U/(f_{n,air}{\cdot}D) < 10.4$, accompanied with a relatively rapid increase in amplitude and a precipitous drop in frequency and vibration stationarity. In addition, the reduced velocity where the transition region is initiated is independent of the system stiffness. The maximum amplitude reaches 3.17 D in the galloping branch. The ratio of the response frequency to the natural frequency of the prism in air remains locked to approximately 0.65 throughout the fully developed galloping branch. Large amplitude responses in an infinite range of flow velocities, excellent vibration stationarity and steady vibration frequencies, which are characteristics of the galloping of the prism, have a positive impact on improving energy conversion.

1. Introduction

Flow induced vibration (FIV), which is commonly encountered in engineering fields, such as long-spanned or high-rise buildings, has been a subject of interest for the past several decades. Vortex induced vibration (VIV) and galloping are the most common FIV phenomena. VIV occurs due to the alternating shedding of vortices from either side of the bluff cylinder [1]. The alternating shedding of vortices results in periodic changes in the pressure distribution on the cylinder surface. Hence, the VIV of bodies are self-excited motions. However, galloping, characterized as the large amplitude and low frequency oscillation normal to the flow, is caused by forces acting on a cylinder as it is subjected to periodic variations in the angle of attack of the flow [2]. Usually the transverse motion of a body gives rise to the periodically varying angle of attack.

The VIV of an elastically mounted circular cylinder has been studied extensively by Sarpkaya [3], Bearman [4], Williamson and Govardhan [5], Khalak and Williamson [6] and others. Sarpkaya [3] and Williamson [5] reported that the oscillation amplitude of a cylinder in VIV is self-limiting, as excessively large vibrations break the wake mode and vortex pattern. They also indicated that oscillations with large amplitude of a cylinder in VIV occur in a certain range of reduced velocities $U_r = U/(f_n{\cdot}D)$, where f_n is the natural frequency of the vibration system, and D is the diameter of the cylinder. This range of reduced velocities is defined as the synchronization range or lock-in range. The parameters, including mass ratio m^* (the ratio of oscillating mass to displaced fluid mass), system damping ratio ζ and combined-parameter $m^*\zeta$, have a great impact on VIV [6]. The VIV regimes for an elastically mounted cylinder with low $m^*\zeta$ are classified into four branches on the basis of amplitude response: the initial branch, upper branch, lower branch and desynchronization branch [7]. Williamson and Roshoko [8] summarized the experimental results and classified three types of vortex shedding patterns, 2S, 2P, and P + S, by the number of vortices shed per vibration cycle of cylinder. The different wake patterns are associated with specific VIV regimes. 2S and 2P patterns represent two single and two pairs of vortices shedding from the body surface per cycle, respectively.

It is well known that flow around an elastically mounted circular cylinder can induce periodic vibration of the cylinder. However, noncircular section bodies with symmetric sharp edges, such as rectangular section prisms as well as isosceles or equilateral triangular cylinders, could be more prone to experiencing FIV because the symmetric apex angles in their geometries appear to be helpful

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for the flow to separate from the body surface. In the last decades, many researchers have devoted great effort to study the FIV features of square or rectangular section bodies [9–17]. Both VIV and galloping of rectangular section prisms with a low mass ratio were observed by Nemes et al. [16] and Barrero and Fernandez [17]. Compared with the studies concerning the FIV of rectangular cylinders, there are only limited investigations related to triangular cylinders immersed in a uniform flow. Iungo and Buresti [18] examined the influences of wind direction and cross-sectional geometry on the flow around a triangular cylinder. A series of triangular prisms with different triangular cross-section apex angles and aspect ratios were tested in a wind tunnel by varying the wind direction. They demonstrated that the fluctuating cross-flow forces connected with vortex shedding vary significantly with incident flow orientation and aspect ratio. Similar studies were also conducted by Camarri et al. [19] and Johansson et al. [20]. Furthermore, Alonso et al. [2,21,22] based on the Glauert-Den Hartog criterion and dynamical tests, comprehensively studied the transverse galloping stability of triangular prisms and concluded that the stability to transverse galloping of triangular cross-section cylinders depends on the cross-sectional geometry and the angle of attack. In addition, FIV perpendicular to the flow of an elastically mounted equilateral triangular prism was numerically researched by Lin Ding et al. [23]. The results showed that the FIV of an elastically mounted equilateral triangular cylinder can be divided into the initial and upper branches of VIV, the transition branch from the VIV branch to the galloping branch, and the galloping branch, regarding the amplitude and frequency responses. Feng Xu and Jinping Ou [24] also performed a numerical investigation of the FIV of elastically mounted cylinders with different sections and confirmed that the vibrations of the square and triangle cylinders change from vortex induced vibration to galloping as the frequency ratio f_n/f_{st} (the ratio of the natural frequency to the Strouhal frequency) decreases.

Contrary to suppressing the FIV usually encountered in engineering fields, Bernitsas et al. [25,26] developed the Vortex Induced Vibration for Aquatic Clean Energy converter (VIVACE). The VIVACE, which utilizes FIV of a cylinder or cylinder array to capture hydrokinetic energy, is an innovative energy harnessing device with a high energy density, low operable flow velocities and low maintenance cost. This device satisfies all of the requirements set by the California Energy Commission and the U.S. DOE [26]. For the VIVACE, enhancement of FIV is required to convert more hydrokinetic energy to mechanical energy and subsequently to electrical energy over a broad velocity range. Therefore, Chang et al. [27], Kim et al. [28] and Park et al. [29] effectively enhanced the FIV of the circular cylinder by altering the cylinder surface roughness with the help of Passive Turbulence Control (PTC). Besides, in order to make the change of spring and damping efficient and accurate, Lee et al. [30] built a device V_{CK} to replace the physical damping and spring of the VIVACE Converter. Sun et al. [31] introduced an Arduino embedded board to control a servomotor instead of Labview, which significantly reduces the controller-induced lag compared to the first generation of V_{CK}.

Apart from the cylinder with PTC, the elastically mounted triangular prism can experience strong FIV in an extremely broad range of flow velocities, as has been reported by some researchers. The prism enters into galloping mode when the velocity of the incident flow exceeds a certain critical value, and the response amplitude in galloping increases with increasing flow velocities. Accordingly, the use of the galloping as an alternative to harvest energy from a fluid flow has obvious advantages. However, as far as we know, almost all of the studies on flow induced vibration of triangular prisms were performed in wind tunnels [2,18,21,22] or by means of numerical simulations [19,20,23,24]. The characteristics of FIV of elastically mounted triangle cylinders immersed in the water flow, which is the objective of the present study, have not been experimentally investigated to date.

In this paper, the motion equation followed by mathematical models for the power extracted from a fluid flow by the elastically mounted equilateral triangle cylinder is derived in Section 2. In Section 3, the experimental apparatus along with the physical model is described. The results of free decay experiments are presented in Section 4. In Section 5, the results of FIV tests are discussed. The conclusions are summarized at the end.

2. Mathematical model

For the case of the one-degree-of-freedom cylinder, a classical mass-spring-damper oscillator model has been presented in the literature [26]. It can be assumed that the FIV of the one-degree-of-freedom cylinder approximates the maximum response at resonance. The x-axis is chosen in the free-stream direction and the y-axis in the vertical direction, z-axis is defined as the axis of the cylinder perpendicular to the direction of the free-stream and y-axis.

The one-degree-of-freedom equation of vibration is given as

$$m_{osc}\ddot{y} + c_{system}\dot{y} + Ky = F_y \tag{1}$$

where m_{osc} is the oscillating system mass, y is the displacement perpendicular to the incident flow and the cylinder axis, K is the system spring stiffness, c_{system} is the damping coefficient of the oscillating system, and F_y is the force exerted by the fluid on the body surface in the y-direction. In this model, the fluid force can be divided into viscous and inviscid components [5,26] as follows:

$$F_{y,\ inviscous} = -m_a\ddot{y} \tag{2}$$

$$F_{y,\ viscous} = \frac{\sqrt{3}}{4}c_y(t)\rho U^2 DL \tag{3}$$

where m_a is the added mass (which is equal to added mass coefficient C_a multiplied by displaced fluid mass m_d), $c_y(t)$ is the lift coefficient, ρ is the fluid density, U is the flow velocity, D is the characteristic dimension of the prism in the direction transverse to the incident flow, and L is the length of the cylinder.

By substituting Eq. (2) and Eq. (3) into Eq. (1), the motion equation can be rewritten as

$$(m_{osc} + m_a)\ddot{y} + c_{system}\dot{y} + Ky = \frac{\sqrt{3}}{4}c_y(t)\rho U^2 DL \tag{4}$$

At this stage, the mass of the displaced fluid of an equilateral triangle prism is introduced, which is defined as

$$m_d = \frac{\sqrt{3}}{4}\rho D^2 L \tag{5}$$

Thus, Eq. (4) can be reduced to

$$(m_{osc} + m_a)\ddot{y} + c_{system}\dot{y} + Ky = \frac{U^2}{D}c_y(t)m_d \tag{6}$$

In the present study, the reduced velocity U_r is introduced, which is defined as

$$U_r = \frac{U}{f_{n,air}D} \tag{7}$$

where $f_{n,air}$ is the natural frequency of the vibration system in air. The reduced velocity U_r is often used as the x-axis on plots in investigations on the FIV of a circle cylinder because it properly collapses many test cases onto the same plot.

The mass ratio of an equilateral triangle prism, m^*, is defined as the total oscillating mass of the prism in FIV m_{osc} divided by the displaced fluid mass m_d.

$$m^* = \frac{m_{osc}}{m_d} \tag{8}$$