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Flow-induced vibration of a locally rough cylinder with two symmetrical strips attached on its surface: Effect of the location and shape of strips

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ABSTRACT

The flow induced vibration of a circular cylinder selectively roughened with two strips is numerically investigated using a two-way fluid-structure interaction (FSI) approach at high Reynolds numbers ($30480 \le Re \le 304800$). The main purpose of the study is to evaluate the effect of the location and shape of strips on the vibration response. The numerical model is validated with the experimental and numerical results reported in previous studies. The results indicate that the response is sensitive to the placement angle and shape of strips. The 12 in. cylinder with rectangular strips at $\alpha = 20^\circ$ has the similar response trend as the 3.5 in. cylinder. The gap between VIV and galloping is filled by placing strips in the front surface of the cylinder. Hard galloping zone 1 (HG1) appears at $\alpha = 20^\circ$ and 60° where the amplitude grows quickly after the onset of galloping, and hard galloping zone 2 (HG2) appears at $\alpha = 0^\circ$ and 74° where the amplitude grows relatively slowly. Among them, placing strips at $\alpha = 20^\circ$ has the best performance in enhancing vibration. However, the vibration is suppressed by placing the rectangular strips at $\alpha = 120^\circ$, where the boundary layer separation point transfers to the strip surface. The galloping is observed using trapezoid I and II strips, while it is not achieved by placing triangular or arc strips. The changes in turbulent intensity, vortex shedding mode and wake width reflect the transition from VIV to galloping.

1. Introduction

Vortex shedding from a bluff body is omnipresent in nature and most practical applications. Asymmetric vortices shed in the wake of a bluff body can lead to unsteady hydrodynamic forces acting on the structure, and then induce structural vibration called vortex-induced vibration (VIV), one well-known form of flow-induced vibration (FIV). VIV is usually treated as a destructive phenomenon because of the fatigue damage it causes. The suppression of VIV has attracted intensive study interests in the past few decades. With the input of external energy and the help of sensors and actuators, some active control measures were developed [1–4]. He and Ge [5] proposed the robust adaptive boundary control to suppress the vibration of a flexible cable. Recently, they designed a cooperative control law [6] and a neural network controller [7] to suppress the vibration of a flexible structure with input deadzone. Although the active control techniques have the advantage of adaption, it is still challenging to implement such control devices in some harsh environment like ocean. In the past decades, many passive control devices were proposed to eliminate the asymmetric vortex shedding from a circular cylinder [8–10]. One type of passive control is disturbing the flow boundary layer by roughing the surface uniformly such as surface protrusions [11], shrouds [12], trip wires [13], to name but a few. There are a variety of shapes for the uniformly distributed surface attachments, including circle, triangle, rectangle, etc.

However, localized surface roughness at some specific positions may enhance the hydrodynamic forces acting on the cylinder and then amplify the VIV [14,15]. From the perspective of energy harvesting, more mechanical energy could be utilized from a vigorous oscillator. In the recent studies by the Marine Renewable Energy Laboratory (MRELab) at the University of Michigan, a hydrokinetic power generating device called VIVACE (vortex induced vibration for aquatic clean energy) converter was proposed and investigated intensively [16–20]. It was observed that selectively placing roughness strips on a cylinder surface could at least double the maximum vibration amplitude and fill the gap between VIV and galloping,

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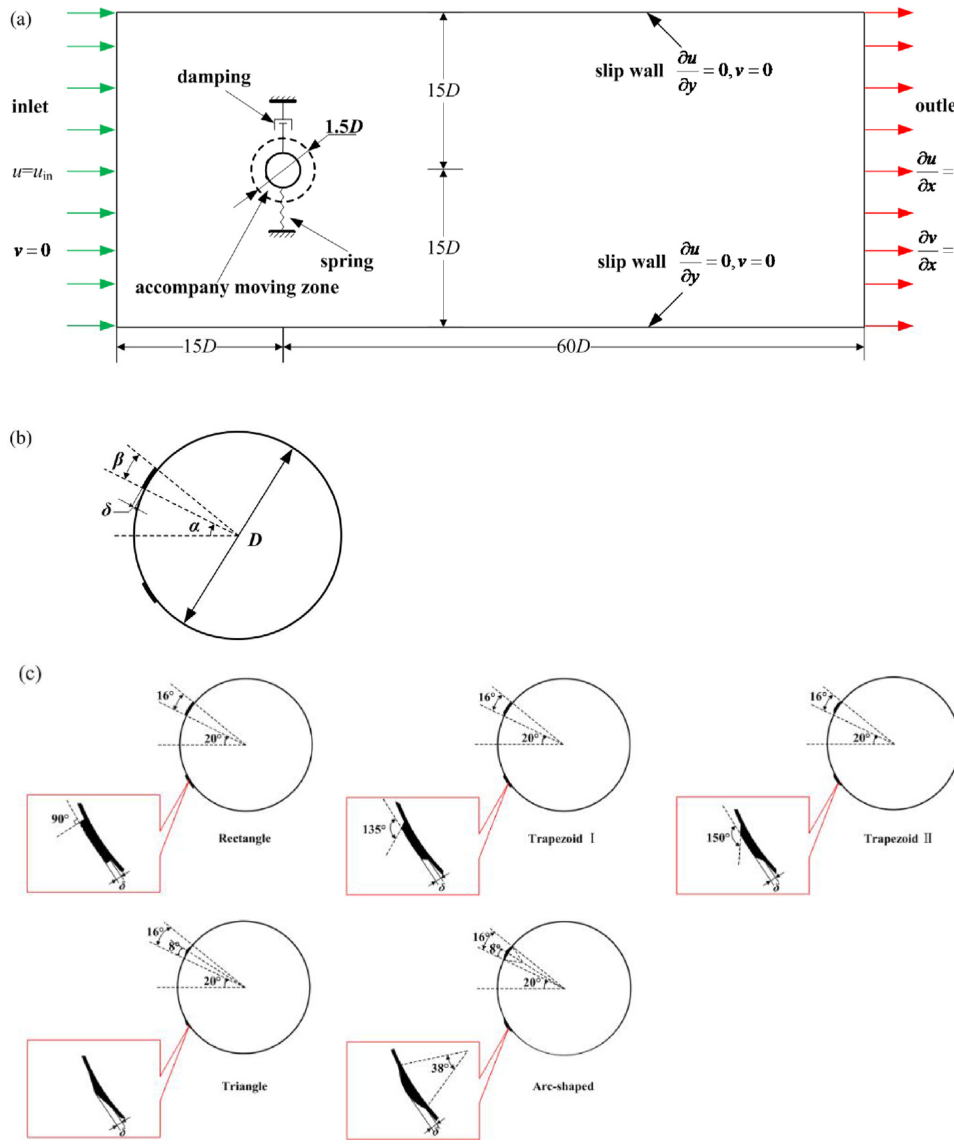

Fig. 1. Sketch and definition of flow over a circular cylinder attached by two symmetric strips: (a) computational domain and boundary conditions; (b) location and angular coverage of the strips; (c) different shapes of the strips.

another form of FIV that is more vigorous than VIV, i.e., the upper branch of VIV is followed by galloping instead of a lower branch ending in de-synchronization [14,21–24]. A pair of rectangular strips symmetrically pasted on the surface of a circular cylinder were introduced to enhance the vibration, and the best performance was found at the placement angle of 20° (α, the degree from the forward stagnation point to the upstream edge of each strip) in the range of α = 20°–64°. It indicates that the vibration response is sensitive to the position of localized surface roughness. It is noted that the diameter of the circular cylinder model in their studies is 88.9 mm (3.5 in.), which is a typical size adopted in experiments.

Further study is needed to address some questions as follows. (1) Whether this method is effective for a cylinder with a diameter as large as 304.8 mm (12 in.)? (2) Could the vibration suppression be achieved by such localized surface roughness? (3) What is the critical placement angle in terms of vibration enhancement? (4) What is the characteristic of the transition from VIV to galloping? (5) Does the shape of strips affect the vibration response? Therefore, in this paper, the effects of the location and shape of strips on the vibration response of a circular cylinder are investigated numerically using a two-way fluid-structure interaction (FSI) approach. The unsteady Reynolds-Averaged-Navier-Stokes (URANS) equations in conjunction with the standard k-ε turbulence model are employed to solve the flow over the cylinder in the range of $30480 \le Re \le 304800$, while an improved fourth-order Runge-Kutta method is adopted to capture the motion of the cylinder according to the hydrodynamic forces acting on the structure. The effects of localized surface roughness on hydrodynamic force coefficients, vibration amplitude, flow wake and boundary layer are discussed in detail to address the above questions and to give some insights into the boundary layer flow control.

2. Problem description

Fig. 1 depicts the sketch of flow over a circular cylinder with a pair of strips attached to its surface symmetrically. The elements of this oscillatory system are a rigid circular cylinder, two supporting linear springs and the system damping due to friction. The cylinder of diameter D = 304.8 mm is mounted elastically with its axis perpendicular to the incoming flow, which is in the x-direction, and it is constrained to move in the y-direction (one-degree-of-freedom). As shown in Fig. 1(b), the placement angle of a strip (α)