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Vortex-induced vibration and structure instability for a circular cylinder with flexible splitter plates

Shengping Liang, Jiasong Wang *, Bohan Xu, Wenbo Wu, Ke Lin

MOE Key Laboratory of Hydrodynamics, Shanghai Jiao Tong University, Shanghai, 200240, China

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ABSTRACT

The research about response of a circular cylinder fitted with rigid splitter plates has been performed previously to control VIV while a structure instability, galloping has been found under some conditions, which has an increasing interest recently. However, the galloping instability attached with flexible splitter plate (FSP[1]) is studied scarcely. In the present study, a FSP of different length ($0.5 \leq L/D \leq 2.5$) (where L is the length of splitter plates, D is the external diameter of cylinder) was proposed to control the vortex induced vibration (VIV). It was found that the vibration can be well controlled for $L/D \leq 1.1$. As a further increase of length of splitter plates, severe galloping occurs. The amplitude response is even higher than that of bare cylinder. Flow visualization showed that shear layers and vortex shedding are controlled by the wave motion of flexible splitter plates. Unlike the classical galloping, it would not persist for all velocities above a certain value. A simple study about the influence of bending stiffness has shown that the response is very sensitive to bending stiffness. FFT spectrums of streamwise velocity obtained from hotwire tests revealed more harmonic components, other than natural frequency, are present when the cylinder is attached with flexible splitter plates. It may be possible that these higher harmonic components are partly responsible for the more violent response.

1. Introduction

In fluid mechanics, flow past a cylinder is a classical problem and has been widely researched in past decades. When alternate vortices are shed from the cylinder, oscillating fluid force is exerted on the latter. While the vortex shedding frequency approaches the natural frequency of structures, the vibration is induced, which is called vortex-induced vibration (VIV). Serious fatigue failure can be caused because of the vortex-induced vibration for risers and pipeline structures, which makes the suppression of VIV remarkably significant in practice.

Plentiful researches have been conducted previously on the suppression of Karman vortex shedding behind a bluff body Great efforts have been made based on the altering the wake and vortex generating conditions to mitigate the drag/lift force. One of the most common approaches is to affix a suppression device on the bluff body, which is called the passive control method. As described by Zdravkovich (1981) and Owen et al. (2001), various suppression devices have been proposed and put into practice, including strakes, splitter plates, fairings, and so on.

Splitter plates have been proved to be a ubiquitous and effective device to suppress vortex shedding for its obstruction of boundary layers interaction. A series of experiments were performed by Roshko (1954), Apelt et al. (1973), Unal and Rockwell (1988), Texier et al. (2002), Akilli et al. (2005). Wang et al. (2010) conducted a numerical investigation about flow control of marine risers with attached rigid plates. The results manifest that splitter plates can lower the drag and lift of structures. Roshko (1954) showed the stabilization effect of splitter plates toward the near wake around a circular cylinder.

However, under certain conditions, the vibration of the cylinder attached with rigid splitter plates is prone to mount unlimitedly with the increase of stream velocity. Assi et al. (2009) showed that flow reattachment tends to happen on the tip of the splitter plates and leads to the strong vibration of the structure. This kind of structure instability is categorized as galloping by Assi et al. (2009), which is common for square cylinders. According to Parkinson and Dicker (1971), the vibration amplitude occurring in galloping is much larger than that of VIV. Previous research about response of a circular cylinder with rigid splitter plates is summarized in Table 1. Researches performed by Kawai (1990) and Nakamura et al. (1994) showed that galloping of a circular cylinder occurs while a stationary rigid splitter plate is mounted in the wake of the cylinder. Stappenbelt (2010) conducted experiments in a water tunnel about a circular cylinder attached with rigid splitter plates. It was found that the severe response is present for $L/D \leq 2.4$ (where L is the length of

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* Corresponding author.
E-mail address: jswang@sjtu.edu.cn (J. Wang).

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Table 1
Summary of response for a circular cylinder with rigid splitter plates.

Investigator (Year)	Method	L/D	Installation of splitter plates	Response
Kawai (1990)	Numerical (DVM)	2.0	detached	galloping
Nakamura et al. (1994)	Experimental	4.2,10.4, 20.8, 31.3	detached	galloping
Stappenbelt (2010)	Experimental	0–4.0	attached	galloping ($L/D \le 2.4$); suppressed ($L/D > 2.4$)
Assi et al. (2009)	Experimental	0.25–2.0	attached	galloping
Assi and Bearman (2015)	Experimental	0.5, 1.0	attached	galloping

splitter plates, D is the external diameter of cylinder). When the splitter plate is further lengthened, both VIV and galloping are absent. More detailed experiments in a water channel have been carried out by Assi et al. (2009) when the cylinder is attached with rigid splitter plates. Assi et al. (2009) has claimed that galloping exists for all the cases ($0.25 \le L/D \le 2.0$).

Various experiments about splitter plates were performed by Assi et al. (2009) to suppress VIV and avoid galloping simultaneously. Free-to-rotate rigid splitter plates have been come up with to overcome the structure instability. Gu et al. (2012) performed experiments about a stationary circular cylinder with a free-to-rotate splitter plate, which showed that the plate would rotate to a new equilibrium position and the drag and lift coefficients can be remarkably reduced. Assi et al. (2009) showed that the separating layer appeared to reattach to the tip of the free-to-rotate plates, which could stable the near flow wake and suppress galloping.

In recent several years, part of gaze has been put on the flexible splitter plates that control wakes, mainly by the numerical method. Most of related numerical researches have focused on the flow control via the interaction between a stationary circular cylinder and a flexible foil undergoing fish-like motion actively. A parametric study by Xiao et al. (2012) on a D-section cylinder drag reduction was performed when placing an undulating foil downstream. It was shown that proper placement of foil can result in the drop of drag and lift. Wu et al. (2014b) researched about the flow characteristics around a stationary circular cylinder with an undulatory plate. A mechanism about the vortex interaction is introduced. It was shown that there exist two different modes of vortex interaction, the constructive interaction and destructive interaction.

One of the most related researches regarding response of cylinder attached with flexible splitter plates is the numerical study performed by Wu et al. (2014a). VIV of a circular cylinder attached with flexible filament in a passive motion was investigated in detail. The suppression effect was illustrated by parametric method. However, all the numerical study in Wu et al. (2014a) was for a single reduced velocity of 5, and the complete amplitude response versus reduced velocity was not present and galloping was not mentioned. Kwon et al. (2002) performed experiments about drag reduction effects of a cylinder attached by flexible ribbons. Besides, the vortex structure for the flow over a heaving cylinder with a flexible tail was researched experimentally in Hu et al. (2014). Different vortex modes in the wake were classified owing to the competition of leading vortex from the cylinder and trailing edge from the tail.

In a word, the research about the VIV control through flexible devices has been insufficient. Especially, related experiments have been rare. This may result from the complicated mechanism of the interaction between fluid and the flexible device. However, flexible devices are characterized as being able to deform in the flow, which may counteract fluid force on the structure. It is worthy of research about the effect of flexible devices towards VIV.

In the present study, a flexible splitter plate (FSP) was proposed to explore its influence on the flow induced vibration of circular cylinder that VIV, VIV suppression or galloping may takes place. A series of VIV experiments in wind tunnel for a cylinder fitted with (FSP) in different lengths were conducted. It showed that some cases can suppress the response, while in some cases a severe galloping occurs. To interpret the results, frequency analysis was applied to interpret the results through hotwire tests. Furthermore, some typical flow field was visualized by smoke wire.

2. Material and methods

2.1. Wind tunnel and experimental setup

The experiments were performed in the low speed wind tunnel at Key Laboratory of Power Machinery and Engineering, Ministry of Education, Shanghai Jiao Tong University. The turbulence level in the test section of the wind tunnel here was less than 1.2%, in the $0.6m \times 0.6m$ cross-section, over the range of free-stream velocities U ($1.0\,m/s$-$20.0\,m/s$) used in the study. The experimental setting in this wind tunnel about VIV was introduced by Sui et al. (2016). The parameters we used are listed in Table 2.

The cylinder model in present experiments was made of rigid hollow perspex tubes, with the diameter of $50\,mm$ and thickness of $3\,mm$. The aspect ratio l/D of the cylinder was 9.88 and the blockage ratio is 8.33%. Corresponding Reynolds number was in the range of 7000–66000. The mass m and mass ratio m^* of the model were listed in Table 3.

The installation of the model in the test was shown in Fig. 1. Each end of the cylinder was attached to four springs. All eight springs were of an equal stiffness $350N/m$ and equal length $80\,mm$. The springs were stretched to long enough for the springs to remain in tension during the test. The sketch of the circular cylinder fitted with flexible splitter plates is displayed in Fig. 2. Initial shape of splitter plates can be observed in Fig. 2(a). When the model vibrates, flexible splitter plates are possible to be in a wave motion, as shown in Fig. 2(b).

The flexible splitter plates chosen here was made of thin and light litmus paper sheets with thickness of about $0.1\,mm$. The bending stiffness of the sheet per unit width was roughly measured by the deflection of the sheet under its own weight. The thin litmus paper was proper here to make sure its motions two-dimensional. A dimensionless parameter Π was introduced here, which was also used in Hu et al. (2014). Here we didn't make deep research about the influence of bending stiffness of splitter plates towards the response of structure because Π is also related to the length of splitter plates and streamwise velocity. The amplitude response versus the free stream velocity was our focus here. Further research about the influence of the flexibility will be made in the future. Π in our experiments here is 2.33×10^{-4}~2.11. All configurations of the splitter plates here were listed in Table 3.

2.2. Vibration measurements and flow tests

The model vibrated in cross-flow direction. The corresponding displacement of the model was measured via a laser sensor (Keyence IL-300 with a full range of $140\,mm$). The calibration curve was present in

Table 2
Parameters used in present study.

D	Cylinder diameter	h	Thickness of splitter plates
ν	Kinematic viscosity		
Re	Reynolds number (Re=UD/ν)	m	Mass of model
f_n	Natural frequency	E	Young's modulus of flexible splitter plates
f_v	Vortex shedding frequency	A	Amplitude
U	Free stream velocity	ρ_f	Fluid density
l	Cylinder length	St	Strouhal number ($St = f_v D/U$)
L	Length of splitter plates	m^*	Mass ratio ($m^* = 4\,m/(\pi\rho_f D^2 l)$)
ζ_s	Damping ratio	$m^*\zeta_s$	Mass damping ratio
U_r	Reduced velocity ($U_r = U/f_n D$)	Π	Effective stiffness ($\Pi = Eh^3/12\rho_f U^2 L^3$)