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# VIV and galloping response of a circular cylinder with rigid detached splitter plates

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ABSTRACT

Researches about the response of a circular cylinder fitted with splitter plates have been performed previously to control VIV. Galloping, as a structure instability has been found under some conditions, which is of great interest recently. However, the mechanism of response for a circular cylinder in the presence of splitter plates has rarely been clarified. In the present study, different vibration characteristics have been observed for a circular cylinder with detached splitter plates ($0.4 \leq L/D \leq 5.0$) (where $L$ is the length of splitter plates, $D$ is the external diameter of cylinder) in a wind tunnel. Combined with previous study for galloping in square cylinders, the patterns were comprehensively described. There exist four kinds of response for different lengths of splitter plates: VIV, which lies in a discrete range of wind velocity (such as $L/D = 0.4, 0.5$); the interaction between galloping and VIV was also found (such as $L/D = 1.0, 1.5$); a combination of the velocity-restricted excitation (which occurs before VIV onset velocities) and interaction of VIV and galloping, where there exists separate branches in the response (such as $L/D = 2.0, 2.5, 3.0$); a combination of the velocity-restricted excitation and pure classical galloping (such as $L/D = 4.0, 5.0$). Besides, it was discovered that the built-up time needed for pure galloping to reach a steady amplitude is much less than that when is related to VIV. Furthermore, the hysteresis loop was found in cases above. FFT spectrums of the streamwise velocity show the appearance of multiple harmonics.

## 1. Introduction

Circular cylinder structures have been widely utilized in practice. While flow passes a cylinder, alternate vortices shed and oscillating force is exerted on the cylinder structure. Under certain circumstances where the vortex shedding frequency is close to the nature frequency of the structure, severe vibrations can be induced. This fluid structure interaction is called vortex-induced vibration (VIV) (Blevins, 1990).

Much attention has been drawn to the suppression of VIV owing to the catastrophic events caused by VIV. Severe resonances due to VIV may cause the fatigue failure of structures. Based on the vortex formation mechanisms, various strategies have been proposed to suppress the vortex shedding. The passive control method has been introduced by attaching a device to the cylinder. These devices include strakes, splitter plates, fairings, and so on (Zdravkovich, 1981; Owen et al., 2001).

Splitter plates have been verified to be effective to obstruct the separate shear layers interaction and suppress vortex formations. Roshko (1954) showed separate points can be stabilized by the splitter plates. Experiments performed by Roshko (1954), Apelt et al. (1973), Apelt and West (1975), Unal and Rockwell (1988), Texier et al. (2002), Akilli et al. (2005), Gu et al. (2012) manifest that the formation length can be extended and fluid force, both the drag and the lift, are greatly lowered.

However, for flexibly mounted cylinders, splitter plates do not necessarily suppress the vibration. Instead, more serious responses can be induced. A result in Assi et al. (2009) showed that the shear layer tends to reattach to the tip of the splitter plates and the strong vibration of the structure ensues. Separate shear layers would interact with the splitter plates, with a higher fluid force exerting on the structure. This structure response is categorized as galloping by Assi et al. (2009), which is common for square cylinders.

The classical galloping occurs typically for all flow velocities above a critical speed (Blevins, 1990). And the vibration amplitude occurring in galloping is usually much larger than that of VIV. Galloping, as with VIV is one of the most common flow induced vibrations in practice. A fluid force is exerted on the structure in flow with noncircular cross section. As the structure oscillates, the fluid force changes with orientation to the flow. If the oscillation fluid force tends to increase vibrations, a large-amplitude response can be induced. Intrinsically, all noncircular cross sections are possible to gallop.

Like the circular cylinder for researching VIV, the square cylinder is suitable for galloping study. Plenty of researches have been performed

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previously about the galloping response. For the square cylinders in the smooth flow, $B$ and $D$ ($B$ and $D$ are streamwise and cross-flow section dimensions) are the key parameters to determine whether galloping is possible to occur. In particular, rectangular cylinders without specific $B/D$ are unable with respect to galloping (Parkinson, 1963). For very small $B/D$, the section is stable at rest. For the intermediate $B/D$ ($0.75 \le B/D \le 3$–4), the sections can gallop from rest. It has been revealed that the shear layers separating from the bluff body is crucial to the galloping phenomenon (Blevins, 1990; Corless and Parkinson, 1988). Reattachments of shear layers would lead to the formation of a fluid force that strengthens the vibration. This interaction of shear layers with the section afterbody is thought to be responsible for the typical galloping. Besides, any section is susceptible to VIV. For those sections that can gallop, it is possible that the two types of flow induced vibrations can interact with each other, where galloping occurs in the range of VIV lock-in region. Scruton (1963) observed an oscillation that starts from the VIV onset velocity and grows unrestrictedly with wind velocities. Parkinson and Wawzonek (1981) investigated the interaction between galloping and vortex resonance by tests of a square cylinder. The onset velocity lies close to or even lower than the vortex resonance wind speed. Consequently, the mutual effects of the two types of responses exist. A simulation and related experiments about a rectangular cylinder ($B/D = 2.0$) by Itoh and Tamura (2002) also indicated the combination of VIV-galloping instability. More recent experiments about a square cylinder performed by Nemes et al. (2012) vigorously support the interaction effect of VIV and galloping, and a transition from VIV to galloping has been found. Mannini et al. (2015) carried out experiments to get insights into the interaction.

Mannini et al. (2014) extensively reviewed the previous literature about VIV and galloping interaction. The response of the section in different situations was drawn as shown in Fig. 1. There exist 'no interaction' where VIV and galloping are separated, 'full interaction' where the response occurs around the range of VIV and it is dominated by galloping, 'partial interaction', and 'the quenching' where a response occurs at velocities lower than the vortex resonance flow speed. The quenching effect was observed by Santosham (1966), Bouclin (1979), Parkinson and Sullivan (1979), Bearman et al. (1987). According to Parkinson and Dicker (1971), for the structures susceptible to both VIV and galloping, it is hard to determine which form is present. Previous researches about galloping of square cylinders have revealed only sections with $B/D$ in a certain range can gallop from rest (Parkinson and Dicker, 1971). These sections are therefore called 'soft oscillators'. For those sections with shorter after bodies ($B/D$ is small), galloping cannot erupt spontaneously unless a sufficient initial transverse velocity is given and they are called 'hard oscillators'.

Studies about response for a circular cylinder with auxiliary devices have been scarce. The auxiliary devices were introduced to suppress VIV while they may also give rise to the potential eruption of galloping. Even both VIV and galloping may be present, which makes the response more complicated. Assi et al. (2014) has investigated the response of a circular cylinder attached with fairings. And the severe response has been observed but in a discrete range of flow velocities. Zheng and Wang (2017) has resurrected the results in Assi et al. (2014) by a numerical method. To suppress the structure instability, free-to-rotate devices were tested by Assi et al. (2014). These include free-to-rotate splitter plates and fairings, which is capable of rotating freely around the main cylinder in the flow. Numerical simulations by Xie et al. (2015) also show the mitigation effect of free-to-rotation devices to VIV.

Limited work has been carried out about the response of a circular cylinder with splitter plates. Related researches are listed in Table 1. Assi et al. (2009) has claimed that the circular cylinder gallops when it is attached with $0.25D$˜$2.0D$ rigid splitter plate (where $D$ is the diameter of the cylinder). However, the test range of reduced velocities is limited and the complete response versus reduced velocity is not available in Assi et al. (2009). Flow visualizations in Assi et al. (2009), Assi and Bearman (2015) indicated the reattachment of shear layers to the splitter plates. The large added mass is present in Assi and Bearman (2015) and the frequency of the response is apparently lower than the natural frequency. The phase jump in VIV of bare circular cylinders vanishes for the response of circular cylinders with splitter plates in Assi and Bearman (2015). The low-frequency galloping can be found in the water tunnel experiments by Nemes et al. (2012). For structures in air when the mass ratio is much larger, the oscillation frequency is roughly equal to the natural frequency (Corless and Parkinson, 1988; Novak, 1972). The galloping response is observed in Kawai (1990) where a stationary rigid splitter plate is mounted in the wake of a circular cylinder. Stappenbelt (2010) conducted water tunnel experiments about the response of a circular cylinder in the presence of splitter plates. It was shown that for the cases of short splitter plates, the vibration is similar to that of vortex-induced vibration, where the response is limited in a discrete range of velocity. For those longer splitter plates, the vibration persists at a high level once the streamwise velocity exceeds a certain value. It must be known that the classical galloping for square cylinders occurs at all velocities above a critical value, which is the same as the circular cylinder with long splitter plates. Above all, a noticeable difference of response mechanism exists for the circular cylinder in the presence of splitter plates. Stappenbelt (2010) has categorized all the response as galloping, the same as Assi et al. (2009). Very few insights have been made previously about the mechanisms of response for a circular cylinder with splitter plates.

In the current study, detailed wind tunnel experiments were carried out to explore the galloping mechanism for circular cylinders with splitter plates. It is found that four kinds of response mechanisms are present for a circular cylinder with detached splitter plates of different lengths.

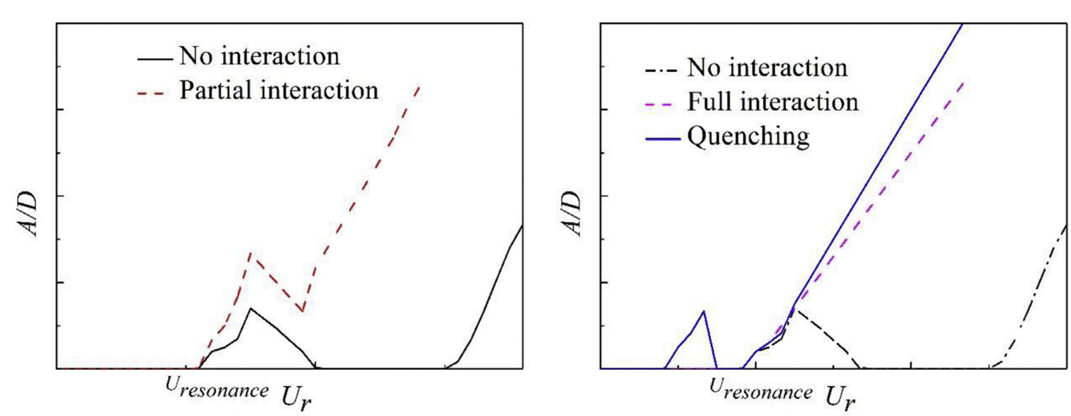


**Fig. 1.** Schematic diagrams in the cases of interaction and no-interaction of VIV and galloping.($U_{resonance}$ is the onset of VIV).