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A Review on Vibration Control of Multiple Cylinders Subjected to Flow-Induced Vibrations

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Abstract

The fatigue damage caused by flow-induced vibration (FIV) is one of the major concerns for multiple cylindrical structures in many engineering applications. The FIV suppression is of great importance for the security of many cylindrical structures. Many active and passive control methods have been employed for the vibration suppression of an isolated cylinder undergoing vortex-induced vibrations (VIV). The FIV suppression methods are mainly extended to the multiple cylinders from the vibration control of the isolated cylinder. Due to the mutual interference between the multiple cylinders, the FIV mechanism is more complex than the VIV mechanism, which makes a great challenge for the FIV suppression. Some efforts have been devoted to vibration suppression of multiple cylinder systems undergoing FIV over the past two decades. The control methods, such as helical strakes, splitter plates, control rods and flexible sheets, are not always effective, depending on many influence factors, such as the spacing ratio, the arrangement geometrical shape, the flow velocity and the parameters of the vibration control devices. The FIV response, hydrodynamic features and wake patterns of the multiple cylinders equipped with vibration control devices are reviewed and summarized. The FIV suppression efficiency of the vibration control methods are analyzed and compared considering different influence factors. Further research on the FIV suppression of multiple cylinders is suggested to provide insight for the development of FIV control methods and promote engineering applications of FIV control methods.

Key words: flow-induced vibration, vibration control, multiple cylinders, tandem, side-by-side, staggered

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1 Introduction

Vortex shedding phenomenon is always observed when a flow past through a cylindrical structure, which generates periodic fluid forces causing the cylinder to vibrate in cross-flow (CF) and in-line (IL) directions, i.e. vortex-induced vibration (VIV). For multiple cylinders immersed in the flow field, the vibrations of a cylinder could be influenced by the adjacent cylinders by means of wake interference. The vibration of multiple cylinders is often referred to as flow-induced vibration (FIV) which is more complex than that of an isolated cylinder due to the mutual interference of the wake flow. VIV or FIV is a phenomenon commonly occurring on many engineering cylindrical structures, such as tall buildings, transmission conductors, heat exchangers, stay cables, mooring lines, marine risers, subsea pipelines, etc. The long-term vibrations may cause structural damage and threaten structural safety seriously. It is necessary to take vibration control measures to reduce the damage of vibration and protect the safety of structures.

In the past decades, a large number of studies have been carried out on VIV control of an isolated cylinder, and exciting results have been obtained (Chen et al., 2013; Do and Pan, 2009; Ge et al., 2010; Lou et al., 2017; Nguyen et al., 2013; Qiu et al., 2009; Wang et al., 2016; Wu et al., 2014; Zdravkovich, 1981; Zhu et al., 2015, 2017). Vibration control methods can be divided into active control and passive control based on whether there is external energy input. The active control adopts active methods to interfere with the structural vibration or influence the flow field near the structure. In the process of active control, it is necessary to monitor the vibration response of the structure and the surrounding flow field in real time, which can adjust the control

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parameters and control strategy in real time according to the actual environment. This real-time adjustment method can achieve better vibration suppression effect, but it needs external energy input, high cost and complex technology. Passive control methods achieve the purpose of controlling the vortex and suppressing the vibration by changing the surface shape of the structure or installing auxiliary devices. Compared with active control methods, the passive control methods are simpler, cost less, and are more widely used in engineering applications. However, passive control methods cannot adjust the parameters of the inhibition device in real time and cannot effectively deal with environmental changes.

The active control on VIV of an isolated cylinder can be divided into two main ways. One is to directly suppress the vibration of the structure through the boundary control or the installation of distributed actuators. The other is to achieve the purpose of vibration suppression by interfering with the flow field around the structures. Some scholars have installed distributed actuators such as piezoelectric plates, tuned mass dampers and etc., to control vibrations of the cylinder (Baz and Kim, 1993; Qiu et al., 2009; Wu et al., 2014). To realize the vibration control, the algorithm should be designed to control the distributed actuators based on the modern control theory. However, the control algorithm design is generally based on the truncated finite-order model, which can only control a limited number of vibration modes. The control forces generated by the distributed actuators may have a significant impact on the vibration of other order modes, resulting in instability of the system. If the vibration of the long flexible cylinder exhibits multi-mode or higher-order modes, the distributed actuator method may be not effective. Boundary control is another active control method that directly suppresses the structural vibration. Applying control force at the end of the cylinder can improve the instability problem resulting from the distributed actuators. The VIV of long flexible cylinder can be suppressed by controlling the rotation angle, displacement, velocity and axial force at the end of the structure (Do and Pan, 2009, 2008; Ge et al., 2010; Nguyen et al., 2013). The Lyapunov method is always employed to determine the system stability when designing the control law. Because the design of the control law is very complex, the fluid load is usually simplified as a periodic load, and the fluid-structure interaction is not fully considered in the design of the control law.

The active control methods for disrupting the flow field mainly include suction, blowing, and rotation of control rods. It is possible to reduce the drag experienced by the cylinder, suppress the development of vortices along the span, decrease velocity fluctuations, and consequently lower the amplitude of lift forces using suction-based flow control. Wind tunnel experiments have demonstrated that fluid suction is effective in decreasing the amplitude of VIV. When the ratio of suction flow velocity to the external flow velocity is smaller than 1.0, the suppression effect is significant (Chen et al., 2013). Blowing fluid to the outside of the cylinder can also change the flow field distribution and thus reduce the drag acting on the cylinder. The frequency and location of blowing significantly affect the suppression effect of VIV (Wang et al., 2016). The rotation of control rods can inject momentum into the boundary layer to delay the separation of the boundary layer. The rotation speed of the control should be adjusted according to the specific marine environmental conditions, which ensures better applicability. The rotation of control rods actively transfers a certain amount of flow momentum and energy from the wake into the mainstream flow, effectively counterbalancing a portion of the momentum flow around the cylinder and thus mitigating the vibration of cylinder. When the installation angle of the rotating control rod is 120° and 150º, the width of the rear wake of the pipeline decreases and the vibration is significantly suppressed (Zhu et al., 2015). The trailing edge of the cylindrical structure can be transformed into the form of traveling wave wall, which can reduce the resistance and prevent flow separation (Liu et al., 2022; Xu et al., 2018, 2024). The main control parameters of traveling wave wall are propagation direction, wave amplitude and wave speed. When the traveling wave propagates downstream on both sides, the alternating leakage vortex is eliminated, and the lift coefficient of the cylinder is significantly reduced. When the ratios between wave speed and the flow velocity are in the range of 1.5−2.0, the oscillation wake at the back edge of the cylinder is basically eliminated, and the mean lift coefficient is reduced to the lowest point, so the control effect is the best. The drag coefficient is more sensitive to the change of the wave amplitude, and increasing the wave amplitude can improve the control effect.

Passive control methods destroy the formation of vortexes by changing the surface shape of the structure or attaching other devices to the surface of the structure. According to the suppression mechanism, passive control methods can be divided into three categories, namely the surface protrusion type, wrapped type and nearwake stabilizer type (Zdravkovich, 1981), as shown in Fig. 1. Surface protrusion type methods, such as helical strakes and spheres, could change the vortex shedding mode by affecting the separation line or the separation shear layer. Wrapped type method, such as control rod and axial slats, could inhibit the formation and shedding of vortex by affecting the entrainment layer. Nearwake stabilizer type methods, such as fairing and splitter plate, could prevent the interaction of the entrainment layer to affect the wake structure and vortex shed pattern. Most of the surface protrusion type and wrapped type methods are omnidirectional, meaning that they can play a good suppression effect on each direction of the incoming flow. The suppression efficiency of the near wake stabilizer type methods is strongly dependent on the incoming flow direction, and this type of suppression devices only have a better suppression

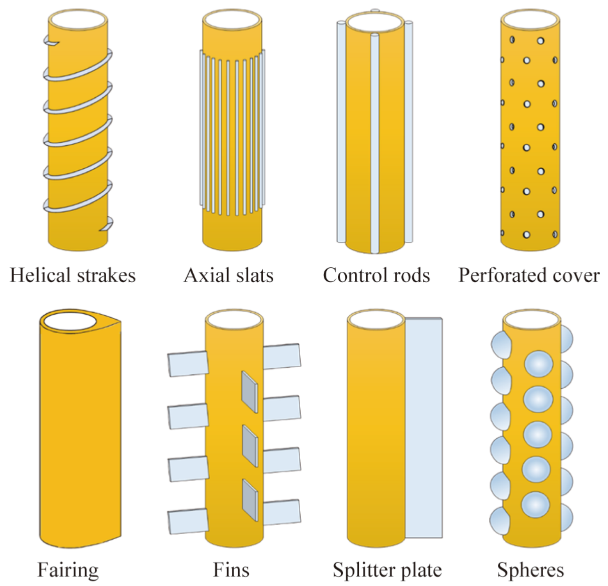

Fig. 1. Passive control methods for VIV (Zdravkovich, 1981).

effect in a few directions of incoming flow conditions.

Helical strakes, fairing and control rod and splitter plate are several kinds of passive control methods which are widely used in engineering applications. Helical strakes spirally wrap around the cylinder and destroy the spatial consistency of the shape of the cross section of the cylinder. Part of the flow around the strakes will flow along the direction of the spiral direction, which realizes the allocation of the flow around the space. The swirls on both sides of the cylinder do not fall off at the same height due to the allocation of the flow, which make the vortex in the wake area become messy and unable to form a stable structured vortex. On the other hand, the strakes can also change the position of boundary layer separation point. The pitch and height of strakes are important parameters affecting the suppression effect. The vibration amplitude decreases with the increase of height, and the lock-in resonance region is directly restricted by the pitch (Gao et al., 2015; Trim et al., 2005). The fairing can not only isolate the upper and lower entrainment layers, but also have a direct effect on the separation point of the boundary layer. When the angle between the edge of the fairing is in the range of 90°−110°, the fairing has a good suppression effect on both the vibration amplitude and the drag. The chord length of the fairing is an important geometric parameter and should be carefully designed. If the chord is too long, the fairing will show hydrodynamic instability (Lou et al., 2017; Zhu et al., 2017). The small control rods can make full use of the auxiliary facilities around the main cylindrical structures, which has the advantages of convenient layout and reducing capital investment. The control rod on the leading edge of the cylinder can split the incoming flow into multiple strands in advance, so that the energy of the boundary layer on the surface of the cylinder is reduced. The control rod on the rear side of the cylinder can disturb the separation of the boundary layer and interfere with the development of the vortex in the wake area. With the increase of the number of control rods, the lift coefficient and the amplitude in the CF and IL directions decrease to a certain extent, but the average drag coefficient and the displacement in the IL direction increase. By comprehensively comparing the inhibition effect and cost input, nine control rods are the optimal choice (Zhu and Yao, 2015). The splitter plate can segment the wake region and prevent the two shear layers from interacting. A fixed splitter plate could reduce the lift by 89%−96%, and a rotating splitter plate could reduce the lift by 70%−91% (Gu et al., 2012). However, the cylinder with fixed splitter plate may excite galloping response at some times, and the vibration amplitudes show a sustainable growth with the flow velocity. The rotating splitter plate is useful for avoiding the galloping behaviour (Assi et al., 2009). Liang et al. (2018) used a flexible splitter plate to suppress the VIV of the cylinder. The flexible splitter plate will twist and swing with the flow, so as to better control the vortex shedding.

The vibration control methods for VIV of an isolated cylinder provide references for the vibration suppression of multiple cylinders subjected to FIV. Some scholars have studied the effect of the VIV control methods on FIV suppression of multiple cylinders. Because of the interference between adjacent cylinders, there are significant differences between the FIV characteristics of multiple cylinders and VIV characteristics of an isolated cylinder. Taking two rigid cylinders as the research object, the mutual interference region, response characteristics, vortex modes and hydrodynamic features have been revealed and summarized during the past several decades. Zdravkovich (1985) divided the mutual interference region of cylinders into the proximity effect region, the wake interference region, and the combined action region of proximity effect and wake interference, as shown in Fig. 2. For a pair of side-by-side cylinders, the gap flow of the two cylinders deviates to form a wide and narrow vortex mode under the small spacing condition, which makes the hydrodynamic force and response frequencies of the two cylinders different (Chen et al., 2022). When the spacing increases and does not exceed the critical spacing for interference, the coupled vortex street behind the two cylinders synchronizes the vibration of the cylinders (Xu et al., 2022a). For a pair of tandem cylinders, the spacing between the cylinders determines whether the upstream vortex can be fully generated and developed. Under the shielding effect of the upstream cylinder, the appearance of the displacement extreme value of the downstream cylinder is delayed (Haider and Sohn, 2022). Under the excitation of the upstream vortex, the vibration amplitude of the downstream cylinder usually grows continuously (Lin et al., 2020). For a pair of staggered cylinders, both the spacing between cylinders and the flow incidence angle have significant effect on the FIV responses. At least nine wake patterns

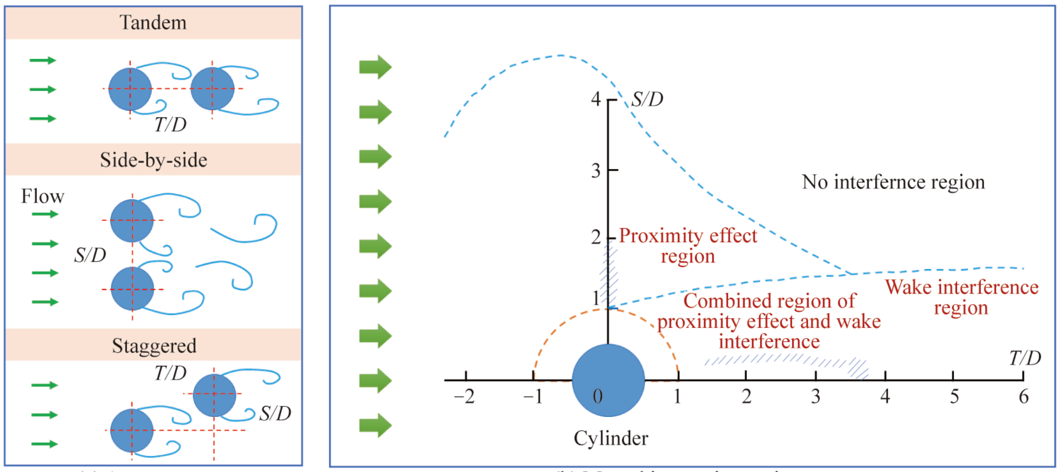

Fig. 2. Sketch of arrangement and mutual interaction region of two cylinders (Zdravkovich, 1985).

can be observed for different combinations of spacing and flow incidence angle conditions. The wake flutter response of the downstream cylinder, featured by a noteworthy rise in IL vibration amplitude and the elliptical shape motion trajectory, is one of the typical characteristics of the FIV of staggered cylinders (Assi, 2014; Xu et al., 2022b). Some scholars have studied the multi-mode responses of two flexible cylinders undergoing FIV. The vibration of two flexible cylinders arranged side-by-side could show a traveling wave property (Xu et al., 2018a), and the critical spacing to generate interference is increased compared with the result of two rigid cylinders (Sanaati and Kato, 2014). For two tandem flexible cylinders, the interference between the downstream cylinder and the upstream vortices is significantly affected by the distributions of the hydrodynamic forces (Lin et al., 2020). The vibration amplitude of the downstream cylinder is no longer increasing persistently because the higher order mode vibration could be excited with the increasing flow velocity (Huera-Huarte and Bearman, 2011; Xu et al., 2018b). For two staggered flexible cylinders, the spectral characteristics vary with the axial direction of the structure, indicating a hybrid feature of the wake induced flutter and VIV (Xu et al., 2020a).

Some researchers have studied the wake interference of the multiple cylinder systems with three or four cylinders (Bansal and Yarusevych, 2017; Han et al., 2013; Ma et al., 2020, 2019; Tu et al., 2020; Xu et al., 2021b; Yang et al., 2020; Zheng et al., 2016). Xu et al. (2018d) experimentally studied the FIV features of three or four side-by-side flexible cylinders. Because the wake flow was difficult to maintain symmetry in multiple cylinder systems arranged side-by-side, the response feature of the cylinders was different, which was also distinct with the FIV responses of two side-by-side cylinders. Wang et al. (2019) found that the middle cylinders of three or four tandem flexible cylinders had weak oscillations due to the wake shielding effect and the incompletely developed vortex. However, the leading and trailing cylinders in the multiple cylinder system behaved similarly to the upstream and downstream cylinders in a two-cylinder system. Yang et al. (2020) declared that wake interference generating from three equilateral-triangular arrangement cylinders exhibited certain resemblances to that observed in two cylinders. However, the inclusion of the third cylinder introduced various flow patterns contingent upon factors like spacing and incidence angle. Gao et al. (2019) carried out a numerical simulation focusing on four quadrilateral-arranged cylinders. The downstream cylinders exhibited motion trajectories with elliptical shape characterized by substantial displacements, which was similar to the responses of wake induced flutter.

It can be found that FIV mechanisms of multiple cylinder systems are significantly different from the VIV mechanisms of an isolated cylinder. Hence, it is not always feasible to crudely apply the VIV control method to the FIV suppression multiple cylinders (Xu et al., 2018c, 2021a). Over the past two decades, some efforts have been devoted to vibration suppression of multiple cylinder systems undergoing FIV. The FIV suppression of multiple cylinder systems should comprehensively consider many influence factors such as, the configuration, the spacing, the flow incidence angle, the incoming flow velocity and etc. Some vibration control methods work well, but some control methods do not perform as well as expected. This paper reviews the existing methods that can be used to suppress the FIV of multiple cylinders. Suppression mechanisms of the FIV control methods, applicability of the methods, wake flow patterns, response features and hydrodynamic characteristics of the multiple cylinder systems are summarized, which is expected to provide insight for the development of FIV control methods and promote the engineering applications of FIV control methods.

2 FIV control of multiple cylinders arranged in tandem configuration

In previous research on FIV control of multiple cylinders, just a few works have been done on the active control methods. Rabiee and Esmaeili (2020) attempted to employ active feedback control method to suppress the FIV of a pair of tandem cylinders at Reynolds number of Re=100. A fully-coupled fluid-structure interaction method was developed to simulate the FIV of the tandem rigid cylinders under a desired control force. The control force, calculated based on the vibration amplitude, was governed by a fuzzy proportion integration differentiation (PID) controller. The main vibration suppression mechanism is to make the natural frequency of the cylindrical structure away from the vortex shedding frequency, which can reduce the vibration amplitude by more than 98%. The system stability was checked by sudden suppressing one of the two cylinders, respectively. The sudden decrease in the vibration amplitude of the downstream cylinder had limited effect on the upstream cylinder. On the contrary, the sudden control on the upstream cylinder might cause transient fluctuations on itself and quickly disturb the flow field. The above efforts provided inspiration for FIV active control, and similar control principles have been used for vibration suppression of square columns (Rabiee et al., 2022).

Passive control methods, such as tripping wires, splitter plates, helical strakes, have been attempted to suppress the FIV of multiple cylinders arranged in tandem configuration. The study condition, suppression mechanisms and suppression effect of the various methods are summarized in Table 1. The tripping wires attached on the surface of cylinder could control the separation of the boundary layer and reduce the vibration of cylinders (Kim et al., 2009). The outer diameter of tripping wires is about 9% of the outer diameter of the cylinder, and the mounting angles are 20°, 30°, 40°, 45° and 60°, as shown in Fig. 3. For the FIV of two tandem cylinders with tripping wires, five regions, namely Region I ($1.1 \leqslant T/D < 1.2$), Region II ($1.2 \leqslant T/D < 1.6$), Region III ($1.6 \leqslant T/D < 3$), Region IV ($3 \leqslant T/D < 3.7$) and Region V ($3.7 \leqslant T/D \leqslant 4.2$) can be identified depending on the spacing ratio. When the mounting angles were 20° and 30°, the vibration of the two cylinders could be remarkably reduced in Regions II, III, and IV. At the above conditions, the shear layer of the upstream cylinder was attached to the downstream cylinder, and then they separated again without forming vortices. In Region I, the downstream cylinder formed vortices and generated significant vibrations, indicating that the tripping wires attached on the surface of downstream cylinder could not disturb the vortex shedding at small mounting angles. In Region V, vortices were generated from the upstream cylinder and impacted the downstream cylinder, resulting in the vibrations of the downstream cylinder. The vibration of the upstream cylinder was a feedback action of the behaviours of downstream cylinder, which led to the failure of vibration control. As for mounting angles of 40°, 45° and 60°, the tripping wires made the the shear layer deviate outward, increasing the lateral spacing between the two shear layers. Such shear layers crossed the downstream cylinder and formed Karman vortex street, leading to the divergent and unstable vibrations. Therefore, special attention must be paid to the installation angle of tripping wires to prevent unstable vibrations from occurring.

Some research works have paid attention to the FIV suppression effect of splitter plates. Sikdar et al. (2023) numerically studied the hydrodynamic features and wake patterns of two fixed rigid tandem cylinders attached with splitter plate. Two different configurations of splitter plates were examined: splitter plate attached to the upstream cylinder only and splitter plate attached to the downstream cylinder only. Four wake pattern types were observed depending on the spacing ratio and configuration of splitter plates. Type I was featured by the periodic vortex shedding behind the downstream cylinder and the form of a stable symmetric recirculation zone in the gap region. Type II was similar to Type I, but Type II formed a larger recirculation region with periodical variation. Type III appeared when the spacing ratio was larger than 5.0. The shear layer detached from the upstream cylinder did not reattach to the downstream cylinder, instead of rolling up in the gap region to form a vortex street. Type IV indicated the situation where the vortex shedding of the two cylinders were both suppressed. If the upstream cylinder was attached with splitter plate, Type IV occurred as the spacing ratio was larger than 3.5 and the splitter length was larger than $0.75D$. If the downstream cylinder was attached with splitter plate, Type IV occurred as the spacing ratio was larger than 3.5 and the splitter length was larger than $0.5D$. Lou et al. (2016) experimentally investigated the FIV response of two tandem cylinders with an isolated splitter plate. The variation of structural vibration strains was presented under different length of splitter plate and spacing ratio of cylinders. The splitter plate with a length of $1.0D$, $1.25D$ and $1.5D$, was beneficial to the reduction of strains as long as the spacing ratio was in the range of 4.0−8.0. The performance in CF direction was better than that in IL direction. The splitter plate suppressed the upstream cylinder better than the downstream cylinder. However, the splitter plate with a length of $0.5D$ could not effectively reduce the vibration strains. Zhao et al. (2023) numerically investigated the vibration of downstream cylinder with a splitter plate under the wake of a bare upstream cylinder. For the spacing ratios of 1.5 and 3.0, the vibration of downstream cylinder was suppressed at low reduced velocity. With increasing velocity, the downstream cylinder behaved like an isolated cylinder undergoing VIV. When the spacing ratio increased to 5.0 and 8.0, the vibration of the downstream cylinder was similar to galloping at high reduced velocity. The upstream vortex shedding resulted in a significant increase of the lift on the downstream cylinder. Two prominent peaks could be identified in the power spectrum of the lift. The lower peak generated by the reconnection of the separated shear layers was the main cause for the

Table 1 Suppression effect of FIV control methods for cylinders in various arrangement

Arrangement	Control method	Primary condition parameter	Suppression mechanisms	Suppression effect
Tandem	Tripping wires	Mounting angles 20°−60°, IL spacing ratio *T*/*D*=1.1−4.2, wire diameter 0.09*D*, *Re*=4365−7420. (Kim et al., 2009)	For mounting angles of 20°−30°, the shear layers separated from upstream cylinder reattach to downstream cylinder, without rolling up to form vortices, producing no vibration.	For mounting angles 20°−30° and *T*/*D*=1.3−1.8, suppression efficiencies exceed 81%.
	Single splitter plate	IL spacing ratio *T*/*D*=1.5−8.0, plate length 0.25*D*−2.0*D*, *Re*=100−6000. (Amini and Zahed, 2021; Lou et al., 2016; Sikdar et al., 2023; Zhao et al., 2023)	For small spacing ratios (*T*/*D*⩽3.0), the plate attached to the downstream cylinder can control the unsteady wake. For large spacing ratios (*T*/*D*⩾4.0), the plate attached to the downstream cylinder can control the unsteady vortex flow at large cylinder gaps. (Sikdar et al., 2023)	For *T*/*D*=4.0−8.0 and plate length 1.0*D*−1.5*D*, the suppression efficiencies of CF vibration strain range from 41% to 93%. The suppression effect of IL vibration is unstable. (Lou et al., 2016)
	Double splitter plates	IL spacing ratio *T*/*D*=4.0, plate length 0.4*D*−2.0*D*, angle between two plates=0°−90°, *Re*=4000−48000. (Assi et al., 2010; Hu et al., 2021)	The double plates can delay the interaction between the shear layers and form a cavity behind the cylinder resulting in weaker vortices. The suppression effect increases with the increasing of plate length and angle between two plates. (Assi et al., 2010; Hu et al., 2021)	For plate length 1.0*D*−2.0*D* and angle between two plates 30°− 90°, the suppression efficiencies range from 68% to 97%. (Hu et al., 2021)
	Helical strakes	Pitch/height=17.5*D*/0.25*D*, 10*D*/0.12*D*, 10*D*/0.15*D*, 10*D*/0.2*D*, strake number 3, IL spacing ratio *T*/*D* =1.5−8.0, *Re*=800−18720. (Blumberg et al., 2012; Korkischko and Meneghini, 2010; Li et al., 2020; Sukarnoor et al., 2022; Xu et al., 2018c)	The unsteady wake from upstream can interact with the downstream cylinder and enhance the response, which is the reason why the helical strakes cannot reduce the vibration amplitude of the downstream cylinder. (Korkischko and Meneghini, 2010)	The suppression efficiency of upstream cylinder can reach 80%. The suppression effect of downstream cylinder is unstable. For IL spacing ratio *T*/*D*=8.0 and pitch/height=17.5*D*/0.25*D*, the mean suppression efficiency in CF and IL vibration is 17% and 1.8%, respectively. (Xu et al., 2018c)
Side-by-side	Control rods	Mounting angles 90°−270°, CF spacing ratio *S*/*D*=2.5, rod diameter 0.25*D*, distance 1.0*D*, rod number=1−4, *Re*=200. (Hammad and Mohany, 2023)	Control rods can introduce stable biased flow, which results in reduction of lift of the two cylinders. Increasing the number of control rods is beneficial to the vibration suppression.	For mounting angles 135° and rod number 4, the suppression efficiencies of CF vibration amplitude can reach 87%.
	Splitter plate	CF spacing ratio *S*/*D*=3.5−7.0, plate length 0.5*D*−1.5*D*, *Re*=3750−6000. (Lou et al., 2016)	The splitter plates can delay the interaction between the shear layers and destroy the vortex generation.	For *S*/*D*=3.5−7.0 and plate length 1.0*D*−1.5*D*, the suppression efficiencies of CF and IL vibration strain are most in the range of 50%−96%. (Lou et al., 2016)
	Flexible sheets	CF spacing ratio *S*/*D*=1.1−4.2, sheet length 2.5*D*, *Re*=4365−74200. (Kim and Alam, 2015)	For *S*/*D*=1.9−4.2, the flexible sheet formed a semi-circular shape, which makes the sheet interact with both the inner and outer shear layers of the cylinders and weakened the vortex shedding.	For *S*/*D*=1.9−4.2, the suppression efficiencies of CF vibration amplitude can reach 90%. For *S*/*D*=1.1−1.2, the suppression effect is poor.
	Helical strakes	Pitch/height=17.5*D*/0.25*D*, strake number 3, CF spacing ratio *S*/*D* =3.0−8.0, *Re*=800−16000. (Jiang et al., 2021; Xu et al., 2020b)	The helical strakes not only make the vortex in the wake area become messy and unable to form a stable structured vortex, but also change the position of boundary layer separation point.	The mean suppression efficiency in CF and IL vibration are in the range of 83%−98% and 74%−96%, respectively. (Jiang et al., 2021; Xu et al., 2020b)
Staggered	Helical strakes	Pitch/height=17.5*D*/0.25*D*, strake number 3, CF spacing ratio *S*/*D*=3.0, IL spacing ratio *T*/*D*=8.0, *Re*=800−16000. (Xu et al., 2021a)	The reason why the downstream cylinder with helical strakes have large vibration amplitude is similar to that of the downstream cylinder of two tandem cylinder.	The suppression effect of downstream cylinder is unstable. The mean suppression efficiency in CF and IL vibration are both 52%. (Xu et al., 2021a)

vibration of the downstream cylinder. The peak generated by the upstream vortex shedding frequency was not consistent with the vibration of the downstream cylinder and contributed little to the vibrations. Amini and Zahed (2021) found that the two tandem cylinders attached with the splitter plate were prone to galloping when the spacing ratio was 3.0−5.0 and the length of the splitter plate was 1.0*D*−2.0*D*. Many wake patterns, such as P (pair vortices with oppose rotation)+S (sing vortex), 2P, 2D (double vortices with same rotation), T(triple-vortex group)+P, 2T, Q (quadruple-vortex group)+T, and 2Q, were observed when the galloping occurred.

The application of freely rotatable parallel plates can also serve for the FIV suppression of tandem cylinders (Assi et al., 2010), as shown in Fig. 4. The vibration of the upstream cylinder with two parallel plates was effectively reduced, meaning that the upstream cylinder can be regarded as a fixed cylinder. Hence, the upstream cylinder with two parallel plates was not allowed to move when the response characteristics of the downstream cylinder was studied. The two parallel plates could decelerate the interaction between the two shear layers trailing the cylinder and the formation of vortices. When only the upstream cylinder was furnished with the parallel plates, the parallel plates did not efficaciously impede the interaction between the upstream wake and the downstream cylinder, thus permitting the downstream cylinder to vibrate with considerable ampli-

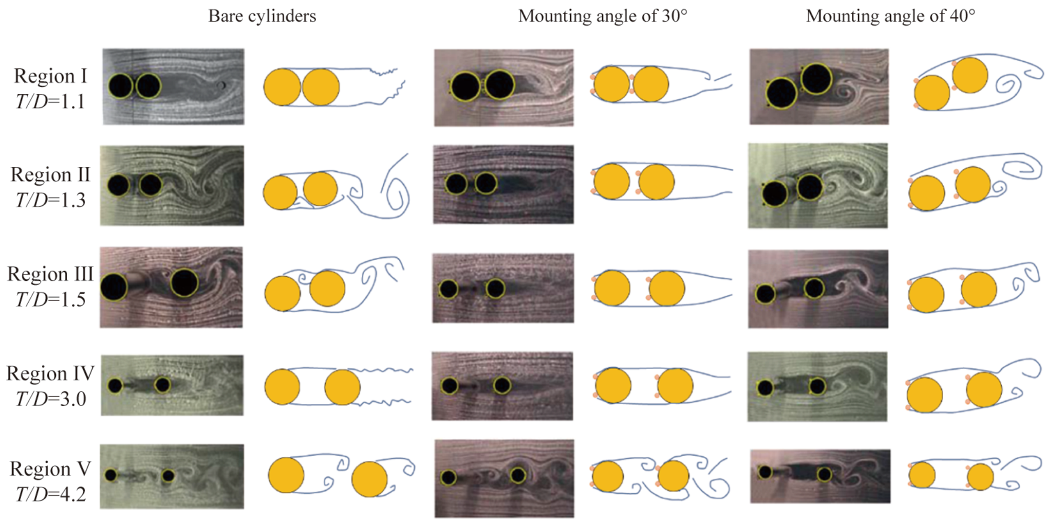

Fig. 3. FIV region of two tandem cylinders with tripping wires (Kim et al., 2009).

tude. Conversely, when the downstream cylinder was equipped with two parallel plates, the displacement of the downstream cylinder was effectively suppressed with the amplitude amounting to a mere 10% of that observed in a smooth downstream cylinder. The parallel plates on the downstream cylinder effectively attenuated the effect of the upstream vortex on the downstream cylinder. It is worth noting that the presence or absence of the parallel plates on the upstream cylinder only have a limited influence on the vibration suppression of the downstream cylinder. Hu et al. (2021) experimentally investigated the suppression effect of two unparallel plates on the FIV of two tandem cylinders. The angle between the two unparallel plates ranged from 0° to 60°, and the length of the plate ranged from 0.4*D* to 1.5*D*. The two unparallel plates had excellent suppression effect of the vibration of the downstream cylinder except for just one case where the angle was 0° and the plate length was 0.4*D*. The unsteady shear layer of the upstream cylinder was more likely to be weakened and destroyed by the two unparallel plates, which was beneficial to the response suppression caused by interaction between the upstream vortex and the downstream cylinder.

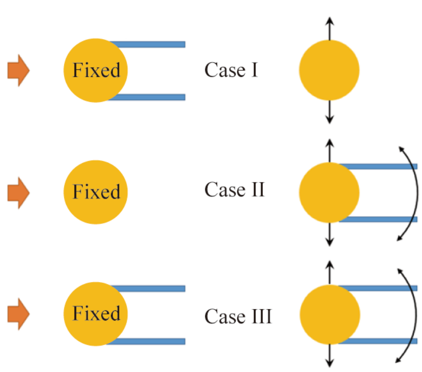

Fig. 4. Sketch of freely rotatable parallel plates (Assi et al., 2010).

Some studies have focused on FIV suppression effects of helical strakes. Blumberg et al. (2012) investigated the FIV response of an elastically-supported rigid cylinder with helical strakes under a wake flow of a fixed rigid cylinder. The height and pitch of the helical strakes was 0.12*D* and 10*D*, and the spacing ratio ranged from 1.5 to 4.0. The suppression efficacy underwent a gradual reduction with the increasing spacing ratios. The percentage reductions in vibration amplitude were 88.5%, 85.9%, 82.4%, and 80.2% for spacing ratios of 1.5, 2.0, 3.0, and 4.0, respectively. Korkischko and Meneghini (2010) considered the helical strakes with the height/pitch of 0.2*D*/10*D*. CF vibration displacement of the downstream cylinder with helical strakes attached to it showed a downtrend when the spacing ratio increased from 2.0 to 6.0. On the other hand, the spacing ratio had significant influence on the response frequency of the downstream cylinder. When the spacing ratios were 2.0 and 3.0, the response frequency remains locked at lower reduced velocity, subsequently increasing linearly along a trajectory parallel to $0.5f_{st}$ (where f_{st} denotes the vortex shedding frequency of a stationary cylinder). When the spacing ratio increased to 4.0, the response frequency underwent oscillatory increments, following the trajectories of $0.5f_{st}$ and f_{st} in an alternating fashion. As for spacing ratios of 5.0 and 6.0, no frequency locking appeared. The wake patterns of the downstream cylinder varied with the spacing ratios and the reduced velocities. At low reduced velocities, the shear layers exhibited pronounced interaction, accompanied by a strongly axial-correlated wake behind the cylinder. As for the spacing ratio of 2.0, the wake pattern transformed from two slightly separated shear layers to alternating vortices with the increase of the reduced velocities. The wake pattern transform was reversed for the case of large spacing ratios and high reduced velocities. Sukarnoor et al. (2022) experimentally studied the vibration response of two tandem cylinders when the helical strakes were installed on the upstream cylinder and the downstream cylinder, respectively. The height and pitch of the helical strakes were 0.15*D* and 10*D*, and the spacing ratio was 3.5. When the downstream cylinder with helical strakes was under the wake flow of a bare cylinder, the vibrations of the downstream cylinder showed small reduction due to the unsteady incoming flow caused by the wake interference. The helical strakes have good suppression effect under steady incoming flow, but worse suppression effect under unsteady incoming flow. If the vibration of the upstream cylinder was reduced by the helical strakes, the interaction between the upstream wake and the downstream cylinder was destroyed, which reduced the vibration of a bare downstream cylinder.

For the FIV suppression of two tandem flexible cylinders, the effectiveness of the helical strakes shows a declining trend. Li et al. (2020) investigated the FIV response of two tandem flexible cylinders with helical strakes with height 0.25*D* and pitch 17.5*D*. The aspect ratio (the ratio of length to diameter) of the cylinder was 111, and the spacing ratios were 4.0, 5.0, 6.0, and 8.0. The upstream vortex shedding could reattach the downstream cylinder with helical strakes and enlarge the lift as the spacing ratio was low. The intensity of gap flow decreased and thus led to a gradual decrease in lift, which made the effectiveness of the helical strakes begin rendering. Within the spacing ratio range of 4.0−8.0, the vibration displacement of the downstream cylinder with helical strakes decreased with the increasing spacing ratio. However, the upstream wake could trigger the wake-induced vibrations (WIV) of the downstream cylinder, reducing the suppression effect of helical strakes. On the other hand, the effect of the downstream cylinder with helical strakes on the bare upstream cylinder varied with the spacing ratio. For a low spacing ratio of 4.0, the upstream cylinder had low amplitude vibrations than an isolated cylinder, meaning that the downstream cylinder with helical strakes could suppress the vibrations of the upstream cylinder. As for spacing ratios of 5.0, 6.0 and 8.0, the vibration of the upstream cylinder was enhanced. The response frequency of the upstream cylinder was similar to that of an isolate cylinder, with the dominant frequency in IL direction doubling that in CF direction. It is important to underscore that the wake generated by the upstream cylinder exerted a discernible impact on the downstream cylinder with helical strakes. The response frequency of the downstream cylinder surpassed that of an isolated cylinder equipped with helical plates. In most flow cases, the dominant frequency in IL direction was equal to that in CF direction. Notably, when the spacing ratios were 5.0 and 6.0, the IL frequency experienced discontinuous jumps with the amplification of reduced velocity, leading to the IL dominant frequency being twice of that in CF direction.

For the flexible cylinders with a larger aspect ratio of 350, the FIV suppression efficiency of helical strakes experienced further attenuation (Xu et al., 2018c). When downstream cylinder with helical strakes was in the wake flow of a bare upstream cylinder, the influence of the downstream cylinder on the upstream cylinder was minimal at spacing ratio of 8.0, making the response of the upstream cylinder closely resemble that of an isolated smooth cylinder. The CF dominant mode of the downstream cylinder was slightly affected by the helical strakes, but the highest attainable vibration mode in IL direction was reduced. The vibration amplitude of the downstream cylinder with helical strakes was lower than that of a bare downstream cylinder, but still higher than that of an isolated cylinder with helical strakes. This outcome underscores the degradation in the suppression efficiency of the helical strakes applied in two tandem flexible cylinders. In CF direction, the suppression efficiency oscillated between 35% and 72%, with an average value of 57.47%. In IL direction, the suppression efficiency fluctuated from 50% to 90%, with an average value of 73.69%. A conspicuous peak in the displacement spectrum of the downstream cylinder was observed, signifying that the vibration energy of the downstream cylinder was still concentrated even after installing the helical strakes. When the upstream cylinder was equipped with helical strakes and the downstream cylinder had smooth surface, the highest order vibration mode of upstream cylinder was higher than that of an isolated cylinder with helical strakes, signifying that the presence of the downstream cylinder diminished the suppressive effect of the helical strakes on the upstream cylinder. The dominant mode of the bare downstream cylinder contrasted with the results observed in an isolated cylinder and two tandem cylinders, arising from the impact of the helical strakes on the upstream vortex shedding and consequently attenuating the influence of the upstream wake on the downstream cylinder. The vibration amplitude of the upstream cylinder closely approximated that of an isolated cylinder with helical strakes. However, as the reduced velocity escalated, the displacement amplitude of the upstream cylinder experienced a notable increase. The average suppression efficiency of the helical strakes in CF and IL directions was 88.64% and 82.29%, respectively. As the reduced velocity surpassed 17.5, the CF suppression efficiency regressed from 96% to 80% and the IL suppression efficiency regressed from 90% to 45%. When both the two cylinders were equipped with helical strakes, the highest mode number of the upstream cylinder decreased, and the displacement amplitude was commensurately reduced, resembling the response of an isolated cylinder with helical strakes. The displacement amplitude of the downstream cylinder surpassed that of an isolated cylinder with helical strakes. The suppression efficiency of the helical strakes on the upstream cylinder in both CF and IL directions reached 81.34% and 90.17%, respectively. However, the suppression efficiency on the downstream cylinder reduced to 16.55% and 1.79%, as shown in Fig. 5.

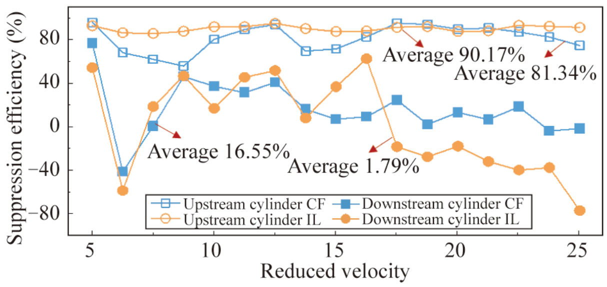

Fig. 5. Vibration suppression efficiencies of helical strakes on two tandem flexible cylinders (Xu et al., 2018c).

3 FIV control of multiple cylinders arranged in side-by-side configuration

Limited studies have been conducted one the FIV suppression of two side-by-side cylinders. Passive control methods, such as control rods, splitter plate, flexible sheets, and helical strakes, have been tried to suppress the FIV of multiple cylinders arranged in side-by-side configuration.

The effects of control rods near two side-by-side cylinders on vortex shed characteristics, fluid dynamics and vibration suppression were investigated by a numerical simulation at Re=200 (Hammad and Mohany, 2023). The spacing ratio of the two cylinders was fixed at 2.5, and the control rod with a diameter of 0.25D was installed at a distance of 1.0D from the center of the cylinder. The angular position of control rods ranged from 90° to 270° with an interval of 11.25°. The presence of control rods near two fixed side-by-side cylinders resulted in three wake flow patterns, as shown in Fig. 6. Pattern I appeared when one rod was installed near one cylinder in the range of 90°−101.25° and 258.75°−270°, causing the high intensity gap flow between the control rod and the cylinder. The wake generated by the rod was separated from the shear layer of the cylinder by the gap flow, and the shear layer intermittently disrupted the gap flow conversely, leading to a bistable flow featured by a narrow and wide wake from the rod. The wake of the cylinder far away from control rod was still not interrupted, but vortex street was deviated from the center of the two cylinders because the cylinder near control rod formed a wide wake. When the control rod was installed near one cylinder in the range of 112.5°−135° and 213.75°−247.5°, Pattern II was observed. The control rod made the shear layer of the cylinder drift in the wake and prevented the production of vortices generated by the interacting shear layers. A stable bias flow was observed, and the second shear layer of the cylinder and the

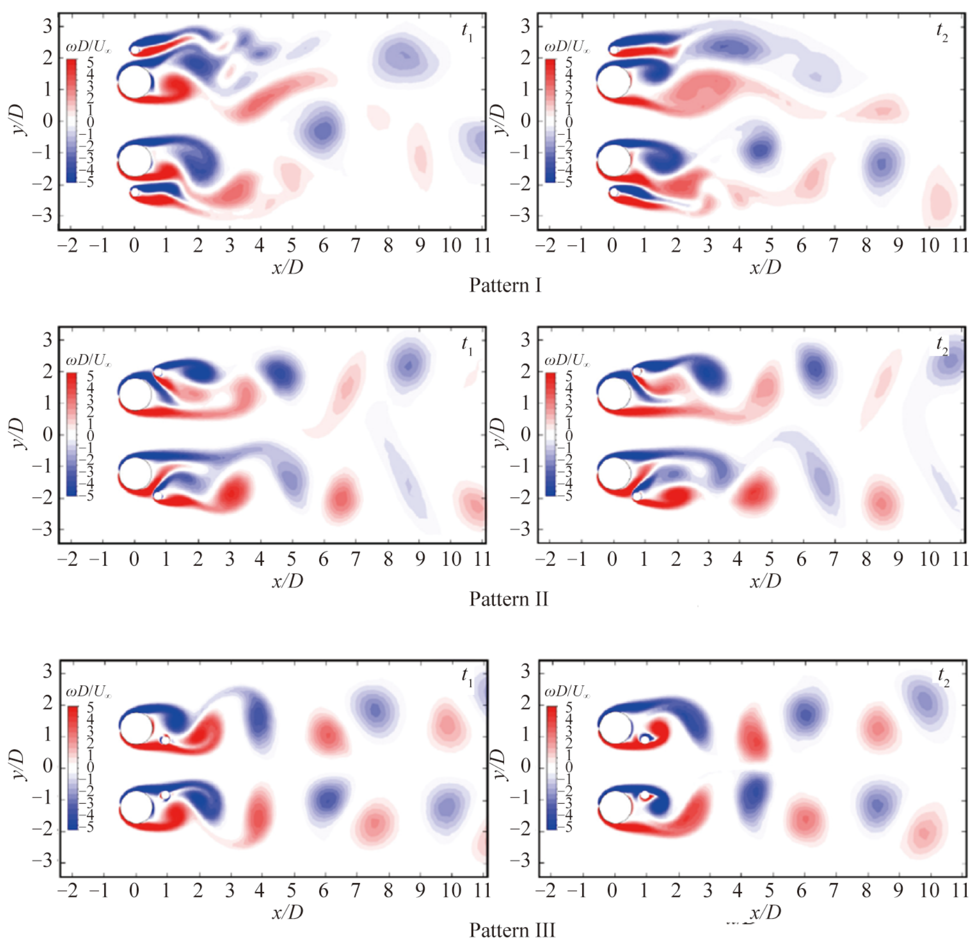

Fig. 6. Wake patterns of two side-by-side cylinders equipped with control rods (Hammad and Mohany, 2023).

outer shear layer of the control rod rolled over to generate vortices regularly. However, the vortex length was increased when the vortex shed from the combination body of the cylinder and control rod, which was accompanied with the increasing period of vortex shedding. Pattern III was observed when the installation angle was in the range of 146.25°−202.5°. The wake of control rod was completely immerged in the shear layers of the cylinder, leading to two distinct vortex sheets with large vortex length and low Strouhal number of the cylinder. The control rods had better performance for the reduction of drag coefficients and fluctuating lift coefficients for the entire range of installation angle. When the two-cylinder system was installed with no more than three control rods, the vibration lock-in region was expanded and the Strouhal number reached 0.2 after locking. For the one or two control rods configuration, the vibration of two cylinders was significantly suppressed in the unlock-in region, instead of lock-in region. For the four control rods configuration, the Strouhal number increased to 0.4, resulting a lock-in region at low reduced velocities. The vibration amplitudes of the two cylinders were significantly reduced, indicating that the control rods were effective in the FIV suppression of two side-by-side cylinders under the reasonable configuration of the control rods.

The splitter plates can also be employed to suppress the FIV of two side-by-side cylinders (Lou et al., 2016). The spacing ratio of the cylinders ranged from 3.5 to 7.0 and the length of the plates ranged from 0.5*D* to 1.5*D*. The splitter plate works by blocking the convergence point in the wake region and inhibiting the vortex shedding, or delaying it further downstream. For the splitter plate with a length of 1.0*D*, the reduction of the CF and IL vibration strains of the cylinders was significant for the entire range of spacing ratios. The splitter plate with a length of 0.5*D* had poor effectiveness on the suppression of the vibration of two side-by-side cylinders, with a reduction percentage being no more than 60% at most conditions. The effectiveness of the splitter plate with lengths of 1.25*D* and 1.5*D* was affected by the flow velocity and the spacing ratio. When the flow velocity was low, the suppression effectiveness maintained a steady level and showed slight fluctuation with the increasing spacing ratio. As the flow velocity increased, the suppression effectiveness generated fluctuations and decreased with the increase of spacing ratio. The vibration response of the two cylinders showed some differences at all the spacing ratio, indicating that the installation of splitter plate may disturb the coupled vibrations of two side-by-side cylinders.

It is evident that the implementation of a flexible sheet effectively suppresses FIV of two side-by-side cylinders (Kim and Alam, 2015), as shown in Fig. 7. The FIV response of two side-by-side cylinders can be classified as four types, namely Type I (spacing ratio of 1.1−1.2), Type II (spacing ratio of 1.2−1.9), Type III (spacing ratio of 1.9−3.1) and Type IV (spacing ratio of 3.1−4.2). The flexible

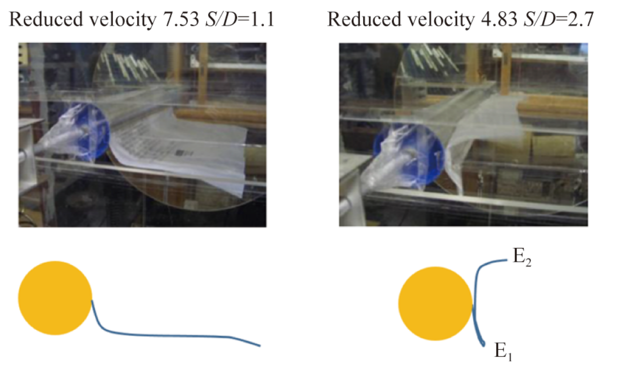

Fig. 7. Shape of the flexible sheet at the back of the two side-by-side cylinders (Kim and Alam, 2015).

sheet had limit suppression effect on the response Type I. Under the influence of the flexible sheet, the resonance region was extended and the maximum value of the vibration amplitude was reduced and reached at a higher velocity. However, the flexible sheet could be able to eliminate the response of Type III and Type IV, resulting from the interaction between the flexible sheet and the shear layers of the cylinders. At the spacing ratio of Types III and IV, the flexible sheet formed a semi-circular shape, which made the sheet interact with both the inner and outer shear layers of the cylinders and weakened the vortex shedding behind the cylinders. Importantly, due to the presence of gap flow between the cylinders, no contact occurred on the inner side of the folded flexible sheet positioned behind the two cylinders. When the suppression effect of the flexible sheet was less pronounced, the flow velocity on the outer side of the two cylinders was higher due to vortex shedding on their outer side. Consequently, the flexible sheet remained in closer proximity to the outer surface of the cylinder and failed to adopt a semi-circular shape, leading to less effectiveness.

Some studies have focused on the FIV suppression effect of helical strakes. Jiang et al. (2021) experimentally investigated the FIV response of the two side-by-side flexible cylinders with the spacing ratios of 3.5, 4.0, 5.0, 6.0 and 8.0. Just one cylinder was equipped with helical strakes with the pitch/height of 17.5*D*/0.25*D*. The response of the two cylinders exhibited significant mutual influence. The vibration amplitude of the bare cylinder could increase due to the wake interference effect when the reduced velocity was below 8.0. With the increase of flow velocity, the helical strakes could make the flow constantly deflect and disturb the wake flow around the bare cylinder, resulting in slight decrease of the vibration amplitude. The wake interference of the two cylinders weakened with the increasing spacing ratio, and the gap flow could generate high-momentum fluid that was beneficial to the excitation of high order vibration mode. For the cylinder with helical strakes, the CF vibration amplitude was much larger than that of an isolated cylinder with helical strakes. However, the growth trend of CF vibration amplitude was not monotonically increasing with the increase of spacing ratio. For the spacing ratio of 3.5, the CF vibration amplitude was higher than that in the other spacing ratio cases at most reduced velocities. The responses for the spacing ratios of 6.0 and 8.0 were slightly lower than that in the case of spacing ratio of 3.5. However, the responses for the spacing ratios of 4.0 and 6.0 were lower than those in other spacing ratio cases, but slightly higher than that of an isolated cylinder with helical strakes. The above phenomenon may be related to the different IL vibration responses at different spacing ratios. It was verified that the wake coupled effect existed between the bare cylinder and the cylinder with helical strakes. The vibration of the bare cylinder was in the lock-in region at reduced velocity of 3.0–8.0, making the cylinder with helical strakes vibrate at a nearly same frequency by the wake interference. The average suppression efficiencies of the CF vibration amplitude at spacing ratios of 3.5, 4.0, 5.0, 6.0 and 8.0 were 83.96%, 93.02%, 91.49%, 90.20%, 92.38%. The average suppression efficiencies of the IL vibration amplitude at spacing ratios of 3.5, 4.0, 5.0, 6.0 and 8.0 were 74.49%, 82.68%, 83.67%, 82.01%, 86.95%.

Xu et al. (2020b) investigated the FIV response of two side-by-side flexible cylinders that were both equipped with helical strakes, as shown in Fig. 8. The spacing ratio of the two cylinders was 3.0, and the pitch/height of the helical strakes was 17.5*D*/0.25*D*. The CF vibration amplitudes of the two cylinders were much lower than that of an isolated cylinder with helical strakes. For the isolated cylinder with helical strakes, the CF vibration amplitude exhibited two localized extreme values, which was not observed for the two side-by-side cylinders. The average suppression efficiencies of the CF vibration amplitude of the two cylinders were, 98.14% and 93.19%, respectively. It could be concluded that the CF vibration suppression efficiency of the two side-by-side cylinders increased at such a small spacing ratio of 3.0. For the IL vibration, one of the two cylinders behaved like an isolated cylinder with helical strakes. However, the other one had much larger IL vibration amplitude compared with the isolated cylinder with helical strakes. For this cylinder, the IL vibration amplitude experienced a substantial increase when the reduced velocity was below 10 and then decreased with the increase of the reduced velocity. The primary reason for these results was related to the wake interaction between the two cylinders. The average suppression efficiencies of the IL vibration amplitude of the two cylinders were 82.43% and 95.85% respectively. It is revealed that the IL vibration should be cautiously considered when the helical strakes was employed to suppress the FIV of two side-by-side cylinders at small spacing ratios.

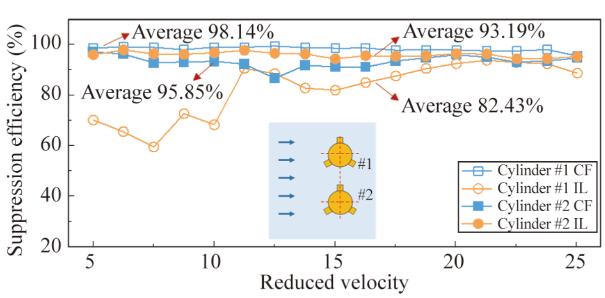

Fig. 8. Vibration suppression efficiencies of helical strakes on two side-by-side flexible cylinders (Xu et al., 2020b).

4 FIV control of multiple cylinders arranged in staggered configuration

Few studies have focused on the FIV control of multiple cylinders arranged in staggered configuration. Xu et al. (2021a) experimentally investigated suppression effects of the helical strakes on two staggered flexible cylinders. The helical strakes had a pitch/height configuration of 17.5*D*/0.25*D*. The CF and IL spacing ratios between the two staggered flexible cylinders were 3.0 and 8.0. Three configurations were considered, namely (I) the upstream cylinder with helical strakes and the downstream cylinder with smooth surface, (II) the upstream cylinder with smooth surface and the downstream cylinder with helical strakes and (III) both two cylinders with helical strakes, as shown in Fig. 9.

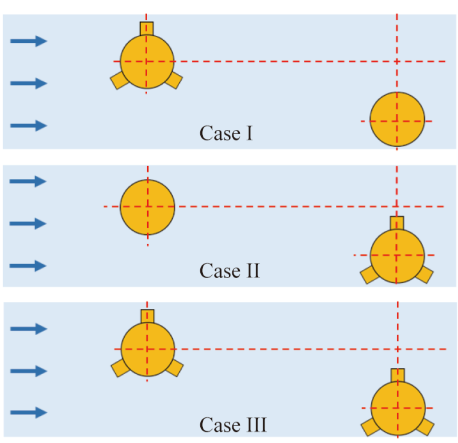

Fig. 9. Three configurations of two staggered flexible cylinders with helical strakes.

When the upstream cylinder was equipped with helical strakes and the downstream cylinder was smooth, the CF and IL vibration amplitudes of the upstream cylinder were similar to those of an isolated cylinder with helical strakes at the reduced velocity in the range of 3.76–21.29. As the reduced velocity increased to 22.55, the maximum root-mean-square (RMS) values of the CF displacement exhibited a slight rise and peaked at approximately 0.3*D*. The above phenomenon showed that the response of the upstream cylinder with helical strakes was minimally affected by the downstream cylinder with smooth surface. The CF vibration amplitude of the bare downstream cylinder essentially agreed with that of an isolated bare cylinder. At some specific reduced velocities, the maximum RMS displacement of the downstream cylinder surpassed that of an isolated bare cylinder, with the maximum value reaching around 1.77*D*. For the IL vibration, the maximum RMS displacement of the downstream cylinder experienced a nearly monotonic growth within the reduced velocity range of 3.76−16.28. The peak value was reached at the reduced velocity of 16.28, with a corresponding maximum RMS displacement of 1.33*D*, approximately three times that of an isolated bare cylinder. It seems that the upstream cylinder with helical strakes could elevate the vibration magnitude of the bare downstream cylinder, which needs cautious attention. The average suppression efficiencies of the helical strakes in the CF and IL vibration amplitudes were 83.9% and 90.4%, respectively. Compared with suppression of an isolated cylinder, suppression efficiency of the helical strakes was slightly reduced. Notably, when the reduced velocity surpassed 20, the suppression efficiency experienced a pronounced decrease in both CF and IL directions. This phenomenon underscores the significant influence of the bare downstream cylinder on the wake flow of the upstream cylinder with helical strakes, further affecting the response of the upstream cylinder and diminishing the suppression effect of the helical strakes.

When the upstream cylinder was smooth and the downstream cylinder was equipped with helical strakes, the vibration behaviour of the bare upstream cylinder showed some differences from that of an isolated cylinder. The maximum RMS value of the CF displacement of the upstream cylinder was 1.40*D*, and then decreased to 0.8*D* within the reduced velocity range of 22.55−23.8, instead of being locked as an isolated smooth cylinder. When the reduced velocity reached 25.05, the CF vibration displacement of the upstream cylinder increased to the levels exceeding that of the isolated cylinder. It is verified that the wake flow of the upstream smooth cylinder could be influenced by the downstream cylinder with helical strakes, leading to a delay of the lock-in region. For the downstream cylinder with helical strakes, the CF vibration amplitude showed good agreement with that of an isolated cylinder with helical strakes within the reduced velocity range of 3.76−8.77. As the reduced velocity increased, the CF vibration amplitude of the downstream cylinder with helical strakes gradually rose and reached a peak value of 0.54*D*, nearly doubling the maximum RMS value of the isolated cylinder with helical strakes. The findings indicated that the influence of the upstream vortex diminished the suppression effect of the helical strakes on the CF vibration of the downstream cylinder. The IL vibration amplitude of the upstream cylinder significantly exceeded the results of an isolated smooth cylinder. Within the reduced velocity range of 8.77−12.52, the IL maximum RMS displacement of the upstream cylinder reached 0.76*D*, nearly twice the value observed under corresponding conditions for the isolated smooth cylinder. The variation of the IL displacement of the downstream cylinder with helical strakes was similar to that of the CF displacement. At low reduced velocities, the IL displacement amplitude approximated that of the isolated cylinder with helical strakes, but the IL displacement amplitude gradually augmented as the reduced velocity increased. Compared with the vibration suppression of an isolated cylinder, the suppression efficiency of the helical strakes on the downstream cylinder showed a decreasing trend. The average suppression efficiencies in the CF and IL displacement amplitude were 77.9% and 79.1%, respectively. As the reduced velocity increased to 25.05, the suppression efficiency in both CF and IL directions dropped to approximately 40%, indicating that the wake flow of the upstream smooth cylinder exerted a negative impact on the suppression effect of helical strakes on the downstream cylinder.

When the two cylinders were both equipped with helical strakes, the displacement amplitude of the upstream cylinder closely resembled that of the isolated cylinder with helical strakes at low reduced velocities. As the reduced velocity increased to around 20, the displacement amplitude began to deviate from that of the isolated cylinder with helical strakes and increased to a peak value of 0.44*D*. The CF maximum RMS displacement values of the downstream cylinder were positioned between that of the upstream cylinder with helical strakes and that of the isolated smooth cylinder. The CF RMS displacement values of the downstream cylinder reached a peak of 0.75*D* at reduced velocity of 25.05. The IL maximum RMS displacement values of the upstream cylinder and the downstream cylinder were 0.08*D* and 0.23*D*, which were much larger than the result of 0.03*D* observed for the isolated cylinder with helical strakes. The presence of helical strakes yielded a discernible restraining influence on CF and IL vibrations of both the two staggered cylinders. However, the complex wake interference between the upstream cylinder and the downstream cylinder made a notable reduction in the suppression efficacy of helical strakes when the cylinders were positioned in a staggered configuration. For the isolated cylinder with helical strakes, the averaged suppression efficiencies in the CF and IL vibration amplitude were 91.5% and 94.6%, respectively. For the upstream cylinder with helical strakes, the suppression efficiencies in the CF and IL vibration amplitudes were slightly decreased to 79.6% and 88%, respectively. Due to the wake flow of the upstream cylinder, the suppression efficiency in the CF and IL vibration amplitude of the downstream experienced considerable fluctuations and a notable decline. The CF suppression efficiency exhibited a gradual decrease with the increasing reduced velocity. The maximum value, approximately 86.4%, was reached at reduced velocity of 3.76, while the minimum value, around 12.4%, was encountered at reduced velocity of 25.05. The average suppression efficiency in CF vibration was 52.1%.

The average value and the minimum value of suppression efficiency in IL vibration were 52.6% and 6.4%, indicating that the upstream vortex had significant effect on the suppression efficiency of the helical strakes, as shown in Fig. 10.

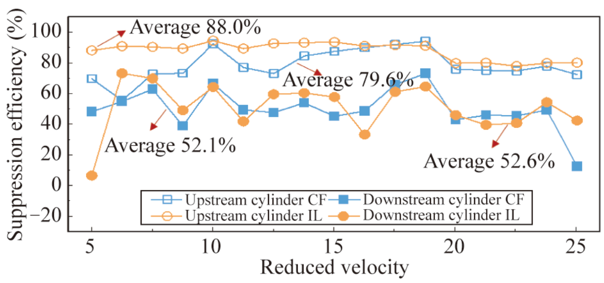

Fig. 10. Vibration suppression efficiencies of helical strakes on two staggered flexible cylinders (Xu et al., 2021a).

5 Concluding remarks

The FIV of multiple cylinders may cause serious fatigue damage on structures, which is one of the major concerns in many engineering applications. The FIV vibration control methods, such as helical strakes, splitter plates, control rods, flexible sheets, were reviewed to check the FIV suppression effects. The FIV response, hydrodynamic features, wake modes of two cylinders with vibration control devices arranged in tandem, side-by-side and staggered configuration were summarized.

(1) In the study of FIV control of multiple cylinder system, active control methods have attracted little attention. Some active control methods, such as boundary control, blowing, suction, rotation of control rods and traveling wave wall, have been verified to be useful for the vibration suppression of an isolated cylinder. These active control methods are worth further investigating to check the vibration suppression effect on multiple cylinder system undergoing FIV.

(2) The suppression effects of some passive control method, such as helical strakes, control rods, flexible sheets, splitter plates, have been studied when these methods are used for the FIV suppression. However, the passive control methods are transplanted on the FIV suppression from the vibration suppression of an isolated cylinder undergoing VIV. Some methods may have negative effects and should be chosen carefully. The configuration and parameters are not redesigned, and it cannot be proved that the method is not applicable when the configuration and parameters are not optimized. It is still very important to optimize the passive control device based on the FIV mechanisms.

(3) In the previous research about the FIV suppression of multiple cylinders, some simplified ideal conditions are set. In practical engineering, the environmental conditions of multiple cylinder system are very complex, which introduces many influences on the vibration suppression. More comprehensive configuration parameters of the multiple cylinder system, such as the number of the cylinder, the spacing ratio, the aspect ratio, the arrangement geometrical shape, are worth further studying. More complex incoming flow conditions and more effects of the structural flexibility should also be considered to improve the FIV suppression efficiency.

Competing interests

The authors declare no competing interests.

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