Ain Shams Engineering Journal 13 (2022) 101502

Contents lists available at ScienceDirect

Ain Shams Engineering Journal

journal homepage: www.sciencedirect.com

Mechanical Engineering

The effectiveness of helical strakes in suppressing vortex-induced vibration of tandem circular cylinders

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ARTICLE INFO

Article history:
Received 21 August 2020
Revised 26 January 2021
Accepted 21 May 2021
Available online 05 June 2021

Keywords:
Vortex-induced vibration
Rigid cylinders
Helical strakes
Suppression

ABSTRACT

An experiment study of vortex-induced vibration (VIV) of two rigid cylinders equipped with and without helical strakes (pitch of 10.0*D* and height of 0.15*D*) in a tandem configuration was investigated at a critical spacing distance of 3.5*D*. Here, the cylinders were attached to a structural test rig, which would allow them to oscillate in the cross-flow direction only. The oscillation amplitude and frequency data were collected. Accordingly, the results revealed that in the case of the two bare cylinders, the amplitude response of the upstream cylinder was higher compared to the case of single cylinder usage. Furthermore, outcomes obtained confirmed that the helical strakes successfully reduced the oscillation amplitude for the upstream and downstream cylinders both, whereas they were ineffective if merely applied at the downstream cylinder. Hence, it can be concluded that the arrangement of the strakes influences the VIV suppression in the context of two-cylinder cases.

1. Introduction

The marine riser is a piece of highly important equipment to connect a subsea wellhead to a floating drilling platform in oil and gas delivery. In the deepwater area, these risers are exposed to vortex-induced vibration (VIV) due to sea waves and current, thus potentially resulting in their structural failure. Accordingly, the VIV emerges when fluid flows through a bluff body, following which an alternating vortex is formed behind the structure and generates the vibration [1]. Then, it produces a large-amplitude vibration during the lock-in resonance phenomenon and accelerates the fatigue damage process encountered by the structure [2]. Hence, the damage occurring to the risers become a topic of serious concern as it will increase the economic losses, cause water pollution due to the oil spill, and lead to other incidents.

Furthermore, the usage of multiple risers during the production works may worsen the VIV situation, wherein it is preferable for their arrangement to be proximity for the purpose of utilising the available subsea space. However, the operation of multiple risers may cause the VIV and the risk of riser collision due to the interaction occurring between the structure and the unpredictable flow environment [3]. Therefore, many researchers have conducted various investigations on the VIV phenomenon for cylinders in order to identify the solutions for a minimised structure vibration. Nevertheless, the studies delineating flow around multiple rigid cylinders are still limited in number due to the complexities behind their responses in comparison with a single-cylinder structure [4]. In particular, most of the prior works on VIV have frequently emphasised the single-cylinder context without involving the effect of flow interferences. In contrast, multiple cylinder-based study can be characterised by the work of Zdravkovich [5], which has reported that the three possible cylinder arrangements in a fluid flow, namely in tandem, side-by-side, and staggered.

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Peer review under responsibility of Ain Shams University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.asej.2021.05.016
2090-4479/

The scholar has further proposed [5] that "when more than one bluff body is placed in a fluid flow, the resulting forces and vortex shedding pattern may be completely different from those found for a single body, even at the same Reynold numbers". Besides, the author has underlined the strong dependence of the flow interference between two cylindrical structures on the arrangement, spacing distance, and number of cylinders present in the cluster. Accordingly, the oscillation of one cylinder can strongly influence the response of other cylinders in the flow. For this present study, the study is focused on the flow interaction from the fundamental perspective, namely by considering two cylinders in the tandem arrangement.

Furthermore, the importance of understanding the interaction of multiple cylinders in flow to identify the problem leading to the risk of collision and damages cannot be denied. In line with this, several researchers have attempted to investigate the vibration behaviour of two cylinders arranged in the tandem configuration. For example, Prasanth and Mittal [6] have opted to numerically compare the vibration response of two tandem cylinders against a single cylinder, wherein the authors have observed the larger oscillation amplitude of the upstream cylinder than in the case of a single cylinder. Meanwhile, the downstream cylinder experiences a very large oscillation amplitude, whereby its value is almost twice to that of the upstream cylinder. Meanwhile, Qin et al. [7] have experimented on the flow-induced vibrations of two tandem cylinders having different natural frequencies. Their findings have led to their claims that the variations of natural frequency may emerge as a technique to suppress the vibration of multiple cylinders.

Moreover, Huang and Herfjord [8] have performed an experiment using two elastically supported rigid circular cylinders that are free to vibrate in the in-line and cross-flow directions at various tandem and staggered configurations. Accordingly, the authors have varied the spacing and cross-flow distances from 2.0 to 5.0 diameters and 0 to 2.0 diameters, respectively, (where *D* is the diameter of a circular cylinder) revealing that the upstream cylinder response is not influenced by the downstream cylinder if they are placed in tandem at the spacing distance greater than three diameters. Besides, Zdravkovich [9] has described that in the case of spacing distance exceeding four diameters, the downstream cylinder effect towards the upstream cylinder becomes remarkably weakened and insignificant. In line with the above, Assi [10] has also investigated the issue by using rigid cylinders at a spacing distance exceeding four diameters, wherein the author notes that the upstream cylinder is not influenced by a fixed or moveable downstream cylinder. According to the study of Korkischko and Meneghini [11], moreover, as the spacing distance is increased, the response of the downstream cylinder becomes similar to a single-cylinder case. In addition, Alam et al. [12] have studied the vortex formation of cylinders in a wind tunnel at different spacing distances, thus showing that the cylinders would form vortices individually beyond the critical spacing distance. The authors have also revealed that the fluctuating lift and drag forces are highly influenced by the spacing distance between the cylinders; in particular, the fluctuating force value at a spacing distance of 1.4 is reportedly larger than that at a critical spacing distance.

From another perspective, Mysa et al. [13] have stated that the critical spacing distance for two tandem cylinders occurs somewhere between 3.5*D* and 5.0*D*, whereas Ishigai et al. [14] have reported the presence of a critical spacing distance at 3.8*D* in which a 'jump' would occur in the context of Strouhal number and both base pressures. Following this, Zdravkovich and Pridden [15] have extended the work to identify the effect of two cylinders on the mean pressure and drag forces, thereby revealing that the gap pressure coefficient is increased to a significantly higher value at the critical spacing distance. Meanwhile, Assi et al. [16] have undertaken an experimental investigation of the VIV for two rigid circular cylinders that are in tandem. Here, the downstream cylinder is free to move in the cross-flow (CF) direction, while the upstream cylinder is kept fixed. As a result, the authors have only discussed the downstream response, thus reporting that the critical spacing distance occurs at 3.0*D*; in particular, the peak amplitude of the downstream cylinder is higher by 50% compared to the oscillation amplitude of a single cylinder. Accordingly, similar results have also been obtained by Korkischko and Meneghini [11]. Furthermore, the works of Meneghini et al. [17] and Haider and Sohn [18] have also underlined their large amplitude response at the critical spacing of 3.5*D* through the respective numerical studies employing a low Reynolds number, *Re*. Meanwhile, Papaioannou et al. [19] have noted that the spacing distance of 3.5*D* is very close to the critical spacing distance in the case of smooth multiple cylinders, whereas the numerical study by Ding et al. [20] has reported this value as the critical spacing distance for two cylinders that are in tandem at a larger *Re* value. Therefore, it is believed that in the case of this spacing distance, a significant influence on the flow pattern surrounding the cylinders is observed due to VIV and the flow interference. This leads to establishing the VIV phenomenon at a critical spacing distance as the focus of the experiment in the present study.

Despite the number of experimental studies previously carried out regarding the VIV of single and two-tandem cylinders, little attention has been given on the procedures for its control in the case of multiple cylinders. In particular, the suppression of VIV for a bluff body is known as one of the most active topics for research and patenting in fluid dynamics over many decades due to its significance in engineering application. In controlling the VIV, it can be categorized into two types, active and passive control. Active control techniques use the input of external energy, which are injected into the control system to control the vortex shedding and reduce the structural vibration. Recently, Liu et al. [21] have reported the usage of water jetting active vibration suppression device for a vertical riser in a wave-current flume. The device has shown 92% of suppression efficiency. Zhu et al. [22] have used a pair of air jets on a circular cylinder at low Reynolds number while Chen et al. [23] have used a suction flow method on the lower side of a circular cylinder to reduce VIV. Both studies have reported excellent effectiveness of the devices in reducing the amplitudes of cylinder vibrations. In the case of multiple cylinders, Rabiee and Esmaeili [24] have studied the performance of active fuzzy proportional-integral-derivative (PID) controller for their cylinders. The PID controller has found to be able to reduce the transverse amplitude of both upstream and downstream cylinders by as much as 99.9% and 98.7%, respectively.

Passive flow control techniques are normally operated by placing the control devices around the cylinder, altering the structure shape, or adding the control device on the structure. This technique can prolong the length of the vortex or destroy the formation of vortices, change the vortex shedding frequency and weaken the hydrodynamic forces. Passive control device is commonly used due to low manufacturing cost, simple manufacturing process and installation. Chen et al. [25] have proposed a passive-jet flow control in reducing the amplitude and frequency in the lock-in ranges. The authors have suggested that the reduction of effectiveness is due to the spacing increment of the adjacent passive jet pipes. Liang et al. [26] have used splitter plates to control VIV. They have discovered that the vibration can be well-controlled with splitter plate's length which is less than 1.1*D*. Li et al. [27] have studied on the effectiveness of bird-wing-shaped suppression device for cylinder. The device has found to be able to operate very effectively depending on the streamer length. Lou et al. [28] have also performed a suppression device study on two cylinders using splitter plate. They have concluded that the VIV suppression is highly dependent the splitter plate arrangements. Assi et al. [29], on the other hand, have studied the usage of free-to-rotate (f-t-r) control plates for tandem cylinders. The f-t-r has found to reduce the VIV of cylinders with a substantial drag reduction.

Among all of the passive suppression devices available, helical strake is one of the most commonly implemented devices for riser [30]. In general, previous researchers have mainly focused on its performance in the context of an isolated rigid or flexible cylinder. For example, in a recent study by Li et al. [2], a type of discrete helical strake on a long riser model under uniform flow have been proposed. By using the proposed control device, the authors have observed the vortex formation has been disrupted into multiple directions, which destroyed the spatial correlation of the vortex from multiple dimensions and hence, altered the distribution of the original pressure field. The suppression efficiency of 93.98% has been achieved for discrete spacings of 0.52*D*. Quen et al. [30] have investigated the VIV of a long flexible cylinder, which yields information that the strakes with pitch = 10.0*D* and height = 0.15*D* are their most effective arrangement. Meanwhile, a numerical investigation by Ranjith et al. [31] on a single rigid circular cylinder and employing the same strake pitch and height as Quen et al. [30] has revealed that the helical strake suppresses the vortex shedding by about 99%. However, the strakes had a higher drag coefficient compared to a smooth rigid cylinder, which is similar to the result of helical strakes utilising the pitch = 10.0*D* and height = 0.1*D* as reported by Huang and Sworn [32]. Moreover, Sui et al. [33] have opted to vary the height, pitch, coverage, and cross-section of the helical strakes for their rigid cylinder experiment, thus underlining the large-mass damping cylinder fitted with the helical strake of pitch = 5.0*D* and height of 0.14*D* ("D"-type) as the most effective strakes for VIV suppression.

The efficiency of suppression device achieved by a single elastically mounted isolated cylinder does not promise the same result in the case of multiple cylinders. Huang and Sworn [32] have investigated the hydrodynamic coefficients of two fixed rigid cylinders in both tandem and staggered configurations. As a result, they have discovered that the drag and lift coefficients of the straked cylinders are the same as fixed smooth cylinders. Hydrodynamic properties of multiple smooth cylinders in tandem configuration have been investigated by Lin et al. [34]. A forced vibration experiment has been carried out on a fixed upstream and downstream rigid cylinder movable in CF direction. The finding has shown that the mean drag coefficient, C_d of a downstream cylinder in the wake of upstream cylinder has been dramatically reduced compared to a single cylinder. Similar results of the negative C_d has been also reported by Bokaian and Geoola [35]. Wang et al. [36] have made a comprehensive review on flow-induced vibration of a single and multiple cylinders. In the study, helical strakes have found to be able to reduce the vibration amplitude but increase the drag coefficient due to the large wake deficit behind the oscillating structure.

Korkischko and Meneghini [11] have conducted their VIV experiment by using rigid cylinders in the tandem configuration and varied the strake pitches and heights accordingly. Subsequently, the outcomes obtained showed that the downstream cylinder fitted with the strakes of pitch = 10.0*D* and height = 0.2*D* in the wake of an upstream fixed smooth cylinder lost its effectiveness. Contrarily, works implementing multiple cylinders and using flexible straked cylinders have also been found. For example, a recent work by Xu et al. [37] has focused on the suppression of flow-induced vibration (FIV) for two flexible cylinders attached to a different helical strake arrangement. Following this, the scholars have noted the poor strake performance of the downstream cylinders at the selected spacing of 8.0*D*. To the best knowledge of the authors then, discussion concerning the upstream rigid cylinder responses has yet to be positioned despite a detailed discourse of both cylinder responses being highly crucial in understanding VIV-focused studies.

In addition, further investigations on reducing the VIV of two rigid cylinders using strakes are sorely needed and require further exploration due to the insignificant attention funnelled to the interaction of two cylinders fitted with a helical strake. According to Huang and Sworn [32], the relationship between a pair of cylinders fitted with helical strakes remains an open question and demands detailed investigation for a better understanding of the underlying mechanism. Besides, data for cylinder responses towards VIV at a critical spacing distance for a different helical strake arrangement in a rigid cylinder has yet to be found in the current literature. These data are crucial to the offshore engineers to predict the VIV phenomenon in a critical condition. Hence, the present study is highly emphasising the relationship between an adjacent bare/straked cylinder towards the VIV at a critical spacing in the tandem configuration.

2. Material and methods

This experiment was conducted in the water flume of the National Hydraulic Research Institute of Malaysia (NAHRIM), whereby the cylinders were tested in the flume that was 50.0 m long, 0.75 m wide, and 0.70 m deep. The designed water level was kept at 0.3 m and the water flume pump generated a uniform flow from 0.1 m/s to 0.6 m/s at an interval of 0.03 m/s and the resulting Reynolds number, *Re* ranging from 3120 to 18720. Besides, the flume operated at a low turbulence intensity, *Ti* around 1.9% at an inflow velocity of 0.3 m/s.

Table 1 lists the key parameters in the experiment. The rigid polyvinyl chloride (PVC) cylinders had an immersed length of l = 270 mm and diameter D = 25 mm, resulting in an aspect ratio of 10.8. Accordingly, the bare cylinder mass ratio is defined as $m^* = 4m/\pi\rho D^2 l$ is 0.69, where m is the cylinder mass and ρ is the fluid density. The structural damping coefficient in air ζ = 0.0954 led to a mass-damping parameter $m^*\zeta$ = 0.06678. The mass per unit length of the bare cylinder model, including the ball bearing block and shaft, was m_b = 0.34 kg/m, while the mass per unit length of the straked cylinder was 0.42 kg/m.

Fig. 1 shows the experimental rig for the present study, whereby the design is in reference to the work of Shaharuddin and Darus [1]. Here, the cylinder was attached vertically to the linear motion ball bearing block with a shaft to allow motion only in a direction transverse to the flow. It was supported by four springs at each side and its bottom ends had a spacing of 30 mm above the flume bottom. Then, the triaxial accelerometers (Dytran) with sensitivity of 10.02 mV/g were attached to the upper part of the cylinder, which was above the water level, to measure the displacement and frequency responses. The sampling rate was 200 Hz.

The strakes attached to the cylinder were made of rubber and designed to have a three-start helical. Here, the helical strakes with

Table 1
Model parameter.

Outer diameter (D)	25 mm
Inner diameter (d)	23 mm
Submerged length (L)	270 mm
Total length (l)	580 mm
Aspect ratio (L/D)	10.8
Spring stiffness (k)	26.93 N/m
Total mass of a cylinder including ball bearing block and shaft (m)	0.199 kg
Mass per unit length of bare cylinder (m_b)	0.34 kg/m
Mass ratio (m^*)	0.69

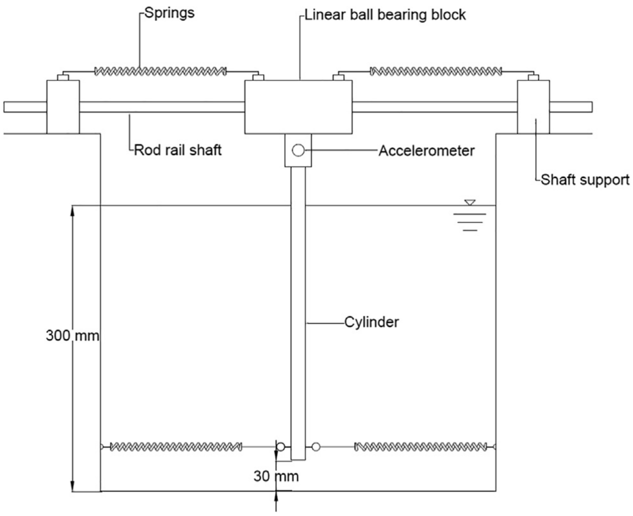

Fig. 1. Schematic of the experimental setup.

a pitch of 10.0*D* and height of 0.15*D* were chosen in consideration of their effectiveness for suppression in view of the experiment conducted by Quen et al. [30] and the numerical study by Ranjith et al. [31]. In the interference test, the upstream and downstream cylinders were elastically mounted, whereby they were either with or without a strake. This investigation implemented the tandem configuration of the cylinder at a spacing distance $S/D = 3.5$ (Fig. 2).

The value of spacing distance was chosen in this experiment as a result of the critical oscillations that occurred following the reports in previous studies [18,20]. To further investigate the suppression performance by using a helical strake, a different arrangement for the structure was implemented. The helical strake arrangement and its details are shown in Fig. 3.

3. Results and discussion

The dynamic responses of the models in this study were presented in terms of the nondimensional amplitude ratio, $A^* = A_y/D$, and the non-dimensional frequency ratio, $f^* = f/f_n$, which were plotted against the reduced velocity ($V_r = u/f_nD$). The amplitudes were then calculated using the average value of 10% highest peaks for each test, which was the same technique utilised by Korkischko and Meneghini [11].

3.1. Single circular cylinder

In this subsection, the dynamic responses of a single rigid cylinder without helical strake is presented as a basic comparison and for the purpose of validating the experimental method. Free decay test in water was carried out and a natural oscillation frequency, $f_n = 2.72$ was thus obtained from the test. A close agreement of only 2.8% deviation was found between the measured f_n and theoretical f_n values. The theoretical f_n is calculated as follows:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k_{Total}}{m_{Total}}} \tag{1}$$

where k_{Total} is the total spring stiffness of the system and m_{Total} is the total mass of the structure. The reduced velocity, V_r range extended to a maximum value of 8.5 is calculated by incorporating the value of f_n into the equation.

Fig. 4 presents the amplitude response of a single cylinder that is free to oscillate in the cross-flow direction, whereby the amplitude response of a circular cylinder reported by Korkischko and Meneghini [11], Khalak and Williamson [38], and Franzini et al. [39] are also represented in the graph. Based on the figure, a good match was obtained against the previous results and the typical three branches of responses could be observed. In particular, the initial, upper, and lower branches are especially well-known from the literature involving low mass-damping system [11,29,40]. Furthermore, the synchronisation range could be clearly seen in the graph; due to the higher damping of the present experimental rig compared to the three correlated works [11,38,39], the amplitude started to increase at $V_r \approx 5.0$ and contributed to a slower lock-in region. Because of the occurrence of the slower lock-in region, the lock-out is came in late also at $V_r \approx 7.6$, as shown in Fig. 4. This finding is in fact consistent with the earlier studies carried out by Govardhan and Williamson [41], Martin and Avila [42] and Soti et al. [43] where high damping postpones the occurrence of lock-in and lock-out. Here, the amplitude response reached its peak value of 0.89 at $V_r = 7.2$ in the upper branch, whereby further increments of the V_r resulted in the amplitude response switching to the lower branch.

Moreover, it should be noted that the Strouhal number, $St = (f_sD/u)$, where f_s is referred to as the vortex shedding frequency, in this experiment as obtained via a linear fit is similar to those shown by Rahman et al. [44], namely 0.1534 (Fig. 5). Here, the Strouhal number is smaller than 0.20 as reported by Williamson and Govardhan [40] due to extremely low cylinder aspect ratio used in this experiment [45]. Fig. 5 shows the CF vibration

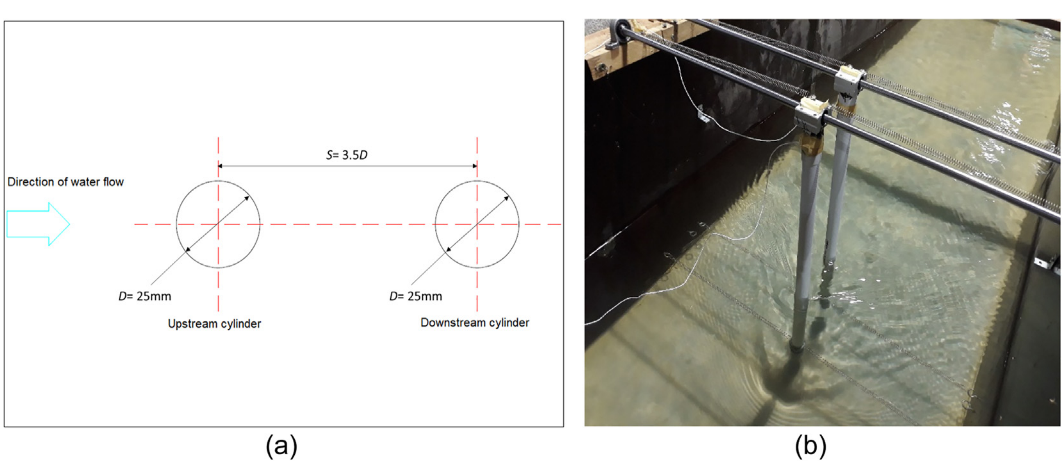

Fig. 2. (a) Schematic diagram of the cylinder arrangement; (b) the experimental set up of the cylinder in the tandem.

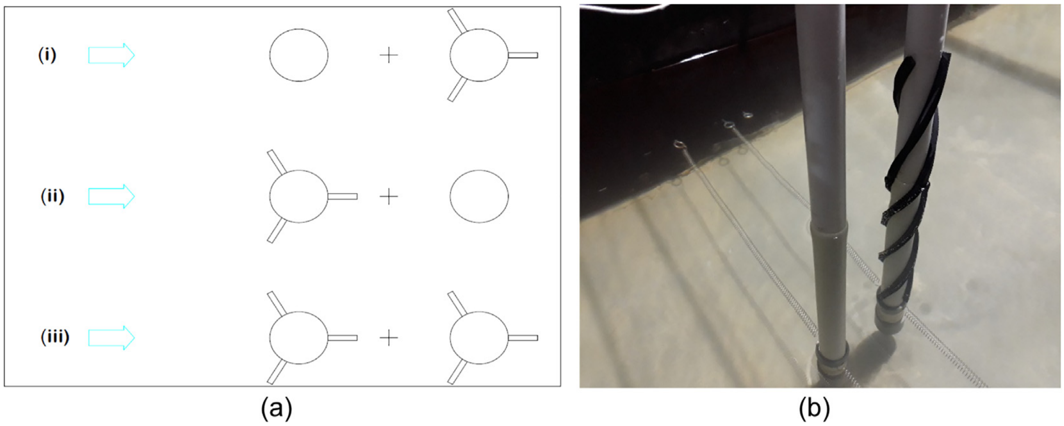

Fig. 3. (a) Helical arrangement of two tandem cylinders: (i) Upstream (Bare) and Downstream cylinder (with helical strake); (ii) Upstream (with helical strake) and Downstream cylinder (Bare); and (iii) Upstream (with helical strake) and Downstream cylinder (with helical strake), (b) Example of helical strake installation for Arrangement (i).

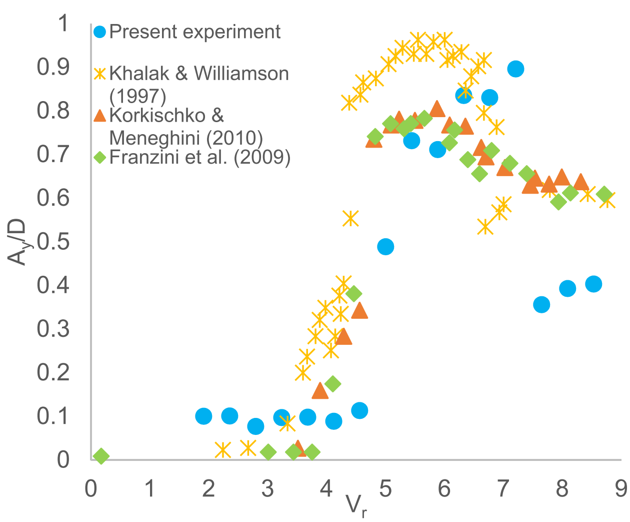

Fig. 4. Amplitude response of a single circular cylinder versus reduced velocity.

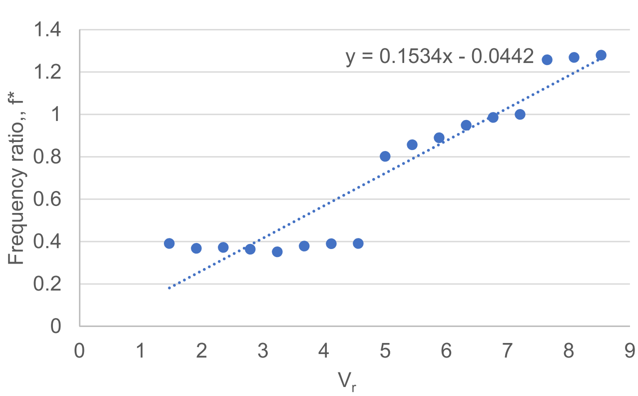

Fig. 5. Frequency response of a single circular cylinder versus reduced velocity.

frequency ratios ($f^* = f/f_n$) for a single cylinder versus reduced velocity. Accordingly, the frequency started to increase at $V_r = 5.0$ and continuously recorded increments in an almost linear fashion ($0.8 \leq f^* \leq 1.0$) at the upper branch. At $6.3 \leq V_r \leq 7.2$, the vibration frequency (f) was locked-on the natural frequency (f_n), $f \approx f_n \approx 1$. Then, they continued to rise to a higher value of $f^* = 1.27$. This is similar to the observations made by Shaharuddin and Darus [1].

Fig. 6(a)-(c) presents the time histories of the vibration displacement at the reduced velocities of 5.0, 7.2 and 7.6 corresponding to the initial, upper and lower branch, respectively. The power spectra of the time histories were also obtained by fast Fourier transform (FFT). Based on Fig. 6, the time series of amplitudes are in coherent with the frequency spectra, and hence, verifying the authenticity of the data.

3.2. Two circular cylinders in tandem

In this section, the responses of the upstream and downstream cylinders presented in Fig. 7 are discussed. Both cylinders were free to vibrate in the cross-flow direction and they were arranged in tandem configuration in a bare fashion at a spacing distance of 3.5*D*. Accordingly, the graph plotting for both cylinders showed a continuous increment in the amplitude response as the reduced velocity increased, whereby the pattern indicated that no lower branch was previously present in the single-cylinder response. Therefore, this result is similar to that of Assi [10], Korkischko and Meneghini [11], Assi et al. [16], and Papaioannou et al. [19]; these scholars have all investigated the vibration of two cylinders when in tandem configuration. In this study, both cylinders were observed to experience the wake-induced vibration (WIV) for $V_r > 5.8$, which indicates that the vibration is not driven by resonance any longer. As presented in Fig. 7, the upstream cylinder amplitude is remarkably high at 1.56*D* and high V_r, which is due to the flow interference between the cylinders. In fact, this amplitude was larger than the responses that occurred for a single cylinder. Regardless, they are similar to the ones previously discovered by Korkischko and Meneghini [11].

Furthermore, the downstream cylinder in this study yielded an amplitude response that was lower by 54% than the upstream cylinder. The same behaviour has also been observed by Lou et al. [28] and Huera-Huarte and Bearman [46] when assessing the flexible and rigid cylinder in two degrees of freedom, respectively. Therefore, this explains that the upstream cylinder experiences a large unsteady force due to the flow velocity. Meanwhile, the maximum fluctuating lift force of the upstream cylinder at a spacing distance of 3.0*D* has been reported by Alam et al. [12], whereby they suggest its occurrence to be due to the phase of flow patterns for both cylinders, which occur simultaneously. When the water flow moved towards the upstream cylinder, a smooth periodic wake was produced and caused a large oscillation at the upstream cylinder. When this periodic wake collided with the downstream cylinder, however, the flow changed and the bound-

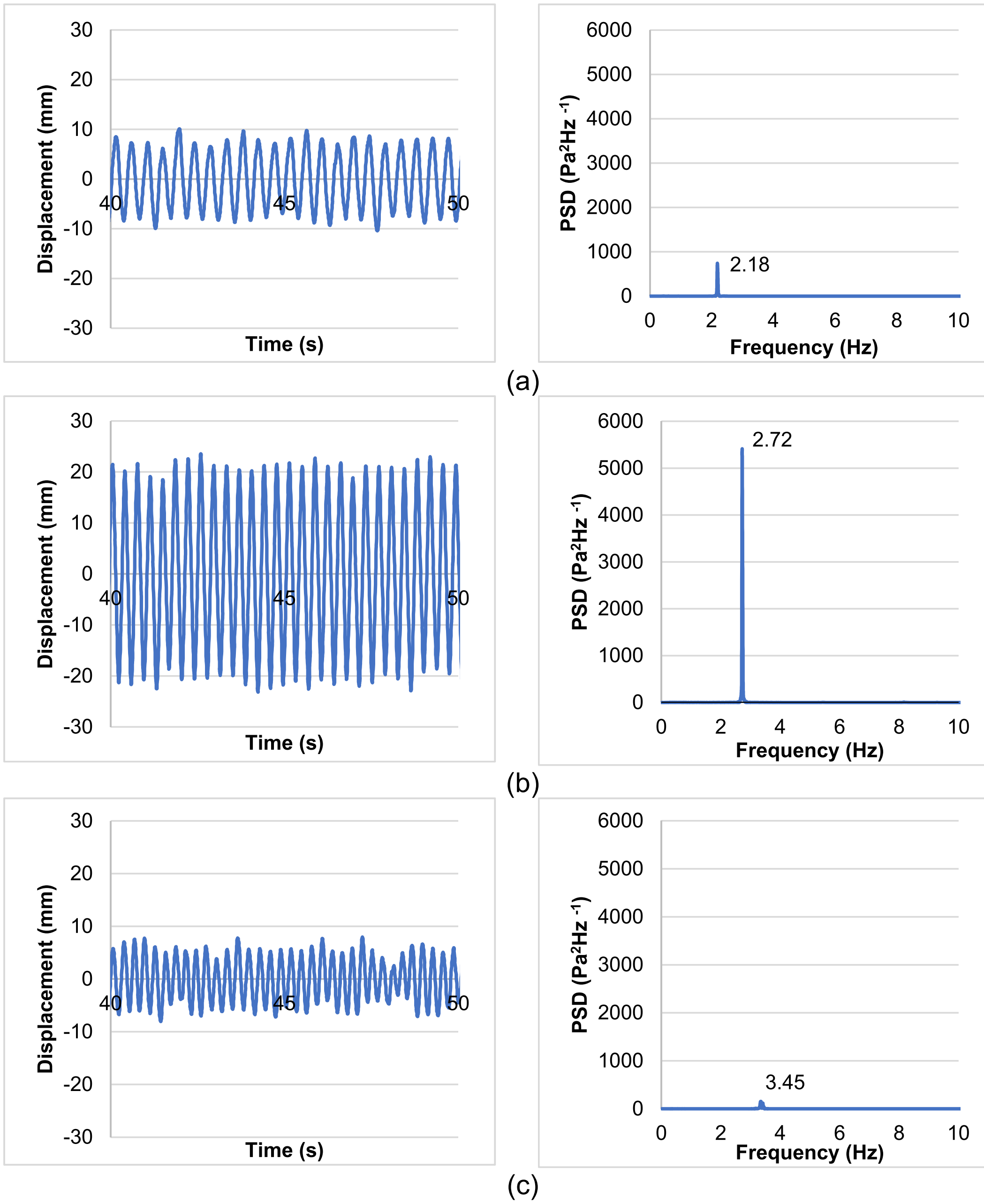

Fig. 6. The time series of displacement and frequency spectra of cross-flow vibrations of single circular cylinder at reduced velocity of (a) 5.0, (b) 7.2 and (c) 7.6.

ary layer separation at this location was altered. This would then cause the vortex shedding, which was generated and became smaller than the upstream cylinder. Similar behaviours have also been reported by Lou et al. [28], who are of the opinion that the wake from the upstream cylinder alters the flows towards the downstream cylinder, which would then interfere the wake dynamics and vortex formation region of the upstream cylinder. Nevertheless, this result differs from that of Papaioannou et al. [19] and Tu et al. [47], wherein both works have numerically simulated the case of two cylinders and observed a larger amplitude ratio on the downstream cylinder in comparison with the upstream cylinder at the same critical distance. Such outcome may be denoted as the effect of two degrees of freedom utilised in their respective studies, which thus contributes to the contrasting results. Besides, Chaplin et al. [48] and Song et al. [49] have reported that the numerical methods failed to yield outcomes that are in agreement with the experimental measurements as they lacked reliability.

By looking at the frequency response in Fig. 8, the frequency ratio for both cylinders is seen to increase along with V_r. At a low and reduced velocity, the vortex shedding did not fully develop and thus resulting in low frequencies and amplitude response. Furthermore, as the *Re* increased, a sudden jump was observed at V_r = 5.0 and signalled the formation of vortex shedding behind the cylinder [50]. Here, the graph shows that the frequency ratio of both cylinders is relatively similar and is mostly at a high velocity, which is thus attributable to them experiencing lock-in or synchronisation for all the higher values of V_r. However, the lock-in phenomenon of the downstream cylinder was slightly slower than the upstream cylinder due to the wake shielding effect, thereby explaining its vibration at smaller amplitudes than the upstream cylinder. Regardless, both frequencies remained almost constant

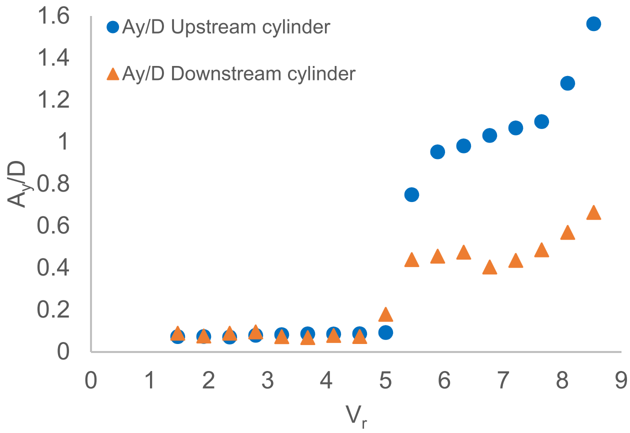

Fig. 7. Amplitude response of upstream and downstream cylinders without helical strake versus reduced velocity.

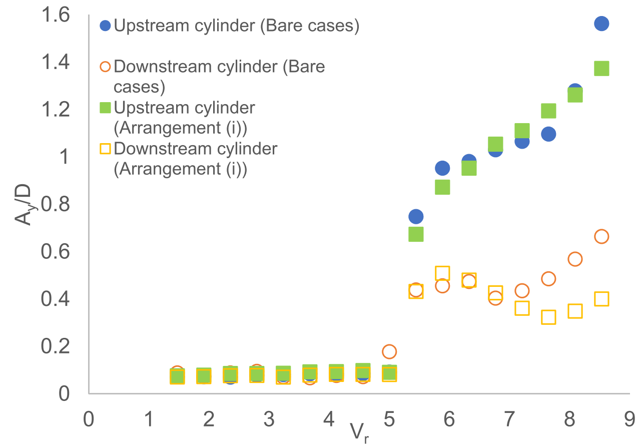

Fig. 9. Displacement response of the upstream bare and downstream straked cylinder versus reduced velocity (Arrangement (i)).

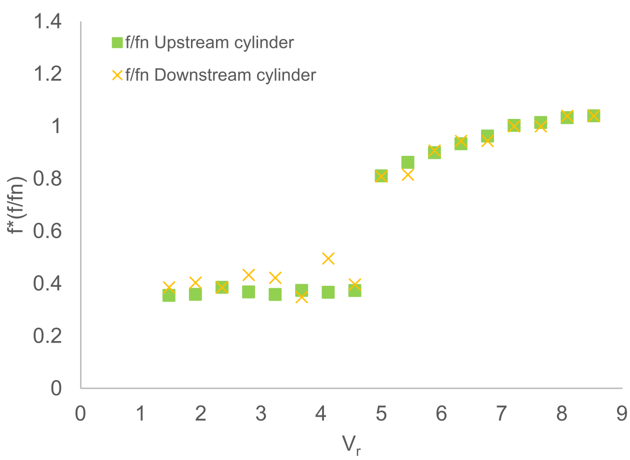

Fig. 8. Frequency response of upstream and downstream cylinders without helical strake versus reduced velocity.

for V_r above 7.2, which indicated the continuous synchronisation for both upstream and downstream cylinders [6].

3.3. Two circular cylinders with helical strake

To investigate the suppression performance of the helical strake, the amplitude response of two cylinders either with or without the helical strakes and in a spacing distance of 3.5D is discussed in this section. Fig. 9 shows the graph depicting the bare cylinders in comparison with the straked cylinders in Arrangement (i) as detailed in Fig. 3 in the Methodology section. As such, the oscillation for both cylinders in the straked cases (Arrangement (i)) was notably reduced and their respective amplitude was smaller compared to the cylinders in the bare cases. Even though the upstream cylinder for the straked cases was not equipped with a helical strake, a slight drop of amplitude ratio was noted regardless due to the suppression effect of the helical strake at the downstream cylinder. However, observing the small reduction offered by the downstream straked cylinder allowed the conclusion that the strake at the downstream cylinder was either ineffective or insufficiently strong to reduce the VIV by itself. As the function of helical strakes is to disrupt the separation point of the flow resulting in the formation of vortices, they will be rendered highly effective when the incoming flow is steady. For the downstream cylinder, the amplitude fluctuation was no longer due to VIV but rather attributable to the wake interference in which the incoming flow was unsteady. Hence, the helical strakes were unable to perform in this case. This is supported by Korkishko and Meneghini [11], who have also reported that the downstream straked cylinder loses its effectiveness in the wake of a fixed bare rigid cylinder with the use of strakes of 10.0D pitch and 0.20D height compared to the isolated case. In addition, the authors have suggested that the height of strakes is an important element in the VIV suppression selection; it can slow down the separation of boundary layers from the cylinder and thus delay the interaction between the shear layers produced behind the cylinder [51].

To further discuss on the higher reduced velocity ($V_r > 9$), Korkishko and Meneghini [11] have found that the downstream straked cylinder in the wake of upstream bare cylinder oscillates constantly with lower amplitude ($9 < V_r < 20$) compare to the typical lock-in range ($4 \leq V_r \leq 6$). Different condition has been reported by the same authors for case of downstream bare cylinder, where the vibration amplitude increases continuously as the reduced velocity increases. This shows that the installation of helical strakes on downstream cylinder is able to constraint the large vibrations at higher reduced velocity range.

In Arrangement (ii), the helical strakes were only installed at the upstream cylinder and successfully suppressed the vortex wake and oscillation for both cylinders at the critical spacing distance despite the lack of strakes at the downstream cylinder. Following this, the coherent vortices produced through the upstream cylinder oscillation were destroyed and the interaction with the downstream cylinder was cut down [29]. This behaviour differed from the observations made when using Arrangement (i), whereby the strakes at the downstream cylinder alone were extremely weak to prevent the oscillation for both cylinders. Therefore, this indicates the significant role played by the upstream cylinder in the flow interference between multiple cylinders.

Moreover, the influential performance of helical strakes in reducing the cylinder oscillation could also be observed in Arrangement (iii), where both cylinders were installed using strakes. Here, the suppression effect in Arrangements (ii) and (iii) is relatively similar to the responses shown in Fig. 10, whereby almost no vibration can be observed in the cylinders and the amplitude response is virtually zero due to the strakes. In line with this, Xu et al. [37] have reported that the strakes can damage the vortex shedding process, which is thus proven in this study when using strakes having the pitch of 10.0D and height of 0.15D. However, this finding also contradicts those of Korkischko et al. [52],

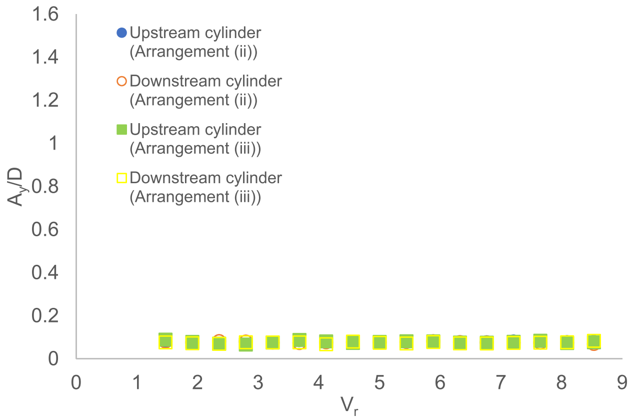

Fig. 10. Displacement response of the upstream and downstream cylinder versus reduced velocity (Arrangements (ii) and (iii)).

who are of the opinion that the helical strake is only effective for isolated cylinder cases.

To have a better understanding of the suppression effectiveness offered by strakes, a comparison of amplitude responses was made against previous experiments. For the upstream cylinder, the comparison was versus the study by Xu et al. [37] at all arrangements carried out. However, it must be noted that the downstream case is not analysed due to the large spacing distance (8.0*D*) employed by the prior work. The authors [37] have performed experiments on the FIV for two flexible cylinders placed in a tandem configuration by using a similar strake arrangement as established in Fig. 3 (i.e. strakes of 17.5*D*/0.25*D*). As a result, similar results were found for all arrangement cases. In particular, Arrangement (i) yielded a large amplitude at the upstream cylinder for both experiments (Fig. 11), which indicated that its vibration was unaffected despite the presence of helical strakes at the downstream cylinder. Due to the flexibility of the upstream cylinder shown by Xu et al. [37], a drastic amplitude response is shown and the lock-in occurs earlier compared to the present study. In contrast, the vibration amplitude of the upstream cylinder in this study was further increased at all reduced velocities, whereas the upstream cylinder by Xu et al. [37] decreased after a certain time. Accordingly, the phenomenon can be attributed to the effect of different spacing distances employed in both studies; when the spacing distance is sufficiently large for both cylinders, the vortices coming from the upstream cylinder are completely separated from the downstream cylinder and yield a small vibration effect for the upstream cylinder [53,54]. Meanwhile, the spacing distance in the current study revealed unsteady vortex-structure interactions between the cylinders in which a bistable range existed [55]. Besides, a complex flow behaviour appeared in the space between the cylinders during the critical spacing distance as well. In particular, Qin et al. [56] have reported that the large vibration amplitude generally occurs at a smaller spacing distance. Therefore, Fig. 11 depicts a strong suppression performance of the helical strake for the rigid and flexible upstream cylinder. Besides, the amplitude response of the upstream cylinder in this study is much lower than Xu et al. [37], which may be due to the structure rigidity.

In the case of the downstream cylinder, the present experimental results were compared to those of Korkishchko and Meneghini [11]. The scholars [11] have experimented with the FIV for multiple rigid cylinders in a tandem arrangement and at a spacing distance ranging from 2.0 until 6.0*D*. Here, the comparison made in Fig. 12 is carried out by choosing the spacing distance of 3.0*D* for the downstream cases; however, the lack of experimental tests for such cases allows only Arrangement (i) to be presented. Due to the rigidity of both cylinders, the lock-in was found to occur in the middle of the reduced velocity range. In comparison, the lock-in obtained by Korkishchko and Meneghini [11] is slightly earlier than that obtained in this study, which can be explained by the lower mass-damping of their structure. Therefore, it is suggested that an additional test carried out between $5.0 \leq V_r \leq 6.0$ for the current study may show a clearly increasing pattern of vibration amplitudes. Similarly, the continuous incremental vibration amplitude can also be seen in the work of Korkishchko and Meneghini [11] at all reduced velocities, wherein their vibration amplitude behaviour is in good agreement with the current study. However, the amplitude observed in this present dropped over a short-reduced velocity after $V_r \approx 6.0$ before increasing again after $V_r \approx 8.0$. Assi et al. [57] have previously suggested that such behaviour is attributable to the change of regime, namely from vortex-induced response to the wake-induced excitation or galloping. This conclusion is made due to similar patterns of curve observed during their experiment. In contrast, Fig. 12 depicts a large vibration amplitude for the downstream cylinder for both studies, further suggesting that the helical strake in such case is insufficient to suppress the VIV at 3.0*D* and 3.5*D* as seen in Arrangement (i).

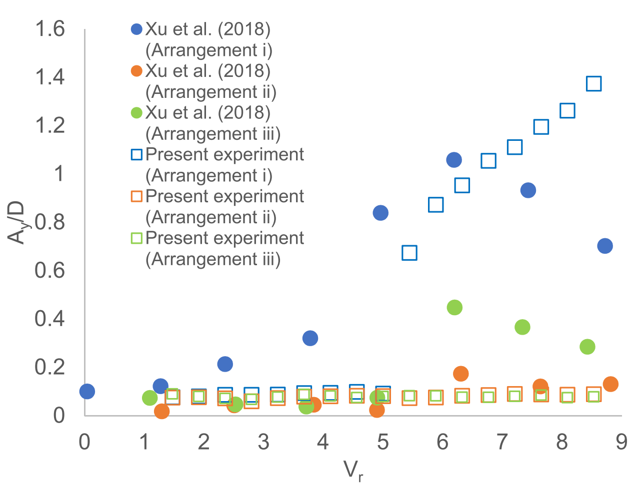

Fig. 11. The comparison of displacement response of upstream without and with helical strake cylinder versus reduced velocity at all arrangements.

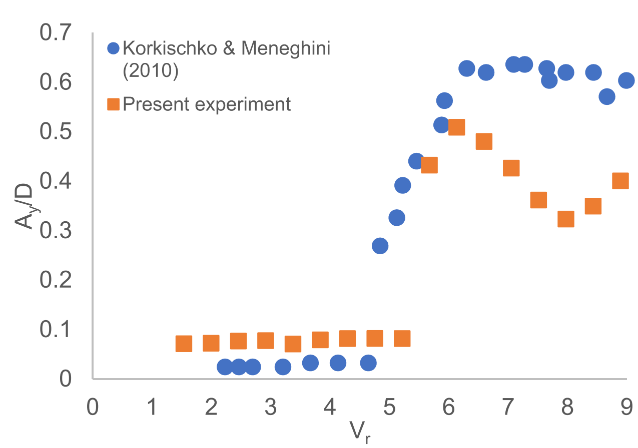

Fig. 12. The comparison of displacement response of downstream with helical strake cylinder versus reduced velocity at Arrangement (i).

4. Conclusions

Experiments were conducted in this study to investigate the influence of multiple cylinders on vortex-induced vibration while concurrently exploring the effectiveness of helical strakes in reducing the cylindrical oscillation. Accordingly, the following conclusions can be drawn:

(1) In the case of two bare cylinders in tandem configuration, the cross-flow responses of the upstream cylinder are larger than those from the downstream cylinder at the critical spacing distance of 3.5*D*. The upstream cylinder oscillation is also found to be greater than a single cylinder case, which demonstrates that the use of multiple cylinders in the application will worsen the VIV phenomenon.
(2) In the case of two cylinders with helical strakes placed at different positions, the strake effectiveness is dependent on their arrangement at the cylinders themselves. A small reduction is found on the downstream straked cylinder in Arrangement (i), thereby indicating the installation of strakes at the structure is ineffective in reducing the VIV.
(3) In the case of helical strakes as seen in Arrangements (ii) and (iii), VIV is strongly reduced and the cylinders have almost no vibration, while the amplitude response is almost zero. Therefore, future experiments should investigate the performance of helical strakes further in the context of different spacing distances in order to achieve a better understanding of the VIV phenomenon for tandem rigid cylinders.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was financially supported by the Malaysian government under FRGS grants R.K130000.7B43.5F297, FRGS/1/2020/TK0/UTM/02/78 and Japan International Cooperation Agency under grant (S.K130000.0543.4Y191). The authors also wish to acknowledge the National Hydraulic Research Institute of Malaysia (NAHRIM) for the facilities provided.

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