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Experimental Study on Vortex-Induced Vibration Coupling Wake Interference of Multi-Riser Groups with Sensitive Spacing

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Abstract

The “riser group−fluid between risers” is taken as the carrier, and the experiment on vortex-induced vibration of tandem riser groups coupling interference effect under sensitive spacing is performed. The least-square method is used to linearly fit the reduced velocity and main frequency, and the rule of Strouhal numbers is analyzed. Each mode is separated based on the mode decomposition theory, and the mode conversion mechanism is also explored. The concept of “interference efficiency” is introduced to study the dynamic characteristics and response evolutions of different riser groups. The results show that the wake shielding effect widely exists in tandem riser groups, and the interference effect of midstream and downstream risers on their upstream risers is significantly lower than that of upstream risers on midstream and downstream risers. The trajectories of midstream and downstream risers lag behind their upstream risers due to multiple shadowing effects, the vibration frequency range of downstream riser is widened and the dominant frequency is extremely unstable. Compared with the isolated riser, wake interference suppresses the vibration displacement of the midstream and downstream risers in the in-line direction, and enhances the displacement of upstream and midstream risers in the cross-flow direction. The interference effect of the fluid between risers at low velocities is stronger than that at higher velocities, and the cross-flow displacements of upstream risers are always in the interference enhancement region. It is urgent to pay attention to the cross-flow displacement of upstream and midstream risers in tandem riser groups considering the safety design.

Key words: vortex-induced vibration, interference effect, multi-riser groups, sensitive spacing, tandem arrangement, dynamic response

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1 Introduction

Complex fluid-structure occurs in marine risers under waves and currents. The instability of the structure produces severe vibrations and accelerates fatigue damage, endangering the service life of the riser (Guo and Lou, 2008). A large number of researchers have described the vortex-induced vibration (VIV) of the isolated riser. However, marine risers are not arranged only in isolation, but also in a variety of layout forms, such as, “string”, “column” and “group”. The wake of the riser acts on the other one which causes the flow separation and vortex shedding when outflow goes through the riser group so that the vibration pattern and dynamic responses become different from those of general VIV, which is called “wake-induced vibration (WIV)” (Huera-Huarte and Gharib, 2011a). Risers in the riser group system are coupled to each other due to the influence of wake and gap flow, and the dynamic responses of VIV are superimposed (He and Low, 2014; Xu et al., 2018a).

At present, the wake interference effect is studied based on numerical simulation, experimental research and empirical model. For the interference of tandem double risers, Mysa et al. (2016) studied the coupled dynamics mechanism of an

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isolated cylinder and a pair of tandem rigid cylinders; Derakhshandeh et al. (2014) compared the efficiency of VIV power obtained by downstream cylinders with different arrangements; Tu et al. (2015) studied the fluid-induced vibration of tandem cylinders with spacings of 2.5*D*−8*D* under the action of plane shear flow based on the finite element method; Zhao et al. (2016) studied the vibration on small cylinders caused by the large cylindrical wake with different cylindrical ratios; Lin et al. (2013) analyzed the vibration displacement, frequency and relative equilibrium position of tandem cylinders; Chung (2017) studied the vibration characteristics of a rigid cylinder and found the trajectory "8" existed only in tandem.

Researchers have conducted experimental studies based on the simplest arrangement of the riser groups. Among them, Assi et al. (2006) carried out two cylinders' interference tests with spacings of 2*D*−5.6*D* based on flow visualization technology, and observed a significant "galloping" phenomenon; Huera-Huarte and Gharib (2011b) studied the dynamic responses of two cylinders in a side-by-side arrangement with the spacings of 2*D*−5*D* under the low mode, and they analyzed the dynamic responses of two tandem risers with spacings of 4*D*−8*D* which immersed in a uniform flow partially. Particle image velocimetry (PIV) was used to visualize the wake for tandem cylinders with spacings of 2*D*−4*D*, and different response mechanisms were determined by Huera-Huarte et al. (2016): VIV, WIV, and a combination of both. Armin et al. (2018) established the optimal distance between two offshore structures by an experimental investigation on VIV of two rigid cylinders in tandem. Xu et al. performed flow-induced vibration (FIV) tests on two kinds of double flexible long cylinders for spacings of 4*D*−16*D* in tandem (Xu et al., 2018b) and side-by-side cylinders with spacings of 3*D*−8*D* (Xu et al., 2018c). They focused on FIV of the two systems from the strain, displacement, main frequency and the average drag coefficient. Besides, Xu et al. (2019) analyzed the fluid forces of the cylinder in tandem arrangement to illustrate the mechanism of interaction, and a series of experimental tests were carried out to investigate the FIV of two side-by-side flexible cylinders with a high aspect ratio (Han et al., 2018). Huang and Herfjord (2013) found that the upstream cylinder was less affected by the downstream cylinder when the spacing was larger than 3*D*. Exploring complex cylinder group systems is the research hotspot in recent years. Chen et al. (2018) studied the relaxation of VIV of a three-cylinder-system in tandem at low Reynolds numbers; Ding et al. (2015) simulated the VIV of 1, 2, 3, and 4 cylinders in tandem under uniform flow; Zhang et al. (2018) conducted a numerical simulation of four staggered cylinders and found that the interference effect of tandem cylinders was greater than that of side-by-side arrangement. Furthermore, Gao et al. (2019) found that the incident angle had a significant influence on the downstream cylinder.

Researchers have extensively discussed the basic arrangement-double risers, but the FIV of more than two risers is limited. Since multi-riser structures are commonly adopted in engineering, the fluid-structure coupling mechanism between risers is relatively complex, and studies show that it is inappropriate to infer the FIV behavior of riser groups from dynamic responses of the two-riser group (Wang et al., 2019). FIV and fatigue failure are prone to happen in multiple riser groups arranged in tandem, and collision may occur due to wake interaction. The interference spacings between 3.5*D* and 4.5*D* are more sensitive for the riser group (Armin et al., 2018; Assi et al., 2010), and investigation of the VIV test and vibration mechanism for riser groups at sensitive spacing is unprecedented. Therefore, the dynamic characteristics and responses of several riser groups under sensitive spacing by changing the flow velocity and the number of risers are explored in this paper.

2 Experimental details

2.1 Experimental facility

The experiment was carried out in the wave-current combined flume in the Engineering Hydrodynamics Laboratory of Ocean University of China. The water flume is with a maximum flow velocity of 1 m/s and a maximum water depth of 1.0 m. The water depth was 0.8 m, the velocity interval was 0.05−1 m/s, and the flow velocity changed from 0.1 m/s to 0.6 m/s. The experimental facility was placed in the water flume at a distance of 22 m from the flow generating system to ensure uniform flow. The experimental facility comprised supports, a top tension system, riser models, signal measurement and acquisition system, etc, and it is shown in Fig. 1.

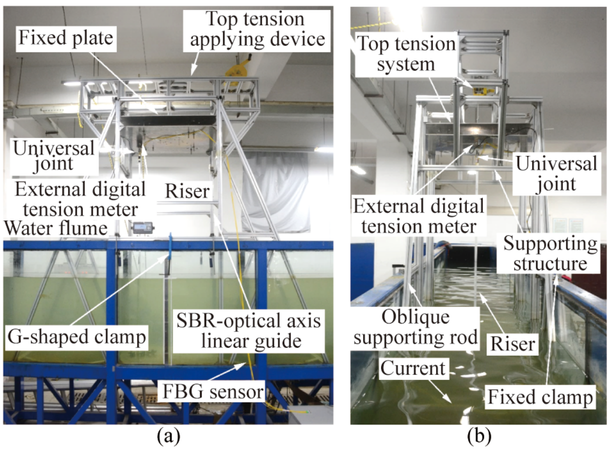

Fig. 1. Experimental device.

2.2 Design of riser models

Transparent polymethyl methacrylate pipes with the wall thickness being 1 mm were selected as the riser models, and a high degree of consistency in the mechanical properties of the polymethyl methacrylate pipes are required. A vertical posture was adopted and 40% of the length was immersed in the uniform flow field (Huera-Huarte and Bearman, 2009). Through multiple free decay tests in still water, we obtained the normalized damping ratio ζ, as well as the riser's natural frequency in the water f_1, and the main parameters are shown in Table 1.

Table 1 Main parameters for the riser models

Parameter	Value
Material M	PMMA
Length L (m)	2.00
Diameter D (m)	0.018
Thickness δ (m)	0.001
Aspect ratio λ	111.11
Submerged length L_s (m)	0.80
Top tension T (N)	19.6
Flexural stiffness EI (Nm^2)	4.63
Unit mass m (kg/m)	0.065
Mass ratio m^*	1.05
Natural frequency (in the water) f_1 (Hz)	3.30
Damping ratio ζ	0.039

2.3 Arrangement of sensors

The Doppler current profiler was placed at 2.0 m upstream of the riser to avoid the influence of the vortex caused by it. The top tension system was formed by the force applying device, fixed pulley, steel wire rope, force guiding rods, fixing plate, and the AXT-S-100 external digital tension meter. The same top tension was adopted for each riser with a sensitivity between 1.5 and 3.0 mV/V.

Fiber Bragg grating (FBG) sensors were used, and six grating measuring points were engraved on each string of optical fibers according to the preliminary estimation of the number of high-order modes excited by the riser. Measuring points were arranged at 90° (CF_1, IL_1, CF_2, IL_2) on the surface of the riser, and CF_1, CF_2 and IL_1, IL_2 were on opposite sides to measure the vibration of the riser along the CF and IL direction respectively. There were four strings of optical fiber and each riser model was placed with 24 measuring points, and from top to bottom are G1−G6, as shown in Fig. 2.

2.4 Design of experimental cases

The isolated riser tests under different velocities and top tensions were carried out before the experiment. The dynamic response of the riser predicted by the numerical model was compared with the experimental results, and vibration responses of the isolated riser under different parameters were studied (Wang et al., 2021), and the dynamic responses of experimental and numerical results agreed well, which verifies the feasibility of the experiment process control system and accuracy of the test.

Afterward, two, three, and five plexiglass risers with the same mechanical properties were used in riser groups. All

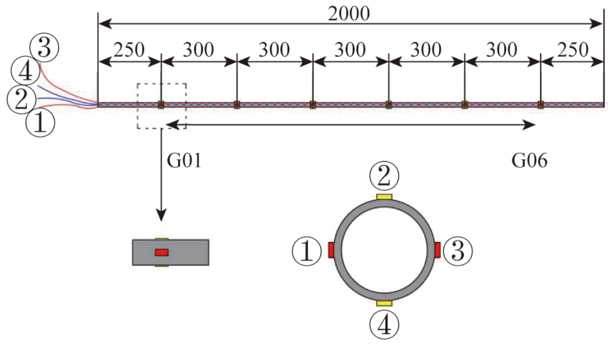

Fig. 2. Arrangements of FBG sensors (unit: mm).

risers were arranged in tandem at spacings of 4D. Risers are identified as Risers #2-1 and #2-2 in the two-riser group; Risers #3-1, #3-2 and #3-3 in the three-riser group; Riser #5-1, Riser #5-2, Riser #5-3, Riser #5-4 and Riser #5-5 in the five-riser group from upstream to downstream, and the isolated riser is identified as IR, as shown in Fig. 3c. The specific experimental layout is shown in Fig. 3 and experimental cases are shown in Table 2.

3 Results and discussions

3.1 Frequency analysis

It is usually dominated by a frequency when a structure vibrates, and the dominant frequency can reflect the main vibration characteristics. Fig. 4 shows the dimensionless dominant frequencies (f_{dy}/f_1, f_{dx}/f_1) of the isolated riser versus reduced velocity, where f_{dy} and f_{dx} are the dominant frequencies in the CF and IL directions. The representative values of Strouhal number of the isolated riser in CF and IL directions are 0.185 and 0.370, which is consistent with previous research findings (Chen et al., 2018; Ding et al., 2015; Zhang et al., 2018). Figs. 5−7 show variations of dimensionless dominant frequencies of two-, three- and five-riser groups versus reduced velocity, Strauhal numbers (St) are fitted, and ratios of IL and CF dominant frequencies are given. It is known that the isolated riser's St is 0.185, the dominant frequency variation trend of Riser #2-1 in the two-riser system (Fig. 5) is similar to that of the isolated riser, and St is larger than that of Riser #2-2, with $St_{2\text{-}1}$=0.161 and $St_{2\text{-}2}$=0.143. The dominant frequency of Riser #2-1 is the same as that of Riser #2-2 when reduced velocity $U_r \leqslant 8.42$, but the dominant frequency of Riser #2-2 decreases abruptly when U_r=9.26, which is caused by the sudden strengthening of the influence of wake shielding effect on the vibration frequency of the structure when the incoming flow velocity increases to a certain value. In addition, the dominant frequency ratio of Riser #2-2 of IL and CF directions is unstable, whereas the dominant frequency ratio of Riser #2-1 is the same as that of the isolated riser, with small fluctuations around 2.

In the three-riser system (Fig. 6), the dominant frequency

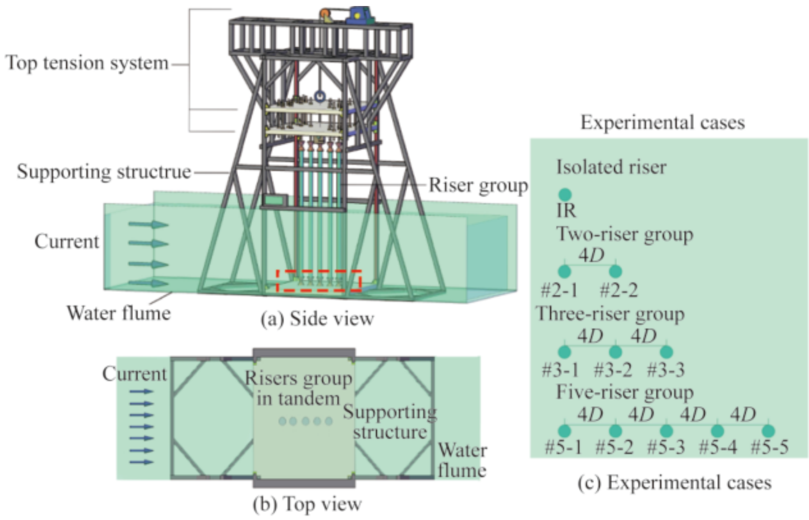

Fig. 3. General layout of the experiment.

Table 2 Experimental cases

Case No.	Riser group	Number of riser(s)	Spacing ratio *S/D*	Current velocity (m/s)	Arrangement
1-10	Isolated riser	1 (IR)	–	0.10–0.60	–
11-20	Two-riser group	2 (Riser #2-1, Riser #2-2)	4	0.10–0.60	Tandem
21-30	Three-riser group	3 (Riser #3-1, Riser #3-2, Riser #3-3)	4	0.10–0.60	Tandem
31-40	Five-riser group	5 (Riser #5-1, Riser #5-2, Riser #5-3, Riser #5-4, Riser #5-5)	4	0.10–0.60	Tandem

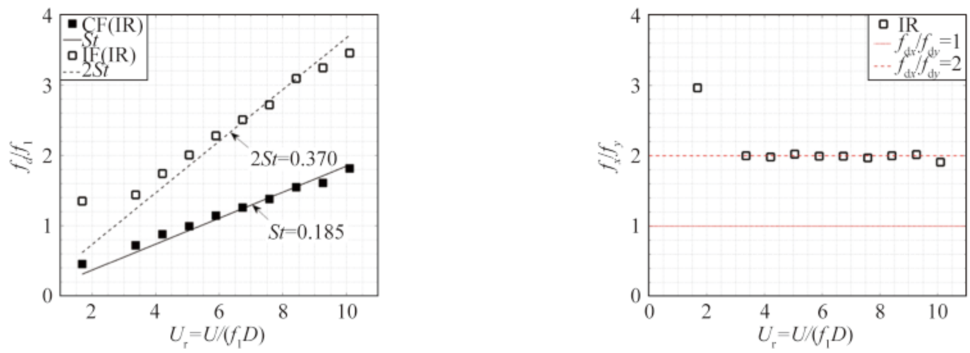

Fig. 4. Dimensionless dominant frequencies and ratios of dominant frequencies of the isolated riser.

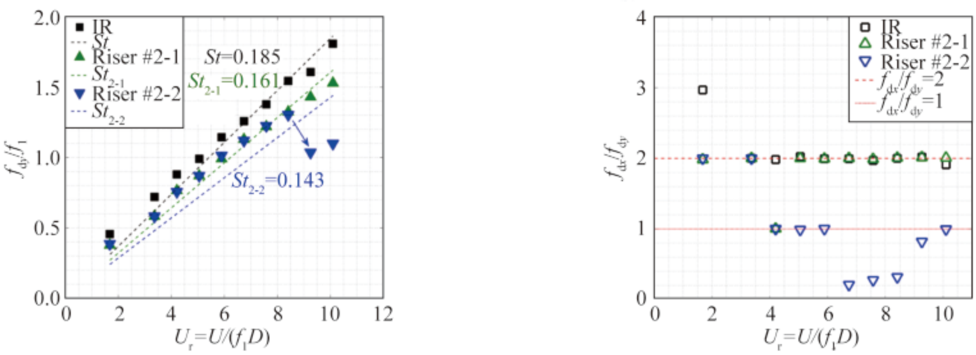

Fig. 5. Dimensionless dominant frequencies and ratios of dominant frequencies versus reduced velocity of the two-riser group.

variation trend of Riser #3-1 is similar to that of the isolated riser, and *St* decreases successively from upstream to downstream, with values of $St_{3\text{-}1}$=0.159, $St_{3\text{-}2}$=0.138 and $St_{3\text{-}3}$=0.126, respectively. The result shows that the dominant fre-

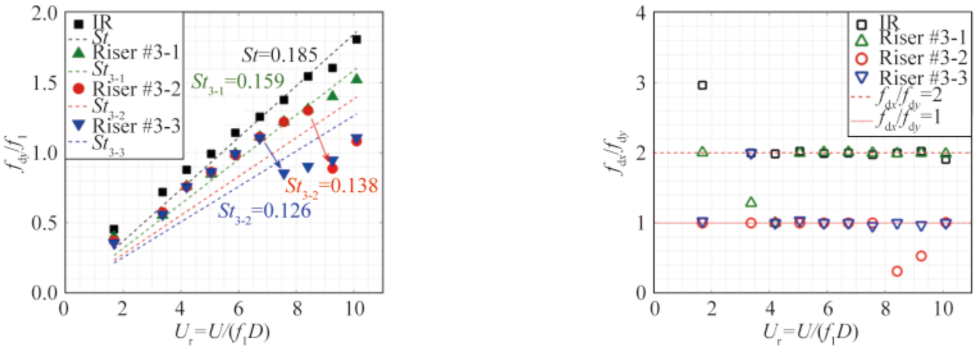

Fig. 6. Dimensionless dominant frequencies and ratios of dominant frequencies versus reduced velocity of the three-riser group.

quencies of Risers #3-1, #3-2 and #3-2 are the same when $U_r \leqslant 6.73$, but when U_r=7.58, the dominant frequencies of Riser #3-3 first drop suddenly, and then the dominant frequencies of Riser #3-2 also drop. The dominant frequencies of IL and CF in Risers #3-2 and #3-3 are similar, and the ratios fluctuated around f_{dx}/f_{dy}=1. The "beat phenomena" occurred in the downstream risers, and wake interference is particularly critical for downstream riser vibration, especially at high flow velocities in riser groups. Downstream risers vibrate in a low mode due to the multiple fluids and the strong shielding effect of the upstream riser on downstream risers (Xu et al., 2021a). The dispersion of vibration frequency is large, and the corresponding frequency energy participation increases. As a result, energy transfer occurs in the cross-flow and in-line directions, which further leads to the occurrence of "frequency overlap" (Tang, 2011).

In the five-riser system (Fig. 7), the trend of the dominant frequency of Riser #5-1 is similar to that of the isolated riser. *St* corresponding to the riser from the upstream to the downstream decreases first then increases, and the intermediate riser is the smallest, with values: $St_{5\text{-}1}$=0.175, $St_{5\text{-}2}$=0.167, $St_{5\text{-}3}$=0.140, $St_{5\text{-}4}$=0.147, $St_{5\text{-}5}$=0.167. The dominant frequencies of Risers #5-4 and #5-5 are different from those of other riser groups when U_r=5.89. The dimensionless dominant frequency rises sharply, and the dominant frequency is restored when U_r=8.42, U_r=9.26, respectively. Analysis shows that the dominant frequency ratios of Risers #5-1 and #5-2 are similar to those of the isolated riser. The dominant frequency ratios of Risers #5-3 and #5-4 are close to 2:1 in U_r=[3.36, 5.05]. The dominant frequency ratio is generally smaller than f_{dx}/f_{dy}=1, that is, the dominant frequency in the CF direction is larger than that in the IL direction at some velocities. And this characteristic is the most evident for Riser #5-5, where the dominant frequency is extremely unstable.

To further investigate the frequency responses of the multi-riser group, Fig. 8 shows the power spectral density of the five-riser group at the measuring point G4 versus reduced velocity. At the same time, Fig. 9 shows time-frequency (G4) in the CF direction. The dominant frequency of the five-riser group decreases from upstream to downstream. The vibration of the upstream and midstream risers increased interference to the downstream risers, destroying the formation and separation of the wake vortex, and multiple interference frequencies are superimposed on the midstream and downstream risers, so that the vibration frequency distribution area becomes wider, and this feature is particularly prominent in the IL direction. In the CF direction, the frequency response weakens from upstream to downstream, and as the flow velocity increases, the dominant frequencies of the midstream and downstream risers appear in sequence.

Fig. 10 summarizes *St* and gives the root mean square. The trends of *St* are different. The two- and three-riser groups are all in a downward trend, which fully shows that the upstream riser wake has a significant wake shielding effect on the downstream riser, and the vortex of the

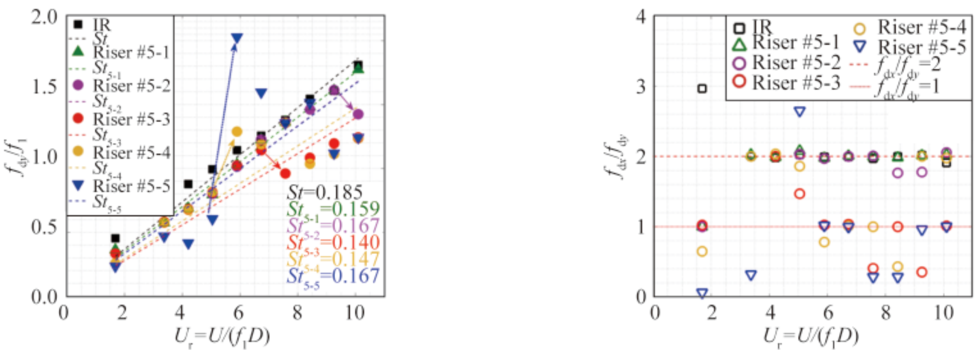

Fig. 7. Dimensionless dominant frequencies and ratios of dominant frequencies versus reduced velocity of the five-riser group.

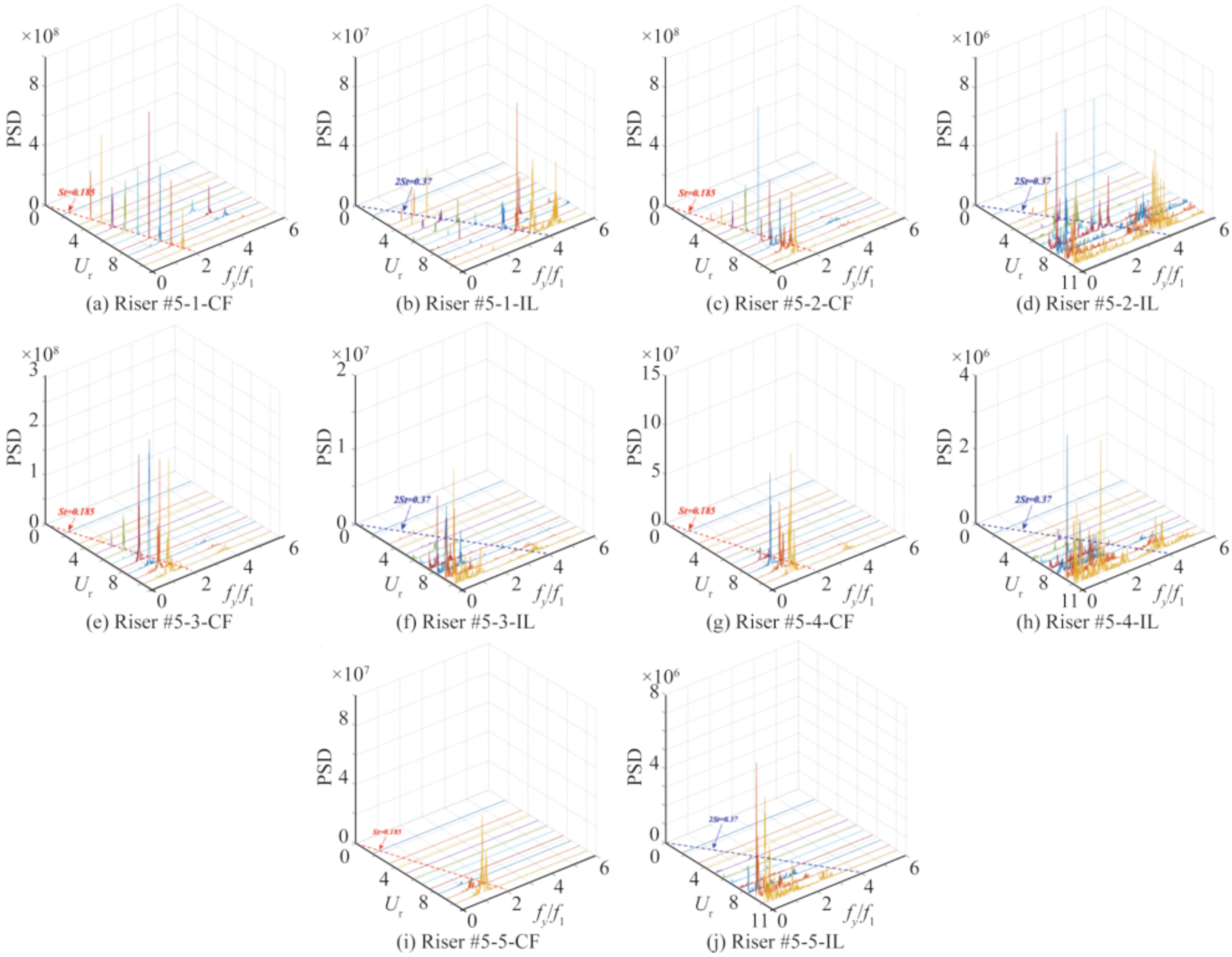

Fig. 8. Response frequencies versus reduced velocity.

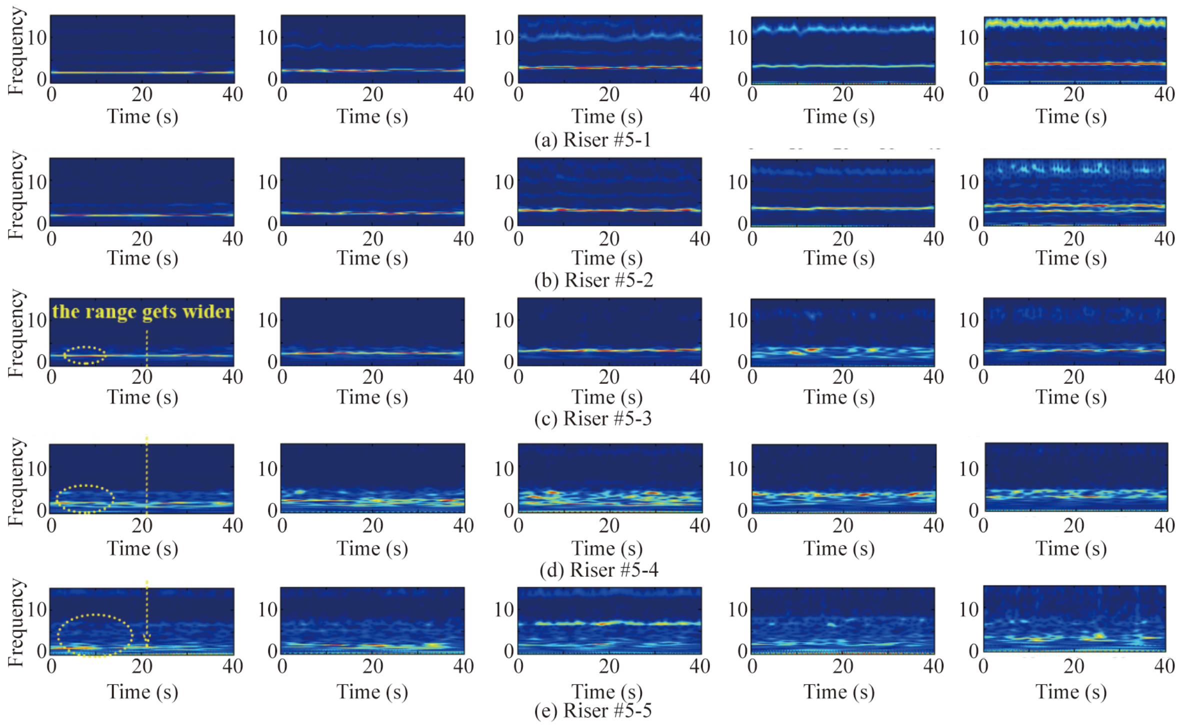

Fig. 9. Time-frequency of the five-riser group at measuring point G4 in CF direction.

upstream riser falls off on the downstream riser, which changes the vortex shedding direction and significantly inhibits the VIV frequency of the downstream riser. The dominant frequency and trend of Riser #1 are the closest to those of the isolated riser, but they are both lower than those of the isolated riser. There is an interference feedback effect, which suppresses the frequency of the upstream riser, but its influence is significantly smaller than the wake shielding effect of the upstream riser on the midstream and downstream risers. In the tandem riser group, the vibration of the downstream riser is the superposition of the WIV of the upstream riser and its own VIV, and this is not a simple linear superposition. An interesting phenomenon occurs in the five-riser group: $St_{5\text{-}5}$ is higher than those of the midstream risers. This is because the shear layers reattachment happens as Riser #5-5 is placed sufficiently far from the first one (Xu et al., 2021b). The reattachment of the shear layer leads to the increase of Riser #5-5's frequency response. In the five-riser group, multiple superimposed wake vortices act on the mid- and downstream risers, causing vibration modes to change, in particular, the response of the downstream risers can no longer be predicted by VIV rule.

3.2 Displacement response

3.2.1 *Displacements versus reduced velocity*

Figs. 11−13 show dimensionless displacement amplitudes versus the reduced velocity of riser groups at z=0.425L. For the two-riser group, in the CF direction, the dimensionless displacement of the two-riser group exceeds that of the isolated riser at most reduced velocities, and the wake interference and its feedback effect both cause the increase of the CF displacement; IL displacements of the upstream Riser #2-1 exceed that of the downstream Riser #2-2 except for the case of U_r=3.36, but the wake shielding effect becomes stronger as the reduced velocity increases. The displacement amplitude is suppressed compared with the isolated riser.

For the three-riser group, the dimensionless displacements of Risers #3-1 and #3-2 both exceed that of the isolated riser, and the displacement and variation trend of Riser #3-1 are similar to those of the isolated riser. Risers #3-2 and #3-3 have sudden rise and fall when U_r=5.89−8.42, but the two are completely different: the WIV of Riser #3-1 and the wake interference feedback effect of Riser #3-3 both act on the midstream Riser #3-2, and it is positively superimposed with its own VIV effect, which is intuitively manifested in the riser displacement response. The dimensionless displacement amplitude of midstream Riser #3-2 fluctuates up and down around 0.8 when U_r>6.73, which completely exceeds the displacement amplitude of the isolated riser, and it is comparable to the upstream Riser #3-1. The downstream Riser #3-3 has a sharp drop in amplitude, which is lower than that of the isolated riser, and the amplitude is

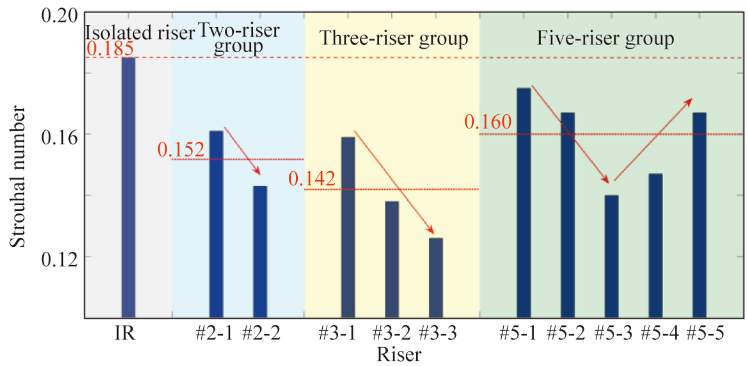

Fig. 10. *St* comparison of riser groups and the isolated riser.

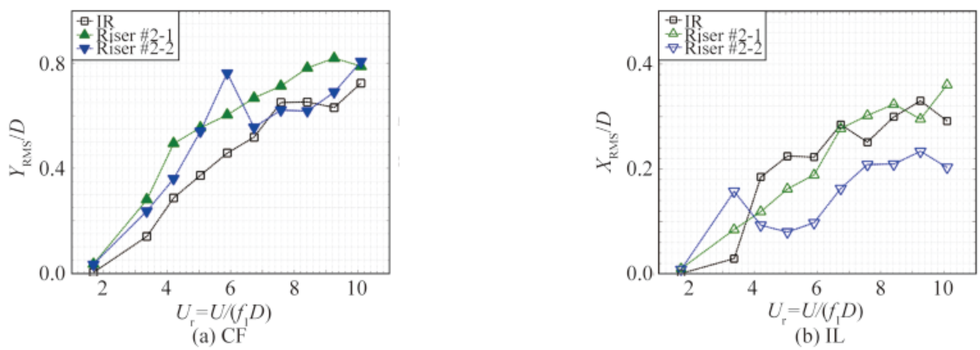

Fig. 11. Displacements of two-riser group versus reduced velocity at z=0.425L.

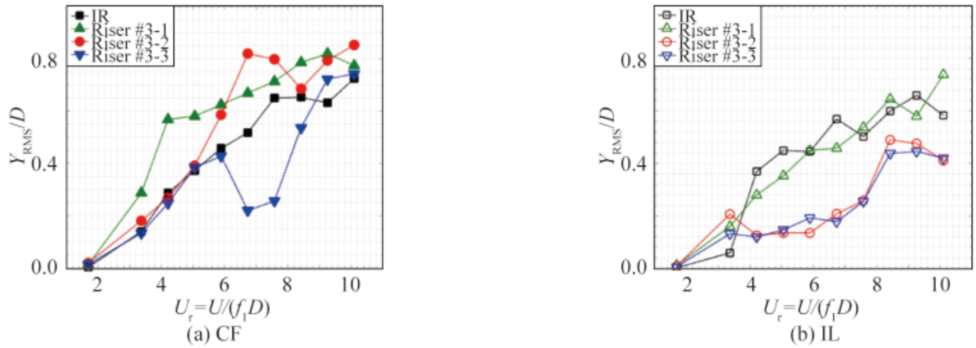

Fig. 12. Displacements of three-riser group versus reduced velocity at z=0.425L.

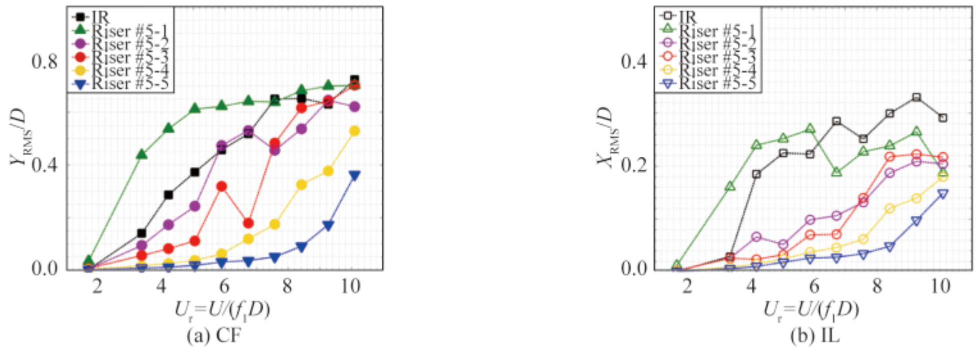

Fig. 13. Displacements of five-riser group versus reduced velocity at z=0.425L.

lower than that of the upstream Riser #3-1 and midstream Riser #3-2, which is due to the wake of the upstream Riser #3-1 and midstream Riser #3-2, and VIV of Riser #3-3 itself, and the effect is reversely superimposed, resulting in the opposite phenomenon to the midstream Riser #3-2.

For the five-riser group, the displacement variation trends are the same in two directions, and the root mean square displacement of the riser from upstream to downstream decreases sequentially, and at the higher reduced velocity, the displacements of midstream Risers #5-2 and #5-3 are very close. In the CF direction, only the upstream Riser #5-1 exceeds the displacement of the isolated riser, which is quite different from other groups. In the IL direction, it is similar to the two- and three-riser groups, the amplitudes of Risers #5-2, #5-3, #5-4, and #5-5 are all smaller than that of Riser #5-1 due to the wake shielding effect. The vibration displacements of the midstream and downstream risers are suppressed compared with those of the isolated riser.

The root mean square of the displacements along with the reduced velocity of the isolated riser, two-, three- and five-riser groups are summarized in Fig. 14. From upstream to downstream, the vortex of the upstream riser falls on its downstream riser, which changes the direction of vortex shedding. The root mean square displacements of the three-riser group in both directions show a downward trend, meaning that the amplitude suppression of the downstream riser is significant due to the wake shielding effect. The wake interference effect has different influences on the displacement of the tandem-arranged riser group in the CF and IL directions. In the IL direction, the VIV displacements of

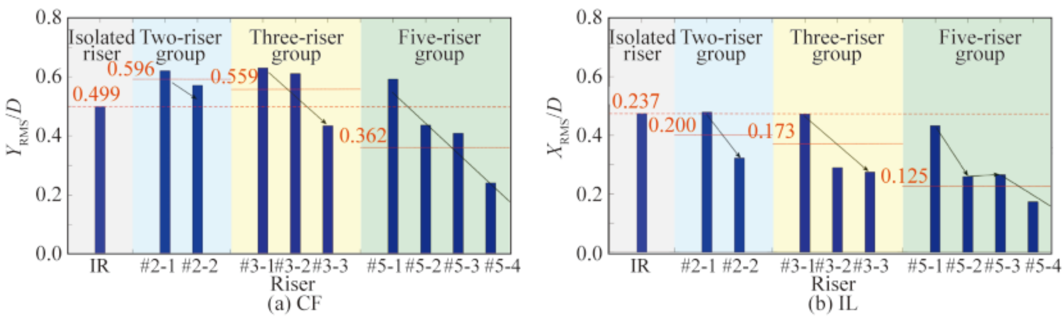

Fig. 14. Root mean square displacements of the isolated riser and riser groups.

the midstream and downstream risers are suppressed; in the CF direction, the vibration amplitude of the two-riser group and the upstream and midstream risers are all promoted.

3.2.2 *Displacements along the axial direction*

Figs. 15−17 show the dimensionless displacement responses from upstream to downstream of the two-, three-, five-riser groups in the CF direction at U_r=8.42, respectively. It is observed that the first and second mode dimensionless displacement weights of risers are reduced respectively in the three riser groups. Values and variations of displacements along the axial direction of the upstream Risers #2-1 and #3-1 are considerably varied, among which displacements of the middle four measuring points are much larger and the amplitude is closer to each other. This corresponds to the significant second mode phenomenon from the envelope diagrams of the displacement. At the same time, the displacement-time curves of the three measuring points that far from the water surface in Risers #2-1, #3-1 and #5-1 show different degrees of "double-peak" morphology, which is due to the transition of the first mode to the second. However, displacements of the middle two measuring points in Risers #3-2 and #3-3 are larger than those of the other measuring points. The first mode is mainly observed, and there are only a few second-mode on the displacement envelope diagrams. In the previous section, it has been found that the wake interference makes the dominant frequencies of Risers #3-2 and #3-3 unobvious. The complex vibration frequencies cause amplitudes of Risers #3-2 and #3-3 to be no longer single and displacement-time curves to appear several peaks, but they still exhibit regular vibrations with clear cycles.

In the five-riser group, all the risers show that the first mode dominants vibration at U_r=8.42, and the second modes of Risers #5-1, #5-2 and #5-3 can be observed in the envelope diagrams. The first mode gradually decreases from upstream to downstream, the same as that of the second mode. The first-order mode weight of the downstream riser decreases the most dramatically, and the displacement is much smaller than that of the upstream riser. Similarly, the "double peak" shape in the displacement-time curve of the upstream riser is not as regular as the upstream riser of the two-, three-riser groups. The waveforms of the midstream riser and downstream riser begin to become irregular but still present in a periodic manner, and mutual interference factors increase as the number of risers increases. Riser #5-3 is interfered by the wake of two upstream risers and also fed back by its two downstream risers. The displacements of Riser #5-3 exceed that of Riser #5-2, and the shape variation

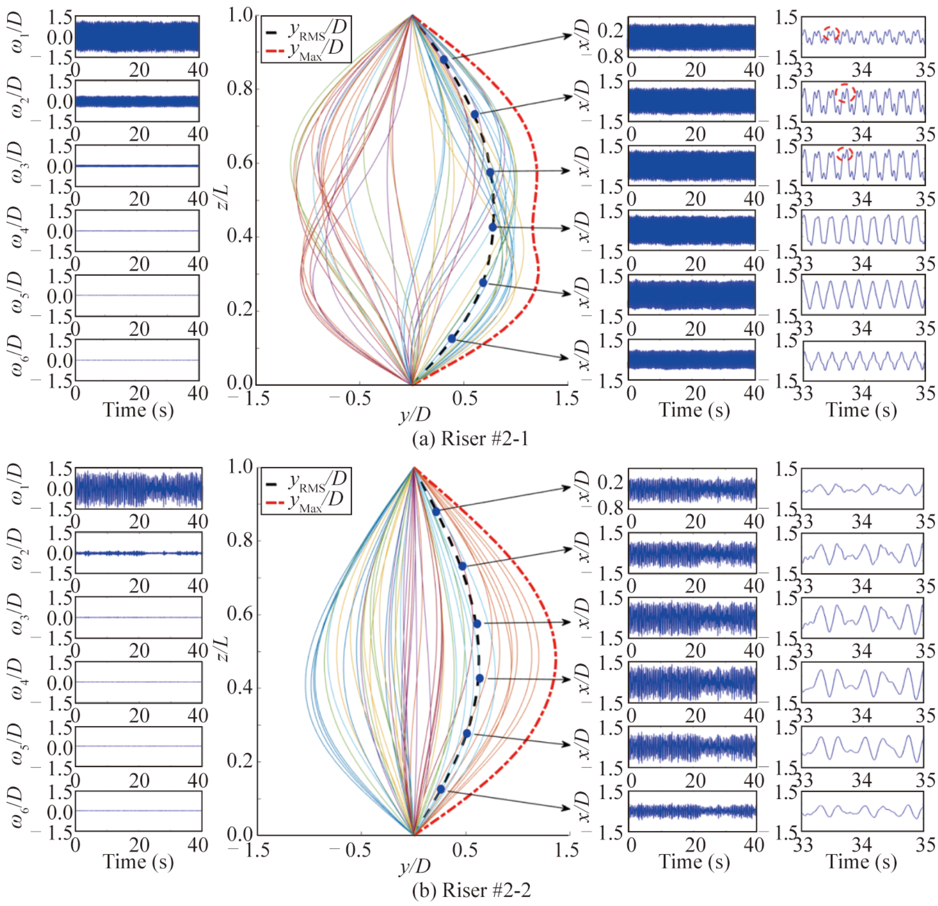

Fig. 15. Dimensionless displacement weights, characteristic displacements of the two-riser group.

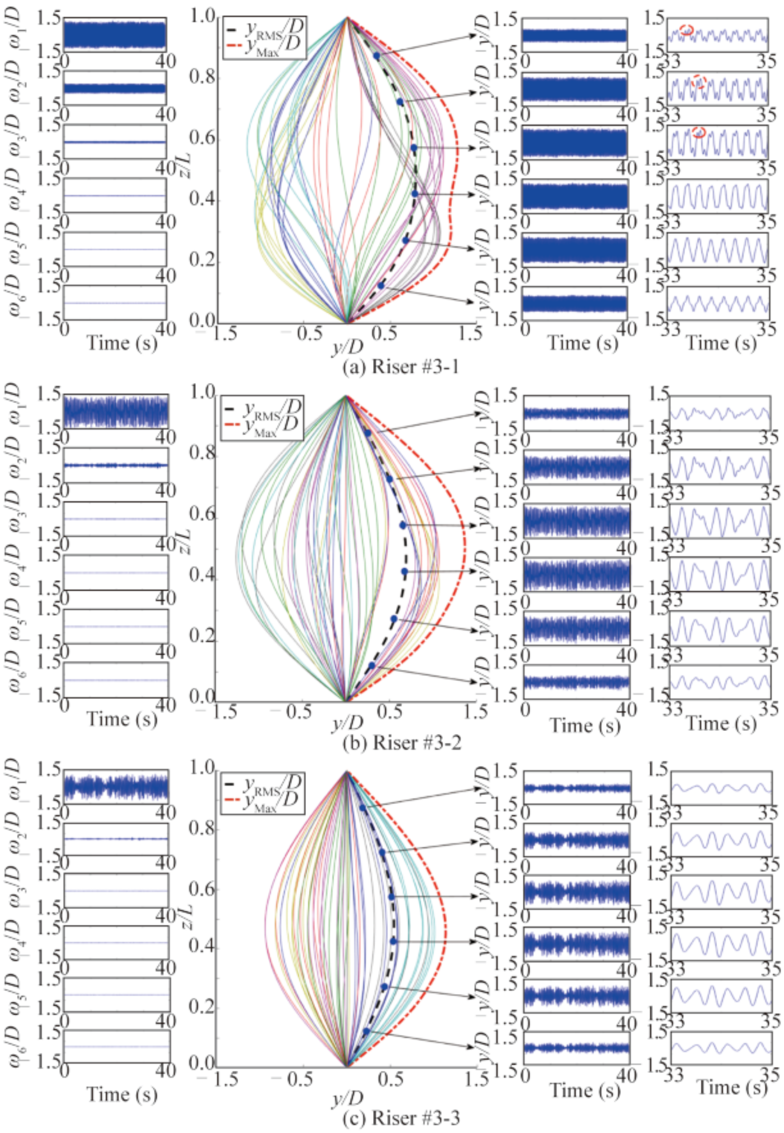

Fig. 16. Dimensionless displacement weights, characteristic displacements of the three-riser group.

of Riser #5-3 is different from that of others. The displacement of Riser #5-1 at z=0.425L becomes smaller, while the displacement amplitude of the riser under the water surface is larger. Because the position of larger amplitude is close to the dominant mode center, and the position of smaller amplitude corresponds to the intersection of adjacent mode. The velocity through the downstream riser is reduced due to the wake shielding effect, in turn leading to a decrease in the displacement amplitude of the downstream riser. Whereas the magnitude of the decrease is not linear, and the downstream riser is reduced much more than the midstream riser.

Figs. 18 and 19 show the displacement response of the five-riser group at U_r=10.10, which shows obvious standing waves in the CF direction caused by the dominant characteristics of VIV single-mode. The difference is that Riser #5-1 shows a slight characteristic of transformation from standing wave to traveling wave, and there is a certain trend of mode transformation in Risers #5-2 and #5-3, showing the characteristic of the gradual evolution from standing wave to traveling wave (Ma et al., 2019), as shown in Fig. 18. Downstream risers show strong standing wave characteristics, and the vibration intensity of Riser #5-5 is relatively weak compared with others. In the IL direction, Riser #5-1 is in the process of intense mode transformation, and so is Riser #5-2, but its intensity is weaker than that of Riser #5-1. Moreover, as the traveling wave direction is always from the power input to the power output area, it can be understood that the riser vibration is transmitted from high energy area to the low. The actual velocity near downstream decreases obviously due to the repeated interference of shielding effect, and all show standing wave characteristics.

3.3 Vibration trajectories and interference efficiency

3.3.1 *Vibration trajectories*

Fig. 20 shows displacement trajectories versus the

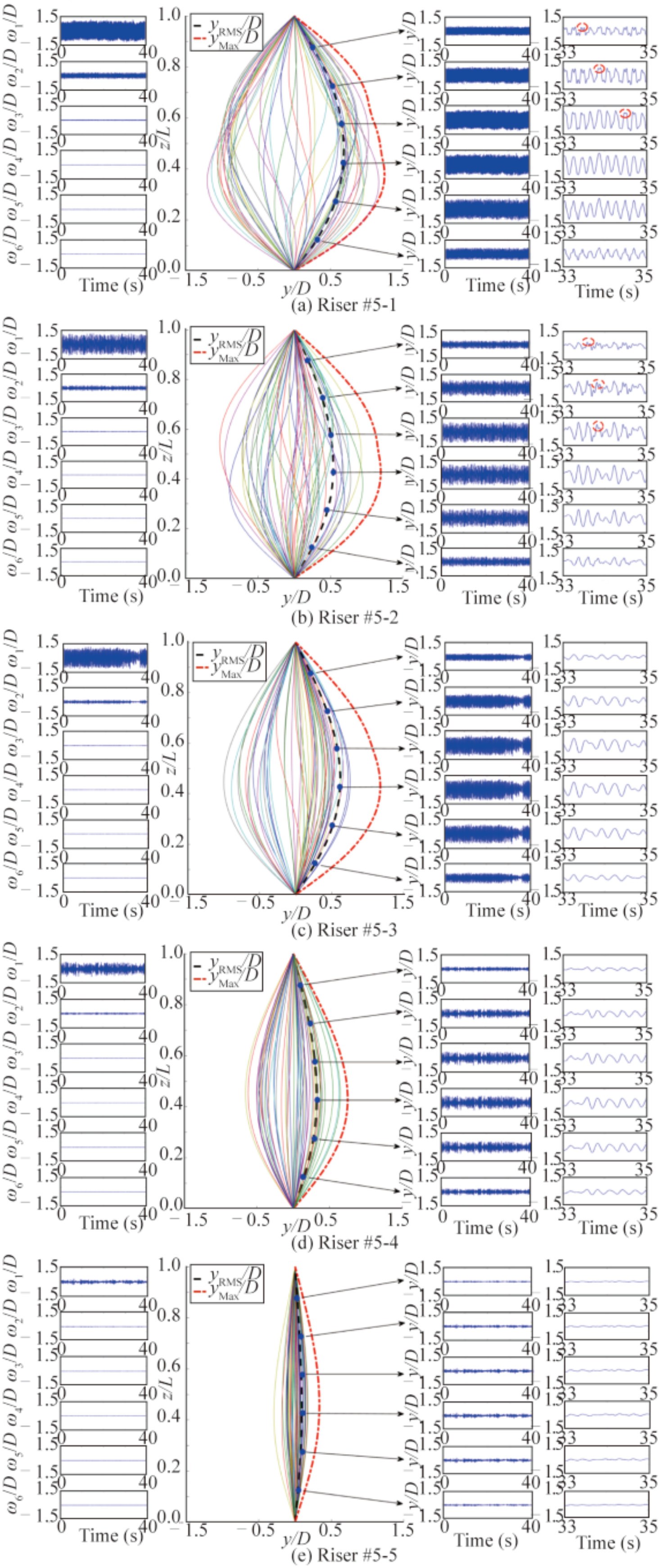

Fig. 17. Dimensionless displacement weights, characteristic displacements of the five-riser group.

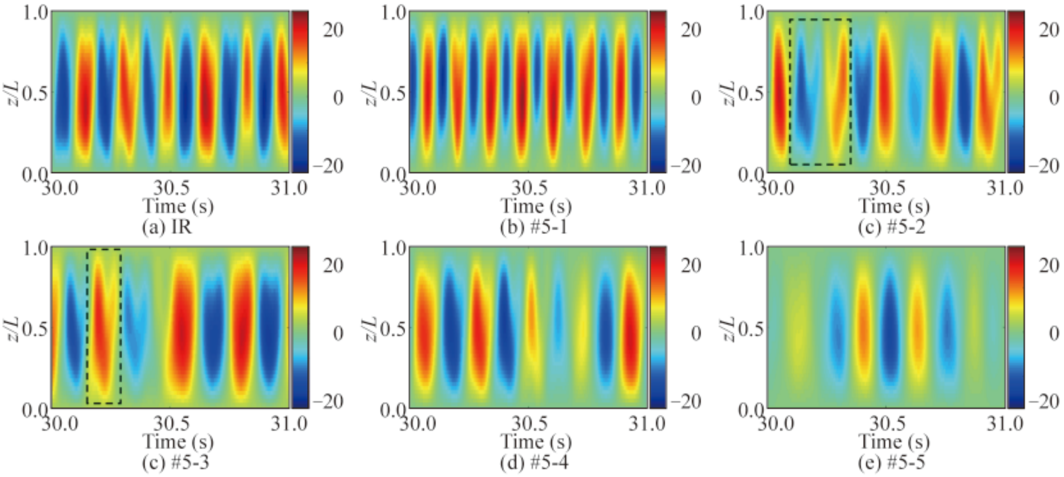

Fig. 18. Space-time varying amplitude contours in the CF direction.

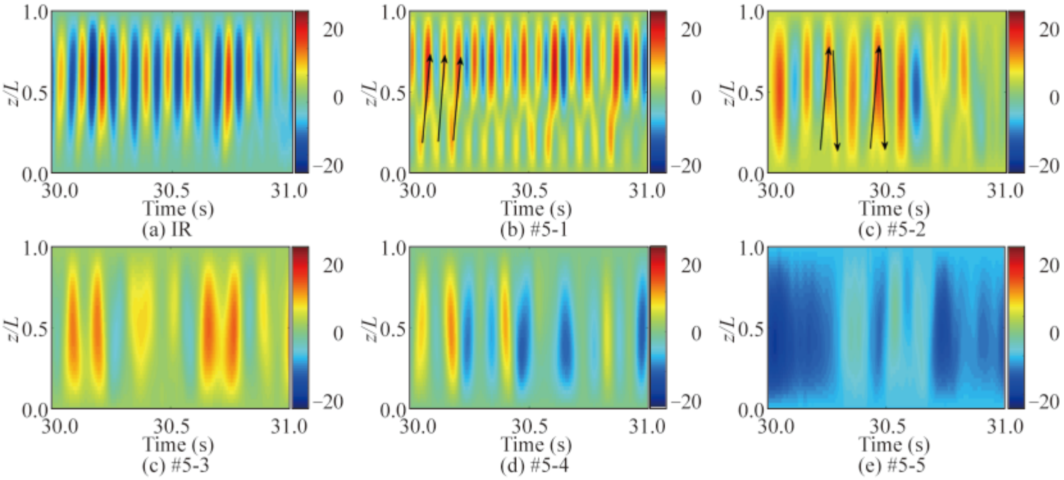

Fig. 19. Space-time varying amplitude contours in the IL direction.

reduced velocity of the isolated riser and riser groups. All risers have small displacement trajectories at low velocities. The trajectories of the upstream riser in two- and three-riser groups at U_r=3.36 first appear as "8-shaped", and the trajectories deviate from the original shape to present "lip-shaped" and "crescent-shaped" when the reduced velocity increases. The two lobes of trajectories point to the downstream at $U_r \geqslant$ 6.73, and the feature is particularly prominent in the range of 4.20<U_r<7.58. Risers have less reaction to the upstream riser, so the upstream riser vibration trajectory is similar to that of the isolated riser, together with a relatively regular motion trajectory. The "8-shaped" trajectories can be observed in Riser #3-2 at 3.36<U_r<5.89. For the five-riser group, only the upstream riser presents a regular "8-shape" at U_r=6.73 and 7.58. After U_r>8.42, the "8-shape" of the upstream riser in the five-riser group deviates from the standard shape, which is different from the isolated riser and upstream riser in other riser groups. From Fig. 20, the vibration amplitudes between adjacent risers are significantly different in the five-riser group, which is consistent with the results of the displacement response. In addition, the vibration trajectory amplitudes of downstream risers (#5-2, #5-3, #5-4, #5-5) always lag behind its upstream adjacent riser in the five-riser group except for the upstream Riser #5-1.

3.3.2 *Interference efficiency*

The concept of "interference efficiency" (η) (Liu et al., 2020) is introduced to further quantify the adjacent interference, which is defined as the ratio of the difference between RMS displacement of riser group and the isolated riser to RMS displacement of the isolated riser. Figs. 21−23 show the interference efficiency, in which η>0 indicates that the displacement response of the riser group is enhanced compared with that of the isolated riser, which is the interference enhancement region (yellow); η<0 indicates that it is suppressed, which is the interference suppression region (blue). The displacement interference efficiencies of most riser groups in two directions are above 100% at $U_r \leqslant$3.36, and the vibration displacement increases greatly with the reduced velocity, which indicates that the interference effect

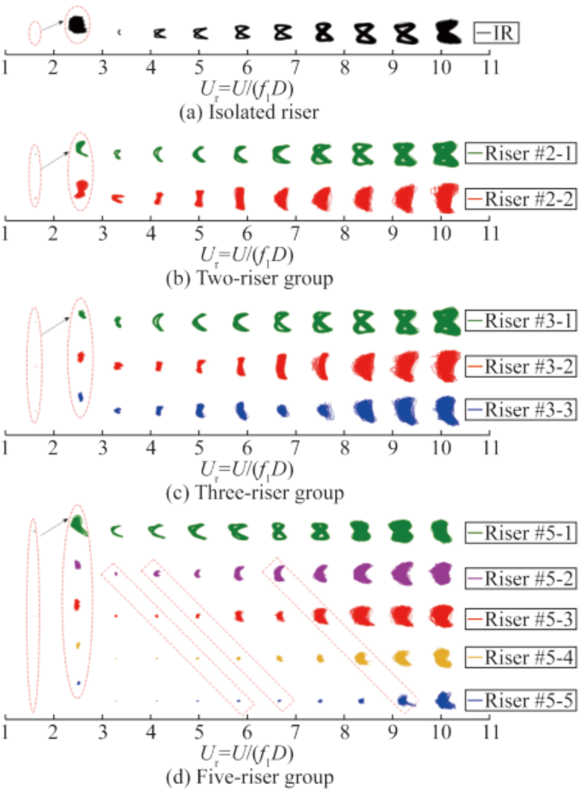

Fig. 20. Dimensionless vibration trajectories.

of fluid between risers is stronger at low velocities than that at high, so the interference effect of wake and clearance flow in low velocities cannot be ignored.

In the CF direction, similar trends emerge in the interference efficiencies of the upstream risers in the three riser groups: the interference efficiency decreases and tends to be stable. For the two-riser group, the riser group is in the displacement enhancement region to a large extent, which is opposite in the IL direction, and the weakened displacement area is widely distributed. For the three-riser group, in the CF direction, the interference effect enhances the rolling up of the separated shear layers on both sides of the midstream and upstream risers, causing them to produce strong vortex shedding, and the trajectory is inclined to the upstream direction. Both Risers #3-1 and #3-2 are in the interference enhancement region. However, in the IL direction, the displacement is suppressed, and the wake shielding effect is significantly stronger than that in the CF direction, which is consistent with the conclusion in Section 3.2. For the five-riser group, the rule is obviously different from others. The maximum interference efficiency appears at low reduced velocity with Riser #5-1, and the interference efficiency gradually decreases. The displacement responses of risers are in the suppression region except for Riser #5-1, and the interference efficiencies of Risers #5-4 and #5-5 are relatively

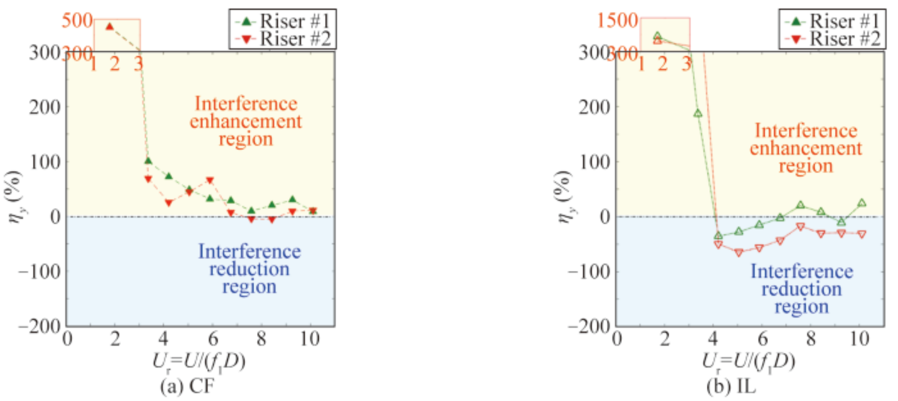

Fig. 21. Interference efficiency of the two-riser group.

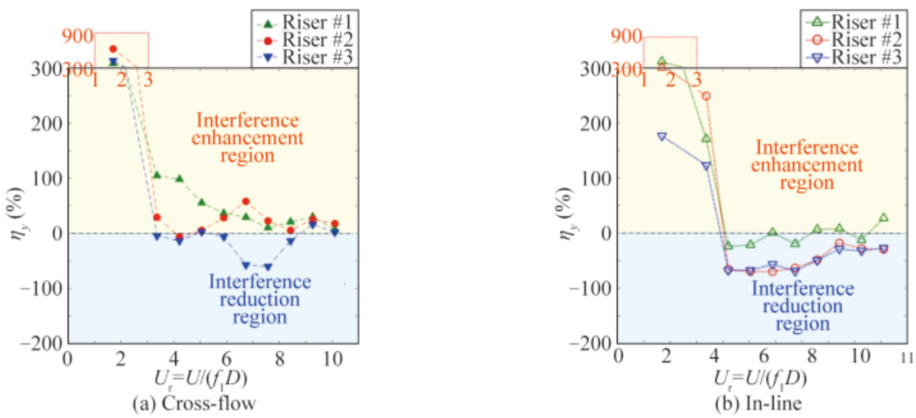

Fig. 22. Interference efficiency of the three-riser group.

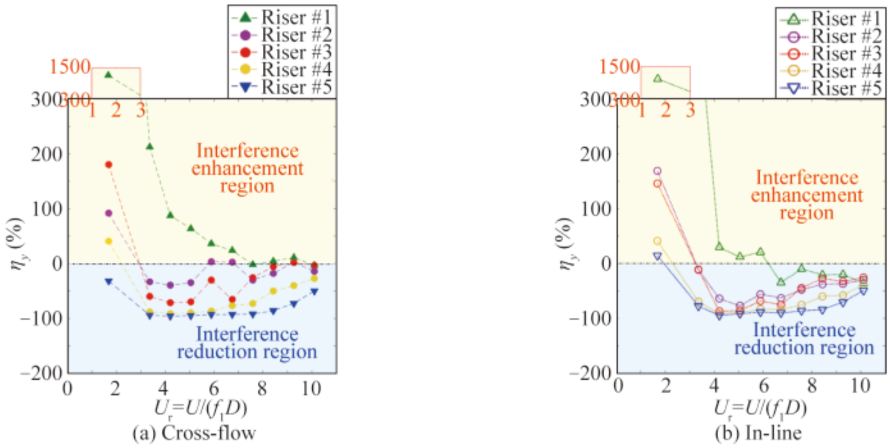

Fig. 23. Interference efficiency of the five-riser group.

stable.

4 Conclusions

(1) The dominant frequency, dimensionless displacement, and variation trends of the upstream riser in the tandem riser group are close to those of the isolated riser. The wake shielding effect is remarkable, and the midstream and downstream risers have interference feedback to its upstream riser, which suppresses the CF dominant frequency of the upstream riser, but enhances the IL displacement. The interference effect of midstream and downstream risers on their upstream risers is significantly lower than that of upstream risers on midstream and downstream risers, regardless of the vibration frequency and displacement response.

(2) The vibrations of midstream and downstream risers are the nonlinear superposition of WIV of upstream riser and its own VIV, and the uncertainty of wake and gap flow leads to the contingency of the riser vibration cancellation or enhancement. Repeated superimposed wake vortices act on the midstream and downstream risers of the five-riser group, resulting in significant variations in their vibration modes, and vibration trajectories lag behind those of their adjacent upstream risers. In particular, the vibration frequency distribution range of downstream risers is widened and the dominant frequency is extremely unstable.

(3) The wake interference effect suppresses the VIV displacement of midstream and downstream risers in the IL direction compared with the displacement of the isolated riser; and promotes the vibration amplitude in upstream and midstream of two- and three-riser groups in the CF direction. The first-order mode weight dominates vibration, but the upstream and midstream risers in the five-riser group show strong mode transformation characteristics. Owing to the multiple wake interference effect, the actual velocity of the downstream riser is reduced, and no mode transition characteristics are observed in CF and IL directions, all of which show standing wave characteristics.

(4) The interference effect of fluid between risers on adjacent risers at low velocities is stronger than that at high velocities, so the interference effect of wake feedback effect and clearance flow at low velocities cannot be ignored. The CF displacements of upstream risers are all in the interference enhancement region. The CF displacement of upstream and midstream risers in tandem riser groups needs to be paid more attention considering the structural design and cost control of the riser group.

Right and permissions

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