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Effect of internal flow on vortex-induced vibration of risers

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Abstract

Although there are many studies dedicated to the problem of vortex-induced vibration (VIV) of marine risers, VIV experiments with internally flowing fluid have not been carried out before. In order to investigate this area, the present experiment with an internally flowing fluid and external current was designed. The riser was towed in the water flume with varying internal flow speeds. The tests in still water and in a current were conducted successfully. Various measurements were obtained including the frequency responses and the time-domain tracing of in-line and cross-flow responses. The experimental results exhibit several valuable features. First, with an increase in internal flow speed, the response amplitude increases while the vibration frequency decreases. Secondly, internally flowing fluid lessens the correlation of the vibration between different sections. In addition, by plotting both in-line strain and cross-flow strain simultaneously, a figure-of-eight for bending strain is also observed, and the trajectories in different cycles are more concordant with the increase of internal flow speed.

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1. Introduction

Vibration induced in elastic structures by vortex shedding is of practical importance because of its potentially destructive effect on marine risers. Vortex-induced forces may excite the riser in its normal mode of transverse vibration. When the vortex shedding frequency approaches the natural frequency of a marine riser, the cylinder takes control of the shedding process causing the vortices to be shed at a frequency close to its natural frequencies. This phenomenon is called vortex shedding "lock-in" or synchronization. Under "locking in" conditions, large resonant oscillations occur. Large responses give rise to oscillatory stress. If these stress values persist, significant fatigue damage may occur.

The vortex-induced vibration (VIV) response of a marine riser is a complicated process involving both the hydrodynamic and the structural properties of the riser. Model testing has given valuable insight into VIV. Different types of experiments have been done, e.g. forced motion with rigid cylinders in a uniform flow (Gopalkrishnan, 1993), spring supported rigid cylinders in uniform flow (Vikestad, 1998) and scaled riser models in uniform and sheared flows (Lie and Vandiver, 1998). Blevins (1990) gives a comprehensive introduction to the phenomenon of VIV in general, while Vandiver (1998) gives an account of the state-of-art when it comes to the VIV of marine risers.

Although some work has been done for VIVs, a system with the inclusion of internal flow inside the pipe has rarely been considered. When the internal fluid travels inside the curved path along the deflected riser, it experiences

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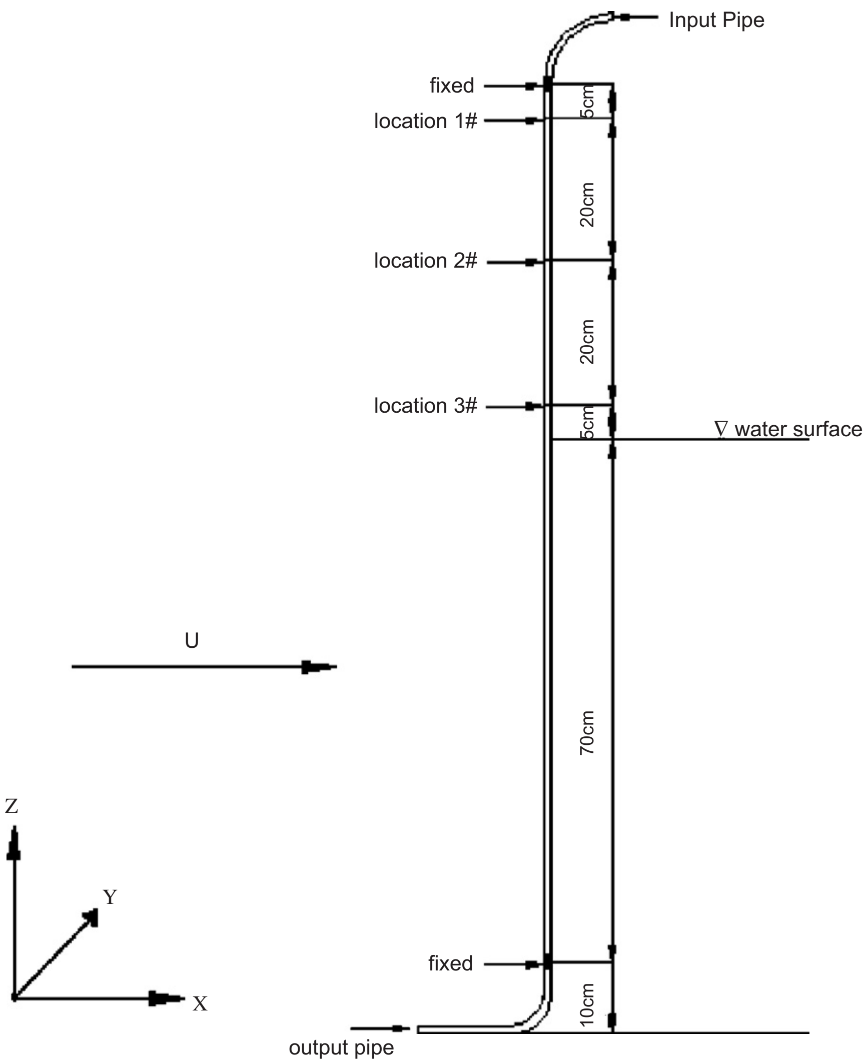

Fig. 1. Diagram of experimental set-up.

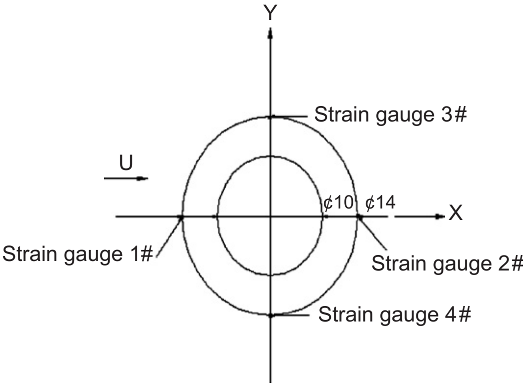

Fig. 2. Cross-section of the riser model.

centrifugal and Coriolis accelerations, respectively, due to the curvature of the riser and the relative motion of fluid to the time-dependent riser motion. Those accelerations experienced by the riser, in turn, affect the dynamic behavior of the riser and cause additional vibrations (Moe and Chucheepsakul, 1988; Païdoussis et al., 2002; Lopes et al., 2002; Semler et al., 2002). In addition, the riser vibration could be "locked-in" with the flow-induced vortex shedding such that they resonate together to produce large deflection and stress. This phenomenon could lead to the failure of the riser system prematurely. Therefore, it remains to be solved how internal flow affects VIV responses. Chen (1992) explored this topic in his paper. Hong (1994) investigated the effect of internal flow on VIVs by using a simple oscillator model. Hong and Huh (1999) developed a mathematical model for the analysis of VIV with the inclusion of internal flow and examined the effect of internal flow on VIVs.

However, up to now, VIV experiments considering an internally flowing fluid and an external marine environment have not been properly carried out. In order to investigate the VIVs of risers more thoroughly, we designed an experiment simultaneously involving internal fluid flow and external current. The instrumented riser with a length of 1.2 m is made of rubber and has fixed ends. Its natural frequency can change with varying top tension. The pipe was towed vertically in the water flume with varying internal fluid speed. Impact tests in still water and tests in different current magnitudes were conducted successfully. Various measurements were obtained from the strain gauges placed on the pipe, and the effect of internal flow on VIV was investigated.

2. Experiment

The present experiment was conducted in a wind-wave-current flume, which is 65 m long, 1.2 m wide and 1.75 m deep. The experiment used a pipe made of rubber with a smooth surface. The pipe had an outer diameter of 14 mm and a thickness of 2 mm. Fig. 1 shows in detail the set-up of the experiment. The instrumented pipe was fixed vertically and allowed oscillations in both the in-line direction (X-direction) and the cross-flow direction (Y-direction). Its effective length was 1.2 m, with 0.7 m below the water surface. For the internal flow, a water pump circulated the water into the riser model through an input plastic pipe at a given speed, and a plastic output pipe drained the water into the flume.

Strain gauges were mounted on the riser to measure the responses. Three locations were selected to place strain gauges, identified as locations 1#, 2# and 3#. At each location, four strain gauges were placed as shown in Fig. 2. The two strain gauges in the X-direction were used to measure the in-line vibrations, while the other two gauges in the Y-direction were used to measure the cross-flow vibrations. After installing the strain gauges on the outer surface of the pipe, the pipe was covered with glue for water proofing.

In order to measure the natural frequency of the riser model, impact tests were conducted on the instrumented pipe in still water with varying internal fluid velocities. From the strain signals, the power spectra of the riser strain were obtained. The natural frequency of the riser system can be inferred from the power spectrum of the strain.

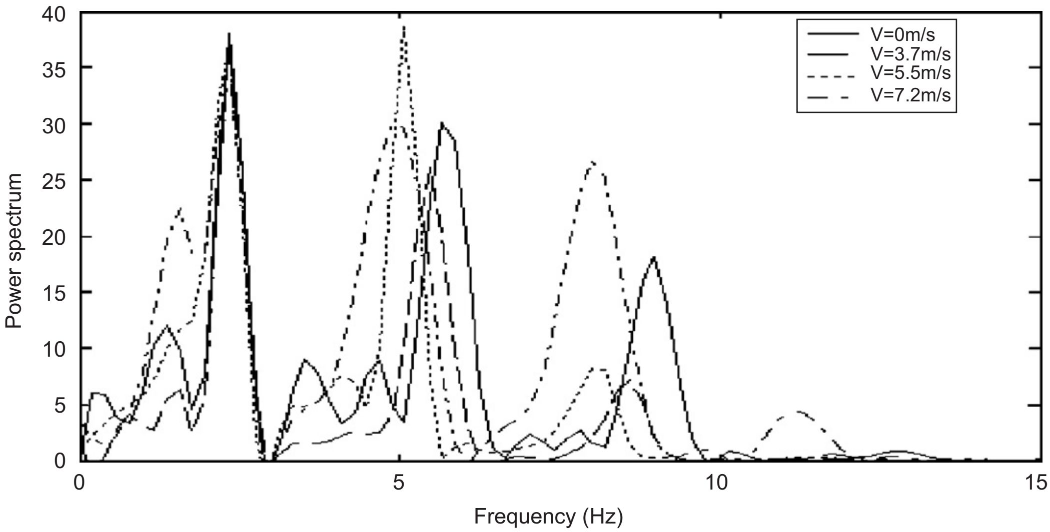

Fig. 3. Natural frequency of the riser with different internal flow speeds.

For the VIV test in the current, the current velocity ranges from 0.16 to 0.60 m/s, with approximate increments of 0.04 m/s. This range of speeds corresponds to Reynolds numbers from 2.24×10^3 to 8.4×10^3. In this range of the Reynolds number, a fully turbulent vortex street is formed in the wake (Blevins, 1990). For each current, the internal fluid speed varied from 0, 3.7, 5.5 to 7.2 m/s. In order to represent better the relative significance of internal flow, the internal flow speed is expressed as a fraction of the current velocity, that is $v = V/U$, where v is the relative internal flow speed, V is the internal flow speed, and U is the current speed.

The sampling frequency was 200 Hz, which allowed us to measure signals up to 100 Hz. The highest shedding frequency was expected to be approximately 9 Hz, and thus the sampling frequency was high enough to avoid aliasing. The length of time for recording was all 2.56 s. From the strain signals, various measures such as the power spectra, time-domain traces of in-line and cross-flow direction motions were obtained. The vibration frequency can be inferred from the power spectrum of the strain.

3. Results and discussion

Fig. 3 shows the natural frequency of the pipes with different internal fluid speeds. At internal fluid speeds $V = 0$, 3.7, 5.5 and 7.2 m/s, the corresponding natural frequencies of the first to the third mode are 2.7, 5.8 and 9.0 Hz; 2.5, 5.5 and

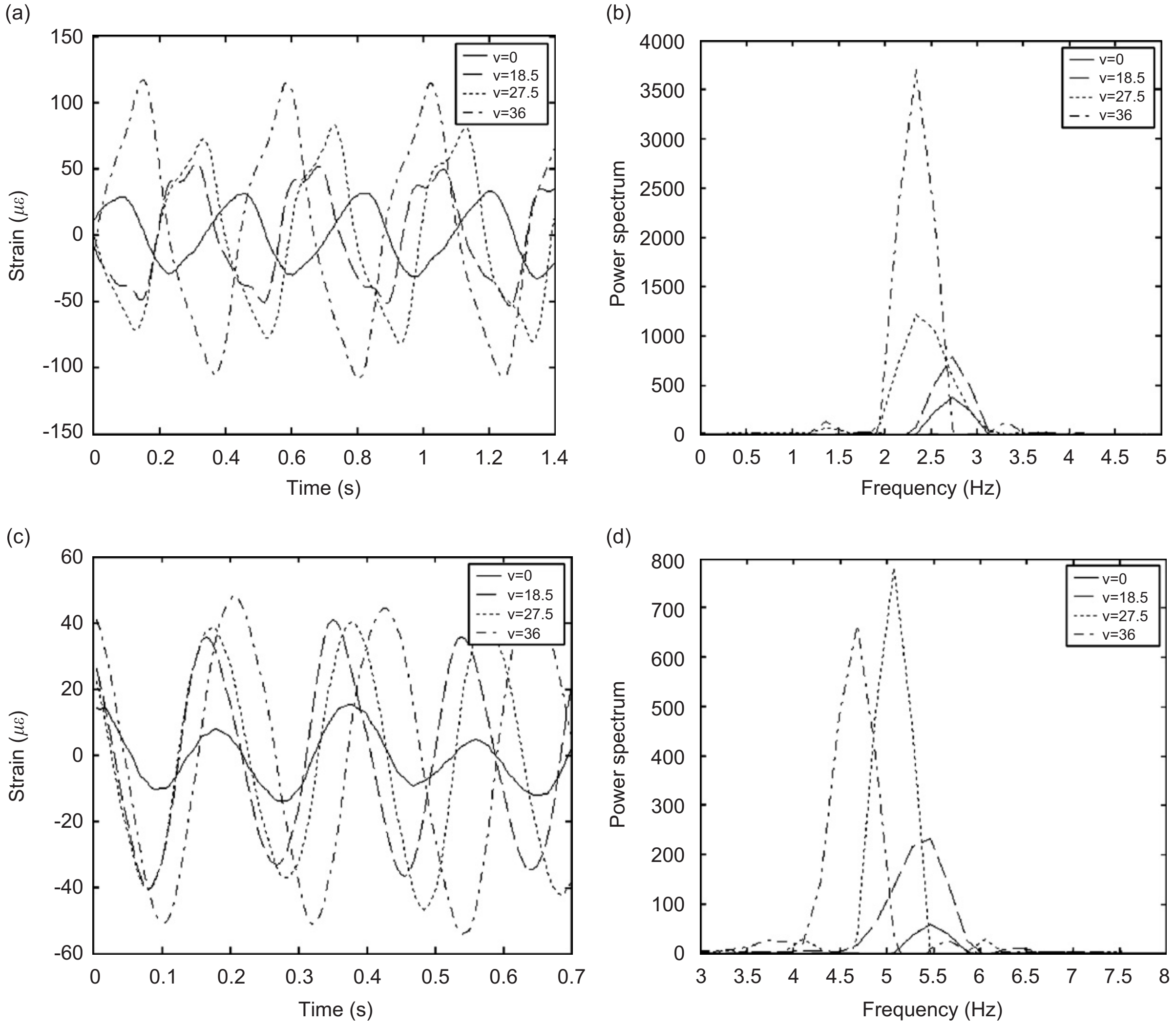

Fig. 4. Strain response at location #3 with a current speed of 0.2 m/s: (a) cross-flow strain time-history, (b) power spectrum of cross-flow strain, (c) in-line strain time-history, and (d) power spectrum of in-line strain.

8.6 Hz; 2.3, 5.1 and 8.0 Hz; 2.1, 4.7 and 7.6 Hz, respectively. Thus, it can easily be inferred that with increasing internal fluid speed, the natural frequencies, from the lower one to the higher one, all decrease, which is similar to the conclusion reached by Housner (1952).

As mentioned above, for the VIV tests in the current, the slowest current speed is 0.16 m/s and the fastest speed is 0.6 m/s. The increment is 0.04 m/s. Therefore, we have 13 cases with different current speeds. In this study, we will take the cases of current speeds $U = 0.2$ and 0.48 m/s as examples.

Fig. 4 is the strain response of the riser at location #3 with a current speed of 0.2 m/s. The results of the other two locations are similar to that of station #3.

Fig. 4(a) depicts the cross-flow strain tracing. The four lines in different line types represent four different internal flow speeds. At relative internal speeds of $v =$ 0, 18.5, 27.5 and 36, the strain amplitudes are about 30, 55, 70 and 110 $\mu\varepsilon$, respectively. This demonstrates that as the internal flow speed increases, the response amplitude also increases.

Fig. 4(b) is the corresponding power spectrum for Fig. 4(a). The response frequency may be easily inferred from the figure. It is well known that the VIV frequency approximately follows the well-known Strouhal relation which is

$$f_s = \frac{\mathrm{St}\, U}{D}, \tag{1}$$

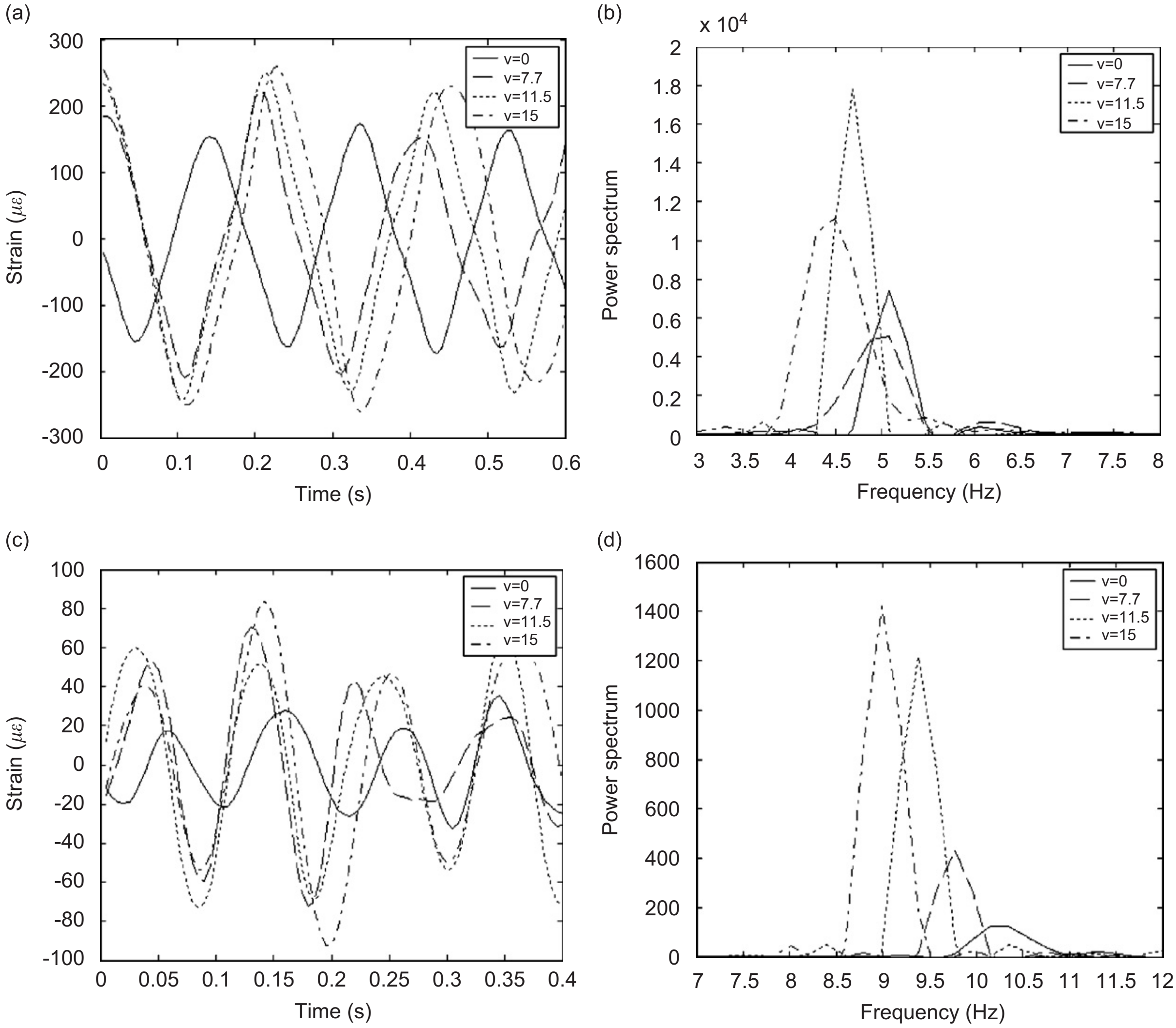

Fig. 5. Strain response at location #3 with a current speed of 0.48 m/s: (a) cross-flow strain time-history, (b) power spectrum of cross-flow strain, (c) in-line strain time-history, and (d) power spectrum of in-line strain.

where f_s is the shedding frequency, St is the Strouhal number, U is the current speed, and D is the diameter of the pipe (Blevins, 1990). At the internal flow speed $v = 0$, the response frequency is 2.7 Hz, while the frequency derived form Eq. (1) is 2.85 Hz. They are very similar. One reason for the difference from the Strouhal relation is that the pipe is not rigid, and the other one is due to the lock-in phenomenon. For the effect of internal flow, at relative internal speeds $v = 0$, 18.5, 27.5, and 36, the response frequencies are about 2.6, 2.5, 2.4, and 2.3 Hz, respectively. In other words, the internal flowing fluid reduces the response frequency.

Fig. 4(c) is the in-line strain time-trace which was measured simultaneously with the cross-flow, and Fig. 4(d) is the corresponding power spectrum. For the effect of internal flow on VIV, the same conclusion can also be drawn from the in-line vibration. For example, at $v = 0$, 18.5, 27.5, and 36, the amplitude of in-line vibration is 18, 32, 47 and 50 $\mu\varepsilon$, while the vibration frequency is 5.5, 5.2, 5, and 4.7 Hz, respectively.

Comparing the cross-flow vibration with the in-line vibration, the difference lies in not only the amplitude but also the frequency. For the amplitude, the cross-flow oscillation is much larger than the in-line oscillation. For example, at $v = 0$, the cross-flow amplitude is about 30 $\mu\varepsilon$, while the in-line one is only about 18 $\mu\varepsilon$. For the frequency, the well-known effect of frequency doubling is quite obvious. At $v = 0$ the cross-flow frequency is 2.7 Hz, as has been mentioned before, while the in-line frequency is about 5.5 Hz, almost doubles the cross-flow value.

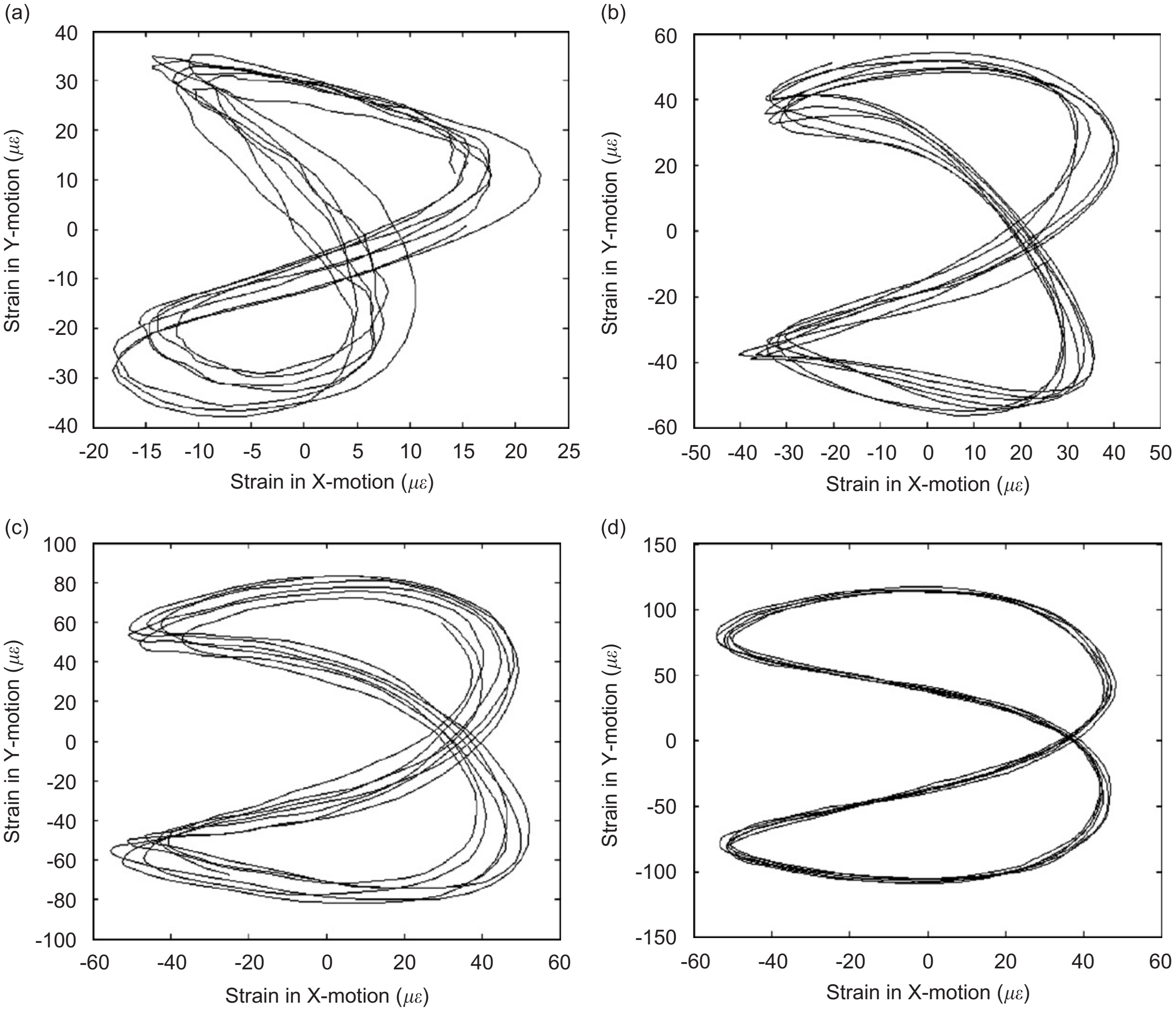

Fig. 6. Strain trajectory at location #3 with a current speed of 0.2 m/s: (a) $v = 0$; (b) $v = 18.5$; (c) $v = 27.5$; and (d) $v = 36$.

Fig. 5 demonstrates the riser response at a current speed of 0.48 m/s. The relative internal flow speed v is 0, 7.7, 11.5, and 15. The same conclusion can also be drawn as for a current speed $U = 0.2\,\mathrm{m/s}$. By comparing Figs. 4 and 5, we can infer that the effect of internal flow in Fig. 4 is more obvious than Fig. 5. It is mainly because the relative internal flow speed in Fig. 4 is much higher than that in Fig. 5.

For internal flow speed $V = 0$, it is well known that when lock-in occurs the trajectory of the structure has a figure-of-eight shape (Vandiver and Jong, 1987; Jauvtis and Williamson, 2004). In this paper, by plotting both the in-line and cross-flow strains simultaneously, a figure-of-eight shape for bending strain was also observed. Figs. 6 and 7 show the strain figure of the riser with different internal flow speed at current speed of 0.2 and 0.48 m/s, respectively. From Fig. 6, we can see that at relative internal flow speed $v = 0$, the figure-of-eight is observed. However, the trajectories are somewhat tangled, and the vibrations in different cycles do not follow the same trajectory. With an increase in relative internal flow, the trajectories become more and more accordant. At relative internal flow speed $v = 36$, the trajectories in different cycles are almost identical. In other words, the vibration of the riser is more accordant with an increase in internal flow speed.

Comparing Figs. 6 and 7, we can see that the effect of internal flow in Fig. 6 is more obvious than in Fig. 7, as in Fig. 4 compared to Fig. 5. It is due to the same reason that the relative internal flow speed is higher than in Fig. 7.

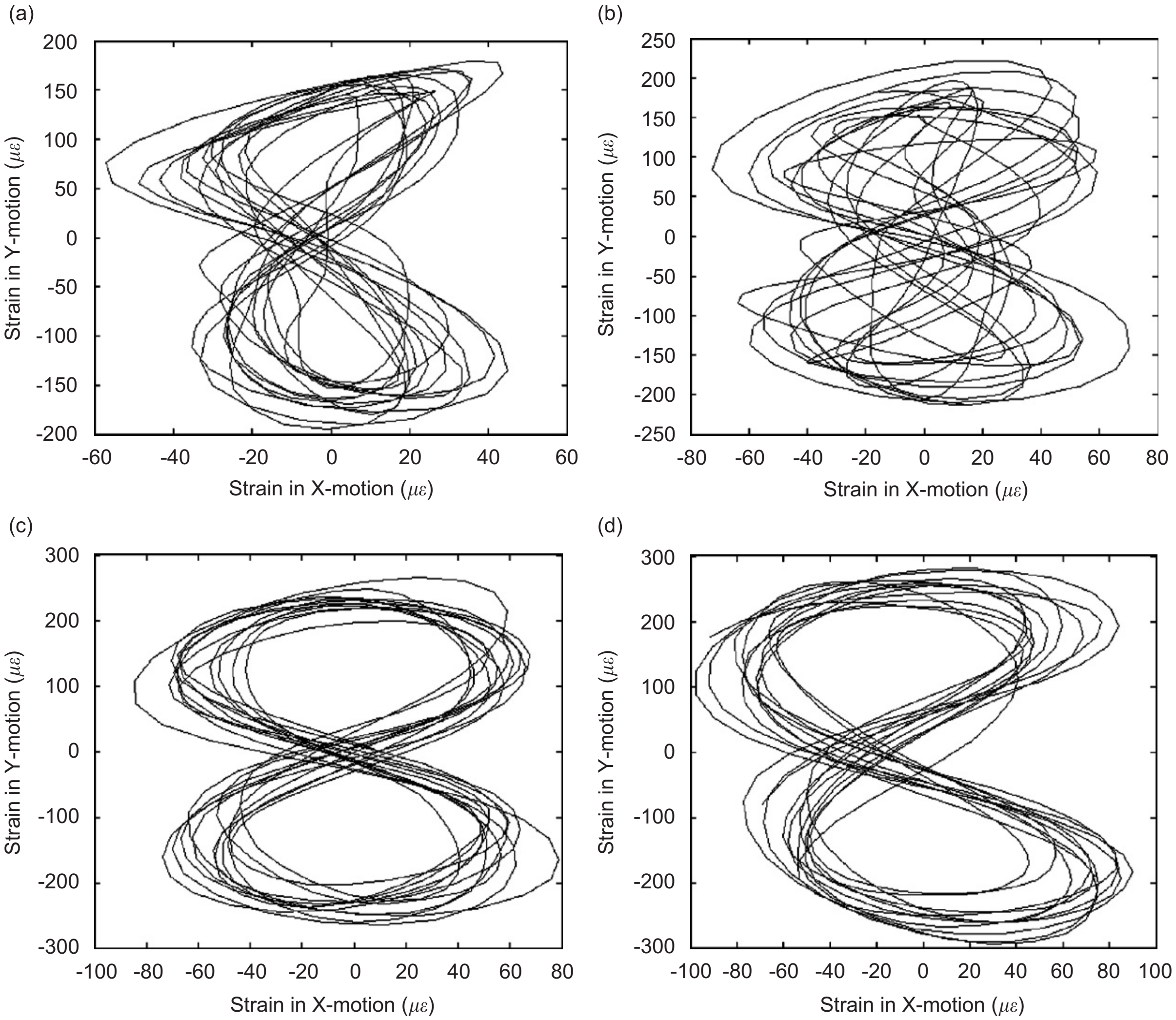

Fig. 7. Strain trajectory at location #3 with a current speed of 0.48 m/s: (a) $v = 0$; (b) $v = 7.7$; (c) $v = 11.5$; and (d) $v = 15$.

Table 1
Correlation coefficient of riser response with a current speed of 0.2 m/s

	Cross-flow			In-line		
	Location 1–2	Location 1–3	Location 2–3	Location 1–2	Location 1–3	Location 2–3
$v = 0$	−0.7950	−0.9858	0.8453	*−0.8260*	*−0.8722*	0.9717
$v = 18.5$	−0.5196	−0.9668	0.4523	−0.9643	−0.9283	0.8491
$v = 27.5$	−0.4998	−0.9636	0.4345	−0.9527	−0.8617	0.7145
$v = 36$	−0.4598	*−0.9790*	0.4114	−0.9307	−0.7780	0.5674

Table 2
Correlation coefficient of riser response with a current speed of 0.48 m/s

	Cross-flow			In-line		
	Location 1–2	Location 1–3	Location 2–3	Location 1–2	Location 1–3	Location 2–3
$v = 0$	−0.9669	−0.9753	0.9257	−0.8247	0.4472	−0.7427
$v = 7.7$	−0.9141	−0.9735	0.8369	−0.8199	0.4119	−0.6688
$v = 11.5$	−0.9101	−0.9511	0.7489	*−0.9578*	*0.6199*	−0.6743
$v = 15$	−0.9004	−0.9322	0.6876	*−0.9692*	*0.7197*	−0.6725

A test of the relationship between the two variables x and y by means of the correlation coefficient ρ is given as

$$\rho(x, y) = \frac{(1/n)\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\mathrm{SD}(x)\,\mathrm{SD}(y)}. \tag{2}$$

Let x and y be the strain data of the riser at two different sections, then the corresponding correlation coefficient of the vibration between different sections is derived using Eq. (2).

In the following, the correlation of both cross-flow vibration and in-line vibration between different sections of the riser model at current speeds $U = 0.2$ and 0.48 m/s are derived, as shown in Tables 1 and 2. From the data, it can be concluded that the correlation between different sections is very strong. Furthermore, the correlation lessens with an increase in internal flow speed. For example, at a current speed of 0.20 m/s, the correlation coefficient of cross flow vibration between locations 1 and 2 at a relative internal flow speed $v = 0$, 18.5, 27.5, and 36 is −0.7950, −0.5196, −0.4998, and −0.4598, respectively. Comparing Tables 1 and 2, another conclusion can be drawn that the effect of internal flow is more obvious with a higher relative internal flow speed.

However, there are some exceptions in Tables 1 and 2, and these are italicized. These exceptions are probably due to external current and internal flow fluctuation. In some cases, they are not very steady.

4. Conclusions

An experimental study on VIV of a riser with different internal flow speeds was performed in a water flume. By processing the experiment data, the following conclusions can be drawn:

(i) In still water, the internal fluid flow will reduce the natural frequency of the riser system.
(ii) In a current, with the increase of internal flow speed, the amplitude of the strain in the in-line vibration and the cross-flow vibration will both increase, while the oscillation frequencies decrease. The cross-flow oscillation frequency approximately follows the Strouhal relation, and the well-known frequency doubling between in-line oscillation and cross-flow vibration is obvious.
(iii) By plotting both in-line strain and cross-flow strain simultaneously, a figure-of-eight plot of bending strain is also observed, and the trajectories are more accordant with an increase in internal flow speed.

(iv) With both the cross-flow vibration and the in-line vibration, the correlation between different sections is very high. With internal flow, the correlation is lessened.
(v) The effect of internal flow is more obvious with higher relative internal flow speed.

Acknowledgments

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