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The experimental research on vibrating characteristics for multiple tubes in cylindrical fluid

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ABSTRACT

Tubular structures induced vibration in cross flows of the surrounding fluid are common in tube strings of deep water oil drilling, marine cluster wells and heat exchangers. This is a typical problem in the fluid-structure coupling dynamics of flow-induced vibration. In this study, the specialized experimental device is designed and built for the vibration of tube bundles in cylindrical fluid. Under the action of cross flow, the vibration test of tubes in the cylinder is carried out by dynamic test technology. Through the test data handing and analysis, it is found that the position of elastic tube bundle has little effect on the vibration cycle and frequency of the tube in the fluid of cylinder. The vibration amplitude of the tube located in the center of cylinder is small, while the vibration amplitude is large for the tube deviation from the cylinder inlet. In order to reduce the vibration of tube bundles, it is advisable to place the tube in the cylinder center and avoid placing the tube at a position that deviates from the fluid inlet. The studied results not only provide experimental data for tubular structure designing on deep water oil drilling, marine cluster wells and heat exchangers, but also provide the basis and evidence for the theoretical research on the fluid-solid coupling.

1. INTRODUCTION

Since the collapse of Tacoma Channel Bridge in 1940, the problems of structural vibration induced by cross flow attract great concern by researchers. Because such slender structures are often long and submerged in cross flows of the surrounding fluid and air, it may induce violent vibrations, which can even cause failure. This phenomenon is common in hanging cable bridge, tall chimney, high buildings, and transmission cables and so on. Especially for tubular structures in marine riser, heat exchanger, nuclear power plant, seen as Fig.1, due to using high-strength materials, the structure becomes lighter and slender and there are existing a lot of problems of tube bundle vibration induced by cross flow. Because it is a catastrophic event caused by the vibration of tube, the dynamic analysis of vibration induced by cross flows of the surrounding fluids has been one of the most active researches in designing tube bundles. With respect to the mechanism of flow induced vibration [1], flow around the tube bundle [2], wave action [3], induced vibration characteristics of the tube [4], dynamic response [5], the form of destruction [6] and vibration prevention [7] have been carried out by many researchers, providing a strong theoretical basis for designing and safety evaluation of tubes [8~11]. X.C.Li et al. [12] designed the parameters for VIV experiments focused mainly on the transition from the first dominant mode to the second one and the vibration characteristics in the range of transition. Z. Kang et al. [13] carried out the experiments on the two-degree-freedom vortex-induced vibration(VIV) of a flexibly-mounted, smooth cylinder was performed at MIT, and the test data were analyzed to predict details of VIV trajectories. H.Lie et al.[14] studied large-scale model testing of a tensioned steel riser in well-defined sheared current, and the signals were processed to yield curvature and displacement and further to identify modes of vibration. J.N. Song et al. [15] built laboratory tests on vortex-induced(VIV) of a long flexible riser towed horizontally in a wave basin. The experimental results confirmed that the riser pipe vibrated multi-modally despite it being subject to a uniform current profile and all of the excited modes vibrated at the Strouhal frequency. J. Xu et al. [16] made wake velocity measurements with the riser freely vibrating in both in-line and cross-flow directions. The VIV results showed that the riser freely oscillated at multiple vibration frequencies and amplitudes at each Reynolds number. Narakorn Srinil [17] focused on the cross-flow VIV modelling, time-domain analysis and prediction of variable-tension vertical risers in linearly sheared currents. Most researches focused on the vibration characteristics for one pipe in cross flow. However, there are few experimental studies on vibration characteristics for multiple tubes with cross flows of the surrounding fluid. Motivated by these, this paper has carried on the related theory of tubing vibration induced by cross flows of the surrounding fluids, then selected the tube's parameters and designed and set up the special experimental device for tube vibration in cylinder fluids. Under the action of cross flow, the vibration test of elastic tubes in cylinder is carried out by dynamic test technology. The vibrating regularities are finally obtained for multiple tubes in the surrounding fluids. It provides abundant experimental data for the safe designing of tubular structure in deep water oil drilling, marine cluster wells and heat exchangers.

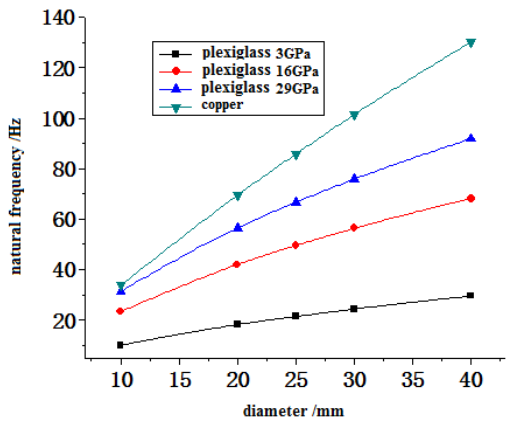
(a) (b)

Figure 1. Tube bundles in engineering systems: (a) marine risers in the ocean, (b) heat exchanger

2. RELEVANT PARAMETERS OF EXPERIMENTAL TUBES

Based on the natural frequency f_n of tube bundles, the frequency f_v of shedding vortex, the main frequency f_t of turbulence pulsation and the critical cross flow velocity V_c of fluid elastic instability, with respect to the influencing factors of natural frequency and resonant flow velocity: material, diameter, tube length, pitch diameter ratio, wall thickness, the natural frequency and resonant flow velocity are calculated by the formula of GB 151-1999 [18]. The influences of each variable on the natural frequency and the resonant flow velocity are obtained and the relevant parameters are thus selected for the experimental tube bundle.

2.1 The influence of tube's diameters



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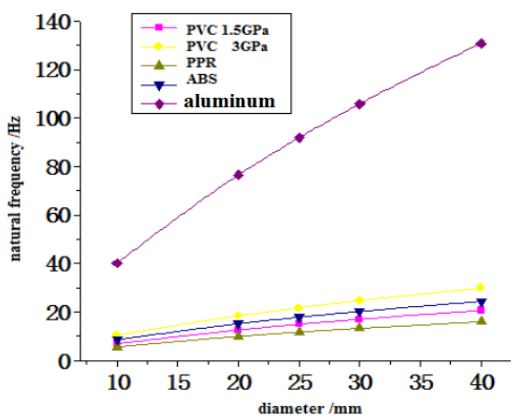
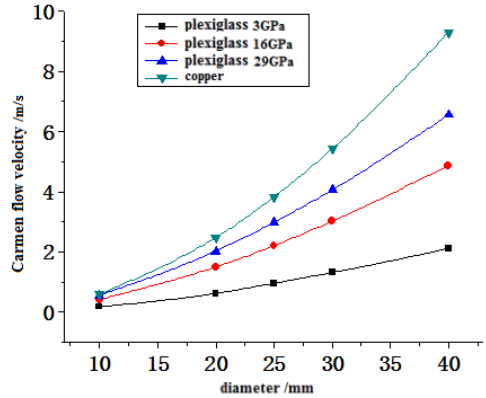


(b)

Figure 3. Regularity of natural frequency with diameters: (a) Plexiglas and copper, (b) PPR、PVC、ABS and aluminum



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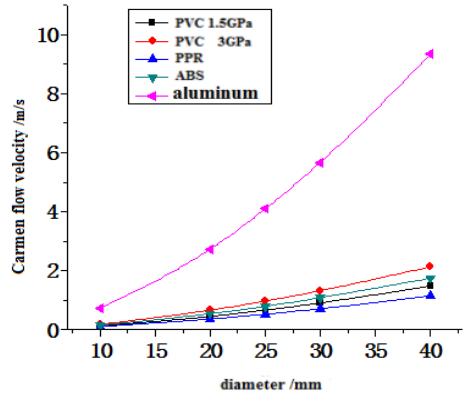
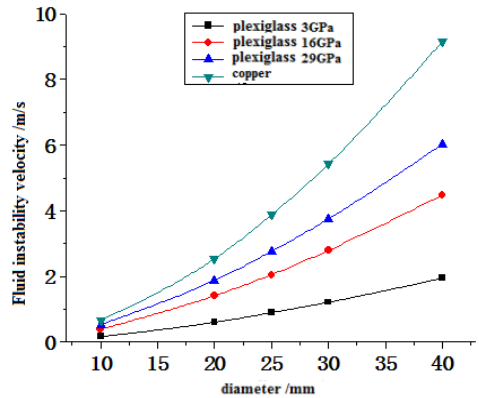


(b)

Figure 4. Regularity of Carmen flow velocity with diameters: (a) Plexiglas and copper, (b) PPR、PVC、ABS and aluminum



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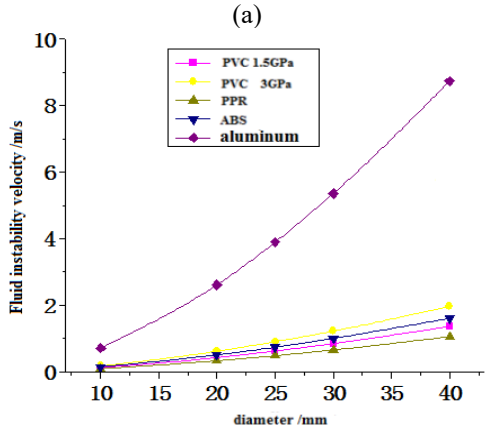


(b)

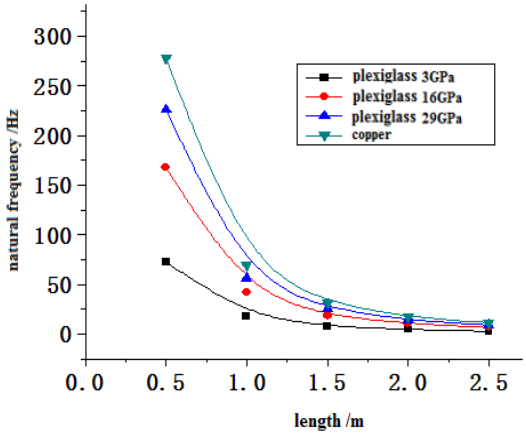
Figure 5. Regularity of fluid elastic instability velocity with diameters: (a) Plexiglass and copper,(b) PPR、PVC、ABS and aluminum

The fig. 3 to fig. 5 show the regularities of the natural frequency, Carmen flow velocity and fluid elastic instability velocity with the change of diameters, when the tube's length is 1m, the pitch diameter ratio is 1.5 and the wall thickness is 2mm.

When the tube bundle is made of PPR, PVC, ABS, Plexiglas, aluminum, copper and other materials, the natural frequency, the Carmen flow velocity and the elastic instability flow velocity are increasing with the increase of tube's diameters. From the point of equipment limitations and cost savings, the diameter should be chosen to be smaller. However, considering the size of the conventional tube (the inner diameter of G 1/2 is 15 mm, the outer diameter is 21.3 mm, the inner diameter of G 3/4 is 20 mm, the outer diameter is 26.8 mm) and the size of the acceleration sensor (one-way Φ5mm×4mm, three-way Φ11mm×11mm×7mm) , the tube diameter should be selected as 20mm.

2.2 The influence of tube's length

The Figure 6 to Figure 8 are the regularities of the natural frequency, Carmen flow velocity and fluid elastic instability velocity with the change of length, when the tube's outer diameter is 20 mm, pitch diameter ratio is 1.5 and the wall thickness is 2mm.



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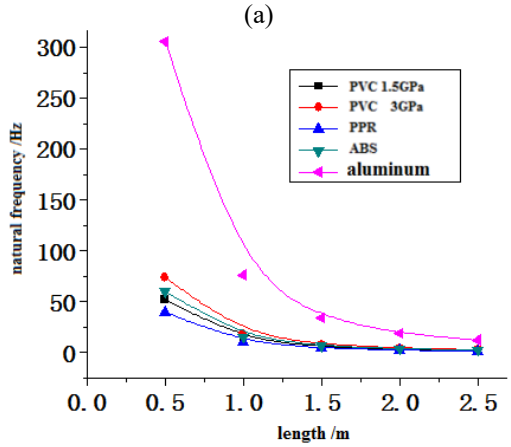
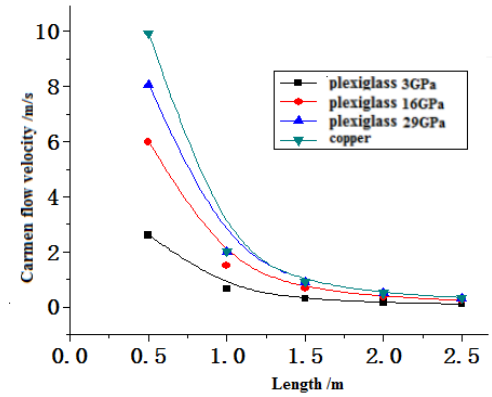


(b)

Figure 6. Regularity of natural frequency with length of tubes: (a) Plexiglas and copper, (b) PPR、PVC、ABS and aluminum



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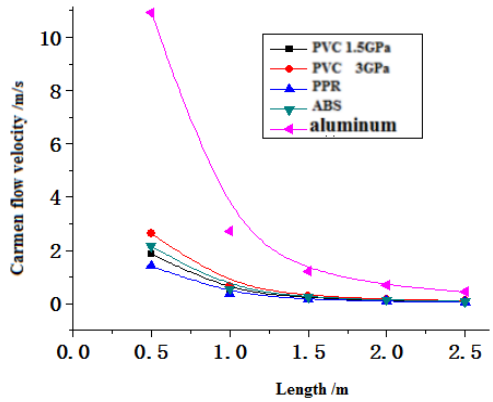

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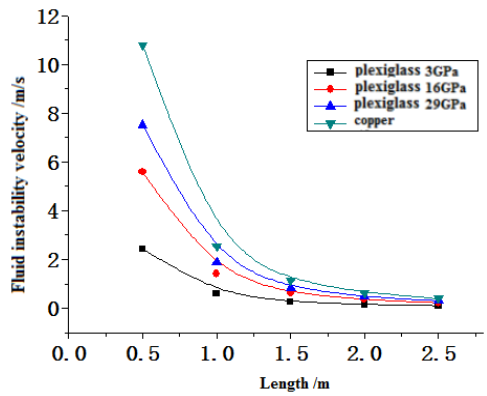
Figure 7. Regularity of Carmen flow velocity with length of tubes:(a) Plexiglas and copper, (b) PPR、PVC、ABS and aluminum



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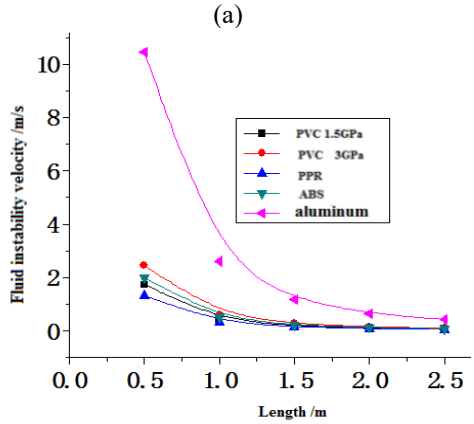


(b)

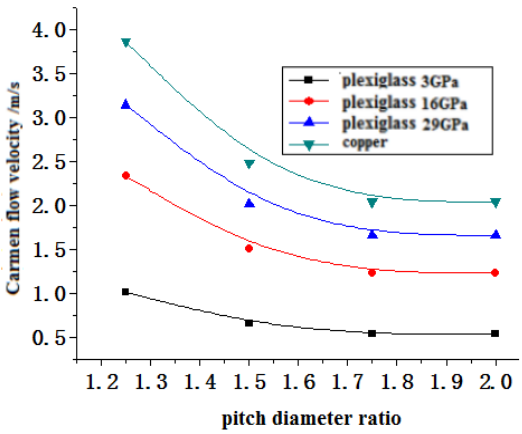
Figure 8. Regularity of the fluid elastic instability velocity with length of tubes: (a) Plexiglas and copper(b) PPR、PVC、ABS and aluminum

When the length of tube is 0.5m, 1.0m, 1.5m, 2.0m, 2.5m, the values of the natural frequency, the Carmen flow velocity and the elastic instability velocity are inversely proportional to the tube's length. If the length of the tube is less than 2.0m, the natural frequency and the resonant flow velocity are decreasing sharply with the increase of the length. If the length of the tube is more than 2.0m, the natural frequency and the resonant flow velocity are almost unchanged with the length. In order to prevent the influence of the length on the test results, it is reasonable to take the length of the tube as 2m.

2.3 The influence of pitch diameter ratio

The Figure 9 and Figure 10 are the regularities of the Carmen flow velocity and fluid elastic instability velocity with the change of pitch diameter ratio length, when the tube's outer diameter is 20mm, the length is 1.5m and the wall thickness is 2mm.

Seen from Figure 9 to Figure 10, the Carmen flow velocity decreases with the increase of the pitch diameter ratio. When the ratio of pitch diameter to diameter is greater than 1.5, the decrease is reduced. While the fluid elastic instability velocity increases with the increase of the pitch diameter ratio. Taking into account the small diameter of the gap between tube bundles is more likely to collide, and the above factors, the pitch diameter to diameter is selected as 1.5.



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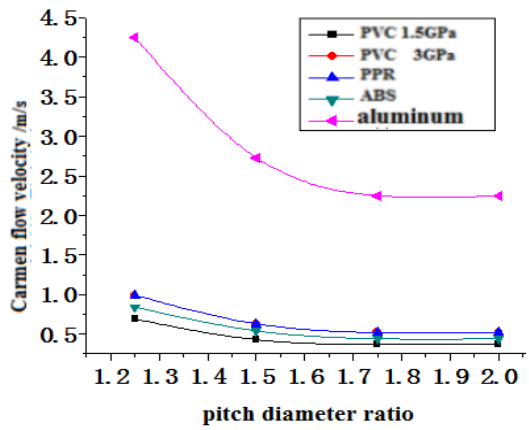
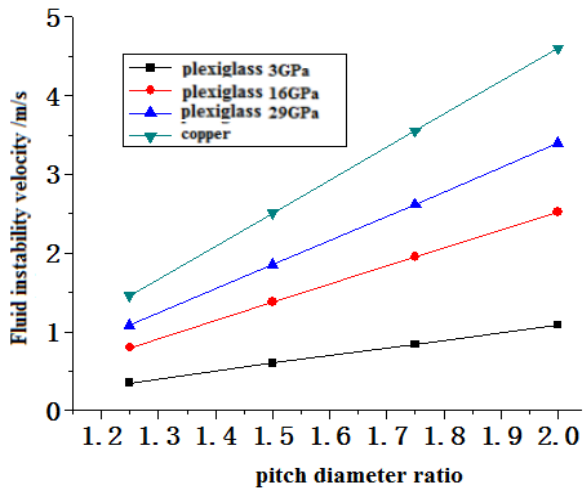


(b)

Figure 9. Regularity of the Carmen flow velocity with pitch diameter ratios of tubes: (a) Plexiglass and copper,(b) PPR、PVC、ABS and aluminum



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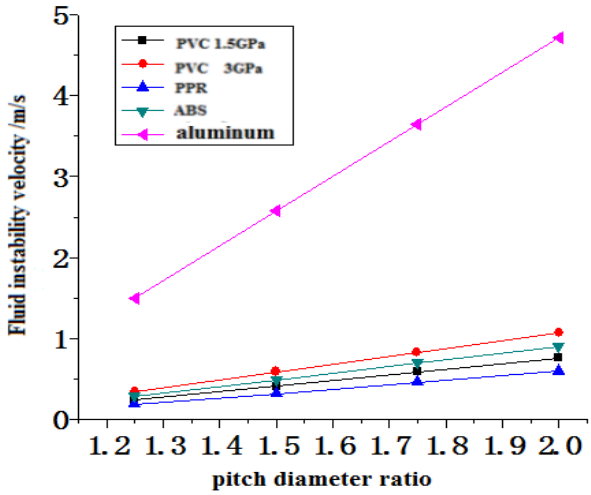
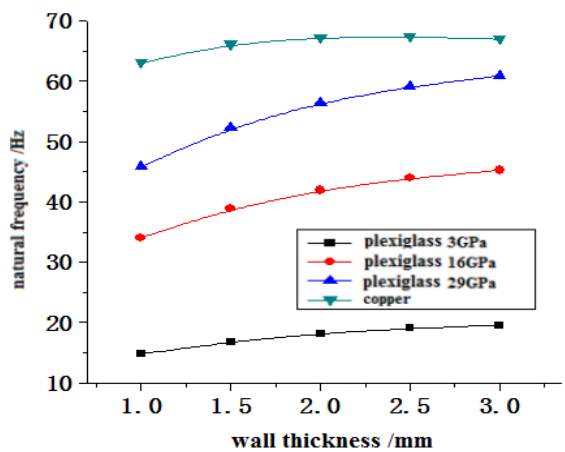


(b)

Figure 10. Regularity of the fluid elastic instability velocity with pitch diameter ratios of tubes: (a) Plexiglass and copper,(b) PPR、PVC、ABS and aluminum

2.4 The influence of wall thickness

The Figure 11 to Figure 13 are the regularities of the natural frequency, the Carmen flow velocity and fluid elastic instability velocity with the change of wall thickness, when the tube's outer diameter is 20 mm, the pitch diameter ratio is 1.5 and the length is 2mm.



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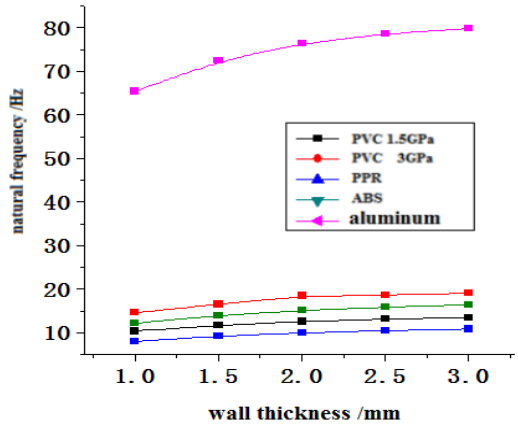
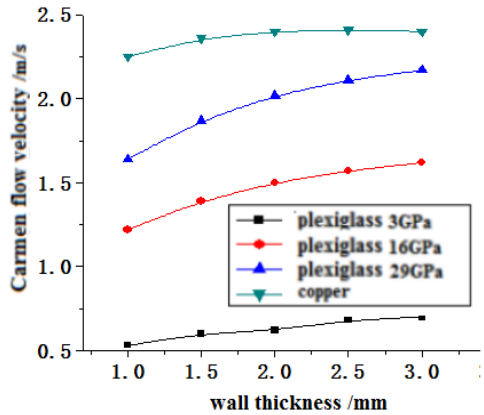


(b)

Figure 11. The regularity of natural frequency with wall thickness: (a) Plexiglas and copper, (b) PPR、PVC、ABS and aluminum



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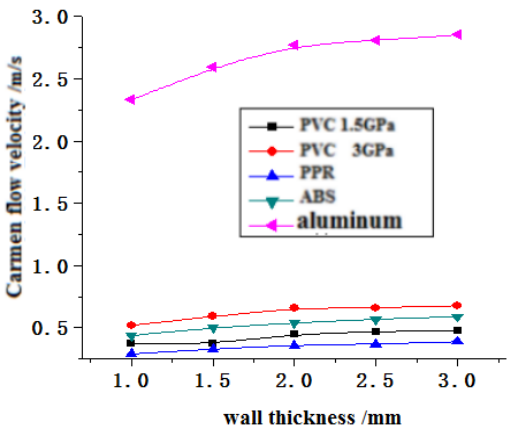
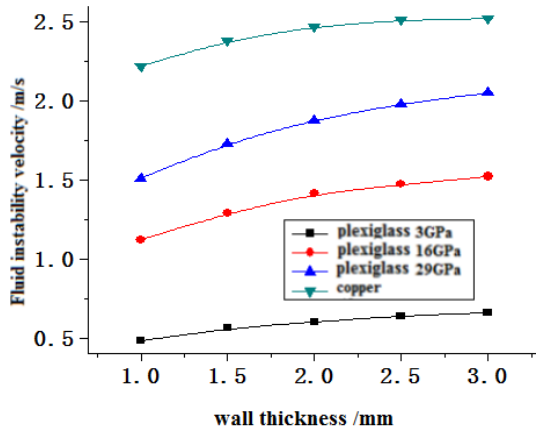


(b)

Figure 12. The regularity of Carmen velocity with wall thickness: (a) Plexiglas and copper, (b) PPR、PVC、ABS and aluminum

The values of the natural frequency, the Carmen velocity and fluid elastic instability velocity are increasing with the increase of wall thickness. While the wall thickness is more than 2 mm, the increase is reduced. Taking into account the size of PVC, PPR, the wall thickness can be selected 2 mm. From the regularities of the natural frequency, Carmen flow velocity and fluid elastic instability velocity, it is found that the outside diameter of tube is 20 mm, the length is 2 m, the pitch diameter ratio is 1.5 and the wall thickness is 2 mm. In all materials, the Plexiglas is easy to observe the experimental phenomenon and easy to purchase, so the material of tube is selected as Plexiglas.



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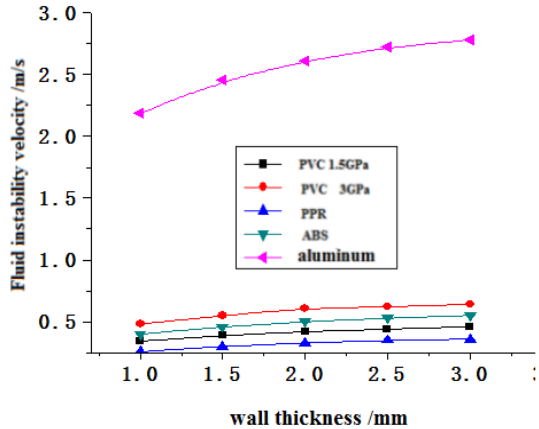
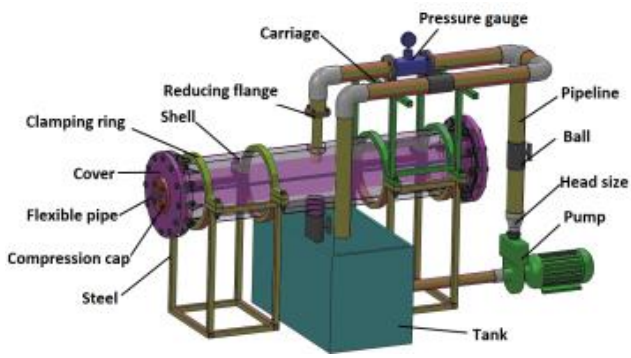


(b)

Figure 13. The regularity of the fluid elastic instability velocity with wall thickness: (a) Plexiglas and copper, (b) PPR、PVC、ABS and aluminum

3. EXPERIMENTAL EQUIPMENT AND TEST INSTRUMENT

According to the geometric parameters of tubes, the experimental device is built for the vibration of tube bundles with cross flow in the cylinder, as shown in Fig.14. The fluids are delivered into the tube from tank 5 by pump 4. Through valve 3, the fluid is flowing into inlet *a* and *b*. The valve 3 is used to adjust the fluid velocity, seen as Fig.15.



(a)

(b)

Figure 14. The vibration experiment device for tube bundles induced by cross flow in a cylinder: (a) The schematic diagram, (b) The experimental device

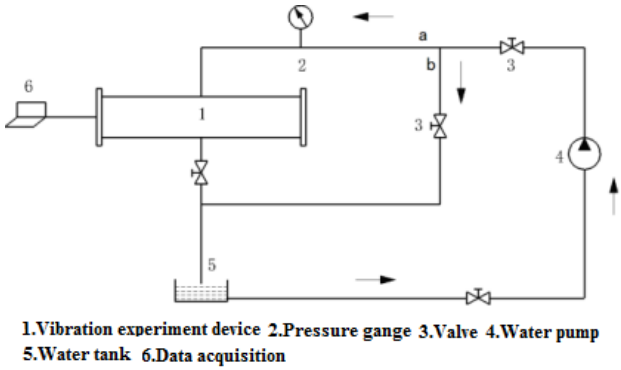


Figure 15. The vibration test circulatory system for tube bundles induced by cross flow in a cylinder

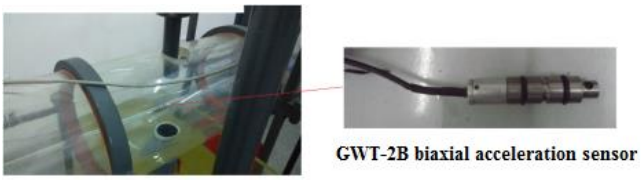


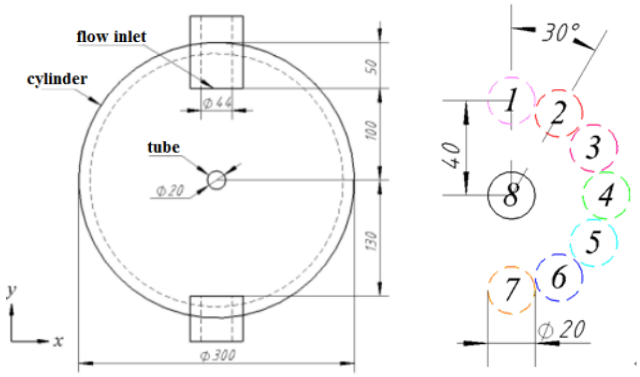
Figure 16. The test instrument of tube bundles induced by cross flow in a cylinder

Seen as Fig.16, the test instrument is a GWT-2B biaxial acceleration sensor, which is placed at the midpoint of the tube axis. The size is Φ12×21 and the frequency is 0~400Hz. The installation method is as following: firstly, the sensor is placed on the sensor holder. Secondly, the slender wire is penetrated into the sensor socket. Finally, the sensor is imported into the Plexiglas tube by the slender wire and rotated to the correct position.

4. EXPERIMENTAL RESULTS

4.1 Experimental program

The inlet flow velocity is 2.236m/s, 1.841m/s, 1.381m/s by adjusting the opening and closing of valve 3 (fully open, half open, fully closed). The experiments are carried out for the tube placed at the position 1~8 of the cylinder, seen in Fig.17. When the fluid is stable in the container, the vibrating acceleration of tube is monitored by GWT-2B biaxial acceleration sensor. The acceleration results are processed to get the vibrating velocity and trajectory, and the vibrating characteristics are then obtained for the single tube induced by cross flow in the cylinder.



(a) (b)

Figure 17. The experimental program of single elastic tube in a cylinder: (a) Geometry, (b) Site population

4.2 Experimental results

(1) Acceleration results

The acceleration signal is seen in Fig.18 for the tube at position 3 with the inlet flow velocity is 2.236m/s. Among them, the channel of 2-1A, 2-2A are the vibrating curves for tube in the y and x direction, respectively.

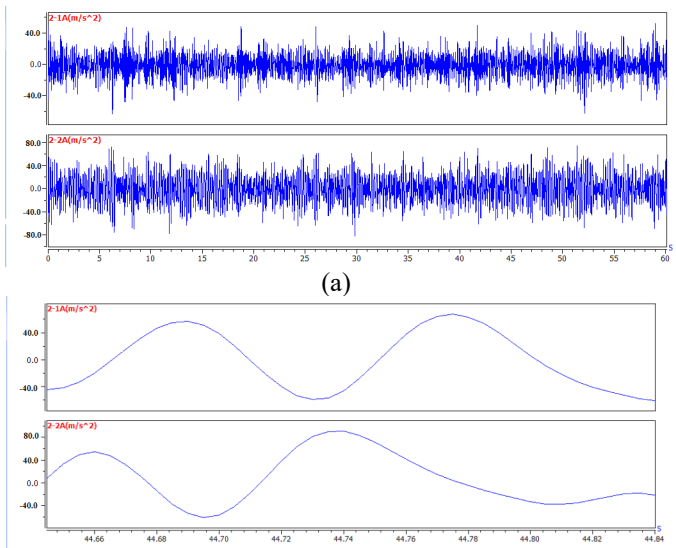


Figure 18. The acceleration test curve for the single tube at position 3 with the inlet flow velocity is 2.236 m/s: (a) Entirety, (b) Local

Seen from Fig.18(a), the acceleration value of the elastic tube is in the range of -40.0 m/s^2~40.0 m/s^2 in the *y* direction, while it is in the range of -80.0m/s^2~80.0m/s^2 in the *x* direction. As shown in Fig.18(b), the acceleration curves are both a sinusoidal (or cosine) curve in the *x* and *y* direction. When the acceleration of elastic tube is reached the maximum in the *y* direction, in contrast, the value is the smallest in the *x* direction. Otherwise, the vibrating acceleration is reached the maximum in the *x* direction, while the value is the smallest in the *y* direction.

The maximum and minimum acceleration are taken out for tubes in the locations 1~8 with the inlet flow velocity of 2.236 m/s, 1.841 m/s, 1.318 m/s, as shown in table 1 and Fig.19.

Table 1. The acceleration of the tube in the positions of 1~8 at different inlet flow velocities

inlet flow velocities		2.236 m/s			1.841m/s			1.318m/s		
Locations	acceleration	Max m/s^2	Min m/s^2	Peak m/s^2	Max m/s^2	Min m/s^2	Peak m/s^2	Max m/s^2	Min m/s^2	Peak m/s^2
1	a_y	42.10	-40.18	82.28	23.53	-24.19	47.72	21.32	-20.21	41.53
	a_x	30.54	-30.93	61.47	27.04	-29.39	56.43	26.71	-26.63	53.34
2	a_y	40.20	-45.98	86.18	26.42	-25.83	52.25	23.21	-21.54	44.75
	a_x	56.32	-56.98	113.3	42.53	-41.1	83.63	35.13	-37.09	72.22
3	a_y	49.23	-48.33	97.56	28.12	-31.49	59.61	24.56	-24.06	48.62
	a_x	35.32	-34.78	70.10	34.44	-32.71	67.15	32.56	-28.57	61.13
4	a_y	47.35	-40.02	87.37	27.13	-25.70	52.83	22.23	-20.98	43.21
	a_x	40.21	-39.58	79.79	35.32	-38.52	73.84	32.46	-31.87	64.33
5	a_y	41.09	-34.89	75.98	23.54	-23.69	47.23	22.21	-17.91	40.12
	a_x	37.55	-37.58	75.13	36.22	-34.45	70.67	31.56	-31.29	62.85
6	a_y	35.75	-40.02	75.77	26.79	-21.33	48.12	21.32	-19.6	40.92
	a_x	32.12	-35.02	67.14	32.55	-30.78	63.33	28.91	-29.21	58.12
7	a_y	41.09	-40.02	81.11	26.52	-24.79	51.31	21.81	-21.72	43.53
	a_x	37.55	-37.58	75.13	34.73	-31.61	66.34	30.91	-30.53	61.44
8	a_y	35.75	-34.89	70.64	21.54	-24.39	45.93	19.51	-18.2	37.71
	a_x	32.12	-35.02	67.14	30.54	-31.97	62.51	29.35	-27.12	56.47

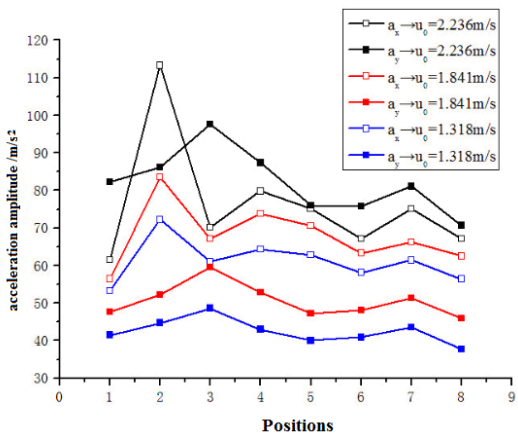


Figure 19. The curves of acceleration amplitude at different flow rates with the change of positions

Seen from table 1 and Fig.19, when the inlet flow velocity is 2.236m/s, the peak acceleration of the elastic tube in the *y* direction is greater than the value in the *x* direction at positions 1, 3, 4, 5, 6, 7 and 8. But the value in the *y* direction is smaller than the value in the *x* direction at position 2, which is caused by the measurement error or the instability of the test instrument and it can thus be ignored. It can be found that when the tube is placed at the positions of 1~8 with the inlet flow velocity is 2.236m/s, the vibrating acceleration in the *y* direction is greater than the value in the *x* direction.

It can also be found that when the tube is placed at the positions of 1~8 with the inlet flow velocity is 1.841m/s and 1.318m/s, the vibrating acceleration in the *x* direction is greater than the value in the *y* direction, which is opposite to that of the inlet flow velocity is 2.236m/s. For the elastic tube in the same position, the vibrating accelerations are increasing with the increase of the inlet flow velocity in the *x* and *y* directions.

(2) Movement trajectory

The displacements of the tube are acquired by integrating the acceleration. Setting the displacement in the *x* direction as X-axis and the displacement in the *y* direction as Y-axis, the vibrating trajectories are obtained for the tube at the position 1~8 with the inlet velocity is 2.236m/s, as shown in Fig.20. And the angle between the main vibration direction and X-axis for the elastic tube is listed in Table 2.

It can be seen from table 2 and Fig.20 that if the elastic tube placed facing the fluid inlet, such as at position of 1,7,8, the main vibration is in the y direction (along the inlet flow direction) and its vibrating amplitude is approximately equal. If the elastic tube is away from the cylinder center, such as at the position of 2, 3, 4, 5, 6, its main vibrating direction is tilted to the x-axis and the angle between the main vibration direction and the negative direction of x-axis is 35o at position 4, which is the most obvious tilt.

It can also be found that when the elastic tube is in the position of 1,7,8, (facing the fluid inlet), the range of motion trajectory is small. While the elastic tube is in the position of 2,3,4(deviation from the inlet flow direction), the range of motion trajectory is large.

(3) Spectrum analysis

The spectrum analysis of vibrating elastic tube at position 1 is shown in Fig.21 with the inlet flow velocity is 2.236 m/s.

It can be found that the frequency is 30Hz in the x(2-2A) and y(2-1A) direction, the acceleration amplitude (ordinate value) is both the largest. Therefore, the main frequency of the tube is 30Hz, suggesting that the vibrating period is 0.033sin x and y direction.

The frequency of the tube at the position of 1~8 is shown in table 3 with the inlet flow velocity of 2.236 m/s, 1.841m/s and 1.318 m/s.

It can be seen from table 3 that when the inlet flow velocity is 2.236 m/s, the vibrating frequency fluctuates in 28.20Hz~34.47Hz for the tube at the position 1~8 in the *x* direction and the vibrating period is 0.029s-0.035s, where the frequency is the largest at position 5 and the lowest at position 2. The frequency is in the range of 27.75Hz-31.22Hz in the *y* direction and the period is 0.032s~0.036s, where the frequency is the largest at position 7 and the lowest at position 4.

When the inlet flow velocity is 1.841m/s, the vibrating frequency fluctuates between 28.00Hz and 31.64Hz for the single elastic tube at the position 1~8 in *x* direction and the vibrating period is 0.032s-0.036s, where the frequency is the largest at position 6 and the lowest at position 2. The frequency fluctuates in 29.00Hz~33.39Hz in *y* direction and the period is 0.030s~0.034s, where the frequency is the largest at position 6 and the lowest at position 2.

When the inlet flow velocity is 1.318 m/s, the vibrating frequency fluctuates between 28.00Hz and 32.59Hz for the

tube at the position 1~8 in the x direction and the vibrating period is 0.030s~0.036s, where the frequency is the largest at position 3 and the lowest at position 2. The frequency is 27.73Hz~2.61Hz in the y direction and the period is 0.031s~0.036s, where the frequency is the largest at position 1 and the lowest at position 4.

It can be summarized that the inlet flow velocity and the position have little effect on the vibrating frequency of the elastic tube in the x direction and y direction.

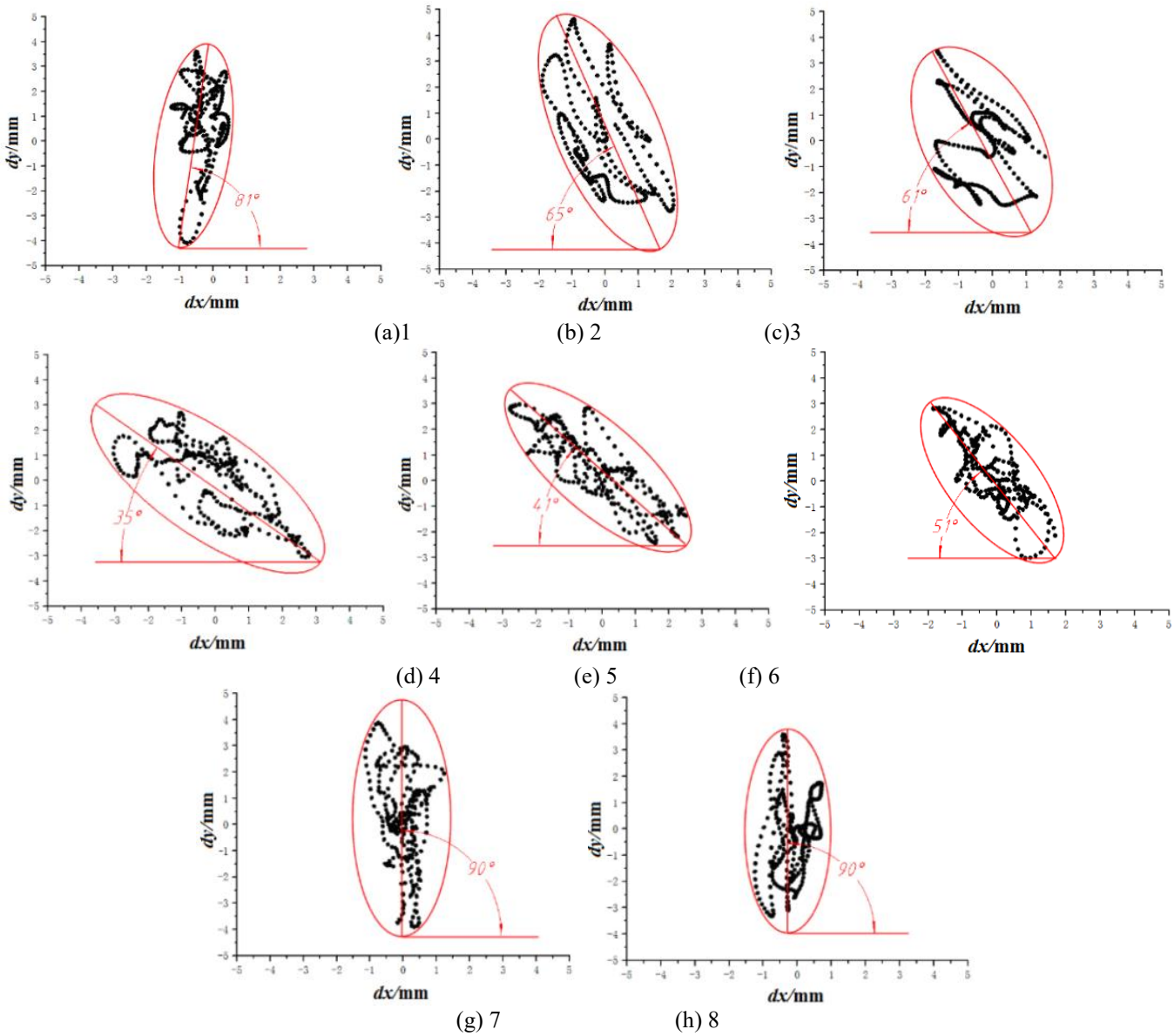


Figure 20. Trajectories of the tube at different positions

Table 2. Angles between main vibration direction and X-axis for the tube at different locations

Positions	1	2	3	4	5	6	7	8
Angles/°	81	65	61	35	41	51	90	90

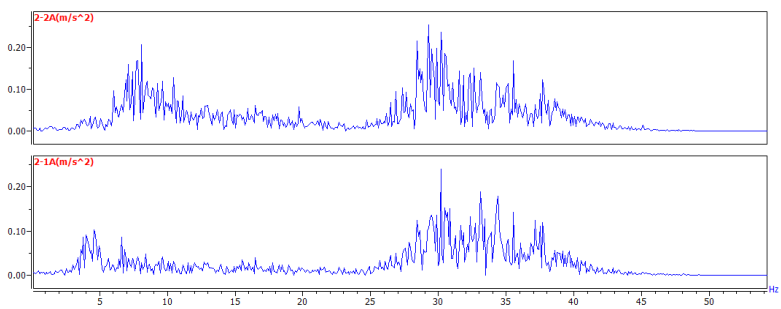


Figure 21. The spectrum analysis of the tube at position 1 with the inlet flow velocity is 2.236m/s

Table 3. The vibration frequency of single elastic tube at different positions with different inlet flow velocities

Velocity(m/s)	Frequency（Hz）	Positions							
		1	2	3	4	5	6	7	8
2.236	f_x	29.29	28.20	29.88	31.06	34.47	32.03	30.17	31.34
	f_y	30.17	30.46	29.29	27.75	28.90	31.15	31.25	30.95
1.841	f_x	28.10	28.00	29.68	30.76	29.59	31.64	30.07	30.37
	f_y	29.78	29.39	29.78	29.78	29.00	33.39	32.03	30.76
1.318	f_x	28.10	28.00	32.59	28.90	30.27	31.15	30.85	32.42
	f_y	32.61	29.78	29.31	29.29	27.73	31.73	30.76	29.98

5. CONCLUSIONS

1)The relevant parameters of the tube is selected via studying the existing theory of tube vibration induced by cross flow, the special experimental device is then designed and built for the vibration of tube bundles in cross flows of the cylinder.

2)Under the action of cross flow, the vibration test of tubes in cylinder is carried out by dynamic test technology. The vibrating acceleration, motion trajectory and frequency are obtained for the elastic tube with cross flows in cylinder.

3)It is found that the fluid velocity and the position of tube in the cylinder have little effect on the vibrating frequency for tube bundles, but it has influences on the vibration of the tube. If the tube placed at center of the cylinder, the vibration is small. If the tube placed close to the fluid inlet, the vibration is greater in the *y* direction (along the fluid inlet flow direction). If the tube deviated from the fluid inlet, the vibration amplitude is larger.

4)In summary, to reduce the vibration, the tube should be placed at the center of the cylinder as much as possible and avoided placing deviate from the fluid inlet.

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