Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference
Maui, Hawaii, USA, June 19-24, 2011
Copyright © 2011 by the International Society of Offshore and Polar Engineers (ISOPE)
ISBN 978-1-880653-96-8 (Set); ISSN 1098-6189 (Set); www.isope.org

Experimental Investigation on the J-pipe in Offshore Oilfield

Zhongyang Li and Mian Lin
Institute of Mechanics, Chinese Academy of Science
Beijing, China

ABSTRACT

The flow field and dynamic response of the J-pipe and straight pipe are investigated synchronously. The flow field is measured by PIV (Particle Image Velocimetry) and dynamic strain by FBG (Fiber Bragg Grating). According to the experiment results, it is found that the difference between both types of pipe is remarkable on amplitude and the frequency of vortex-induced vibration starting. On the other hand, it is proved that there is a time difference between the vortex shedding and the J-pipe oscillations.

KEY WORDS: J-pipe; Vortex-induced vibration; Vortex shedding

INTRODUCTION

J-pipe in offshore oilfield usually has a curving configuration near seabed. For this special form of pipe, free span section occurs very frequently as a result of the seabed scour, which may undergo VIV (Vortex-Induced Vibration) when subjected to ocean current. This phenomenon shortens the service lifetime of submarine pipelines. There are many investigations about VIV response; most existing researches can be divided into two categories.

Oscillation characteristics of a horizontal cylinder, such as Yamamoto et al. (2004), Yang Bing (2006), Wang Guoxing (2006), Sha Yong (2007). The aspect ratio of model is 63.8 in the experiment by Wang Guoxing (2006), and the rules of horizontal straight pipe vibration amplitude subject to different current velocities are same in the regular and irregular waves. Sha Yong (2007) found that cross-flow (CF) amplitude is much larger than in-line (IL), and dynamic response is sensitive to the length of span, through testing models with different aspect ratio.

Testing the response of large-scale vertical riser, such as King (1995), Huse et al (1999), Chaplin (2005), Lie (2006). Chaplin (2005) described measurements of a vertical tension riser model with aspect ratio of 468.8 and found the response included significant contributions from several modes, all at a frequency controlled by lock-in of the dominant mode. The aspect ratio of the vertical riser reached 3000 in the experiment by Lie (2006). The peak frequency taken from the spectra of the CF displacement at riser midpoint shows approximately to be equal to the Strouhal frequency. The peak frequency in IL direction was typically twice the Strouhal frequency. In this paper, we consider a particular type of pipe in offshore oilfield: J-pipe, which is the important part of subsea transportations. This type of pipe near seabed with a curve configuration is a key component that affects the safety of pipeline.

Base on the experiments of J-pipe oscillations near sea bed, this paper presents the effects of gap ratio and configuration on the characteristics of oscillation. The phase relationship between the period of vortex shedding and displacement are illustrated by the simultaneous measurements. Because the CF oscillation is usually dominant, data collection focused on the CF strain in this study.

EXPERIMENT SETUP

Water Flume

The experiments are carried out in a semi-closed circulating water flume. The size of test section is 2.2m×0.3m×0.54m (L×W×H), in which current velocity is adjustable from 0 to 0.5m/s for uniform flow. Before the test, preliminary measurements of the flow field using the current meter with turbulence indicated that the test section of the flow field is uniform.

Model of pipe

In this paper, experimental models are two types: straight pipe and J-pipe, which are both made of ABS (Acrylonitrile Butadiene Styrene); the main parameters of model are listed in Table 1. The ends of model are both simply supported by joints in CF, which can ensure that the ends can only rotate under the cross-flow bending moment. The joints and organic glass plates with a fixed link are close to the glass in the flume, so that PIV system can measure the flow field. The details of test set are shown in Fig. 1~3.

Table 1. Key data of model in the experiment

Configuration	Length	Diameter	Thick	Modulus
J-pipe	345mm	4mm	0.5mm	1.17Gpa
Straight pipe	275mm	4mm	0.5mm	1.17Gpa

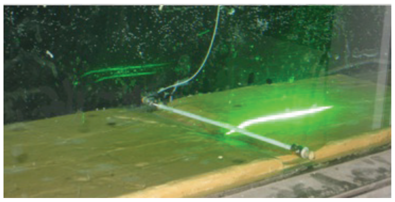

Fig. 1 The model of straight pipe in water flume

Fig. 2 The model of J-pipe in water flume

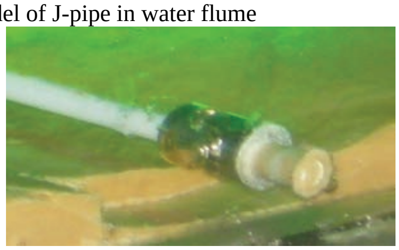

Fig. 3 The condition of model's end mounting

Measuring Instruments

Fiber grating strain sensors (FBG) is selected as the strain measurement of the model. FBG can measure the strain during the transient changes occur on the surface with high sensitivity; the accuracy of measurement can be 1 nm. Particle image velocimetry (PIV) is used as the experimental flow test equipment; the system has high precision with the high-speed camera, the frequency of sampling can reach 6 KHz, which can ensure that the velocity and vortex structures of the whole flow field are well measured.

EXPERIMENT DESIGN

Experimental Parameters of Strain Test

Firstly, to determine the number and location of the grating arrangement, the vibrations of straight pipe and J-pipe are analyzed by ANSYS. The response frequency and vibration displacement of each mode is calculated. Specific parameters are shown in Table 2.

Table 2. The frequency of model oscillations in modes

Configuration	Frequency (Hz)		
	First mode	Second mode	Third mode
J-pipe	29.45	96.42	200.97
Straight pipe	17.45	69.63	156.12

The maximum uniform flow rate of the experimental tank is 0.5m/s, so the frequency of vortex shedding is up to 25 Hz. It can infer the maximum lock-in modes of models are both first. According to the results, the grating arrangement should be in the place with the maximum displacement and avoid the positions where the displacement is zero. Three FBG are arranged along the tube model (Fig. 4), and the three points of straight pipe and J-pipe are in the same positions.

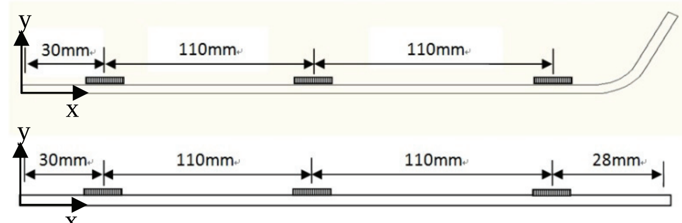

Fig. 4 Arrangement of FBG along two types of model

Experimental Parameters of Fluid Test

In order to analyze the effects of the shape and gap ratio on the vibration of the cylinder, the experimental conditions of straight pipe and J-pipe are consistent with each other. If the gap ratio is too small, model will be too close to the bottom and the vibration is inhibited, so the gap ratio are 0.7, 1.0 and 1.8 in the experiment; while at high current velocity, displacement of the pipe is too large along the in-line direction, the oscillations of CF will be seriously inhibited, therefore the speed is limited to 0.345m / s. Specific test parameters are shown in Table 3, the parameter e^* is gap ratio, and U is the current velocity measured by the current meter at 0.1 m above the tube model. The overall Reynolds number (*Re*) range for the experiments was Re=540~1,380.

Table 3. Experimental parameters of J-pipe and straight pipe

e^*	0.7	1	1.8
U(m/s)	0.135	0.135	0.135
	0.154	0.154	0.154
	0.186	0.186	0.186
	0.232	0.232	0.232
	0.303	0.303	0.303
	0.345	0.345	0.345

DATA PROCESSING

In order to case comparison, the strain data measured by FBG needs to be converted into displacement data. The origin point is located in the tube model of the left end (Fig. 4), *x*-axis is along the axial direction of the right, *y*-axis is vertical upward, *z*-axis is along the flow. According to the structural dynamics theory, the vibration displacement of the model which has an axial length L, *y (x, t)* can be written as:

$$y(x,t)=\sum_{n=1}^{\infty}\omega_n(t)\varphi_n(x), \qquad x\in[0,L] \tag{1}$$

In the formula above, y is the vibration displacement, $\omega_n(t)$ is the mode weight function, n is the mode number, $\varphi_n(x)$ is the n th mode of the structure. The modes of vibration are up to first order or second order according to previous calculation, so n equals 1-3, which has been taken to meet the requirements. The mode functions of straight pipe are simple, considering the model is pinned-pinned, vibration mode function can be taken as the sine function according to vibration theory:

$$\varphi_n(x)=\sin\frac{n\pi x}{L}, \qquad x\in[0,L] \tag{2}$$

The J-pipe vibration mode function is complex; CF displacement along the tube is calculated in the mode of 1-3 order with ANSYS modal solution on the J-pipe. Through the inversion, J-pipe oscillation polynomial fitting functions of 1-3 modes can be calculated on the condition of simply support. The functions are shown in Table 4, *x* is the axial distance to the left end of the J-pipe.

Table 4. Polynomial fitting functions of J-pipe modal shape in modes of 1-3 order

Order	First Mode	Second Mode	Third Mode
x^0	-9×10^{-3}	3×10^{-2}	2.5×10^{-2}
x^1	12.4	-34.3	50
x^2	-0.3×10^{2}	0.65×10^{3}	-1.4×10^{3}
x^3	0.9×10^{3}	-1.4×10^{4}	4.3×10^{4}
x^4	-0.2×10^{4}	2.1×10^{5}	-9.9×10^{5}
x^5	0.3×10^{5}	-0.16×10^{7}	1.1×10^{7}
x^6	-0.8×10^{5}	0.6×10^{7}	-7.1×10^{7}
x^7		-0.11×10^{8}	2.5×10^{8}
x^8		0.8×10^{8}	-4.7×10^{8}
x^9			4.5×10^{8}
x^{10}			-1.4×10^{8}

According to the elastic theory, strain is second derivative of displacement, so we can get the following equations:

$$\begin{bmatrix} \left.\frac{\partial^2\varphi_1(x)}{\partial^2 x}\right|_{x=x_1} & \cdots & \left.\frac{\partial^2\varphi_3(x)}{\partial^2 x}\right|_{x=x_1} \\ \vdots & \ddots & \vdots \\ \left.\frac{\partial^2\varphi_5(x)}{\partial^2 x}\right|_{x=x_3} & \cdots & \left.\frac{\partial^2\varphi_3(x)}{\partial^2 x}\right|_{x=x_3} \end{bmatrix} \times \begin{bmatrix} w_1(t) \\ w_2(t) \\ w_3(t) \end{bmatrix} = \begin{bmatrix} \varepsilon(t,x_1)/R \\ \varepsilon(t,x_2)/R \\ \varepsilon(t,x_3)/R \end{bmatrix} \qquad (3)$$

The column vectors on the right of the equation are ratio between strain by grating testing and the radius of model. The measured response signals after processing by band pass filter are put into the Eq. 3 to calculate. According to frequency of pipe oscillations in the modes of different orders, we can make the range of band-pass filter set at 15~60Hz, which can remove noise signals of high and low frequency. On the basis of weighting function of modes by solving Eq. 3, the vibration displacement along the straight pipe and J-pipe can be calculated respectively.

In the flow field measurements, the tracer particles which PIV used are hollow glass beads of 20-40 micron diameter, and *U* is between 0.12-0.35m/s in the experiment. The grid point velocity is obtained by calculating the raw particle images of PIV measurements, while the point vortex value has been differential calculated either. In the flow field, velocity at each grid point is line integral calculated to get the corresponding value of the vortex in the direction of *z*.

In order to achieve good contrast of simultaneous measurement, frequency sampling of the fluid and solid are consistent. As the image of a same particle in two adjacent frames can't overlap, so the frequency of sampling can not be higher than 2.5 KHz; the first-mode frequency of model oscillation is 16-29Hz, in order to test a complete cycle, the frequency of measuring can not be lower than 500Hz. Therefore, after considering two factors above, frequency of sampling in the experiment remains 1 KHz.

EXPERIMENTAL RESULTS

Effects of e^* on the Vibration

The experiments of a variable e^* were done on the condition of fixed *U*. When current velocity reaches 0.135m/s and the e^* is 0.7, the straight pipe oscillates with little amplitude, but when the e^* equals 1 or 1.8, the straight pipe has been observed in a marked oscillation (Fig. 5). This reflects the cross-flow onset value of current velocity decreases as the e^* increases. When the fluid speed reaches 0.34m/s, the e^* is 0.7, the vibration amplitude of the J-pipe is only 0.1d, and the amplitude increased to 0.2d when the e^* reaches 1, when the e^* is 1.8, the amplitude of straight pipe has reached 0.4d (Fig. 6). That means when the e^* increases, vibration amplitudes of two models both increase on the same condition of *U*.

The results show that the bottom has a significant inhibition on the model oscillations, which will increase the value of *U* causing the cross-flow oscillations and also reduce the vibration amplitude of straight pipe and J-pipe.

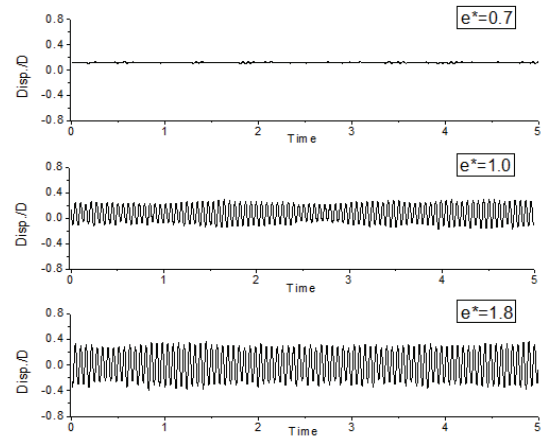

Fig. 5 The oscillations of straight pipe subjected to different e^* when *U* reaches 0.135m/s

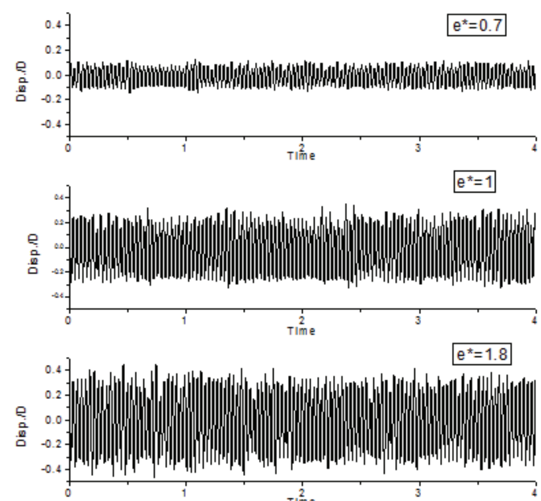

Fig. 6 The oscillations of J-pipe subjected to different e^* when *U* reaches 0.34m/s

Effects of Model Shape on the Oscillation

We did a series of experiments on J-pipe and straight pipe on the same experimental conditions. The onset value of current velocity (U_o) and frequency of cross-flow oscillation are tested. Table 5 indicates that U_o

of J-pipe in the first-mode is higher than that of straight pipe when the e^* is fixed, the parameter U_o is onset velocity. When the e^* equals 1.8, U_o of straight pipe reached 0.135m/s, while U_o of J-pipe has reached 0.312m/s. Although e^* of J-pipe is larger than that of the straight pipe, the first-mode frequency of J-pipe oscillation is higher than that of straight pipe. By analysis of Fourier, when e^* equals 1, the first-mode frequency of J-pipe oscillation reaches 28Hz, while the first-mode frequency of straight pipe oscillation is only 17Hz. The amplitude of J-pipe oscillation is much less than that of straight pipe under the same conditions. As shown in Fig. 7, when U reaches 0.345m/s and e^* is 1.8, the amplitude of J-pipe oscillation is only 1/3 of the straight pipe.

Table 5. Oscillation characteristics of J-pipe and straight pipe

Configuration	e^*	U_o (m/s)	Frequency(Hz)
J-pipe	0.7	0.345	28
	1	0.312	
	1.8	0.312	
Straight pipe	0.7	0.156	17
	1	0.135	
	1.8	0.135	

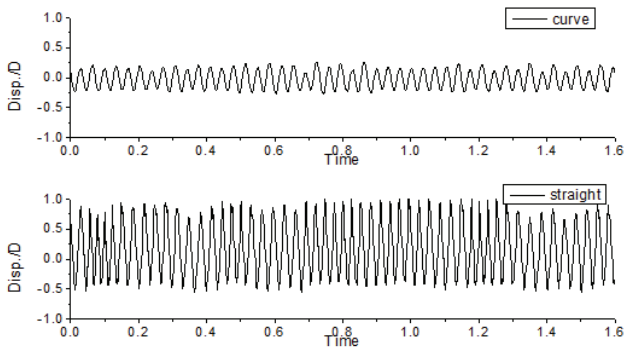

Fig. 7 Oscillation amplitudes of J-pipe and straight pipe when U reaches 0.345m/s

Relationship Between the Amplitude of Oscillation and Vortex Pattern

The track of displacement and vortex patterns of the corresponding moment can be distinguished by high-speed video camera of the PIV system. Fig. 8 and Fig. 9 are flow diagrams for a displacement cycle of J-pipe and straight pipe on the same experimental condition (e^* is 0.7, U is 0.345m/s). As shown in the Fig. 10, the J-pipe has a significant displacement along the in-line direction, so its patterns of vortex shedding are much more complex than that of the straight pipe. When J-pipe reaches top, the vortex are separated from the upper surface of the pipe, so as the bottom. This result presents that displacement of J-pipe has a lag response of the vortex shedding. In the experiment on the straight pipe, it reaches top or bottom just when the vortex appear above or below the pipe, that means displacement and vortex patterns are synchronized. This result is different from the result of Caberry (2005), who found that displacement of straight pipe has a lag response of vortex patterns through a series of experiments on straight pipe forced oscillating, which is more like J-pipe. The tracks of both models are different from that in ordinary VIV, as shown in Fig. 10. The reason is probably that the ends of models are both simply supported by joints only in CF. The IL displacement of J-pipe is much larger than that of the straight pipe because that the axial length of J-pipe is larger.

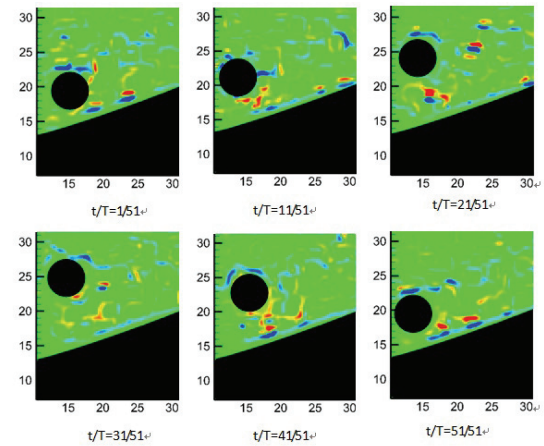

Fig. 8 Oscillation displacement and vortex patterns of J-pipe in a period (T=51ms)

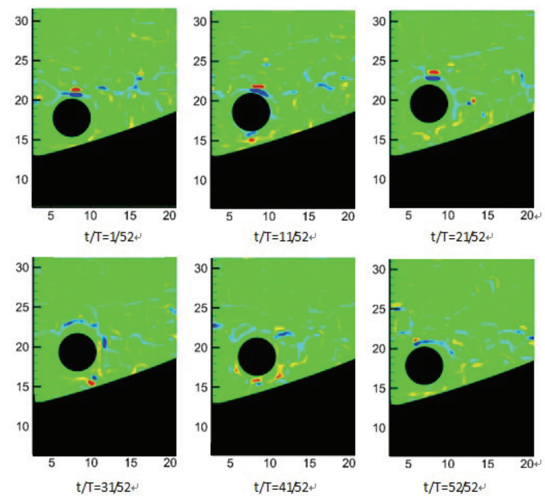

Fig. 9 Oscillation displacement and vortex patterns of straight pipe in a period (T=52ms)

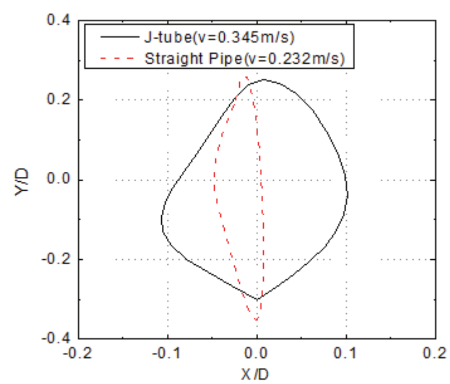

Fig. 10 Centre track of J-pipe and straight pipe in a cycle time

The cycles of vortex shedding are studied at different current velocities in the experiments of straight pipe. The Strouhal number (*St*) is depended on *Re*. In this range of *Re* for the experiments, *St* is approximately 0.23 by analyzing the data of PIV. As shown in Table 6, the frequency of oscillation and vortex shedding is consistent on the conditions of different current velocity. As U_r increases, period of vortex shedding slightly decreases, while the oscillation frequency of straight pipe also increases slightly. This indicates the frequency of straight pipe vibration is very sensitive to the frequency of vortex shedding.

Table 6. Period of vortex shedding of straight pipe in different U_r

U_r	Period (s)	Frequency (Hz)
3.22	0.059	17.6
4.12	0.058	17.8
4.79	0.052	18.2

CONCLUSIONS

According to the test with synchronized measurements of fluid and solid on pipes with different types of shape, the main conclusions are as follows:

1. The results show that the bottom has an inhibition on the vortex-induced vibration. In the experiments of both models, as the e^* increases, value of U_o is reduced; in the meantime, the vibration amplitude will increase.
2. J-pipe is harder to oscillate than the straight pipe. The U_o of J-pipe is much larger than that of the straight pipe. And the first-mode vibration frequency of the J-pipe is nearly twice of that of the straight pipe, while the vibration amplitude of J-pipe is only about 1 / 3 of the straight pipe. It shows that the effect of model shape on the VIV is very significant.
3. The oscillation of J-pipe shows a lag response relative to the vortex shedding, but the vibrations and vortex shedding of straight pipe are synchronized. This phenomenon needs a further study.

ACKNOWLEDGEMENTS

The work is funded by the projects of CAS (KJCX2-YW-212-2 and KJCX2-YW-L07) and NSFC (Grant No. 40776057).

REFERENCES

Caberry, J, and Sheridan, J (2005). "Controlled oscillations of a cylinder: forces and wake modes," *Journal of Fluid Mechanics*, Vol 538, pp 31-69.

Chaplin, JR, and Bearman, PW (2005). "Laboratory measurements of vortex-induced vibrations of a vertical tension riser in a stepped current, " *Journal of Fluids and Structures*, Vol 21, pp 3-24.

Huse, E, and Kleiven, G (1999). "VIV-induced axial vibrations in deep sea risers," *Proceedings of the Offshore Technology Conference*, Houston, Texas, OTC 10932.

King, R (1995). "An investigation of vortex induced vibrations of sub-sea communications cables," *Proceedings of the Sixth International Conference on Flow Induced Vibrations*, London, UK, pp. 443–454.

Lie, H, and Kaasen, KE (2006). "Modal analysis of measurements from a large-scale VIV model test of a riser in linearly sheared flow," *Journal of Fluids and Structures*, Vol 22, pp 557–575.

Sha Yong (2007). "Experimental and Numerical Studies on Dynamic Response of Submarine Suspended Pipeline," Ph.D. Thesis. Dalian University of Technology, Dalian, China.

Wang Guoxing (2006). "Numerical and Experimental Studies on Vortex-induced Vibrations with Fluid-structure Interaction for Submarine Free-span Pipelines," Ph.D. Thesis. Ocean University of China, Qingdao, China.

Yamamoto, CT, and Meneghini, JR (2004). "Numerical simulations of vortex-induced vibration on flexible cylinders," *Journal of Fluids and Structures*, Vol.19, pp 467–489.

Yang Bing (2006). "Local Scour and Vortex-Induced Vibration of a Submarine Pipeline in Ocean Currents," Ph.D. Thesis. Institute of Mechanics, Chinese Academy of Science, Beijing, China.