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Numerical investigation of vortex-induced vibration of a triple-pipe bundle

Hongjun Zhu*, Zhaoxin Sun, Yue Gao

State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, China

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ABSTRACT

Pipe bundles are commonly observed in offshore oil and gas engineering. In this work, the vibration response of a typical triple-pipe bundle with cylinders arranged in a row in size order is examined numerically. The unsteady Reynolds-Averaged-Navier-Stokes equations and shear stress transport k-ω turbulence model coupling with an improved fourth-order Runge-Kutta method are employed to capture the fluid flow over the structure and the vibration response of the oscillator with varying reduced velocities ranging from 3.0 to 18.0. The numerical results indicate that the vibration response undergoes dramatic changes when the isolated cylinder is changed to be a bundle. The in-line amplitude has an obvious increase due to the great fluctuation of pressure difference and shear stress of the bundle. However, the cross-flow amplitude of the bundle is smaller than the single cylinder at a certain flow velocity range, exhibiting a good suppression effect. The separation of boundary layer moving back and the narrow wake can illustrate this effect. The vortex structure of the bundle varies with the change in flow velocity, and the vortices are scatted and unstable. Therefore, the bundle oscillates in an irregular motion and its motion in turn affects the vortex shedding.

1. Introduction

Flow over a bluff body, particularly a cylindrical structure, is usually observed in nature and practical engineering applications. Flow separation accompanied by vortex shedding occurs behind a bluff body, and the alternate vortex shedding brings fluctuating loads on the body, which is the main source of structural vibration. Hence this structural vibration is called as vortex-induced vibration (VIV). VIV of a circular cylinder has been studied extensively due to its damage to the structure, as summarized in the reviews by King (1977), Griffin and Ramberg (1982), Naudascher and Rockwell (1993), Sumer and Fredsoe (1997), Khalak and Williamson (1999), Sarpkaya (2004), Gabbai and Benaroya (2005), Williamson and Govardhan (2004, 2008), Bearman (2011) and Wu et al. (2012).

Riser, as an essential pipe in offshore oil and gas engineering, is used to connect the subsea wellhead and the floating structures and provide a transporting channel for oil and gas. As a long and elastic circular cylinder, the riser inevitably experiences VIV exerted by the waves and currents. High amplitude oscillation may be caused if the vortex shedding frequency is close to the structural natural frequency, resulting in a fatigue failure. With the increasing of water depth in deepwater exploration, VIV of risers becomes more complex and the failure risk becomes greater. Therefore, ocean researchers and engineers pay great attention to the VIV of risers.

VIV of a rigid cylinder is a canonical problem of flow-structure interaction, which has been examined both experimentally and numerically in the past decades. However, in early studies, the cylinder was forcibly oscillated at a specified amplitude and frequency, which had not coupled the fluid motion and the motion of the cylinder (Griffin and Ramberg, 1976; Sarpkaya, 1979; Staubli, 1983; Hover et al., 1997; Carberry et al., 2001). Then much work has been performed in the analysis of the self-excited vibration, but they only focused on the cross-flow oscillation (Khalak and Williamson, 1996, 1997; Saltara et al., 1998; Guilmineau and Queutey, 2004). In recent studies, the freedom has been extended to two or more (Fujarra et al., 2001; Jauvtis and Williamson, 2003; Sanchis et al., 2008) and flexible cylinder has been considered (Sun et al., 2012; Xie et al., 2011; Song et al., 2011; Zhu et al., 2016a). In previous studies of the VIV of rigid and flexible cylinders, the three branches of amplitude response (the initial, upper and lower branches) and 2S (two single vortices are shed in each period of vibration), 2P (two pairs of vortices are shed in each period of vibration) and P+S (a single vortex and a pair of vortices are shed in each period of vibration) vortex shedding pattern proposed by Williamson's research group (Govardhan and Williamson, 2000; Jauvtis and Williamson, 2003; Morse and Williamson, 2010) are typically identified. These observes improve the understanding of VIV and provide references for the selection and operation of marine risers.

However, risers do not always serve independently. Accompanying tubes and cables, such as injecting tube, heat tracing pipe and umbilical, are usually installed together with the risers. They form into

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* Corresponding author.
E-mail address: ticky863@126.com (H. Zhu).

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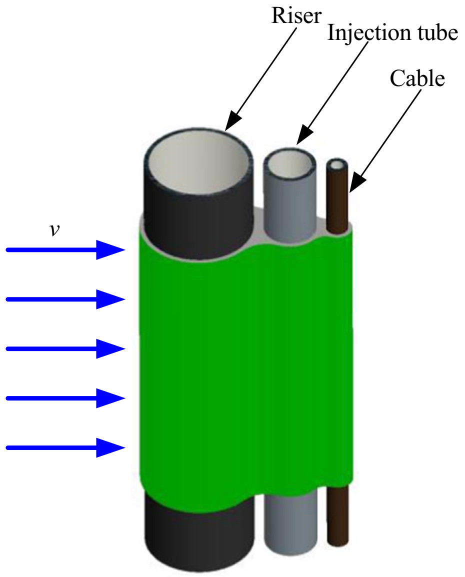
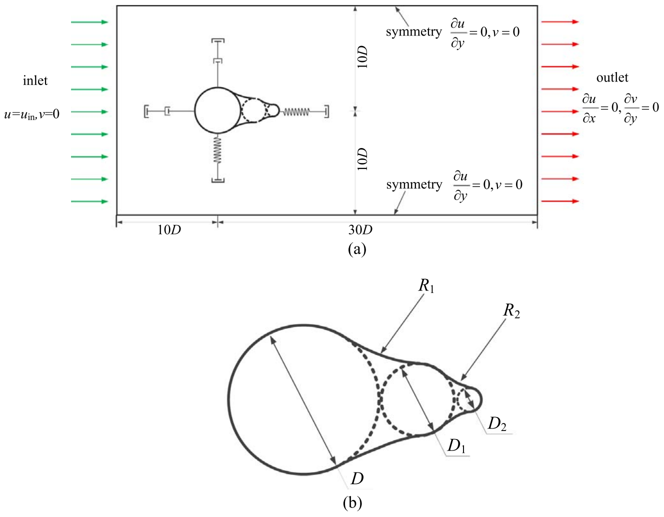


Fig. 1. Diagram of a triple-pipe bundle commonly used in offshore oil and gas engineering.



(a)

(b)

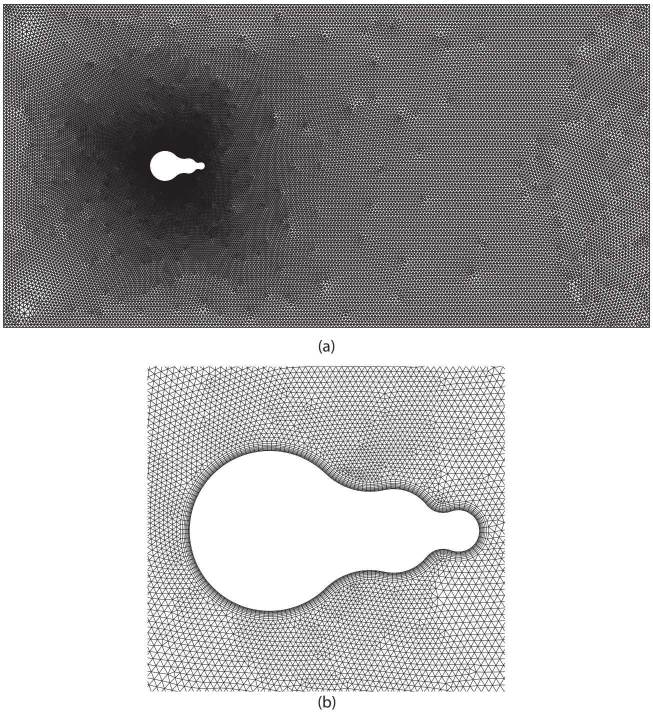
Fig. 2. Diagram of the flow geometry: (a) the computational domain and boundary conditions; (b) geometry for the triple-pipe bundle.

Table 1
Calculation parameters.

Parameters	Isolated main cylinder	Triple-pipe bundle
D (m)	0.0381	0.0381
D_1 (m)	/	0.0200
D_2 (m)	/	0.0100
R_1 (m)	/	0.0500
R_2 (m)	/	0.0300
m (kg)	7.895	10.614
k_x (N/m)	49.82	59.36
k_y (N/m)	45.82	520.42
f_{nx} (Hz)	0.400	0.377
f_{ny} (Hz)	0.400	1.115
ζ_x	1.4557×10^{-3}	1.1494×10^{-3}
ζ_y	1.4557×10^{-3}	0.3882×10^{-3}

Table 2
Simulation cases.

Case	u_{in}	Re_D	U_{rD}	U_{rT}
1	0.0457	1740	3.0	1.43
2	0.0670	2550	4.0	2.10
3	0.0762	2900	5.0	2.38
4	0.0914	3480	6.0	2.86
5	0.1067	4070	7.0	3.34
6	0.1219	4640	8.0	3.81
7	0.1372	5230	9.0	4.29
8	0.1524	5810	10.0	4.77
9	0.1676	6390	11.0	5.25
10	0.1829	6970	12.0	5.72
11	0.1981	7520	13.0	6.20
12	0.2134	8130	14.0	6.68
13	0.2286	8710	15.0	7.15
14	0.2438	9290	16.0	7.63
15	0.2591	9870	17.0	8.11
16	0.2743	10,450	18.0	8.58



(a)

(b)

Fig. 3. Computational mesh: (a) grid structure; (b) close-up view of the mesh around the bundle.

Table 3
Mesh resolution test (Case 4 for the bundle with u_{in} = 0.0914 m/s).

Mesh	Elements	A_x/D	A_y/D	$\overline{C}_D$	C_L'
M1	21,976	0.0927	0.0287	1.612	1.002
M2	32,966	0.0788 (14.99%)	0.0244 (14.98%)	1.384 (14.14%)	0.861 (14.07%)
M3	49,448	0.0724 (8.12%)	0.0224 (8.19%)	1.264 (8.67%)	0.796 (7.55%)
M4	74,172	0.0696 (3.87%)	0.0215 (4.02%)	1.207 (4.51%)	0.765 (3.89%)
M5	111,258	0.0690 (0.86%)	0.0213 (0.93%)	1.200 (0.58%)	0.761 (0.52%)

a larger pipe or a pipe bundle. A larger pipe is still an isolated circular cylinder, which have been examined extensively. Few studies have focused on the VIV of a pipe bundle. Fig. 1 shows a typical triple-pipe bundle. The three cylinders are arranged in a row in size order. Lightweight material is used to cover the whole surface and fill the gaps. The cross-section of the bundle likes a gourd. How the existence of accompanying tubes affect the vibration response, enhancing or suppressing? In this work, flow over a triple-pipe bundle is investigated