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Flow and flow control modeling for a drilling riser system with auxiliary lines

Wenbo Wu [a], Jiasong Wang [a,*], Shiquan Jiang [b], Liangbin Xu [b], Leixiang Sheng [b]

[a] School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Research Institute of CNOOC, Beijing 100028, China

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ABSTRACT

In this numerical study, it was mainly intended to investigate the flow and flow control for a practical drilling riser system with auxiliary lines at various incidence angles. The flow past the riser system was simulated through solving the Reynolds averaged Navier–Stokes equations and $k-\omega$ turbulence model. The cases about fluid flow past single cylinder, two staggered cylinders and eight even-distributed auxiliary lines around main line were simulated first, and the results match well with previous researches. The Reynolds number (*Re*) used here was 35,000, which belongs to the subcritical Reynolds region, and the flow in this Reynolds region can shows the typical flow characteristics in practical drilling operator. The effects of the incidence angle, which was in the range of 0–360° and at 30° intervals, on the drag and lift coefficients, the pressure distribution around the main line, the vortex shedding frequencies and the flow structure were investigated. The mean and RMS values of the drag and lift coefficients of the main line vary with the incidence angle irregularly due to the complexity of the geometry of the riser system. The flow patterns can be classified into six types based on the time-averaged streamlines. The effects of the auxiliary lines on mean force coefficients of the main line in different flow patterns were discussed in detail based on the distributions of the pressure on the main line. The auxiliary lines can suppress the vortex shedding on the main line at all incidence angles. Especially, in the CVP (clamped vortices pair, $\alpha=210°$ and $\alpha=330°$) pattern, the vortex shedding behind the main line is suppressed most effectively by multiple downstream auxiliary lines. The mean value of the drag coefficient is just about 45.5% of that of the single cylinder, and the RMS value of the lift coefficient is about 1.5% of that of the single cylinder. This is the favorable condition for drilling operation. The worst effect of suppression occurs in the SLA (shear layers afflux, $\alpha=90°$) pattern, and the RMS value of the lift coefficient is about 76.8% of that of the single cylinder. Due to the interaction between the vortices shed from different lines in riser system, the frequencies of the lift coefficients of the lines in riser system change largely, and some higher frequencies appear in the lift coefficients of the main line. As $\alpha=60°$ and $\alpha=120°$, the Strouhal number of the main line is about 0.75.

1. Introduction

During the development of offshore oil and gas, drilling risers are immerged in deep sea. The flow analysis and flow control for risers are concerned by researchers and engineers to prolong the service life of the risers and optimize the drilling operating environment. Roughly two flow control methods are known with respect to energy expenditure, active method and passive method. In the active method, such as surface heating (Lu et al., 2012), blowing and/or suction (Sohankar et al., 2015), external energy should be input into the system. While the passive method is concerning about the geometrical modification of the flow system without any additional energy consumption, such as splitter plate (Qiu et al., 2014, Gu et al., 2012b), fairing (Assi et al., 2011,Wang and Zheng, 2015), helical strakes (Gómez et al., 2013) and control rod (Firat et al., 2015, Lee et al., 2004) can be used to change the flow structures around the cylinder. The auxiliary lines located close to the main line of the drilling risers are necessary to achieve special functions for drilling operation, and can also be expected to control the flow around the risers to some extent, which can be classified into the passive method. Due to the lack of the knowledge about the influences of the auxiliary lines on the main line, the current design practice of the risers simplifies the riser system with auxiliary lines as a single cylinder, which cannot reveal the real flow and fluid force characteristics. The issue about flow past drilling riser system relates to flow around multiple cylinders with

* Corresponding author.
E-mail address: jswang@sjtu.edu.cn (J. Wang).

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different diameters, which has been scarcely studied up to now.

Flow around cylinders is a common phenomenon in engineering practice. A lot of researchers have paid considerable attentions to this issue, and many important insights into this problem have been achieved. In the early researches, the main point was focusing on flow around a single cylinder, both experimentally and numerically, for several decades, as reflected in the reviews of Williamson (1996) and Norberg (2003). Although the geometry is simple, the interesting flow features are abundant. Fung (1960) and Roshko (1961) investigated the flow around a single circular cylinder at supercritical Reynolds numbers and high Reynolds numbers respectively. The relationship between the lift coefficient, the drag coefficient, the Strouhal number and the Reynolds number were summarized systematically.

Up to now, the flow past two cylinders has been studied extensively, both experimentally and numerically, for several decades, as reflected in the reviews of Zdravkovich (1977) and Sumner (2010). The flow around a group of structures is different from and more complicated than that around a single structure. In the issue about the flow past a group of cylinders, the main parameters are the Reynolds number and the configuration of the cylinders. Spivac (1946) studied the flow past two parallel cylinders at different gap ratios. It was found that the flow around the two parallel cylinders is characterized by a single frequency. Wang and Zhou (2005) investigated the flow behind two side-by-side circular cylinder experimentally based on laser-illuminated flow-visualization. According to different gap ratios, the flow was classified into three regimes: single street, asymmetrical flow and two coupled flow. It was found that the flow structure and its downstream evolution are closely linked to the phase relationship between the gap vortices in the wide wake and in the narrow wake. Meneghini and Saltara (2001) observed sub-harmonics at the gap L=3D, and the power-spectrum estimation of the lift coefficient shows a very distinctive peak at the Strouhal frequency. Gu and Sun (1999) investigated the interference between two parallel circular cylinders arranged in staggered configurations at high subcritical Reynolds number using a wind–tunnel, three pressure-distribution patterns on the downstream cylinder and two switching processes were observed at different incidence angles. The corresponding flow patterns were classified as wake, shear layer and neighborhood interference. Sumner et al. (2000, 2003) and Li and Sumner (2009) found that the behavior of the Strouhal number could also be broadly classified according to pitch ratio into three types: closely spaced configurations, moderately spaced configurations and widely spaced configurations. The small changes in the incidence angle (wind direction) can lead to marked changes in the vortex shedding (dominant) frequencies. Zhou et al. (2009) investigated the effect of the Reynolds number on the wake of two cylinders arranged in staggered configurations based on the measured/reported Strouhal number and the flow structure. The St-Re relationship was classified into four distinct types. Each is linked to distinct initial conditions, namely, interactions between the four shear layers around the cylinders. It should be noted that, the researches mentioned above were based on two cylinders with the equal diameter. Zhao et al. (2005, 2007) investigated the viscous flow and turbulent flow past two circular cylinders with different diameters numerically using a finite element method. The effect of the gap ratio and the position angle of smaller cylinder on drag coefficient, lift coefficient and vortex shedding frequency were discussed detailedly.

Besides the work listed above, more investigations (Hu and Zhou, 2008a, 2008b; Zhang et al., 2006; Mittal et al., 1997) about the flow past two cylinders arranged in different configurations can be found. However, the work about the flow past more cylinders is scarce. Sun and Gu (1995) studied the flow past two and more cylinders and pointed out that, the interference of flow around groups of structures, or simply the group-effect, is important and essential both from viewpoints of fundamental research in fluid dynamics and engineering applications. Lam and Fang (1995) studied the static pressure distribution on four cylinders arranged in a square configuration subjected to cross flow for spacing ratios ranging from 1.26 to 5.8 and incidence angles ranging from 0–45°. It was found that a cluster of cylinders would result in a reduction in drag coefficient and hence a reduction in total drag. Sewatkar et al. (2012) studied the flow around six inline square cylinders numerically and experimentally, four basic flow regimes were initially proposed as a function of spacing ratio for $Re=100$. Gu et al. (2012a) and Zhao et al. (2012) studied the effects of the auxiliary lines on the vortex shedding on the main line experimentally and numerically respectively based on an ideal riser model. It was found that, the auxiliary lines can suppress the vortex shedding, and the effect of suppression is closely related to the arrangement of the auxiliary lines and the incidence angle of the flow. Lu et al. (2014) studied the laminar flow past a circular cylinder with multiple equally distributed small-diameter control rods numerically. The effects of rod-to-cylinder spacing ratio, rod to cylinder diameter ratio, Reynolds number, number of control rods and angle of attack on the hydrodynamics of the main circular cylinder were investigated. Four different flow regimes were identified based on the mechanism of lift and drag reduction.

In this paper, the flow analysis and flow control for a real drilling riser system with six auxiliary lines were studied numerically. The drilling riser system was modeled as seven circular cylinders with different diameters, it was expected that the flow structures were more complex than previous researches mentioned above. It should be noted that the work in this paper was based on a drilling system currently used in offshore oil industry, and the geometry of the system was fixed. The aims of this study were to investigate and evaluate the effects of the auxiliary lines on suppression of the vortex shedding behind the main line at different incidence angles, and to study the new phenomenon that appears in complex cylinder configuration (multi-cylinders with different diameters). The flow structure around the multiple cylinders was validated based on the insights of the flow past single cylinder, two staggered cylinders and eight even-distributed auxiliary lines around the main line. The effects of the incidence angle on flow structure, hydrodynamic force and vortex shedding frequency at $Re=35{,}000$ were studied systematically.

Based on the diameter of the main line, the Reynolds number investigated in this paper was selected to be 35000, which was based on following considerations. First, $Re=35{,}000$ belongs to a subcritical Reynolds region, and the flow in this Reynolds region can shows the typical flow characteristics in practical drilling operator. Second, the first natural frequency of the drilling riser with the length of 1000 m may be estimated about 0.0244 Hz, and the reduced velocity ($Ur=UD/\nu$, U is the free-stream velocity, D is the diameter of the cylinder, ν is kinematic viscosity of the fluid) corresponding to this Reynolds number mentioned above is about 5, which is a typical value that is cared about in vortex induced vibration (VIV) research.

The outline of this paper was arranged as the followings. In Section 2, the problem description of the flow past the riser system was given. Some parameters used to describe the issue were defined. In Section 3, the governing equations and the turbulence model were introduced. In Section 4, the model and numerical method were validated by comparing with the classic researches on flow past single cylinder, two identical staggered cylinders and riser with eight even-distributed auxiliary lines. The computational grid had also been tested using four different meshes. The simulation results were presented and discussed in Section 5. In the final section, some conclusions were drawn.