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Impacts of top-end vessel sway on vortex-induced vibration of the submarine riser for a floating platform in deep water

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ABSTRACT

The dynamic coupling between moving top-end vessel and submarine riser becomes more remarkable for floating platform in deep water due to its larger amplitude of top-end motion, compared to fixed platform in shallow water. The impacts of top-end motion on the riser undergoing vortex-induced vibration (VIV) are explored in this study. A coupled hydrodynamic force approach, involving the vortex-induced lift force along with the fluid drag force, is developed, which takes into account the interaction between fluid dynamic force and instantaneous riser motion. Then the dynamic behaviors of the riser suffering both top-end motion and VIV are examined by means of finite element simulations. The effects of the amplitude and frequency of top-end vessel sway on riser's VIV are studied. During the riser's dynamic responses, an interesting phenomenon, called nonlinear response amplification, is observed, which demonstrates that top-end motion may be amplified as the motion propagates along riser length. Our numerical results show that the riser's displacement becomes several times larger than that of the case without top-end motion. Moreover, the nonlinear amplification gets more pronounced as the number of mode order drops, but the amplification factor just slightly changes with the increase of sway amplitude.

1. Introduction

Submarine riser of deep water platform has been becoming longer and longer as the oil and gas exploration extends toward deeper ocean. Since the aspect ratio (the ratio of structural length to diameter) of deep water riser, connecting top vessel and sea bed, is getting larger, i.e. to a magnitude order of 10^2 or 10^3, structural modal frequencies are often low and dense. And in practice, the fluid field characters, including speed value and direction of sea current or wave, are no longer uniformly distributed along riser length. Therefore some complicated phenomena, e.g. multi-mode vibration and wider-band random vibration, of the vortex-induced vibration of long flexible risers are frequently observed (Chen et al., 2006; Gu et al., 2012; Heurtier et al., 2001; Lou et al., 2010; Stansberg et al., 2002; Tahara and Kim, 2003). On the other hand, compared to fixed platform in shallow water, floating platform in deep water has more significant motion amplitude, and the coupling between top-end vessel and submarine riser appears to be more remarkable. Moreover, new issues such as additional lock-in region, parameter excitation and nonlinear amplification, due to coupling effects are introduced (Garrett, 2005; Lei et al., 2010; Wang and Ling, 1998). It is found that the tension fluctuation due to top-end heave may introduce new riser's VIV involving higher-order modes and larger dynamic responses, e.g. riser's displacement and shear stress are respectively 10% and 20–100% larger than the case without vessel motion (Wang and Ling, 1998).

Among those research on the dynamic coupling between top-end vessel and marine structures (like riser, tension leg and mooring lines), most of them focus on dynamic response of top-end vessels rather than submarine structures. Generally, the analysis methods concerning interactions of top-end vessel and marine structures can be classified into two kinds: the quasi-static method (Ormberg et al., 1997; Kim et al., 2001; Spanos et al., 2005; Wichers et al., 2001; Xu et al., 2009) and the coupled method (Bosman and Hooker, 1999; Chen et al., 2006; Gu et al., 2012; Li et al., 2010; Tahara and Kim, 2003). In the quasi-static method, riser is simplified as a spring with lumped mass. In that case, only the static restoring force, due to wet weight and (or) elastic stiffness of risers, is taken into account. For example, Spanos et al. (2005) studied the influence of riser stiffness on the overall dynamic response of a SPAR platform by using a simplified model, in which the top-end vessel mass was concentrated at the gravity center and a horizontal spring was used to simulate the interaction between riser and vessel. Xu et al. (2009) considered the structural nonlinear property of a tension leg and presented the comparison between two different tension leg models, i.e. the nonlinear beam and the massless spring model. He pointed out that the dynamic responses of tension leg platform based on different models are significantly different. Ormberg et al.

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(1997), Kim et al. (2001) and Wichers et al. (2001) investigated the interactions of floating top-end and riser (or mooring system) of deepwater platforms so as to compare the coupled approach in time-domain and the quasi-static approach. Their results show that the capability of mooring system bearing external loads may be underestimated by using the quasi-static approach.

Actually, the coupled methods might be further classified into fully-coupled method and weakly-coupled method. In fully-coupled method, dynamic response of a system involving top-end and submarine structures is analyzed by considering at least two dynamic interactions, one is the interaction between environmental loads and floating vessel, another one is the interaction between floating vessel and submarine structures. In weakly-coupled method, one (or two) of the above interactions is simplified or even neglected. In most of the coupled methods, fully or weakly coupled, submarine riser and hydrodynamic force exerted by ocean current or wave are mostly simplified (Lee and Wang, 2000; Li et al., 2010; Tahara and Kim, 2008), e.g. the Morison formula is employed to model hydrodynamic force. The primary concern of the existing research lies in riser's dynamic responses rather than riser's VIV. Lee and Wang (2000) used a linear tensional string to simulate tension leg and analyzed the leg dynamic response as the top-end vessel experiencing periodical surge. His results showed that there is a leg vibration mode similar with the platform while the vibration amplitude changes with wave period. Tahara and Kim (2008) employed the empirical formula of the Young's modulus suggested by Bosman and Hooker (1999) to examine the mooring system response of a SPAR undergoing heave. By comparing his result with that of a linearly elastic mooring system, he found a remarkable difference between the two results.

In addition, it is worthwhile to point out that the dynamic coupling mechanisms, between top vessel and submarine riser, due to different kinds of vessel motions are essentially different. Taking vessel heave as an example, it introduces a fluctuating tension of riser, which presents a periodically-varying structural property. Thus, the consequence is a parameter excitation of riser. Whereas, if taking horizontal motions, i.e. sway or surge of vessel, under consideration, the transverse vibration of top-end will propagate along riser length. This transverse vibration may directly interact with riser's VIV. Moreover, the vibration might be amplified during its propagation along riser length. This effect of top-end sway, in essence, introduces a quite different issue from parameter excitation due to top-end heave. Here, only the dynamic interaction between top-end vessel sway and riser's VIV is addressed. And, we consider the weakly-coupling issue, since the fully-coupled approach is costlier than the weakly-coupled approach in terms of computer source and time.

First, we develop a hydrodynamic approach to model the vortex-induced lift force which essentially depends on structural motion. Then the dynamic response of the riser simultaneously suffering top-end sway and VIV is examined by means of finite element simulations during which the top-end is assumed to be in a, for representation and simplicity, periodically sinusoidal motion. Effects of top-end sway amplitude and frequency on riser's response displacement as well as vibration propagation are examined so as to have a deeper insight into impacts of top-end vessel sway on riser's VIV.

2. Numerical model of dynamic response analysis for integrated system

2.1. Structure model

The system including the top-vessel and riser is shown in Fig. 1. In Fig. 1a, the origin point of the coordinate system is located at the bottom end of the riser (fixed to the sea bed). The flow U directs along the axis y. The sway motion of top vessel, $b(t) = Be^{-i\omega_0 t}$, is along the axis x, where B and ω_0 are respectively the amplitude and frequency of the sway motion. In the finite element model (shown in Fig. 1b), the vessel and the riser respectively consist of 3D cubic solid and 1D Euler beam elements. The rotational motions around the axis x, y, and z of all those grids of the top-end body are constrained during the numerical simulations so as to avoid a probable singularity introduced by the extremely large mass of the top-end. Additionally, the multi-point constraint (MPC) is used at the joint grid connecting the top-end vessel and the riser, where different elements meet together, so that the constraints can be applied effectively and smoothly upon different degrees of freedom.

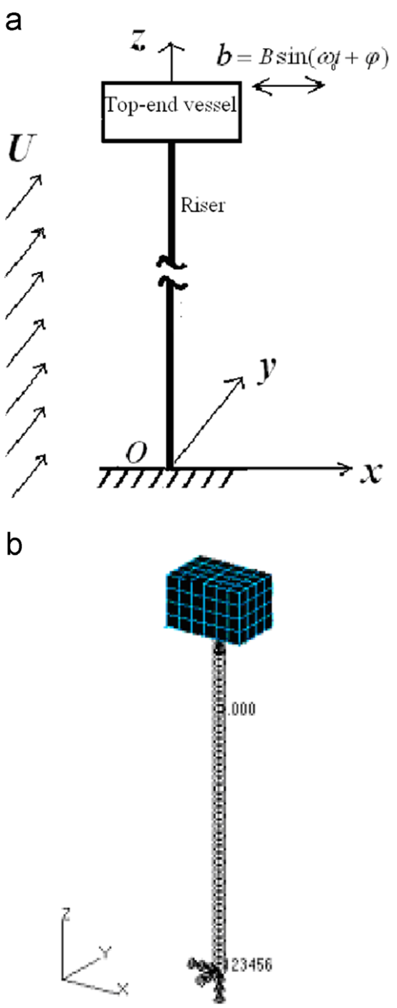

Fig. 1. The platform-riser system sketch: (a) the platform-riser system sketch and (b) the finite element model of platform-riser system.

The governing equation of the riser dynamics can be written as

$$EI\frac{\partial^4 x(z,t)}{\partial z^4} - T\frac{\partial^2 x(z,t)}{\partial z^2} + c\frac{\partial x(z,t)}{\partial t} + m\frac{\partial^2 x(z,t)}{\partial t^2} = F(z,t) \tag{1}$$

where EI is the bending stiffness, T is the top tension, c is the structural damping, and m is the structural mass per unit length. $F(z)$ is the hydrodynamic force, of which the expression model will be presented in Section 2.2. The boundary conditions at two ends of the riser are

$$\begin{matrix} x(0,t) = 0 \\ \partial^2 x(0,t)/\partial z^2 = 0 \end{matrix} \quad \text{and} \quad \begin{matrix} x(L,t) = b(t) \\ \partial^2 x(L,t)/\partial z^2 = 0 \end{matrix}. \tag{2}$$

2.2. Hydrodynamic force model

The fluid wake field of a riser undergoing VIV is too complicated to directly get a theoretical solution because of the uncertainties like