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Review

Vortex-induced vibrations and control of marine risers: A review

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A B S T R A C T

This paper reviews the dynamics and vibration control techniques for marine riser systems. The riser pipes are modeled as Euler-Bernoulli beams that vibrate under the effects of ocean loads and the movements of the surface vessel, resulting in hybrid ODE-PDE equations. Chronological development of such hybrid models is first discussed, and their approximated ODE models for simulation are examined. Theoretical and experimental techniques for instability and fatigue analyses on the riser systems are also summarized. To increase the fatigue life against ocean currents, passive vibration suppression devices (e.g., strakes and spoilers) were mounted on the surface of the riser. Whereas to tackle the instability problem caused by sea waves, active control techniques utilizing the movements of the vessel were employed. In Conclusions, as future riser technologies, seven research issues are identified.

1. Introduction

A marine riser, an essential component of subsea oil/gas production systems, acts as a conductor pipe between an offshore platform floating in an ocean (i.e., a storage platform or a vessel) and a well on the seabed (Chakrabarti and Frampton, 1982). As shown in Fig. 1, the riser is connected to the well through the blowout preventer (BOP) valve that prevents leakages of the fluid transported through the riser. The riser system is exposed to harsh environmental loads like ocean currents and waves. The currents act along the length of the riser, whereas the waves inflict the movements of the vessel. A severe current and a large movement of the vessel can result in a large deflection of the riser, which causes a disconnection of the riser from the BOP valve or a failure due to fatigue in the riser system. In the past fifty years, to ensure the safety and to enhance the productivity of riser systems, several investigations on the dynamics analyses and vibration controls of various riser systems have been reported in the literature.

The main objective of this paper is to review the works on the dynamics and control of the riser itself comprehensively under the influence of ocean currents and waves. The issues of laying and reentry of the riser and its contact with the seabed are important (Elosta et al., 2016; Jensen et al., 2009a, 2010; Wang et al., 2016); however, those will not be touched due to page limitation. At the end of the review, future research directions to improve riser technologies will be identified. This paper intends to portray a comprehensive picture on the evolution of mathematical modeling, analyses, and the vibration control strategies applicable to riser systems to the present state-of-the-art.

Riser systems can be classified into production and drilling risers from the operational view point. A production riser transports oil/gas from the seabed to the vessel; a drilling riser provides a pathway for drilling and transports drilling mud (Chakrabarti, 2005; He et al., 2014). Risers can be further classified into flexible or rigid according to the material used in their construction. A rigid or straight top-tensioned riser is usually utilized for shallow water operations, whereas a flexible or steel catenary riser is typically used for deep ocean operations (i.e., >2000 m) (Mekha, 2001; Meng and Zhu, 2015).

When a riser moves in the presence of currents, vortices are shed along its surface, resulting in the formation of an unstable wake region around it. Vortex shedding takes place at different frequencies and amplitudes, thus effecting different vortex patterns. According to Xu et al. (2009), the formation of different patterns of vortices depends upon the Reynolds number (Re) of the incident flow. Fig. 2 shows three different patterns of the vortices (i.e., 2S, 2P, and P + S) shed by the structure of the riser upon its interaction with the incident flow. The 2S pattern is a combination of two single vortices shed in opposite directions relative to each other during one cycle (i.e., Von Karman vortex shedding); the 2P pattern represents two pairs of vortices shed in one cycle, in which each pair consists of vortices in opposite direction relative to each other; and the P + S pattern denotes the asymmetric combination of a pair of vortices with a separate single vortex during each cycle (Williamson and Govardhan, 2004). Vortices inflict a periodically varying transverse force on the riser (i.e., perpendicular to the direction of the flow), resulting in

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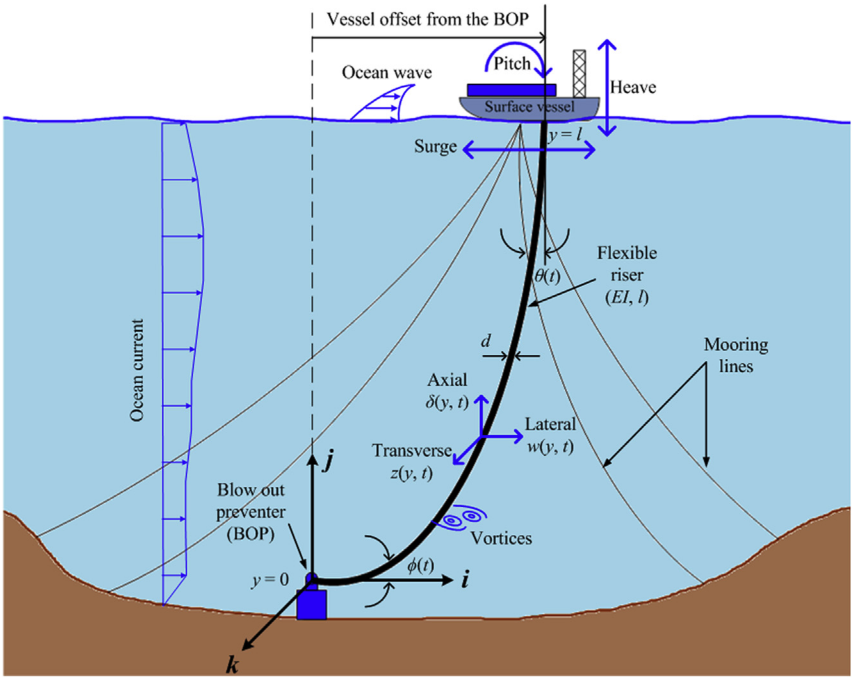

Fig. 1. Schematic of a subsea production system.

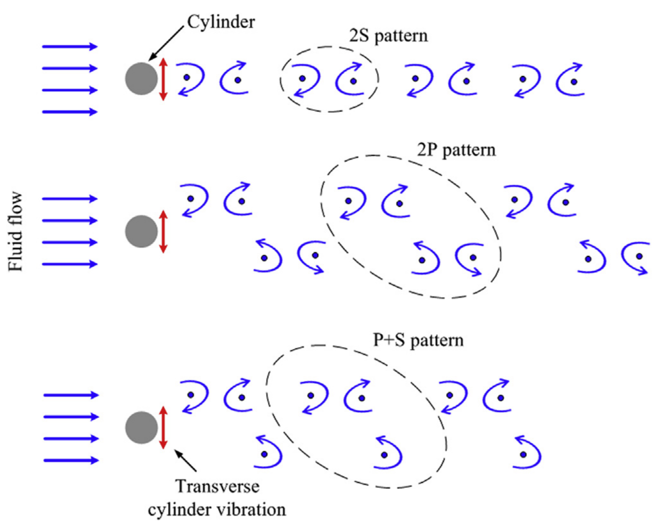

Fig. 2. Different patterns of vortex shedding from a cylinderical object to inline forces.

periodic transverse vibrations known as the vortex-induced vibrations (VIVs) (Wu et al., 2012b). According to Modarres-Sadeghi et al. (2011), the vortex-induced response of a riser is a complex phenomenon, and continuously shifts between a stationary state and a chaotic state. Also, when the frequency of the vortices (i.e., the vortex-shedding frequency) is close to one of the natural frequencies of the riser, the so-called lock-in phenomenon occurs, whereby the riser manifests large vibrations. Xue et al. (2008) noted that the riser can experience either single- or multi-mode (i.e., excitation of multiple modes) lock-in responses. For more details, interested readers can refer to the papers on the topic of VIV (Sarpkaya, 1979; Vandiver et al., 2009).

Risers ought to confront continuous loads (Jeans et al., 2003), which are the main cause of fatigue damage (Collette, 2011; Collette and Incecik, 2006; Elosta et al., 2014; Hodapp et al., 2015; Jensen, 1990, 2015; Marsh et al., 2016; Yuan et al., 2014; Zhu and Collette, 2017). Fatigue, the main concern reflecting the structural integrity of a riser, is caused by both the inline (i.e., in the direction of a flow) and the transverse (i.e., perpendicular to the direction of the flow) forces (Xue et al., 2014). Early works ignored the contribution of the inline forces to fatigue damage; however, later investigations revealed that the fatigue-causing effects of the inline forces and the transverse forces are equally important (Lie and Kaasen, 2006; Trim et al., 2005). According to Baarholm et al. (2006), the contribution of the inline forces to fatigue damage is particularly evident for the lower modes of vibration (i.e., the first and second modes), whereas that of the transverse forces is clear at the higher modes. Several subsequent investigations (Iranpour et al., 2008; Song et al., 2011) were concurrent with those results. More recent findings of Gao et al. (2011) and Zhang and Tang (2015) have reported that the maximum fatigue damage usually incurs at the boundary ends of the riser.

Along with the damage induced by the currents, the one resulting from the movements of the vessel is also a concern with regard to the integration and safety of the riser and the production system. According to Kuiper et al. (2008), the heave (i.e., vertical) motion of the vessel can result in i) instability caused by the periodic variation of the tension at the top portion of the riser and ii) a local dynamic buckling of the riser. The latter can be potentially resulted from the occurrence of high bending stresses that can exceed the yield stress of the riser. Vessel movements will also change the contact angles at the top and bottom ends of the riser with the vessel and the BOP of the well, respectively. According to Nguyen et al. (2010), if the end angles increase beyond a specific threshold (usually 2°), the connection between the riser and the BOP can be broken.

The control problem of a riser system is mainly concerned with the suppression of its vibrations caused by the currents and the movements of the vessel (caused by the waves). The two main control objectives, accordingly, are the prevention of both the fatigue and instability of the riser. In a deep sea, the damage caused by the movements of the vessel is significantly less than that caused by the currents, as they act over the entire submerged length of the riser (Trim et al., 2005). At a shallow depth, however, the instability of the riser caused by the movements of the vessel is the main concern (Perunovic and Jensen, 2003). The heave motion of a vessel is normally suppressed by mooring the ship to the seabed (see the mooring lines in Fig. 1), which is a passive method. Rotations such as pitch and yaw, meanwhile, are more effectively