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Dynamic analysis of a hang-off drilling riser considering internal solitary wave and vessel motion

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ABSTRACT

Hang-off mode of a drilling riser is occasionally needed during subsea installation/platform relocation operations or evacuation after an emergency disconnection. A suspending riser without any restriction at its bottom is more flexible and more dangerous in complex sea states than a connected riser with excess axial tension. Internal solitary waves (ISWs) can particularly exert a sudden impact and shearing force on risers, and vessel motion can expand horizontal dynamic responses of the risers. In this paper, considering vessel motion and the combined excitation of ocean currents, surface waves and ISWs, a dynamic model is constructed based on the Euler-Bernoulli theory, in which ISW is simulated by the Korteweg-de Vries (KdV) equation with a two-layer seawater model. Then, the structural governing equation is numerically solved by the Wilson- θ method and preconditioned generalized minimal residual method (GMRES) with a self-developed MATLAB program. Case calculation shows that ISW can largely increase the envelopes of riser properties in the upper seawater layer and dramatically expand the horizontal deviation of the bottom of a hang-off riser during ISW spreading. Particularly, the dynamic responses of a riser will be larger with ISW amplitude augmentation, and larger with an increase in the density difference between the two seawater layers. In addition, vessel motion can increase the horizontal deviation along the entire length of a riser with a range that is nearly the same as that of the vessel motion amplitude, and increase the envelopes of bending moment and shearing force at the lower section of the riser near the riser bottom. Therefore, limiting the vessel motion amplitude, optimizing the vessel towing speed, maintaining a lower marine riser package (LMRP) at the riser bottom to strengthen axial tension, and using slick joints with larger wall thicknesses in the upper depth may be effective engineering considerations. More importantly, much attention should be paid to avoid the riser bottom/LMRP striking other subsea equipment in oceans in which ISWs occur frequently.

1. Introduction

Oil and gas resources are rich in oceans, such as the South China Sea, Gulf of Mexico, North Sea and Persian Gulf. To exploit more crude oil and natural gas, offshore floating drilling is a fundamental operation in deepwater. During floating drilling, hang-off mode of a drilling riser is occasionally needed during subsea installation/platform relocation operations, or evacuation after an emergency disconnection (API RP 16Q, 2001). A hang-off riser is suspended under a platform, and its bottom is free from any restriction; accordingly, the platform can only support the entire weight of the riser, but not provide excess top tension to maintain the riser string in a tensional state. Therefore, in harsh sea states, hang-off risers have larger deviations and more drastic dynamic responses than risers fixed on a subsea wellhead. Such riser responses may lead to some of the following issues and dangers:

① Difficulty determining the distance between the rise bottom and subsea wellhead during riser installation;
② Possible striking of the moon pool or damaging the upper flex joint (UFJ) due to the large rotation and deflection at the riser top;
③ Undesirable striking between the LMRP and seafloor or between the risers and other subsea equipment due to the large offset or drastic swing at the riser bottom;

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Abbreviations

CNOOC	China National Offshore Oil Corporation
BOP	blowout preventer
DOF	degree of freedom
FEM	finite element method
GMRES	generalized minimal residual method
iLU	incomplete LU-decomposition method
ISW	internal solitary wave
KdV	Korteweg-de Vries
LMRP	lower marine riser package
UFJ/LFJ	upper flex joint/lower flex joint

④ Severe fatigue damage at weak points along a riser cause by the large dynamic responses.

Researchers analysed the mechanical behaviours of drilling risers in hang-off mode or during installation. Patel and Jesudasen (1987) presented a theoretical and experimental investigation of the lateral dynamics of free hanging marine risers. Ambrose et al. (2001) and Bybee (2002) discussed the possibilities of using a soft hang-off option and compared the performance characteristics of a drilling riser in soft hang-off and hard hang-off configurations, particularly for ultra-deepwater applications. Dai et al. (2009) analysed the dynamic behaviour of a deepwater drilling riser under hang-off working conditions using ABAQUS software. Williams (2010) discussed optimization of drilling riser operability envelopes for harsh environments, in which the soft/hard riser hang-off configurations for storm events were assessed. Wu et al. (2014) researched the dynamic response of a drilling riser in hard hang-off mode, in which the platform motion as well as wave and current effects were considered. Wang and Gao et al. (2014, 2015) studied the static behaviour and lateral vibration of a drilling riser during installation, and considered different hanging weights at the blowout preventers (BOPs). Qi et al. (2015) calculated the evacuation speed range of a hard hang-off drilling riser due to a typhoon using a commercial finite element method (FEM) software, OrcaFlex.

Normally, vessel motion has six patterns: heave, surge, sway, yaw, roll and pitch. Compared with four other patterns, horizontal deviations (surge and sway) are the two main factors that affect the transverse motion of risers, and both can add the effect of lateral drag force along a riser. Sexton and Agbezuge (1976) researched the influence of both random waves and vessel motion on connected drilling risers. Head et al. (2013) and Royer et al. (2014) evaluated various potential concepts of a steel catenary riser for high-motion vessels operating in ultra-deepwater. Wang and Fu et al. (2014, 2015) analysed the out-of-plane vortex-induced vibration of a steel catenary riser caused by vessel motions and evaluated its fatigue damage. Chen et al. (2015) evaluated the impacts of top-end vessel sway on the vortex-induced vibration of a submarine riser for a floating platform in deep water. Iwona et al. (2015) analysed the influence of vessel motion on riser dynamics by the rigid finite element method.

ISWs are another important factor in ocean engineering, and have been a hot topic in recent oceanographic research. Internal waves are gravity waves that oscillate within a fluid medium rather than on its surface. To exist, the fluid must be stratified: the density must decrease continuously or discontinuously with height due to changes, for example, in temperature and/or salinity. If the interfacial waves have large amplitudes, they are called ISWs or internal solitons. In oceans, ISWs are especially common over continental shelf regions and where brackish water overlies salt water at the outlet of large rivers. In fact, ISWs occur frequently and distribute widely in most oceans, such as the Estremadura Promontory off the West Iberian Coast (Magalhaes and Silva da, 2012), Mascarene Plateau of the Indian Ocean (New et al., 2013), and northwestern South China Sea (Xu et al., 2016). For example, in the western South China Sea, ISWs have amplitudes of 170 m, half widths of 3 km, and phase speeds of 2.9 ± 0.1 m/s (Klymak et al., 2006). ISWs can cause strong shear flow in seawater during its spreading (Osborne and Burch, 1980), and exert strong shearing force as well as a large lateral deviation to a riser in a sudden time, which may eventually unexpectedly destroy the entire pipe system (Guo et al., 2013). ISWs occur frequently and are difficult to predict them in time, so there is a strong possibility that a drilling riser suffers impacts from ISWs during installation/relocation or evacuation in harsh environments. Particularly, such an ISW impact is more serious on a hang-off riser than a normal connected riser.

Some scholars studied the loads on structures exerted by internal waves. Cai et al (Cai et al., 2003, 2006, 2008; Xie et al., 2010, 2011). adopted Morison's empirical formula and a modal separation method to estimate the forces and torques exerted by internal solitons on cylindrical piles. Zha et al. (2012) estimated the force and torque exerted by ocean internal waves on a submerged vertical cylindrical pile by using nautical X-band radar observations and in-situ buoyancy frequency data. Song et al. (2011) compared the actions by surface waves and ISWs on a Spar platform with a mooring system. Si et al. (2012) studied the shearing forces and torques by large-amplitude ISWs on a supposed rigid pile in the South China Sea. Guo et al. (2013) researched the dynamic responses of a top tensioned riser under combined ISW excitation, surface wave and vessel motion. Deng et al. (2015) proposed a quasi-static procedure to evaluate the impact of ISWs on a connected drilling riser under combined loads of ocean currents, surface waves and ISWs.

In previous research, various authors introduced solution methods, assistant software and response characteristics of hang-off riser dynamics. However, influences, such as damping forces and vessel motion, in the existing methods were normally neglected, and there is room to improve the numerical procedures. As for ISWs, most existing articles focused on their generation and distribution as well as the wave characteristics. Some articles discussed the impact of ISWs on fictitious cylindrical piles; however, few papers have reported the influence of ISWs on top tensioned drilling risers in detail. More importantly, few reports have evaluated the impact of ISWs on hang-off drilling risers.

In this paper, a time-domain dynamic FEM method is established by the Wilson- θ algorithm for a hang-off drilling riser, and dynamic envelopes of the hang-off riser properties are compared in different situations. Innovations in this paper are reflected in the following two aspects: in the hang-off dynamic procedures, the preconditioned GMRES is adopted to solve the large, sparse nonsymmetric linear system; and the combined excitation of a nonuniform current, surface wave, ISW and vessel motion are considered in hang-off riser dynamics for the first time. Moreover, a dynamic envelope analysis of hang-off risers is visualized to reveal the extreme properties rather than the detailed dynamic variations over time, and this method is more convenient for drilling riser design and hang-off riser operation.

2. Riser model and calculation equations

2.1. Riser model and governing equation

Fig. 1 displays a riser model in hang-off mode. The bottom end of the riser has no constraints, but may connect with a mass block