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Active control of axial dynamic response of deepwater risers with Linear Quadratic Gaussian controllers

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ABSTRACT

Active control of axial dynamic stress response of deepwater risers with Linear Quadratic Gaussian controllers is presented in this paper. The risers are installed between the subsea wellhead and the Tension Leg Deck located in the middle of the moon-pool in the Floating Production, Drilling, Storage and Offloading unit. The inevitable heave motion of the floating hull causes a time-varying axial tension in the risers. As a result, the frequent occurrence of axial dynamic stress response of relatively large amplitude may cause fatigue damage to steel risers. This paper thus explores the possibility of using a winch to reduce axial dynamic stress response of deepwater risers. The equations of motion of actively controlled risers against waves are first established. Axial dynamic stress response of the system is then determined in terms of the complex dynamic characteristics and the pseudo-excitation method. Based on the derived formulae, the performance of the winch for reducing axial dynamic stress response of risers is numerically assessed. The investigations show that the winch not only provides great flexibility for selecting system parameters but also significantly reduces the axial dynamic stress response of risers under wave excitation.

1. Introduction

The Floating, Production, Drilling, Storage and Offloading (FPDSO) concept has attracted much attention in ocean engineering in recent years. This concept combines the functions of a separated Floating Production, Storage and Offloading (FPSO) and a drilling unit into one single unit. One of the proposed forms of FPDSO benefits from the mature technology of the Tension Leg Deck (TLD) developed by the SBM offshore company (Pollack et al., 2000). TLD is based on using the gravity of weights, instead of buoyancy as in existing dry tree concepts, as a means to pretension risers. The rigid production risers used for oil transportation are suspended from the TLD located above the water level in the middle of the FPDSO moon pool, as shown in Fig. 1. If the FPDSO hull heaves up by one meter, the TLD remains in place while the weights move up two meters. The weights used to pretension the risers therefore accelerates and decelerates with the FPDSO heave motions. Although the TLD is a heave compensation system to reduce the influence of FPDSO heave motions, these accelerations can cause fluctuation of axial tension in the risers. When the risers are located in deeper water, one of the grave concerns is associated with the fluctuation of the axial tension in the riser caused by heave motion of the FPDSO hull in waves. The fluctuation of the axial tension due to the FPDSO heave motions leads to cyclic stresses and can develop into an unacceptable level of high cycle fatigue damage in ultra deep waters (>1500 m). This danger not only exists in the design of TLD systems in FPDSO, but also in other platforms, even when heave compensators are used to reduce the fluctuation of top tensioned risers (Kuiper et al., 2008). Besides this, the riser will suffer considerable vortex-induced vibration and wave-induced lateral vibration which can last for almost the whole design life in harsher environments. However, if the current velocity and waves are assumed to be small and lateral vibration is not an issue, then the vortex-induced vibration and wave-induced lateral vibration of the riser can be discounted.

The dynamics of the riser system modeled by a tensioned Euler–Bernoulli beam structure with a partial differential equation (PDE) is difficult to control due to its infinite number of dimensions. The control methods based on the truncated model may cause instability in the uncontrolled modes because of spillover effects and require a large number of actuators to achieve a good performance. Alternatively, a cost-effective and practical means for reducing vibration is through a mechanism acting on the boundary of the structures. This approach leads to boundary control problems which have been extensively studied by some researchers. Baicu et al. (1996) used the boundary control

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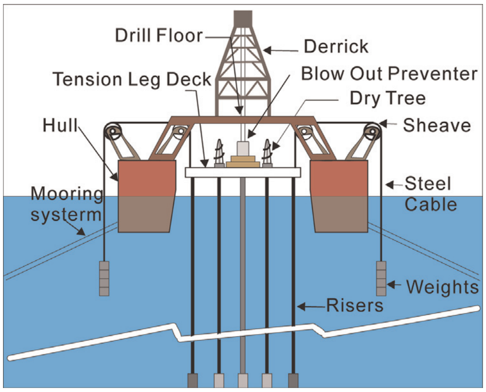

Fig. 1. Sketch of FPDSO.

actuators to stabilize the motion of the cable based on Lyapunov theory for the distributed model. Shahruz and Kurmaji (1997) designed a linear boundary controller for a non-linear model of axially moving strings by Lyapunov's direct method. Sloss et al. (1998) proposed a maximum principle for optimal boundary control of one dimensional structures undergoing transverse vibrations. Fung and Tseng (1999) studied the active vibration control of an axially moving string system through a mass-damper-spring controller at its right-hand side boundary and designed a new boundary control law by sliding mode associated with Lyapunov method. Zhang et al. (2000) introduced boundary controllers for a general class of non-linear string-actuator systems. Fard and Sagatun (2001) designed a boundary control law consisting only of feedback from the slope and velocity of the beam at the boundary to stabilize the transversal vibration of a beam exponentially and shown that exponential stability can be achieved via boundary control without resorting to truncation of model. Guo and Guo (2005) constructed a high-gain adaptive control and regulator to guarantee asymptotic stability of an Euler–Bernoulli beam with control and uncertain amplitude of harmonic disturbance at free end. Tanaka and Iwamoto (2007) proposed active boundary control of an Euler–Bernoulli beam permitting the structure to possess desired properties characterized by the boundary condition. Do and Pan (2008a) presented a boundary controller to reduce transverse motion of flexible marine riser with actuator dynamics based on Lyapunov's direct method and the backstepping technique. How et al. (2009) applied boundary control to a marine riser for riser angle and forced vibration reduction through a torque actuator at the upper riser end. Do and Pan (2009) investigated a control problem of global stabilization for a three-dimensional nonlinear inextensible flexible marine riser system using boundary controllers which were designed based on Lyapunov's direct method and the backstepping technique. Nguyen and Hong (2010) developed a robust adaptive boundary control for an axially moving string by employing adaptation laws that estimate unknown system parameters and an unknown boundary disturbance. Ge et al. (2010) developed boundary control for a coupled nonlinear flexible marine riser with two actuators in transverse and longitudinal directions to reduce the riser's vibration. He et al. (2011) proposed robust adaptive boundary control for a flexible marine riser with vessel dynamics to suppress the riser's vibration based on Lyapunov's direct method. Nguyen et al. (2013) designed a boundary controller for global stabilization of two-dimensional marine risers with bending couplings under environmental disturbances. All controllers developed in these studies have been found effective in suppressing vibration of structures. However, only a little information is available at present on how to reduce dynamic stresses of risers under random wave loadings. Since wave excitation is a random disturbance in nature, it seems to be more reasonable to determine the statistical responses of risers in frequency domain than in time domain. Linear Quadratic Gaussian (LQG) control, and its frequency domain analog H_2 control (Doyle et al., 1989) can be used for control synthesis purposes, so as to get the statistics of the controlled system. By using LQG controllers or H_2 controllers, the estimation and control design processes can be fully separated with the estimator design independent of feedback to the structure. Thus, much of the stability and performance of LQG controllers can be achieved despite partial state information and noise corruption (Housner et al., 1997). Accordingly, LQG controllers are employed in this study for controlling the weight motion with a winch against waves.

Active structural vibration control has been investigated and utilized to sustain the safety and serviceability of civil engineering structures in the last four decades (Housner et al., 1997; Korkmaz, 2011). A number of real implementations have been also realized in many places (Spencer and Sain, 1997). However, very few investigations have contributed in the area of active heave compensation of compliant offshore structures. Korde (1998) proposed an active heave compensation system on drill-ships based on linear control techniques. Johansen et al. (2003) studied active control of heave compensated cranes or module handling systems during the water entry phase of a subsea installation or intervension. A concept referred to as wave synchronization which reduces the hydrodynamic forces by minimizing variations in the relative vertical velocity between payload and water using a wave-amplitude measurement was introduced. The moonpool wave amplitude feedforward control was utilized in order to achieve wave-synchronized motion of the payload through the water-entry zone. Skaare and Egeland (2006) proposed a parallel force/position controller for the control of loads through the wave zone in marine operations. The controller structure has similarities to the parallel force/position control scheme used in robotics. Do and Pan (2008b) presented a comprehensive and systematic procedure for designing nonlinear controllers that resolves some practical problems of marine risers. Saturation in both actuator response rate and actuator magnitude was investigated to the situation where a system is vulnerable to destabilization. Huang et al. (2013) designed a new type of semi-active drawworks heave compensation system to simplify the structure of the ocean drilling heave compensation system and reduce the energy consumption of active drawworks heave compensation system. The double loop control scheme was put forward and the internal model Proportional Integral-Derivative (PID) robust displacement controller was designed for outer loop frequency conversion control system. All these studies have come up with encouraging results for heave compensation if control devices are arranged and designed properly. However, to the best of the writers' knowledge, no relevant research has been found on active control of axial tension in the TLD production risers. Therefore, an effort is made in this paper to investigate the active control mechanism to regulate the weight motion in suppressing TLD vibration.

This study is aimed to reduce axial dynamic stress of risers by application of a winch at the top of the risers. Since fatigue is one of the crucial structural safety issues and the reduction of dynamic stress is the problem with which engineers and managers are mostly concerned, the objective function to be minimized was formulated in terms of strains instead of displacements. Axial strains of the risers are selected as input variables for the controllers because strains are much easier to measure than displacements. Compared to boundary control, stresses can be used in the control design and minimized directly in this study. With frequency domain method, the control at high frequencies is rolled-off and the adverse effects of high frequency measurement noise can be minimized. This paper first establishes the partial