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Dynamic response of a deepwater riser subjected to combined axial and transverse excitation by the nonlinear coupled model

S. Lei [a], X.Y. Zheng [a,*], D. Kennedy [b]

[a] Division of Ocean Science and Technology, Shenzhen Graduate School, Tsinghua University, 518055, Shenzhen, China
[b] School of Engineering, Cardiff University, Cardiff CF24 3AA, Wales, UK

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ABSTRACT

In offshore engineering long slender risers are simultaneously subjected to both axial and transverse excitations. The axial load is the fluctuating top tension which is induced by the floater's heave motion, while the transverse excitation comes from environmental loads such as waves. As the time-varying axial load may trigger classical parametric resonance, dynamic analysis of a deepwater riser with combined axial and transverse excitations becomes more complex. In this study, to fully capture the coupling effect between the planar axial and transverse vibrations, the nonlinear coupled equations of a riser's dynamic motion are formulated and then solved by the central difference method in the time domain. For comparison, numerical simulations are carried out for both linear and nonlinear models. The results show that the transverse displacements predicted by both models are similar to each other when only the random transverse excitation is applied. However, when the combined axial dynamic tension and transverse wave forces are both considered, the linear model underestimates the response because it ignores the coupling effect. Thus the coupled model is more appropriate for deep water. It is also found that the axial excitation can significantly increase the riser's transverse response and hence the bending stress, especially for cases when the time-varying tension is located at the classical parametric resonance region. Such time-varying effects should be taken into account in fatigue safety assessment.

1. Introduction

The offshore oil and gas industry is moving into deeper waters and facing the challenge of harsher environments. The last three decades have seen a number of floating offshore structures such as tension leg platform (TLP), spar, and semi-submersible platforms deployed in the Gulf of Mexico, South China Sea, and offshore Brazil pre-salt fields. As an important system supporting drilling and production activities, long slender marine risers are widely used in these regions. A riser system can be essentially a conductor pipe or a cluster of pipes connecting the floater on the sea surface and the wellheads at the seabed. For the safety of risers in their service lives, it is important to look into their dynamic characteristics of vibration and the related responses under environmental loads.

In order to enhance the geometrical stiffness of a marine riser in practical marine operation, a considerably large axial tension load is usually imposed by tensioners at the riser's top end. Such top-tensioned risers (TTR) have been qualified for use in water depths up to 1500 m. When the water depth reaches 2000 m and beyond, there are specific concerns that prevent the offshore industry from using TTRs. One of these concerns is related to the fluctuation of the top tension which is caused by the heave motion of the floater in waves. Although heave compensators are used to significantly reduce the fluctuation, the time-varying tension is a potential threat for operation. For a particular parametric excitation such as the varying periodically top tension, it may destabilize the vertical equilibrium of the riser with merely a small disturbance in the lateral direction. This effect is the so-called Mathieu instability [1]. Thus, it is important to investigate the effect of time-varying tension on the riser's dynamic motion.

Many researchers have paid attention to parametric excitation induced instability problems in offshore engineering. Hsu [1] was the first to report the parametric resonance phenomenon of offshore cables. Patel and Park [2] investigated the dynamics of the tethers with reduced pretension of a TLP according to the chart of Mathieu stability. Patel and Park [3] then investigated the tether response combined with the forcing excitation and parametric excitation at the top end. Chatjigeorgiou and Mavrakos [4] applied a numerical approach to study the transverse

* Corresponding author.
E-mail address: zheng.xiangyuan@sz.tsinghua.edu.cn (X.Y. Zheng).

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motion of offshore cables with parametric excitation at the top. Chatjigeorgiou [5] further discussed the damping effect on riser stability of parametric excitation, while Chatjigeorgiou and Mavrakos [6] subsequently presented a closed-form solution for a parametrically excited riser based on the first two modes. Kuiper et al. [7] discussed two qualitatively different mechanisms of stability loss of TTRs suffering fluctuating top tension. Xu et al. [8] gave the Hill instability analysis of TLP tethers subjected to combined platform surge and heave motions. Franzini and Mazzilli [9] employed a three-mode reduced-order model to analyze the non-linear behavior which affects the region of Mathieu instability. In addition to the above theoretical and numerical investigations regarding the Mathieu instability of risers, Franzini et al. [10] presented an experimental model which was designed with a high level of dynamic similitude to a real riser. A curious finding is that the Mathieu instability may simultaneously occur in more than one mode, leading to interesting but complicated dynamic behavior. Yang et al. [11] predicted the parametric instability of TTRs in irregular waves using a multi-frequency excitation. The instability diagram differed significantly from that for single-frequency parametric excitation.

From the above review, it is seen that a number of investigations have focused on the Mathieu instability problem while ignoring transverse loading on the TTRs. It should be recognized that when the risers are used in deep waters, ocean waves not only induce motion of the floater, but also generate hydrodynamic loading directly on the riser. The wave-induced transverse vibration causes bending and stresses in risers, associated with fatigue damage. As shown in the industry standards (API [12], DNV [13]), dynamic analysis and fatigue assessment of risers by waves is an important routine procedure for design. To assess the accurate dynamic response of risers by waves, Spanos et al. [14] developed a model for a TTR system in deep water conditions. Based on the concepts of equivalent linearization and a time averaging method they obtained the maximum stress. Han and Benaroya [15,16] developed a nonlinear model for the coupling axial and transverse displacements of tendons of a TLP. A comparison of linear and nonlinear responses to random wave forces was obtained by a numerical method in the time domain. Further work has been done by Gadagi and Benaroya [17] who analyzed the effect of end tensions on a TLP tendon, both for a reduced model and for an actual tether. Wang et al. [18] gave a static analysis of a marine riser during installation and suggested that increasing the motion of the floating platform can greatly increase the total riser stress. Mao et al. [19] established a dynamic model considering the actual riser string configuration to analyze the mechanical behavior of a drilling riser under ocean environment loadings. However, in all these models, the top tension was constant or time invariant, which is inconsistent with the actual situation.

As a matter of fact, a riser suffers time-varying top tension and wave load simultaneously, but only a few works have reflected this. Park and Jung [20] presented a numerical analysis of lateral responses of a riser under combined parametric and forcing excitations employing finite element method. Lei et al. [21] calculated the frequency domain responses of the parametrically excited riser subjected to the random wave. Wang et al. [22] investigated the dynamic response of a marine riser under combined forcing and parametric excitation. Nevertheless, in these works the riser is modeled as a linear beam, in which the axial extension and the geometric nonlinearity are ignored.

It is therefore the main interest of this research to simulate the riser dynamic behavior more consistently with the actual situation. It should be noted that the axial and transverse motions of a riser are coupled if the geometric nonlinearity is considered [15,16,23,24]. When a riser is long, the coupling between the axial and transverse motions can be significant. Hence, this paper aims to investigate the behavior of a riser under the combination of fluctuating top tension and transverse wave excitation using the more comprehensive coupled analysis, which is derived from the geometrically nonlinear strain displacement relation. This paper hereafter confirms that the nonlinear coupled axial and transverse vibration model is more suitable than the classical linear Euler–Bernoulli beam or Rayleigh beam models, especially for cases where the deepwater riser is subjected to combined axial and transverse excitation.

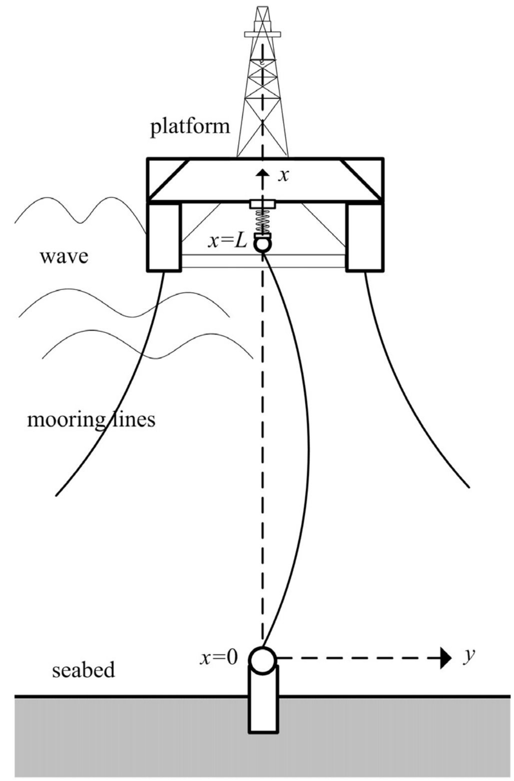

Fig. 1. Sketch of a top-tensioned riser hinged to a floating platform and wellhead in deep water showing (x, y) coordinates.

2. Modeling of a marine riser

2.1. Formulation of the nonlinear coupled model

As shown in Fig. 1, a TTR is connected to a floating platform by means of a heave compensator at the sea surface, and the bottom end is connected to a wellhead at the seabed. For a proper mathematical modeling of the dynamics of TTRs, the following assumptions are introduced to describe the motions of the floating platform and the environmental loads.

- The riser moves only in the plane of the figure, where the x axis is along the vertical body of riser and the y axis is parallel to the wave traveling direction. The unique source of external load in the transverse direction is waves and the current speed is assumed to be small though in is some waters the current speed is comparable to the fluid velocity. With this assumption and the use in engineering practice of vortex suppression instrumentation like thin strakes, the notorious vortex-induced vibration (VIV) and related non-planar motions are not treated in this study.
- The riser is assumed to be ideally uniform from the bottom end to the top end, so the physical properties are identical along the x axis. Also, the riser length L is much greater than its diameter (i.e. $L/r >> 1$, where r is the gyration radius of section) so that the effects of shear on the riser dynamics can be ignored.
- In consideration of the effect of mooring constraints and dynamic positioning systems, the horizontal surge and sway motions of the platform are assumed to be very small, so that the primary motion affecting the riser's axial load is heave. Coupling of risers and floater is not the main concern of this study.
- Generally speaking, the wave-induced heaving motion of the platform is a stationary random process. However, this paper is focused on the special cases where heave motion is modeled by a