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Dynamic analysis and multi-objective optimization of an offshore drilling tube system with pipe-in-pipe structure

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ABSTRACT

A complete dynamic model of an offshore drilling tube system with pipe-in-pipe structure is developed in this paper. Specifically, the riser and well are connected at well head to constitute an outer pipe, within which, the drillstring stretching from the drilling platform to downhole is viewed as an inner pipe. The interactions between the inner and outer pipes are described by a series of spring-friction units along the pipe-in-pipe structure. Comparing with the previously published models which mainly focus on the drilling riser, the pipe-in-pipe structure is applied in this new model; moreover, the tube system under the mud line is also considered as an extension of the tube system submerged in the sea. The developed dynamic model is simulated using the finite element (FE) method in Abaqus. Under the same ocean environmental loads, the maximal lateral deflection for the pipe-in-pipe structure is less than that only considering the drilling riser. This finding indicates that, for an actual offshore drilling tube system with the pipe-in-pipe structure, it has stronger capacity of maintaining reliability under heavy ocean environmental loads. Based on the newly developed dynamic model, multi-objective optimization design of the offshore drilling tube system is conducted in Isight. A new flow path of the optimization is designed. Specifically, six-sigma method is adopted to drive genetic algorithm to run the multi-objective optimization, and simultaneously drive Monte Carlo method to analyze the reliability of the obtained optimal solution. Comparing with a series of single-objective optimization designs, the global optimization degree of the obtained multi-objective optimal design is verified as the best.

1. Introduction

Offshore drilling is different from onshore drilling since drilling rigs and drilling fluids reach wellhead through a riser system whose length is determined by the sea depth. The bottom side of a riser system joins with a blowout preventer (BOP) which is installed on the wellhead; while its topside is connected with a drilling platform via a flexible joint and a telescopic joint. Within the riser, a drillstring rotates; and both of them deflect under the effects of ocean environmental loads. Their deflections trigger the intermittent contacts and frictions between the inner and outer pipes along the whole pipe-in-pipe structure including the tubes under the mud line.

The analyses of the dynamic responses of an offshore drilling tube system are significant for offshore drilling engineers to determine the correct operation strategy. Preliminary studies in this field focused on the dynamic responses of a drilling riser working in shallow water; while the influences of drillstring were not taken into considerations. Burke [1] built up the static and dynamic models of a riser system for 800 ft sea depth. Simmonds [2] used the finite difference method to solve Burke's differential equations, and analyzed the distribution of the riser deflection along the sea depth. Patel et al. [3] applied the FE method to analyze the riser dynamics, in which the ocean loads were set as regular, and the hydrodynamic damping was considered at the first time. Different from other researchers, Yazdchi and Crisfeld [4] applied the Reissner-Simo beam rather than the Euler-Bernoulli beam to consider the hydrodynamic effect on the shear deformation of the riser. Nair and Baddour [5] divided a riser system into pieces which were connected by spring-damper units. Mao et al. [6] designed an experimental system based on HYSY-981 to test the dynamic responses of a riser system in deep water.

As the rising demand for the oil and gas resources, the offshore drilling steps towards deep sea where the main challenges come from the longer drilling tube system and the variable ocean environmental loads. In order to ensure the safety of the drilling operation, more precise description about the dynamics of an offshore drilling tube system becomes necessary. Under such circumstances, the pipe-in-pipe structure, which is extracted from the actual offshore drilling tube system, starts to be investigated. Bueno and Morooka [7] designed a series of springs along the riser

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to simulate the drillstring-riser contact force. Harrison and Helle [8] proposed an equivalent model for a tube system with pipe-in-pipe structure by combining the stiffnesses of the inner and outer pipes. This approach is fine when the pipes move together uniformly under external and internal loads. Liu et al. [9] studied the wear of a deepwater drilling riser with pipe-in-pipe structure. They found that the contact was interval distribution, and the maximal contact force occurred at the lower flexible joint. The aforementioned researchers discussed the influences of the pipe-in-pipe structure from different aspects; however, the tubes under the mud line have not been considered in their works. Actually, the interactions between the drillstring and the well also affect the dynamics of the whole tube system via the movement of drillstring. Therefore, a complete dynamic model of the drilling tube system including the tubes under the mud line should be proposed.

The precise dynamic analysis of the offshore drilling tube system is the precondition of its optimization design; since the obtained dynamic responses should satisfy a series of engineering constraints. As a start, the optimization parameters need to be confirmed. Chang et al. [10] analyzed the environmental and operational factors for designing ultra-deepwater drilling tube system. The environmental factors include sea depth, wave, current, and the operational factors consists of drilling fluid density, hang-off mode after disconnection, buoyancy modules distribution, and vortex-induced vibration suppression devices. Subsequently, a number of researchers carried out the single-objective optimization designs for the offshore drilling tube system. When Housner and Dixon [11] conducted the optimization design, their optimization objective focused on reducing the steel volumes to save the potential cost. Similarly, Qin et al. [12] presented a parametric sensitivity analysis and an optimization of a deepwater riser, whose optimal objective was also the minimum of the riser total weight to reduce the project cost. Aiming at the minimum variance of the rotation angle of the lower flexible joint, Wang et al. [13] optimized the top tension of the riser system. Based on single-objective optimization designs, the idea of the multi-objective optimization attracts researchers' attentions. Zheng et al. [14] conducted multi-objective optimization whose purposes were to make the total weight of the riser minimizing and simultaneously make the maximum equivalent stress under allowable level. Yang et al. [15] applied an island-based genetic algorithm whose purposes were to minimize the riser cost while keeping all constraints satisfied. Different from the aforementioned investigations, in this paper, reliability analysis is intended to be integrated into the multi-objective optimization. Since the ocean environmental loads in the deep sea are variable and hard to be predicted; the safety of the designed offshore drilling tube system should be secured especially when the perturbations of the optimization parameters appear. For this purpose, Isight [16], which is a generic software framework for integration, automation, and optimization of design processes, will be adopted. The recent applications of Isight can be found in different disciplines [17–19].

This paper is organized as follows. Section 2 introduces the mathematical modeling of an offshore drilling tube system with pipe-in-pipe structure. In Section 3, a FE model based on the developed mathematic model is built in Abaqus, and the influences of pipes' interactions are analyzed. In Section 4, the parametric sensitivity analyses are carried out to confirm the parameters for the following optimization design. In Section 5, the main effects analyses and the multi-objective optimization are carried out successively. At last, concluding remarks are provided in Section 6.

2. Mathematical modeling of an offshore drilling tube system

The dynamic model of an offshore drilling tube system considers the deformation of the pipe-in-pipe structure under the effects of the ocean environmental loads (see Fig. 1 (a)), and also considers the contacts and frictions between the inner and outer pipes (see Fig. 1 (b)). Two independent coordinate systems are applied in describing the movements of the outer pipe (x–y–z) and the inner pipe (x'–y'–z'), respectively; and their correlations connect the two pipes together to form a complete dynamic model for the investigated offshore drilling tube system. All the system parameters for this dynamic model are listed in Table A1 in Appendix A.

Primarily, in order to describe the ocean environmental loads around the pipe-in-pipe structure, Ekman drift theory [20] is adopted to calculate the flow speed of sea current

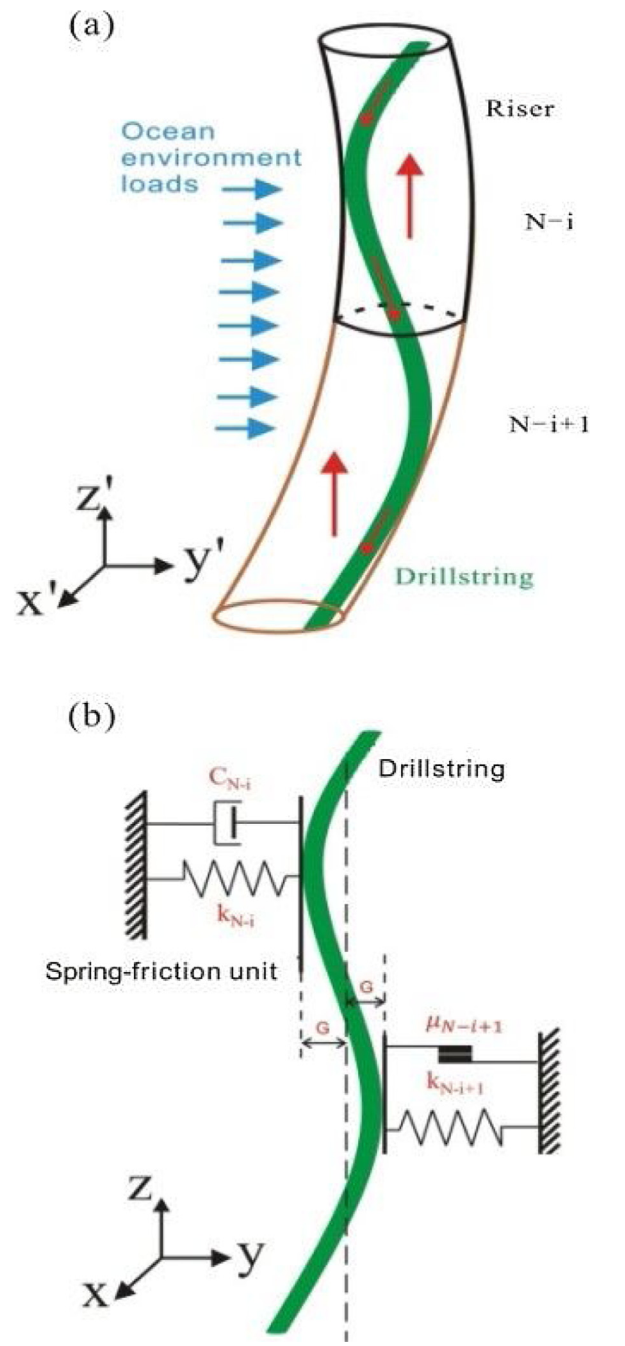

Fig. 1. Physical model of an offshore drilling tube system, (a) deformation of the pipe-in-pipe structure and (b) interactions between the inner and outer pipes.