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Four-level screening method for multi-variable truncation design of deepwater mooring system

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ABSTRACT

The truncation design of a mooring system is the foundation of hybrid model testing techniques used in experimental research on deepwater floating platforms owing to the limited size of wave basin. Screening multi-variables for multi-objectives leads to difficulties in truncation design aimed at achieving acceptable equivalence, especially for an asymmetric mooring system. This paper proposes an efficient four-level screening method for the truncation design. The selected multi-variables of each mooring line are screened individually to generate feasible regions according to pretensions and initial hang-off angles. Subsequently, the feasible regions are concentrated by the second- and third-level screening: design truncated mooring lines and truncated mooring systems according to static equivalence. Finally, numerical forced oscillation is employed as the fourth-level screening to fulfil dynamic equivalence. Case studies of the truncation design of symmetric and asymmetric mooring systems have verified the proposed method.

1. Introduction

Oil and gas exploitations have spread to the deep seas. Many floating production systems such as semi-submersibles, spars and floating production, storage and offloading (FPSO) units operate in deepwater harsh environments. Therefore, it is essential to carry out model testing before a floating system becomes operational. However, the large depth of seas and the large-scale spread of the moorings make it difficult to perform model testing owing to the limited size of wave basins.

One practical method to solve this problem is to use an ultra-small scaling ratio. Moxnes and Larsen [1] and Stansberg et al. [2] have verified the feasibility of ultra-small-scale model testing. Although ultra-small-scale testing can estimate certain global responses, particular attention should be paid in model testing and the results cannot be generalized to other situations. In addition, ultra-small-scale testing produces viscous scale effects because Froude similarity rather than Reynolds similarity is applied to model testing.

Therefore, to undertake deep-water model testing at a normal scaling ratio, researchers proposed the hybrid model testing method, which is a combination of experiments and numerical simulation. In the experiments, a full-depth model is substituted with a truncated model to perform model testing. Two types of truncated models are available: an active equivalent mooring system and a passive equivalent mooring system [3]. An active equivalent mooring system can virtually model a full-depth system by using a mechanical system to simulate the part of the mooring system below the truncated

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depth. However, its accuracy highly depends on the numerical simulation before design and on the accuracy of the mechanical system. An alternative solution is the passive equivalent mooring system, in which the static characteristics of a full-depth system are modelled by adjusting the length, submerged mass and axial stiffness. The dynamic characteristics of a full-depth system are modelled by adjusting the diameter and dry mass and numerical simulation should be performed to verify the dynamic equivalence. A passive mooring system has much simpler mechanism than an active mooring system, but a truncated model design requires extra work. Numerical coupled analysis [4] on truncated and full-depth models is called numerical reconstruction and extrapolation, respectively. Guidelines for carrying out coupled analysis are summarized by Hansen et al. [5].

The validity of a passive equivalent mooring system has already been confirmed. Stansberg et al. [6] carried out model testing of both truncated and full-depth models of a semisubmersible platform. The numerical extrapolation results agree well with the results of full-depth model testing. In addition, Waals and Radboud [7], Zhang et al. [8], Baarholm et al. [9], Kendon et al. [10], Zhang et al. [11], Wang et al. [12] and Ji and Xu [13] have carried out hybrid model testing and confirmed the feasibility of the method.

In summary, hybrid model testing using a passive equivalent mooring system involves three phases:

(1) Design of a truncated model
(2) Model testing using the truncated model
(3) Numerical reconstruction and extrapolation

The design of a truncated model is the foundation of hybrid model testing. However, it is complex and time-consuming because multiple parameters such as the length, diameter, mass, axial stiffness, pretension, and initial hang-off angle play important roles in the static and dynamic characteristics of a mooring system. Researchers have spent years developing method to design truncated models automatically and efficiently.

To achieve static equivalence, Waals and Radboud [7] proposed an optimum strategy to generate a truncated model from a full-depth model by adjusting properties according to factors that indicate deviations in the stiffness curve. Truncated models are designed for catenary and taut systems, and equivalence is observed after numerical simulation. Zhang et al. [14] applied a baton pattern simulated annealing algorithm to the truncation design of a turret mooring FPSO. The numerical results confirm the feasibility of this algorithm. Su et al. [15] used a non-dominated sorting genetic algorithm to design the truncated model of a cell truss spar. Experimental and numerical results showed that the truncated model can properly model the characteristics of the full-depth model. Felix-Gonzalez and Richard [16] have proposed a weighted sum method using Genetic Algorithm to realize the truncation design of a semisubmersible with a symmetric polyester mooring system. Good equivalence is achieved between the full-depth and truncated model.

To achieve dynamic equivalence, Luo et al. [17] and Qiao et al. [18] compared the dynamic characteristics of full-depth and truncated mooring lines and found that the truncation of a mooring line can lead to the underestimation of hydrodynamic forces. Argyros et al. [19] employed a mechanism consisting of springs and dampers to replicate the static and dynamic characteristics of a full-depth mooring line. Agreement is observed between the full-depth and truncated lines. This method highly depends on analytical formulation to calculate the parameters of the mechanism. Fan et al. [20] calculated the damping of a truncated mooring under regular excitation and considered damping coefficients in optimization design. The deviation between the full-depth and truncated models is acceptable.

Although the automatic design of a truncated model is feasible in terms of static and dynamic equivalence, further research is necessary to overcome the following problems:

(1) Efficiency of the algorithm: In the existing methods, each time a feasible solution is generated, systematic tension characteristics should be determined to test the equivalence. For a mooring system with a number of mooring lines, this requirement generates a large workload and the failed solutions have little effect on the final results.
(2) Equivalence of the tension characteristics of each line: Current algorithms mainly focus on systematic characteristics and only a 'representative' mooring line is considered. However, each mooring line's tension characteristics are important parameters in estimating the reliability of a mooring system, especially those of an asymmetric system whose mooring lines are all 'representative'.
(3) Equivalence of the vertical force and initial hang-off-angle of mooring lines: In truncation design, to fulfil equivalence, the strategy of reducing the initial hang-off-angle is always applied [15], which results in a deviation in the vertical force of the mooring system. Parameters that are sensitive to the vertical force, such as the heave motion, may not be equivalently modelled. Therefore, the tolerance of the initial hang-off-angle should be controlled in the algorithm.
(4) Design of an asymmetric system: An asymmetric system might encounter different water depths and might have mooring lines with different properties. The layout of the mooring system might also be asymmetric. The truncation design of an asymmetric system is more complex than that of a symmetric system, and current methods are insufficient for the design of an asymmetric system.

Truncation design is actually a multi-objective optimization problem. For the truncation design of an asymmetric mooring system, it is inevitable to increase the number of objectives. For example, for a mooring system with 12 mooring lines, if we