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Optimized design of statically equivalent mooring systems

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ABSTRACT

Due to size limitations of wave basins worldwide it is necessary to employ statically equivalent mooring and riser systems to test floating oil and gas drilling, production and storage facilities to be deployed in deep and ultra-deep waters. Heuristic search techniques appear to be best suited for the design optimization because of the nonlinear behavior of the catenary mooring lines and risers, the large number of independent variables and constraints involved in the design, and the multi-dimensional objective function. A procedure for the optimized design of the statically equivalent mooring system using a Genetic Algorithm is investigated using, as an example case, a semisubmersible with a symmetric polyester mooring system.

1. Introduction

The increasing worldwide oil demand has created the need to develop oil fields in deeper water; these new fields are a technological challenge for all infrastructure required to be installed. One of those technological challenges is to design the floating systems required to accommodate the equipment for processing the oil produced and for controlling all the subsea equipment.

A station keeping system is required for any floating offshore structure to maintain its position over a specified location with certain allowable offset limits, so that the floating structure can perform its intended functions in a safe way. The station keeping system is selected based on the floating structure's service requirements and characteristics, including the water depth where the system is to be deployed.

Apart from vertical mooring systems which are inherently taut, passive mooring systems can be categorized as either catenary, taut or semi-taut, the main difference being the degree to which weight or axial stiffness play an important role in the mooring system restoring force. In the catenary mooring system the restoring force is mainly due to the submerged weight (w) of the mooring line components. In the taut mooring system the restoring force is mainly contributed by the axial stiffness (EA) of the mooring line, while in the semi-taut mooring system both mooring line component properties, submerged weight and axial stiffness, play an important role in developing the restoring force.

A floating, deep water drilling or production system requires a mooring system to keep it in position. The mooring system comprises sets of single mooring lines. Commonly each line is composed of three segments: chain at the bottom segment, steel wire or polyester rope for the middle segment and chain at the upper segment. In the case of a production system, a number of catenary risers may be used to transport produced fluids from the subsea wells to the floating facility, and to export oil and gas from the facility to shore via pipelines.

Numerical simulations and model testing are used in designing a floating system to assess its behavior in operational conditions and in extreme weather conditions, always looking to preserve the safety and functionality of all the components involved. The adequacy of a conceptual floating system design is verified through model testing of a prototype to evaluate its behavior (Fryer et al., 2001). There are critical parameters that are verified from model testing, including floating system motions, maximum tensions in mooring lines and in risers, under-deck air gap, wave run up, wave impact loads, and collision between mooring lines, risers and/or hull (Stansberg et al., 2002).

For water depths less than about 500 m it is feasible with existing deep water wave basins to test a model with a directly scaled, full depth mooring and riser system at reasonable model scales (commonly scale ratios between 1:50 and 1:70). However testing the response of a floating system in deep and ultra-deep water is a challenge, because the basin dimensions required to accommodate the scaled full depth mooring/riser system are beyond the capabilities of available facilities worldwide, both now and for the foreseeable future. Fig. 1 illustrates the truncation requirement for model testing in a basin; it shows a typical full

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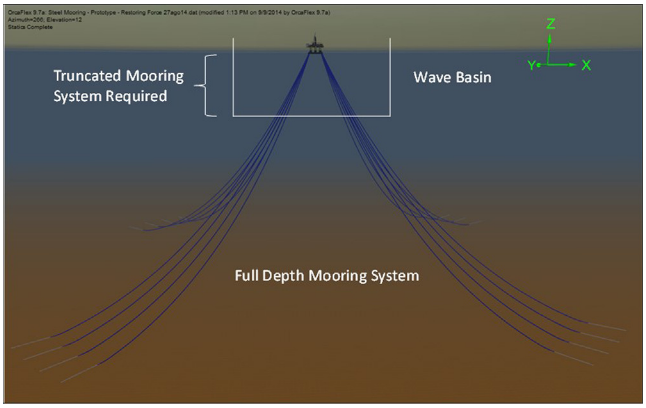

Fig. 1. Scaled mooring system truncation required for model testing in a wave basin.

depth mooring system with the outline of a wave basin at a typical test scale ratio. Since further reducing the size of the floater relative to the basin dimensions would lead to measurement issues it is necessary to truncate the scaled full depth mooring system so that it fits within the basin dimensions.

Due to basin dimension limitations it is necessary to establish a truncated mooring and riser system that is somehow equivalent to the prototype mooring system. The truncated mooring/riser system combined with the scale selected for the model testing introduces uncertainties in the test results. In order to reduce the uncertainties related to the extrapolation of the test results from a truncated mooring/riser system to a full depth system it is required to design the truncated mooring/riser system so that it results in the same motion responses of the floater as would result if the floater was attached to the full depth mooring/riser system.

The truncation of the mooring/riser system implies that the departure and declination angles for the mooring lines and risers change faster with horizontal offset than in the full depth system. To compensate for these geometric differences between the full depth and the truncated system, the anchor locations and the length, submerged weight and axial stiffness of the model mooring line and riser components must be adjusted so that the full depth mooring/riser system static response is reproduced as closely as possible. However, those changes in line orientation, submerged weight (mass or diameter) and axial stiffness will change the dynamic behavior of the mooring lines and risers. The level of complexity required in matching the static and dynamic responses of the prototype with an equivalent truncated mooring and riser system is currently beyond reach.

Stansberg et al. (2000, 2002) and ITTC (2005) proposed that the equivalent truncated mooring reproduce, as close as possible, the total horizontal restoring force, the quasi-static coupling between vessel responses (i.e. coupling between surge, heave and pitch for semisubmersibles and spars), a representative level of mooring and riser system damping and current force, and the individual line tension force. The smaller the scaled depth of the wave basin relative to the full depth of the prototype, the more difficult it is to reproduce tensions in individual mooring lines, as well as associated damping contributions, consequently these requirements are often relaxed so that higher priority test objectives, such as accurate simulation of under-deck air gap, can be met.

The offshore industry, through proprietary model tests of a wide array of floating systems, has investigated various strategies for design of truncated mooring systems. Two different design philosophies involve the use of a passive or an active truncated mooring system. In the passive truncated mooring system the equivalency to the full depth system is reached by passive mooring line components (i.e. clump weights, cables, springs, buoys, etc.). In the active truncated mooring system the equivalency to the full depth system is reached by using actuators and controllers to reproduce the full depth response at the truncation point (Cao, 2013). With either approach the goal is to design the equivalent system so that the net forces and moments imparted by the truncated mooring system to the floater in its six rigid body degrees of freedom are as closely reproduced as practically possible.

Because of the focus on reproducing the net forces and moments imparted by the model mooring to the floater, regardless of how that is achieved, we prefer to use the term equivalent mooring/riser system rather than truncated mooring/riser system. Indeed the equivalent mooring system is not constrained to mimic in any way the behavior of single prototype mooring lines. What is important here is not reproducing the top tension and angle of each individual prototype line but rather the total forces and moments imparted to the floater by the equivalent mooring/riser *system*.

It is currently the common practice to focus the design effort entirely on reproducing the net *static* restoring forces and moments that the mooring and risers impart on the floater over some pre-defined range of offsets. Because of the highly nonlinear behavior of mooring and riser systems over large offset ranges, achieving the design objective typically involves significant effort and challenges the skill of the designer.

There are different approaches for the design of passive equivalent mooring systems that have been proposed (Waals and Van Dijk, 2004; Elgamiel, et al., 2006; Udoh, 2008; Zhang, et al., 2009, 2012). In the literature it is commonly mentioned that the design of the equivalent truncated mooring system is focused on the static response characteristic for restoring force in surge and heave and on the static tension in individual mooring lines (Udoh, 2008; Zhang, et al., 2009, 2012). Here the design strategy used by the Offshore Technology Research Center will be adopted, which focuses exclusively on reproducing the net six-degree-of-freedom restoring forces and moments exerted on the floater with a statically equivalent system whose individual lines are not constrained to bear any resemblance to individual lines of the prototype system but rather are as simple as possible so that they can be robustly represented in a numerical model.

Recently a few studies involving use of heuristic methods for optimized design of equivalent mooring systems have been reported (Zhang et al., 2009, 2012; Fan et al., 2014). Zhang et al. (2009) investigated a simulated annealing algorithm and a complex algorithm for the design optimization, using an objective function with weighting factors for the similarity of the overall system restoring force and for forces in individual mooring lines. They did not specify the degrees of freedom considered in the floating system response, but it can be assumed that they considered just one degree of freedom (surge response).

Zhang et al. (2012) used a non-dominated sorting genetic algorithm to optimize the design of an equivalent truncated mooring system for a FPSO (Floating Production, Storage and Offloading system). They used a multi-objective fitness function focused on the static characteristics related with the restoring forces in the horizontal and vertical direction and the tension in a single mooring line for a set of offsets. Their results showed that they had a similar static response between the truncated and the full scale mooring system, for the variables selected in their fitness function.

A procedure for designing equivalent mooring systems considering the static and damping characteristics of the full depth mooring system was developed by Fan et al. (2014). The characteristics considered in the design optimization process are: horizontal restoring force, vertical restoring force, mooring line top tension and mooring induced damping coefficient at low