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Influence of the setdown of a tension leg platform on the extreme airgap response

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ABSTRACT

One distinguishing characteristic of a tension leg platform (TLP) is the setdown of the hull when the platform moves in its compliant modes (surge, sway and yaw). The nonlinear setdown has profound implications in various aspects of TLP design, but this paper focuses on its impact on the available airgap. Although there is general consensus that setdown should be included in the airgap assessment, to date there is no systematic procedure of analysis, and related literature is scarce. This paper aims to develop a simple method for incorporating setdown in the extreme response prediction of the airgap. The proposed method requires only the covariances of the platform motions, and these are available from a frequency domain analysis. From a case study, the crossing rates calculated by the proposed method is found to be in good agreement with Monte Carlo simulation, with only a slight disparity at high threshold levels. This work has also afforded physical insight; for example, it is discovered that the wave-frequency (WF) motions are more critical to the extreme airgap compared to the low-frequency (LF) motions, because the surface elevation is correlated with the WF motions, but not with the LF motions.

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1. Introduction

The tension leg platform (TLP) is a type of offshore floating structure that is permanently attached to the seabed by pre-tensioned vertical tendons (or tethers). The tendons are kept continually taut by the excess buoyancy of the platform. In this way, the heave, roll and pitch motions are effectively constrained, making the TLP the most stable of all floating systems. To a lesser extent, the tendons also provide restoring forces in the lateral modes (surge, sway and yaw) through the inverted pendulum action. The lateral modes are compliant, with natural periods that are much longer than the periods of ocean waves (typically 5–25 s). As a consequence of the low natural frequencies, the TLP undergoes slow drift motions when exposed to irregular waves, due to the presence of second-order low-frequency wave forces.

Dynamic analysis is fundamental to the design of floating structures, including TLPs. In the early stages of a TLP design, the platform is often modeled as a rigid body, and the effects of the tendons are incorporated as massless springs. This approach is known as an uncoupled analysis. The prediction of the extreme motions of a floating structure subjected to random waves has been topical for many years. Central to this problem is the combination of the wave-frequency (WF) and low-frequency (LF) motions, and the distinctly non-Gaussian behavior of the LF response. Techniques for extreme response analysis include Monte Carlo simulations [1], detailed statistical analysis [2,3], and approximate formulae [4].

One distinguishing characteristic of a TLP is the vertical submergence of the hull when the platform translates laterally. This phenomenon, known as setdown, originates from the pendulum-like motion. The setdown effect has profound implications in various facets of TLP design. First of all, it produces nonlinear changes to the tendon tension, and this in turn is chiefly responsible for the nonlinearity of the platform restoring forces [5]. As the draft increase affects the wave loading, DNV-OS-C105 [6] recommends that the WF analysis should be based on at least two offset positions. Setdown also affects the riser performance, especially the stroke capacity of the tensioner system [7,8]. Last, and perhaps most importantly, setdown reduces the available airgap. Given that the statistical analysis of platform motions has been studied extensively, it is somewhat surprising that a probabilistic treatment of the setdown has not received much attention. Setdown is inherently nonlinear, being approximately of second order with respect to the platform excursion, and it is governed by a combination of surge, sway and yaw motions [9,10]. These complications suggest that the study of setdown response statistics should be a challenging endeavor. However, an isolated study of the extreme setdown response, although fascinating, is not necessarily of practical relevance, unless an associated effect is considered in conjunction. The airgap is a critical parameter for column-based platforms. Insufficient airgap may lead to wave impacts under the deck, whereas

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an excessive deck elevation is detrimental to various functional requirements. Accordingly, the influence of the setdown on the airgap response is selected as the subject of this work.

Inasmuch as there is general consensus that setdown should be included in TLP airgap design [6,7,10], to date a systematic procedure of analysis has not been established, and moreover literature on the subject is scarce. Banon et al. [11] analyzed the crossing rates of the airgap by considering the setdown induced by only the LF motion in a chosen direction; the WF motions are disregarded. Interestingly, in a subsequent work, Banon et al. [12] proposed that the minimum airgap should be determined from the maximum setdown and the extreme wave crest, both associated with a design storm. This approach is obviously conservative, as the TLP excursion and the wave elevation are not perfectly correlated, and hence the peaks of the setdown and wave elevation are unlikely to coincide.

The aim of this paper is to develop a consistent framework for incorporating setdown in the extreme airgap assessment. The method is targeted for repetitive use during the iterative design process, and thus it should be simple and efficient. The setdown is defined as a function of the surge, sway and yaw offsets to better reflect reality, instead of considering the offset in just one direction as is customary in prior investigations. Moreover, the phase relationships between the motions and the wave elevation should be properly modeled. Both the WF and LF motions will be included in the study in order to understand their impacts. Finally, the suitability of the method will be assessed by using Monte Carlo simulation as a reference.

In fact, the complexities of airgap prediction extend far beyond the boundaries of setdown. Although the WF vessel motions can be computed with reasonable accuracy using linear diffraction theory, the same cannot be said of the wave elevation, which is known to be appreciably nonlinear and non-Gaussian. Another complicating feature is the wave run-up on columns. Several studies [13,14] have attempted to incorporate second-order diffraction into the modeling of the local surface profile, with modest success. Because of the uncertainties relating to the airgap analysis of a TLP, DNV-OS-C105 [6] requires that the results must be verified by model tests. In this regard, there is a multitude of experimental studies concerning the airgap of TLPs [14–16].

Evidently, it is impossible to address the entire range of practical issues within the span of a single paper. For this reason, the present work focuses on the interaction between the setdown and the wave profile on a fundamental level. To this end, the surface elevation will be modeled as a linear Gaussian process as an initial step towards developing a better understanding of the interaction. Nonetheless, the imperativeness of nonlinearities is acknowledged, and a pragmatic but approximate procedure will be proposed for incorporating the results from existing nonlinear wave models into the present analysis.

2. Dynamic response of a TLP

Frequency domain analysis can be used to evaluate the mean-squared response statistics very rapidly. This section summarizes the basic steps in the frequency domain analysis of a TLP, following which the response variances will feature in the airgap analysis in the next section.

Consistent to the subject matter of setdown, it is sufficient to delimit the exposition to the in-plane motions. Let the displacement vector be

$$\mathbf{X}(t) = \begin{bmatrix} X_1(t) \\ X_2(t) \\ X_3(t) \end{bmatrix}, \tag{1}$$

representing surge, sway and yaw sequentially. The equation of motion is then stated as

$$\mathbf{M}\ddot{\mathbf{X}} + \mathbf{B}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = \mathbf{F}(t), \tag{2}$$

where $\mathbf{M}$, $\mathbf{B}$ and $\mathbf{K}$ are 3×3 matrices corresponding to mass, damping and stiffness, respectively, $\mathbf{F}(t)$ is the external forcing vector, and $\dot{\mathbf{X}}$ and $\ddot{\mathbf{X}}$ are the velocity and acceleration vectors. It is implied that the equation of motion is linear (or linearized). In reality, the damping is nonlinear owing to the drag force, and the restoring force is also nonlinear, as mentioned in Section 1. To facilitate a frequency domain analysis, the equation of motion must be linearized. Linearization of the drag force is well documented. The statistical linearization of the platform restoring force in six degrees of freedom (DOFs) has been recently investigated by Low [3].

The external force vector may be decomposed as

$$\mathbf{F}(t) = \bar{\mathbf{F}} + \mathbf{F}^{(1)}(t) + \mathbf{F}^{(2)}(t), \tag{3}$$

where $\bar{\mathbf{F}}$ denotes the mean force, $\mathbf{F}^{(1)}$ the first-order WF force, and $\mathbf{F}^{(2)}$ the second-order LF force. It should be mentioned that the second-order mean drift is included in $\bar{\mathbf{F}}$. The high-frequency forces affect primarily the "stiff" modes and are irrelevant to the present discussion. The WF and LF forces can be solved via diffraction analyses in the frequency domain, and they are conventionally defined as

$$\mathbf{F}^{(1)}(\omega) = \mathbf{T}^{(1)}(\omega)\eta(\omega) \tag{4}$$

$$\mathbf{F}^{(2)}(\omega_m, \omega_n) = \mathbf{T}^{(2)}(\omega_m, \omega_n)\eta(\omega_m)\eta(\omega_n), \tag{5}$$

where $\mathbf{T}^{(1)}$ and $\mathbf{T}^{(2)}$ are the vectors of the first- and second-order transfer functions with reference to the incident wave profile, η.

The Fourier transform of Eq. (2) is expressed as

$$\left(-\omega^2\mathbf{M} + \mathrm{i}\omega\mathbf{B} + \mathbf{K}\right)\mathbf{X}(\omega) = \mathbf{F}(\omega). \tag{6}$$

Hence, the WF response can be written in the form

$$\mathbf{X}^{(1)}(\omega) = \mathbf{R}^{(1)}(\omega)\eta(\omega), \tag{7}$$

where

$$\mathbf{R}^{(1)}(\omega) = \mathbf{H}(\omega)\mathbf{T}^{(1)}(\omega) \tag{8}$$

is the vector of response amplitude operators (RAOs), with

$$\mathbf{H}(\omega) = \left(-\omega^2\mathbf{M} + \mathrm{i}\omega\mathbf{B} + \mathbf{K}\right)^{-1}. \tag{9}$$

From the theory of random vibrations [17], the spectral density matrix of the WF response is given as

$$\mathbf{S}_X^{(1)}(\omega) = \mathbf{R}^{(1)}(\omega)S_{\eta\eta}(\omega)\mathbf{R}^{(1)}(\omega)^{*T}, \tag{10}$$

where $*$ signifies the complex conjugate. Likewise, the LF spectral response matrix is expressed as

$$\mathbf{S}_X^{(2)}(\omega) = \mathbf{H}(\omega)\mathbf{S}_F^{(2)}(\omega)\mathbf{H}(\omega)^{*T}, \tag{11}$$

where $\mathbf{S}_F^{(2)}$ is the spectral matrix of the LF forces, given as [18]

$$\mathbf{S}_F^{(2)}(\omega) = 8\int_0^\infty \mathbf{T}^{(2)}(\mu, \omega+\mu)\left[\mathbf{T}^{(2)}(\mu, \omega+\mu)\right]^{*T} \times S_{\eta\eta}(\mu)S_{\eta\eta}(\omega+\mu)\mathrm{d}\mu. \tag{12}$$

It can be noted that the off-diagonal terms of $\mathbf{S}_F^{(2)}$ are complex and are imperative for upholding the phase relationships between the forces in differing DOFs.

Subsequently, from the response spectral matrix, the covariances of the displacements and velocities can be evaluated as

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