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Design wave method for the extreme horizontal slow-drift motion of moored floating platforms

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ABSTRACT

The present study introduces a design wave method for estimating the extreme horizontal slow-drift motion of moored floating offshore platforms under extreme conditions. Here, the design wave refers to an irregular incident wave of short duration that induces the extreme response of the desired return period. The present method is composed of the following four steps: linearization of the dynamic system, probabilistic analysis of the second-order Volterra series, generation of the irregular design waves, and the fully-coupled nonlinear simulations. For generating the design waves, two different conditioning methods are presented and compared: the conditioning of the extreme response amplitude and the conditioning of the most likely extreme response profile. The procedure was applied to a deep-water semi-submersible, and the results appeared to be promising compared to the full-length nonlinear simulations.

1. Introduction

In the design of mooring systems for floating offshore structures under ultimate limit state (ULS) conditions, prediction of the vessel offset under severe sea states is essential. Especially, the slow-drift motion of the floater is crucial to the mooring lines due to its significant contribution to the overall offset. However, the slow-drift motion is governed by various sources of nonlinearity including the coupling effects between the floater and the mooring lines, and the nonlinear exciting, restoring and damping forces, which necessitates direct nonlinear time-domain simulations for accurate prediction. Many studies have been conducted over several decades which have proven that numerical simulations can successfully model the slow-drift motion of moored floaters [1–3].

Despite the success of numerical modeling, estimating the extreme value of slow-drift motion from simulation remains a challenge. This is because the statistical behavior of the slow-drift motion is generally unknown prior to the simulations. Even if the random sea is well-described with a Gaussian model, the second-order wave loads that excite the slow-drift motion is strictly non-Gaussian [4], and the nonlinearities of the dynamic system further complicate the response statistics. Hence, a massive amount of numerical simulation is required to obtain the converged probability distribution, especially for the tail region where extreme values lie. When the design return period is very long, as is generally the case for offshore structures, the computational burden becomes too heavy to be handled by direct nonlinear simulations.

Similar issues have been raised in ship design when estimating nonlinear responses like the vertical bending moment. To resolve this issue, the so called 'design wave method' was first used in ship design. The main concept of the design wave method is to perform the nonlinear simulations with waves of short time series that induce the design responses of a much longer return period. In the classical design wave method, the nonlinear ULS response is calculated by using the regular design wave whose amplitude is determined by dividing the linear ULS response by the peak value of the linear response amplitude operator (RAO). The period is then set to the peak period of the RAO. This often leads to unphysically steep waves, however, and the assumption of extreme events occurring repeatedly and regularly is also considered to be unrealistic. Several studies developed irregular design wave methods to address those problems. Tromans et al. [5] introduced the 'New Wave' model, which is the expected irregular wave profile of a conditioned extreme amplitude, and Friis-Hansen and Nielson [6] extended this model to include the instantaneous frequency. Later, Adegeest et al. [7] applied this model to derive the most likely profile of the extreme linear response and suggested using the corresponding irregular wave of a limited number of cycles in the nonlinear simulations. Another famous approach is the 'Critical Wave Episodes' model introduced by Torhaug et al. [8], where the

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critical wave episodes are identified based on the time histories of the linear simulations. More recently, Jensen [9] adopted the first-order reliability method (FORM) in generating the irregular design wave to deal with highly nonlinear problems, and Alford [10] and Kim [11] developed the 'Design Loads Generator', which calculates the non-uniform phase distribution rather than one specific phase set to account for the randomness of the extreme events.

In this study, a new design wave method for estimating the extreme nonlinear slow-drift motion of moored offshore platforms is introduced. Like the previous methods described above, the new method assumes that the slow-drift motion from the linearized dynamic system, which can be represented as a second-order Volterra series, behaves analogously to that of a nonlinear dynamic system. More specifically, it is assumed that the irregular wave inducing an extreme response from the linearized dynamic system is likely to induce the extreme response of the same exceedance level from the nonlinear dynamic system. The method is composed of the following four steps: linearization of the dynamic system, probabilistic analysis of the second-order Volterra series, generation of the irregular design waves, and the fully-coupled nonlinear simulations. Two different conditioning methods were compared in generating the irregular design waves. Details are described in the following sections.

2. Background theory

When simulating the motion response of moored offshore platforms under severe sea states, the slow-drift motion is often decoupled from the wave-frequency motion. This is done to enhance computational efficiency because the low-frequency component dominates over the wave-frequency component and the dynamic interference between them is small. Hence, the wave-frequency motion is not considered in the present model. In the fully coupled platform-mooring lines dynamic simulation, the governing equation for the slow-drift motion of the platform is given as follows.

$$(\mathbf{M}+\mathbf{M}_{\mathrm{A}})\ddot{\mathbf{x}}+\mathbf{B}_{\mathrm{WD}}(t)\dot{\mathbf{x}}+\mathbf{C}_{\mathrm{H}}\mathbf{x}+\mathbf{f}_{\mathrm{V}}(\dot{\mathbf{x}},\ t)+\mathbf{f}_{\mathrm{M}}(\mathbf{x},\ \dot{\mathbf{x}},\ \ddot{\mathbf{x}},\ t)=\mathbf{f}_{\mathrm{W}}^{(2)}(t) \tag{1}$$

In Eq. (1), $\mathbf{x}$ is the nonlinear slow-drift motion vector, and $\mathbf{M}$, $\mathbf{M}_{\mathrm{A}}$ and $\mathbf{C}_{\mathrm{H}}$ are the inertia matrix, zero-frequency added mass matrix, and the hydrostatic restoring coefficient matrix, respectively. The time-varying wave-drift damping coefficient matrix converted from the wave-drift damping quadratic transfer function (QTF) is represented by $\mathbf{B}_{\mathrm{WD}}(t)$. The viscous drag force acting on the slender members of the platform is $\mathbf{f}_{\mathrm{V}}$, and $\mathbf{f}_{\mathrm{W}}^{(2)}$ is the second-order difference-frequency wave load converted from the corresponding QTF. Finally, $\mathbf{f}_{\mathrm{M}}$ represents the mooring line force acting on the platform, resulting from a fully nonlinear simulation of the mooring line dynamics.

As mentioned in the introduction, the first step of the present design wave method is to linearize the dynamic system, i.e. equation of motion, which enables us to represent the slow-drift motion with a second-order Volterra series. This is beneficial because the second-order Volterra series can equivalently be represented with a frequency-domain QTF, and the probability distribution can be obtained analytically. The linearized equation of motion is given by

$$(\mathbf{M}+\mathbf{M}_{\mathrm{A}})\ddot{\mathbf{x}}_{\mathrm{L}}+\mathbf{B}\dot{\mathbf{x}}_{\mathrm{L}}+(\mathbf{C}_{\mathrm{H}}+\mathbf{C}_{\mathrm{M}})\mathbf{x}_{\mathrm{L}}=\mathbf{f}_{\mathrm{W}}^{(2)}(t) \tag{2}$$

where $\mathbf{x}_{\mathrm{L}}$ is the slow-drift motion vector from the linearized dynamic system, and is termed hereafter the linearized slow-drift motion. The linearized total damping coefficient matrix and the mooring line restoring coefficient matrix are represented by, $\mathbf{B}$ and $\mathbf{C}_{\mathrm{M}}$, respectively. The damping matrix $\mathbf{B}$ should account for all the sources of damping in Eq. (1), including the wave-drift damping and the viscous drag forces on the platform and mooring lines. Nevertheless, precise tuning of the damping coefficients is not necessary in the present design wave analysis, which will be explained later. From Eq. (2), the slow-drift motion QTF $\mathbf{H}(\omega_1,\omega_2)$ is given by

$$\mathbf{H}(\omega_1,\ \omega_2)=\left[-(\omega_1-\omega_2)^2(\mathbf{M}+\mathbf{M}_{\mathrm{A}})+i(\omega_1-\omega_2)\mathbf{B}+(\mathbf{C}_{\mathrm{H}}+\mathbf{C}_{\mathrm{M}})\right]^{-1}\mathbf{H}_{\mathrm{F}}(\omega_1,\ \omega_2) \tag{3}$$

where $\mathbf{H}_{\mathrm{F}}$ is the QTF for the difference-frequency wave loads.

To simplify the problem, it is assumed that the sea state is long-crested and the wave incident direction is parallel to the surge motion of the floater. Then, the incident wave elevation at the motion reference point can be represented as

$$\eta(t)=\sum_{j=1}^{N}A_j\cos\left(\omega_j t+\varepsilon_j\right) \tag{4}$$

$$A_j=\sqrt{2S(\omega_j)\Delta\omega} \tag{5}$$

where A_j, ω_j, and ε_j are the amplitude, frequency, and phase of individual discretized wave components respectively, and N is the number of discretized wave components. The incident wave spectrum is $S(\omega)$, and $\Delta\omega$ is the increment between the discrete frequencies. The consequent linearized slow-drift surge motion from Eq. (2) and its response spectrum can be represented as

$$x_{\mathrm{L}}(t)=\sum_{j=1}^{N}\sum_{k=1}^{N}A_jA_k|H_1(\omega_j,\ \omega_k)|\cos\left[(\omega_j-\omega_k)t+(\varepsilon_j-\varepsilon_k)+\Theta_1(\omega_j,\ \omega_k)\right] \tag{6}$$

$$S_{xL}(\omega)=8\int_0^{\infty}|H_1(\omega-\mu,\ \mu)|^2S(|\omega-\mu|)S(|\mu|)d\mu \tag{7}$$

where H_1 and Θ_1 are the surge motion complex QTF and its phase, respectively.

For the linearized slow-drift motion $x_{\mathrm{L}}(t)$, which is assumed ergodic, the probability distributions of both the response and its extreme values can be readily estimated by solving an eigenvalue problem given by [4,12]

$$\int_{-\infty}^{\infty}K(\omega_1,\ \omega_2)\psi_j(\omega_2)d\omega_2=\lambda_j\psi_j(\omega_1) \tag{8}$$

$$K(\omega_1,\ -\omega_2)=\begin{cases}\sqrt{S(|\omega_1|)S(|\omega_2|)}H_1(\omega_1,\ \omega_2)\,, & \omega_1\omega_2\ge 0\\ 0\,, \ \omega_1\omega_2<0\end{cases} \tag{9}$$

where λ_j and ψ_j are the eigenvalue and eigenfunction, respectively, of the Hermitian kernel $K(\omega_1,\ \omega_2)$. Then, the first four statistical moments of $x_{\mathrm{L}}(t)$ are given by

$$m_{xL}=\sum_{j=1}^{N}\lambda_j,\quad \sigma_{xL}=\sum_{j=1}^{N}2\lambda_j{}^2 \tag{10}$$

$$\alpha_{3,\,xL}=E\left[\frac{(x-m_{xL})^3}{\sigma_{xL}{}^3}\right]=\frac{1}{\sigma_{xL}{}^3}\sum_{j=1}^{N}8\lambda_j{}^3 \tag{11}$$

$$\alpha_{4,\,xL}=E\left[\frac{(x-m_{xL})^4}{\sigma_{xL}{}^4}\right]=3+\frac{1}{\sigma_{xL}{}^4}\sum_{j=1}^{N}48\lambda_j{}^4 \tag{12}$$

where m_{xL}, σ_{xL}, $\alpha_{3,xL}$, and $\alpha_{4,xL}$ are the mean, standard deviation, skewness, and the kurtosis of $x_{\mathrm{L}}(t)$, respectively. Using these four statistical moments, a mapping function g, that transforms a standard normal process $u(t)$ to $x_{\mathrm{L}}(t)$ can be defined as follows [13].