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Long-term extreme response analysis of offshore structures by combining importance sampling with subset simulation

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ABSTRACT

Accurate prediction of the long-term extreme response for dynamic offshore structures is challenging in view of small failure probabilities arising from long-term and short-term uncertainties. The sea state fluctuates extensively over the long term, whereas in the short term, the wave elevation is a stochastic process. The rigorous "all sea states" approach considers all conceivable sea states, where each sea state involves a stochastic dynamic analysis. This approach would be computationally prohibitive if the dynamic analyses are performed in the time domain, which may be essential because of nonlinearities. The environmental contour lines approach has emerged as a fast practical method for estimating the extreme response; nevertheless, it is approximate and needs to be validated. This paper presents an efficient simulation approach for evaluating the long-term extreme response through time domain analysis. The method produces an unbiased result, as well as an error estimate. The premise is to apply subset simulation to tackle the short-term variability, while importance sampling is used to reduce sampling variability arising from long-term uncertainty (whose characteristics are more amenable to an approximate treatment for constructing an importance sampling density). Case studies are performed on a floating structure subjected to first-order and second-order (non-Gaussian) wave loads. The computational efficiency of the proposed method is found to be vastly superior to Monte Carlo simulation, with the efficiency factor exceeding five orders of magnitude for certain cases. Moreover, the proposed method is faster compared to classical subset simulation, with the improvement depending on the relative dominance of the long-term and short-term uncertainties.

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1. Introduction

Of central importance to the design of dynamic offshore structures is the prediction of the extreme response due to environmental loading. To ensure a sufficient level of safety, it is desired that the extreme response associated with an annual exceedance probability q does not exceed some failure threshold. This is equivalent to designing for an extreme response with a return period of $n = 1/q$ years.

For a floating production system, pertinent response quantities include the floater motions and stresses/tensions along the mooring lines and risers. The environmental conditions, comprising wind, wave and current, fluctuate extensively over the long term. However, in the short term, the sea state can be deemed to be statistically stationary. The wave statistics can then be characterized by the significant wave height H_S and spectral peak period T_p. The variability of H_S and T_p over the long term is specified by a wave scatter diagram, or a joint probability density function (jpdf) fitted from data.

The most rigorous method for extreme response analysis is the long term (or *all sea states*) approach, which amounts to analyzing a sequence of all conceivable sea states. Each sea state constitutes a short-term stationary condition that necessitates a full dynamic analysis. Generally, a dynamic analysis can be performed in the time domain or frequency domain. Frequency domain analysis is fast, although it depends on considerable simplifications regarding the nonlinearities and response statistics. The dynamic behavior of floating systems is nonlinear and non-Gaussian, hence a time domain analysis is still necessary for an accurate response prediction. Unfortunately, time domain simulations are costly, not least because the short-term variability originating from irregular waves would necessitate multiple realizations to attain statistical convergence. Monte Carlo simulations with time domain analyses for predicting the long-term extreme response would be computationally intractable for real complex systems, unless approximations are made.

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An alternative approach for extreme response prediction is the short-term (also known as *design sea state*) approach [1,2] in which a sea state with an n-year H_S and associated T_p is identified; subsequently the associated response is taken as the n-year extreme response. This approach is fast and simple, but it has several shortcomings. For one, it discounts smaller storms that can also contribute significantly to the extremes due to their higher frequency of occurrences. In addition, dynamic effects are governed not only by the intensity of the loads, but also their periods. Accordingly, the critical n-year sea state may be one with a smaller H_S but of a more onerous T_p.

In a landmark paper, Winterstien et al. [3] proposed the environmental contour lines approach, providing a rationale means for identifying the most damaging n-year sea state using inverse-FORM (first order reliability method). The extreme response can be reasonably estimated on the basis of several short-term conditions, and for this reason, the environmental contours approach has gained wide acceptance [2]. Nevertheless, the method has certain limitations; for instance, recent studies [4] have revealed that environmental contours may not work well for certain unconventional offshore structures. In any event, the environmental contours approach is approximate, thus it should be calibrated and validated with a full long-term analysis [1], especially for novel situations.

Over the years, researchers have proposed diverse strategies for long-term extreme analysis, both in conjunction with frequency domain analysis [5,6], and time domain simulation [7–9]. For time domain simulation, in general the existing methods seek to alleviate the massive computational time through approximations, which may work well in particular situations, but cannot be guaranteed to be always favorable. This objective of this paper is to develop an efficient and accurate simulation method for evaluating the long-term response through time domain simulations. In contrast with prior studies, no arbitrary approximations will be made, in order that the predicted extreme can be as accurate as possible.

The proposed approach will be useful in at least two ways. First, it can serve as a robust benchmark for approximate methods such as the environmental contours approach. In addition, it can be applied directly in practical design for verifying the reliability of an offshore structure. It is vital that the method can furnish information regarding the degree of accuracy. The present problem is challenging, as the uncertainties arise from both long-term and short-term conditions, and the ensuing reliability problem is high-dimensional owing to the representation of a stochastic process. The high-dimensionality makes it difficult to implement classical variance reduction techniques such as importance sampling to enhance the efficiency of Monte Carlo simulation.

In the specialist literature of structural reliability, Subset Simulation [10] is a popular technique for efficiently computing small probabilities in high dimensions. However, to the authors' knowledge, this technique seems to be relatively unknown in offshore engineering; therefore it would be interesting to investigate the performance of Subset Simulation for the problem at hand. Subset simulation is superior to Monte Carlo in terms of efficiency, but still requires a large number of dynamic analyses. The present work aims to improve the efficiency of Subset simulation by combining it with an importance sampling technique that exploits the specific features of the problem.

2. Theoretical background

2.1. Wave conditions

The environment loading on an offshore structure originates from wind, wave and current. In this study, only wave loads are considered. The modeling of the wave characteristics generally falls under long-term and short-term considerations. In the short term, typically taken as 3 h, the sea state is assumed to be stationary. The wave elevation $\eta(t)$ is represented as a Gaussian stochastic process, following which the short-term statistics can be completely defined by a wave spectrum $S_{\eta\eta}(\omega)$. The wave spectrum adopted herein is the JONSWAP spectrum, which has the functional form

$$S_{\eta\eta}(\omega) = \hat{\alpha} g^2 \omega^{-5} \exp\left[-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right]\gamma^{\exp[-(\omega-\omega_p)^2/2\hat{\sigma}^2\omega_p^2]} \tag{1}$$

$$\hat{\alpha} = 5.061\left(\frac{H_S^2}{T_p^4}\right)(1-0.287\ln\gamma),\quad \omega_p = \frac{2\pi}{T_p},\quad \hat{\sigma} = \begin{cases} 0.07, & \text{if } \omega \leqslant \omega_p \\ 0.09, & \text{if } \omega > \omega_p \end{cases}, \tag{2}$$

where H_S is the significant wave height, T_p the spectral peak period, and γ is a shape parameter taken as 3.3.

The spectral representation method is commonly used to generate sample time series for a Gaussian process. The wave spectrum is discretized into R components of equal frequency interval $\Delta\omega$. Subsequently, the time history of the wave elevation is the summation [2]

$$\eta(t) = \sum_{r=1}^{R} a_r \cos(\omega_r t + \phi_r) \tag{3}$$

where ϕ_r are independent random phase angles distributed uniformly between 0 to 2π, whereas a_r are independent random wave amplitudes that follow the Rayleigh distribution with a mean-square of $2S_{\eta\eta}(\omega_r)\Delta\omega$. It is convenient to define a vector

$$\boldsymbol{\theta} = [a_1, a_2, \ldots a_R, \phi_1, \phi_2, \ldots, \phi_{R,}]^T \tag{4}$$

comprising all the random variables pertaining to the short-term variability. The above random amplitude scheme is the preferred approach as it guarantees that $\eta(t)$ is exactly Gaussian. An alternative is to specify A_r deterministically as $A_r = \sqrt{2S_{\eta\eta}(\omega_r)\Delta\omega}$, in which case $\eta(t)$ is only asymptotically Gaussian when R is large, leading to misrepresentation of the tail statistics when discretization is inadequate.

The long-term statistics of H_S and T_p can be characterized by a bivariate histogram known as the wave scatter diagram. As pointed out by Naess and Moan [1], one should be judicious when applying wave scatter diagrams to estimate extremes, due to possible discretization errors and poor representation of the tail statistics. Instead, it is often better to fit the data to a continuous joint probability density function (jpdf). The jpdf model proposed by Haver and Nyhus [11] has the form

$$f(H_S, T_p) = f(H_S) f(T_p|H_S) \tag{5}$$

$$f(H_S) = \begin{cases} \frac{1}{\sqrt{2\pi}\xi H_S} \exp\left[-\frac{(\ln H_S - \mu_h)^2}{2\xi^2}\right], & \text{if } H_S \leqslant \hat{\eta} \\ \frac{\hat{\gamma}}{\rho}\left(\frac{H_S}{\rho}\right)^{\hat{\gamma}-1} \exp\left[-\left(\frac{H_S}{\rho}\right)^{\hat{\gamma}}\right], & \text{if } H_S > \hat{\eta} \end{cases} \tag{6}$$

$$f(T_p|H_S) = \frac{1}{\sqrt{2\pi}\sigma T_p} \exp\left[-\frac{(\ln T_p - \mu_t)^2}{2\sigma^2}\right] \tag{7}$$

$$\mu_t(H_S) = a_1 + a_2 H_S^{a_3},\ \sigma^2(H_S) = b_1 + b_2 \exp(-b_3 H_S) \tag{8}$$

This study adopts the following parameters provided by Haver [12] for the North Sea region: ξ = 0.6565, μ_h = 0.77, $\hat{\eta}$ = 2.90, ρ = 2.691, $\hat{\gamma}$ = 1.503, a_1 = 1.134, a_2 = 0.892, a_3 = 0.225, b_1 = 0.005, b_2 = 0.120, b_3 = 0.455. Based on these values, the contours of $f(H_S, T_p)$ are illustrated in Fig. 1.

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