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Analytical Methods for Non-Gaussian Stochastic Response of Offshore Structures

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ABSTRACT

The non-Gaussian dynamic response of offshore structures with nonlinear random wave loading is studied using analytical methods. The response PSD is obtained with the nonlinear excitation PSD derived from a power series expansion of the nonlinear wave force. The non-Gaussian response is computed through a new linear filter method in which the wave loading is modeled as a filtered δ-correlated non-Gaussian process. Procedures for selecting proper filter parameters are developed. The filter method is found to give more accurate response kurtosis than a method based on the fast Fourier transform. Analytical results of important characteristics of the response for both fixed and compliant offshore structures are presented and compared with simulation results.

INTRODUCTION

In general, the wave elevation in an open sea is modeled as a Gaussian stochastic process. The commonly used dynamic analysis methods for offshore structures under random wave loading are mostly based on spectral analysis assuming linear structural response and Gaussian distribution of the response time history (API RP 2A, 1993). However, the Gaussian idealization of the structural response time history may be inadequate in situations involving significant nonlinearities due to nonlinear wave loading and/or nonlinear structural behavior. Recent studies by the authors suggest that the rate of accumulation of fatigue damage could be increased by as much as 100% by a level of non-Gaussian response that might be realistic for certain seastates encountered by an offshore structure (Wang and Lutes, 1991 and 1994). It has been recognized that the characterization of non-Gaussianity requires knowledge of moments or cumulants higher than the second order. Furthermore, techniques (analytical as well as numerical) considered satisfactory for evaluating the second moment properties may not be adequate for higher moment calculations. Analytical evaluation of the response kurtosis and mathematical expressions for the related fourth cumulant function and trispectral density function are much more complex than the corresponding relationships for the variance, ordinary autocorrelation function and power spectral density function.

In this paper, the stochastic dynamic response of offshore structures under non-Gaussian wave loading will be investigated based on analytical nonlinear non-Gaussian modeling of both the random wave loading and the dynamic structural response. To study the modeling effects of various versions of the Morison equation for describing the hydrodynamic wave loading, four different Morison equation models will be used. Numerical simulation results of key statistical response properties such as the rms, average frequency, spectral shape factor and kurtosis will first be discussed. Subsequently the problem will be approached using analytical methods. In particular, nonlinear frequency domain spectral analysis techniques will be employed to obtain the response PSD of the system based on a nonlinear excitation PSD derived from a power series expansion for the nonlinear wave force. A new non-Gaussian modeling approach based on the idea of filtered δ-correlated process will be discussed in depth for predicting the response kurtosis.

PROBLEM FORMULATION

For simplicity the offshore structure will be idealized as a single degree of freedom system (SDOF) in this study, and the wave loading will be based on the water velocity at the mean water level. Better modeling of the structure could be achieved by using a multi-degree of freedom system, but the SDOF model will serve to illustrate the method. Similarly, better modeling of the wave loading could be achieved by integrating over the submerged depth of the structure, but this would be unlikely to change significantly the nature of the dynamic response. The equation of motion for a linear SDOF system may be written as:

$$m\ddot{x}+c\dot{x}+kx = f \tag{1}$$

where m, c and k denote the structural system mass, damping and stiffness, respectively, and f denotes the external wave force that may be given by the generalized version of the commonly used Morison equation including the relative velocity effect:

$$f = -m_a\ddot{x}+K_m\dot{u}+K_d(u-\dot{x})|u-\dot{x}| \tag{2}$$

where u and $\dot{u}$ are the water particle velocity and acceleration, K_m and K_d are constants corresponding to the inertia and drag term, $\dot{x}$ and $\ddot{x}$ denote the structural response acceleration and velocity, respectively, and m_a denotes the added mass. As the relative velocity with the nonlinear drag term poses the main difficulties in analytical solutions for the dynamic response, simplifying approximations of the full nonlinear interactive Morison equation given by Eq. 2 are often made by neglecting the structural response velocity and/or equivalent linearization of the nonlinear

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KEY WORDS: Stochastic dynamics, offshore structure, nonlinear wave force, non-Gaussianity.