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Slow Motion Responses of Compliant Offshore Structures

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ABSTRACT

An efficient methodology is developed to predict slow-drift responses of slender compliant offshore structures due to ocean waves. It uses a hybrid wave model for computing the incident wave kinematics and the Morison equation for wave loads. An iterative-incremental Newmark-Beta approach is employed to simulate the structure responses in the time domain. The hybrid wave model considers the nonlinear interactions between the wave components in incident waves and hence is able to predict wave kinematics accurately up to the second order of wave steepness. It is observed that when the hybrid wave model is used for computing wave kinematics, the predicted slow-drift responses of a JIP (Joint Industry Project) spar are in excellent agreement with the measurements of the model tests. However, the corresponding predicted slow-drift responses using Wheeler stretching and linear extrapolation methods for wave kinematics do not agree with the measurements.

INTRODUCTION

As offshore oil and gas exploration and production are pushed into deeper and deeper water, many innovative floating offshore structures are being proposed for cost savings. To reduce wave-induced motions, the natural frequencies of these newly proposed offshore structures are designed to be far away from the spectrum-peak wave frequency. For example, a spar buoy, studied by a Joint Industry Project (Johnson, 1995), is being considered the next generation of deep-water offshore structures by many oil production companies. The natural periods of its surge and pitch motions are 1 to several min, which are much greater than typical wave periods observed in the Gulf of Mexico and the North Sea. Laboratory tests show that the responses of the JIP spar buoy at the wave frequency (near the spectrum-peak frequency) are small as expected but relatively large near its natural frequencies, although elevation measurements show incident waves involve insignificant energy at these low frequencies. It is known that the large slow-drift (low-frequency) motions of the spar can not be well predicted using linear wave theory. Studies based on nonlinear wave-wave and wave-body interactions indicate second-order difference-frequency loads are the dominant source of the exciting forces at very low frequencies (close to the natural frequency of the spar). This paper addresses the development of a deterministic dynamic analysis and the corresponding numerical scheme for predicting the responses of the spar buoy. It should be noted that the analysis and numerical scheme presented here are not limited to the spar buoy, but can also be applied to other slack-moored deep-drafted offshore structures, such as the floating jacket platform (Lou et al., 1995).

Several methods for computing second-order wave loading have been developed by Newman (1974) and Pinkster (1980), and a more complete solution using second-order diffraction theory has been studied by Kim and Yue (1989, 1990). Typical numerical schemes based on these methods solve first- and second-order diffraction potentials using a boundary element or panel method, and then derive the wave loads through integrating pressure on the surface of a structure at its mean position. The results are given in terms of linear and quadratic transfer functions in the frequency domain (Ran et al., 1995). For computing the structure responses, the wave loads resulting from the potential flow are combined with viscous drags computed using the Morison equation for calculating the structure responses in the time domain. Because of complexity of body and free surface boundary conditions, this kind of numerical schemes often require intensive computations and therefore may not be suitable for preliminary designs.

A simplified alternative proposed in this study is to predict slow-drift responses of a deep-drafted offshore structure based on the slender body approximation, that is, without explicitly considering the diffraction and radiation potential due to the presence of the structure. For typical deep-water offshore structures such as spars, the ratio of the structure dimension to spectrum-peak wavelength is small. Hence it may be assumed that the wave field is virtually undisturbed by the structure and that the Morison equation is adequate to calculate the wave exciting forces (Kim and Chen, 1994). The wave loads on a structure are computed by integrating forces along the structure centerline from the bottom to the instant free surface at the displaced position. Ambient flow near the structure is calculated using the hybrid wave model (Zhang et al., 1993; Ye and Zhang, 1994). The hybrid wave model considers the wave interactions in an irregular wave field up to second order of wave steepness and is able to accurately predict incident wave kinematics, including the contribution from nonlinear difference-frequency interactions. Additional second-order contributions from convective accelerations, free-surface fluctuation and structural displacement from the mean position, and axial divergence (Rainey, 1990) are also included in the simulation. A unique feature of this approach is that measured wave elevation time series can be used as input, and the structure responses to measured incident waves can be deterministically obtained. This allows us to validate the numerical model through direct comparison with measurements, and it may also be used to examine ongoing laboratory measurements.

FORMULATION AND NUMERICAL SCHEME

Governing Equations

The spar buoy is modeled as a rigid body with 2 degrees of

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KEY WORDS: Wave-wave interaction, Morison equation, slow-drift motion, hybrid wave model.