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Calculating crest statistics of shallow water nonlinear waves based on standard spectra and measured data at the Poseidon platform

Yingguang Wang *

Department of Naval Architecture and Ocean Engineering, School of Naval architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

This paper introduces a new approach for the calculation of the wave crest distribution of shallow water nonlinear waves by utilizing a Transformed Rayleigh method where the second order nonlinear wave model is incorporated. The proposed Transformed Rayleigh method is based on a deterministic and time instantaneous functional transformation. It is very efficient and accurate and can be used for engineering purposes. Meanwhile, the correction for the effect of bottom on the wave spectrum, a procedure that is frequently overlooked by some researchers, has been integrated into the Transformed Rayleigh method. The proposed new approach has been first applied for calculating the wave crest height exceedance probabilities of sea states with standard JONSWAP spectra corresponding to different water depths, and the calculation results have been favorably validated against Monte Carlo simulation results. Meanwhile, the wave crest height exceedance probabilities of these sea states obtained from using the Jahns and Wheeler finite depth wave crest height distribution model have also been included for comparison purpose. It is found that in all cases the Transformed Rayleigh method can offer better predictions than the Jahns and Wheeler model. The Transformed Rayleigh method is then applied to calculate the wave crest height exceedance probabilities of a combined sea state with a bimodal Torsethaugen spectrum corresponding to a water depth of 25 m, and its accuracy and efficiency are again favorably validated by using Monte Carlo simulations. Finally, the Transformed Rayleigh method is applied to predict the wave crest height exceedance probabilities of a sea state with the surface elevation data measured at the Poseidon platform in the Japan Sea, and its accuracy and efficiency have been once again convincingly substantiated.

1. Introduction

Accurate prediction of the wave crest height exceedance probabilities is of vital importance to the design of both offshore platforms and offshore wind turbines. An important parameter regarding the structural safety of an offshore platform is the height from the still water level to the lowest deck level of the platform, and the value of this parameter is commonly denoted to be a still-water airgap distance in the offshore engineering literature (Sweetman and Winterstein, 2001). In order to choose a proper value for this still-water airgap in the design process for the platform, accurately predicting the wave crest height distribution at the location of the offshore platform is inevitably required. On an offshore wind turbine, there are some parts of the turbine structure (such as the blades) which are not designed to be exposed to hydrodynamic loads. These parts shall be positioned at a height with a minimum clearance relative to the expected value of the highest crest elevation with a specific recurrence period. This also requires the designer to accurately calculate the wave crest height exceedance probabilities at the location of the offshore wind turbine. This paper concentrates on the calculation of the wave crest height distribution of shallow water nonlinear waves. The motivation for carrying out this research is twofold. First, at present offshore wind turbines are usually installed in shallow water areas. The author of this article has studied the papers written by some wind turbine researchers (such as Colwell and Basu (2009), Trumars et al. (2005), Shi et al. (2013); to name just a few). These researchers were found to have overlooked the correction for the effect of bottom on the wave spectrum during their offshore wind turbine analysis. As pointed by Graber and Madsen (1988), shoaling of waves as they propagate in water of slowly varying depth and dissipation through bottom friction will affect the evolution of the wave field. This author has thus developed a particular interest in figuring out the negative impact on the wave crest prediction when an uncorrected wave spectrum is used for the offshore wind turbine analysis. Second, it is well known that in the ocean engineering

* Tel.: +86 21 34206514; fax: +86 21 34206701.
E-mail address: wyg110@sjtu.edu.cn

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Nomenclature

h	crest height g the acceleration of gravity
H_s	significant wave height
Φ	velocity potential
η	surface elevation
k	wave number
ω	angular frequency
L	wavelength
g	the acceleration of gravity
$\hat{m}_\eta$	mean
σ_η^2	variance
m_3	skewness
m_4	kurtosis
A	wave amplitude
T_p	spectral peak period

literature there exist some empirical wave crest distribution models (such as those in Tayfun (1980), Huang et al. (1983), Kriebel and Dawson (1991) (1993), Forristall (2000), etc.) that can be conveniently used for engineering purposes. However, the previous research work of this author's research group (Wang and Xia, 2012) has pointed out that "these empirical wave statistics formulas in the existing literature should be used with caution. Although these formulas are generally very concise and easy to use, sometimes they predict wave statistics results deviating considerably from the true ones". Therefore, there is a strong motivation for this author to develop a computationally efficient method for calculating the shallow water wave crest distribution that is more accurate than the empirical wave crest distribution models.

Summarizing the research work of the author of this article, this paper introduces a new approach for the calculation of the wave crest distribution of shallow water waves by utilizing a Transformed Rayleigh method where the second order nonlinear wave model is incorporated. The proposed Transformed Rayleigh method is a deterministic and time instantaneous functional transformation that is very efficient and accurate and can be used for engineering purposes. Meanwhile, the correction for the effect of bottom on the wave spectrum, a procedure that is frequently overlooked by some researchers, has been integrated into the Transformed Rayleigh method. The proposed new approach will be first applied for calculating the wave crest height exceedance probabilities of sea states with standard JONSWAP spectra corresponding to different water depths, and the results will be validated against Monte Carlo simulation results. Meanwhile, the wave crest height exceedance probabilities of these sea states obtained from using the Jahns and Wheeler finite depth wave crest height distribution model will also be included for comparison purpose. The Transformed Rayleigh method will also be applied to calculate the wave crest height exceedance probabilities for a combined sea state with a bimodal Torsethaugen spectrum corresponding to a water depth of 25 m, and its accuracy and efficiency will again be validated by using Monte Carlo simulations. Finally, the Transformed Rayleigh method will be applied to predict the wave crest height exceedance probabilities of a sea state with the surface elevation data measured at the Poseidon platform in the Japan Sea, and its accuracy and efficiency will once again be substantiated.

This paper begins in Section 2 by introducing the knowledge of the second order nonlinear irregular waves. It continues in Section 3 by elucidating the theoretical background of the proposed Transformed Rayleigh method, and in Section 4 the method is applied to calculate the wave crest height exceedance probabilities of shallow water nonlinear waves based on standard spectra and measured data at the Poseidon platform. These results are compared with those from Monte Carlo simulations and from empirical distribution models, with concluding remarks provided in Section 5.

2. The second order nonlinear irregular waves

The small oscillation amplitude ocean waves in a sufficiently deep sea are considered to be a Gaussian random process (Ochi, 1998). The wave crest distributions in a Gaussian random sea are generally regarded as to obey the Rayleigh probability law (Longuet-higgins, 1952; Chakrabarti, 1987) as shown in Eq. (1):

$$P(A_c < h) = 1 - \exp\left[-8\left(\frac{h}{H_s}\right)^2\right] \tag{1}$$

In Eq. (1) h is the crest height, H_s is the significant wave height. In the Gaussian sea model the individual cosine wave trains superimpose linearly (add) without interaction. Therefore, the model is also called the linear sea model.

However, it is known that as the water depths decrease, the non-linearities of sea waves become more and more relevant, and the ocean surface elevation process deviates significantly from the Gaussian assumption, i.e. the observed surface process is positively skewed with higher crests and shallower troughs than expected under the Gaussian assumption (Ochi, 1998). Meanwhile, it should be pointed out that wave nonlinearities are not only due to bottom effects (shallow water conditions). They can also be present in deep water conditions, as found by Casas-Prat and Holthuijsen (2010), for instance. In the following we briefly introduce the theoretical background of the second order nonlinear irregular waves.

The fluid region is described using three-dimensional Cartesian coordinates (x, y, z), with x and y the horizontal coordinates, and z the vertical coordinate – with the positive z-direction opposing the direction of the gravitational acceleration. Time is denoted by t. The free surface is located at $z=\eta(x, y, t)$. If the fluid is assumed to be ideal, incompressible and inviscid, and the fluid motion irrotational, so that the velocity potential $\Phi(x, y, z, t)$ exists, then for constant water depth d the potential $\Phi(x, y, z, t)$ and the surface elevation $\eta(x, y, t)$ are determined by the following boundary value problem (see, for example, Toffoli et al., 2006):

$$\nabla^2\Phi = 0 \tag{2}$$

$$\frac{\partial\Phi}{\partial t} + \frac{1}{2}(\nabla\Phi)^2 + gz = 0 \quad \text{at} \quad z=\eta(x,y,t) \tag{3}$$

$$\frac{\partial\eta}{\partial t} + \frac{\partial\Phi}{\partial x}\frac{\partial\eta}{\partial x} + \frac{\partial\Phi}{\partial y}\frac{\partial\eta}{\partial y} - \frac{\partial\Phi}{\partial z} = 0 \quad \text{at} \quad z=\eta(x,y,t) \tag{4}$$

$$\frac{\partial\Phi}{\partial z} = 0 \quad \text{at} \quad z=-d \tag{5}$$

Eq. (2) is the Laplace equation and Eqs. (3)–(5) are respectively the dynamic free surface boundary condition, the kinematic free surface boundary condition, and the bottom boundary condition. Solutions of system (2)–(5) can be sought using the following expansion (see, e.g., Toffoli et al., 2006):

$$\begin{cases} \Phi = \Phi^{(1)} + \Phi^{(2)} + \ldots \\ \eta = \eta^{(1)} + \eta^{(2)} + \ldots \end{cases} \quad \text{where} \quad \frac{\Phi^{(n+1)}}{\Phi^{(n)}} = \frac{\eta^{(n+1)}}{\eta^{(n)}} = O(\varepsilon) \tag{6}$$

Here ε is a small parameter in expansion (6) and it is typically proportional to the wave steepness $\xi=kA$, where $k=2\pi/L$ (L=wavelength) is the wave number, and A is the wave amplitude which is equal to half the wave height. For an irregular sea state