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Numerical study of wave impact on the deck-house caused by freak waves

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ABSTRACT

Freak waves are large and unexpected surface waves with huge wave heights that can lead to severe slamming to ships and marine structures. However, there are only few researches conducted to investigate the wave impact on the deck-house caused by freak waves. In order to understand the phenomena and be able to calculate the structural response of the deck-house structures, a 2-D numerical wave flume is built in which freak waves are generated. A simplified method is proposed to approximate the deck-house wall as an Euler beam with intermediate elastic bearings. By applying an implicit iterative algorithm, the fluid-structure interaction (FSI) is considered. Three simulations are performed, including a regular wave impact against a rigid wall, a laboratory-scale freak wave impact against an elastic wall, and the deck-house impact caused by a full-scale freak wave. Visual snapshots are taken to show the entire wave slamming phenomena. Fluid pressures adjacent to the wall are reported to indicate the influence of hydroelasticity. The displacements of the vertical wall and the deck-house wall from a semi-submersible barge are analyzed with the fast Fourier transformation (FFT) and wavelet transformation method.

1. Introduction

Freak waves, which are also called rogue waves, giant waves or episodic waves, are type of waves that occur unexpectedly in the ocean with huge wave height. Draper (Draper, 1965) first proposed this concept in 1965. Accidents such as shipwrecks and offshore structure destructions caused by freak waves happened occasionally due to the huge wave heights of freak waves (Kjeldsen, 2005). For example, the tanker 'World Glory' (built in the U.S.A. in 1954) under the Liberian flag while travelling along the South African coast in 1968, encountered a freak wave which broke the tanker into two parts and led to the death of 22 of its crew members (Lavrenov, 1998). However, existing researches on the fluid-structure interaction between freak waves and ships or offshore structures are still inadequate.

In order to study the phenomena of freak wave impact, a proper way of generating freak waves should be explained. From the perspective of its physical mechanisms, freak wave formation models could be divided into two categories, the linear models and the nonlinear models. On the aspect of linear models, one of the most comprehensive linear model which has been deeply studied and successfully generated in numerical flumes is the superposition model, which treats the freak wave as the superposition of a series of waves with different frequencies and phases. Kriebel and Alsina (2000) gave an approach to generate freak waves by combining a background random sea and an extreme transient wave. Fochesato et al. (2007) conducted a typical simulation of an overturning rogue wave, and analyzed the sensitivity of its geometry and kinematics to water depth and maximum angle of directional energy focusing. Zhao et al. (2010) simulated extreme waves by using the Volume of Fluid (VOF) method. On the aspect of nonlinear model, the nonlinear Schrödinger (NLS) equation model that explains freak wave as driven by modulational instability (Osborne et al., 2000) or by breather solutions which present time-spatial focusing effects (Peregrine, 1983), is commonly used to describe the modulation of wave envelop. One of the solutions named the Peregrine breather solution (Peregrine, 1983) which gives the leading order of free surface elevation and velocity potential of the nonlinear freak wave, is widely studied by researchers. For example, Chabchoub et al. (2012a), (2012b) generated freak waves in an experimental tank using the deep-water-based Peregrine breather solution of NLS equation. Onorato et al. (2013) generated freak waves in their laboratory under finite depth of water with the Peregrine breather solution of NLS equation. Perić et al. (2015) numerically simulated Peregrine breather solution with a two-phase-flow Navier-Stokes model and studied the initial stage of freak waves' breaking. Hu et al. (2015a) simulated Peregrine breather solution based freak waves in a numerical wave flume under finite water depth.

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Since freak waves occur in the ocean unexpectedly and the significant wave height of the wave train is usually much smaller than the wave height of the freak wave, it is possible that ships and marine structures designed according to normal wave conditions may experience violent on-deck wave impact caused by freak waves. When ships and offshore structures meet with freak waves, green water might happen with a large amount of water on deck, which usually leads to severe slamming phenomena (Graham et al., 2000). Therefore, researches on green water and deck-house impact caused by freak waves are necessary. On the aspect of wave impact, Zhang et al. (1996) presented a numerical method of the impact of a 2-D plunging wave on a rigid vertical wall using potential flow theory. The initial stage of the impact is characterized by an oblique impact of a water- wedge and is solved through a similarity solution. Cox and Ortega (2002) conducted a small-scale laboratory experiment to quantify the transient wave overtopping on a deck. Faltinsen et al. (2002) studied the green water loading in the bow region of an FPSO by numerical means, in which a 2-D method satisfying the exact nonlinear free-surface conditions within potential-IF theory has been developed. Greco et al., (2001, 2004) studied the whole process of wave overtopping and the deck-house impact experimentally and numerically. A boundary element method was used for the numerical solution of the water-on-deck phenomena. The fluid–structure interaction was studied by coupling the nonlinear potential flow model with a linear Euler beam to represent a portion of the deck-house under the action of the shipped water. Huijsmans and van Groesen (2004) calculated the wave loads of a rigid structure slammed by “freak waves” which were substituted by solitary waves with huge wave heights. Gómez-Gesteira et al. (2005) analyzed green water overtopping with the SPH method, indicating that a fixed horizontal deck above the mean water level modifies strongly the wave kinematics. Wu (2007) analyzed the hydrodynamic impact due to a column of liquid hitting on a solid wall. The problem is solved using the boundary element method based on the potential theory. Duan et al. (2009) investigated the initial stage of plunging wave impact obliquely on coastal structures. The impact event is described by a similarity solution method based on the potential theory and solved by a boundary element method. Lu et al. (2012) presented a numerical time domain simulation model using the VOF technique and studied the green water phenomena and their impact loading on a FPSO. Zhao et al. (2014) developed a numerical tool for modeling freak waves impact on a floating body undergoing large amplitude motions, in which the freak wave is generated by the focusing wave theory. The results of distorted free surfaces and large amplitude body motions are compared with experimental data. Hu et al. (2014) researched on the response of a beam hit by a freak wave based on the superposition model numerically, in which the hydroelasticity of the beam is taken into account. Hu et al. (2015b) presented a simplified model named CWDB to predict the water depth and the sectional velocity of the on-deck green water based on the traditional dam-breaking model. However, research on freak-wave-induced deck-house impact, considering the hydroelastic effects and the complex structures of the actual deck-house, was seldom conducted.

In this paper, a 2-D numerical wave flume is built, in which the incompressible Navier-Stokes equations are solved. The free surface is reconstructed by a VOF-Youngs method (Youngs, 1982). Before generating freak waves, a simulation of a normal-wave-caused impact is conducted, the results of which are compared to the experimental data by Greco et al. (2004) to validate the numerical method. The freak waves are generated using both the linear superposition model and the nonlinear Peregrine breather solution. Simulations of the shipped water slamming on vertical walls caused by freak waves are conducted, where local fluid-structure interaction is considered. An approximate simplification method of the actual deck-house structure is proposed, and the simulation of the deck-house of a semi-submersible barge in full-scale slammed by a real-measured freak wave is carried out. Additionally, two comparative simulations are performed as comparisons with the simplified deck-house model. Node displacement time series in each case are further processed with the fast Fourier transformation (FFT) and the wavelet transformation. Comparisons between different models are reported, and meaningful conclusions are drawn.

The contents of this paper are organized as follows. Section 2 and Section 3 give a brief introduction to the numerical wave flume, the simplification of the deck-house structure and the fluid-structure interaction (FSI) method. In Section 4, a regular-wave-induced deck-house slamming is simulated and compared to the experimental data. In Section 5, the simulation of a vertical wall under the impact of a laboratory-scale freak wave is conducted. Also, the comparison of the impact induced by the nonlinear freak wave and a regular wave based on the 5th-order Stokes theory are reported. In Section 6, the simulation of the deck-house from a semi-submersible barge against a measured freak wave is performed, together with two comparative simulations using different models. The results of the three models are compared and discussed. Finally, the conclusions are listed in Section 7.

2. Numerical wave flume and freak wave generation

2.1. Freak wave based on the Peregrine breather solution

In this section, the Peregrine breather solution is briefly introduced by listing the essential expressions. More details of the Peregrine breather solution can be seen in related researches (Peregrine, 1983; Mei, 1983; Akhmediev et al., 2009; Slunyaev et al., 2013; Hu et al., 2015a). This freak wave model is used under assumptions that the viscosity and compressibility are omitted and the depth of water is finite.

Usually, a multiple scale perturbation expansion is used on the original Euler equation (Mei, 1983), and the Euler equation can be divided into a series of sub-equations. The 1st-order solution can be written as (Hu et al., 2015a):

$$\phi_1 = \phi_{10} - \frac{g \cosh Q}{2\omega \cosh q}(iAe^{i\psi} + c.\,c.) \tag{2.1}$$

$$\zeta_1 = \frac{1}{2}(Ae^{i\psi} + c.\,c.) \tag{2.2}$$

Here, ϕ_1 and ζ_1 represent the 1st-order velocity potential and surface elevation respectively. $c.\,c.$ means the complex conjugate of $iAe^{i\psi}$, $\omega^2 = gk\tanh(kh)$, $Q = k(z+h)$, $q = kh$. h is the water depth, g is the acceleration of gravity, k is the wave number of the carrier wave, and ψ describes the wave phase. ϕ_{10} and A represent the mean flow and the envelope of carrier waves respectively, governed by the well-known nonlinear Schrödinger equation. Peregrine (1983) gave a breather solution to the standard formed NLS equation, which can be written as the following form for the problem of wave propagation.

$$A = A_0 e^{-i\beta A_0^2 \tau}\left[\frac{4\alpha(1 - 2i\beta A_0^2 \varepsilon t_1)}{\alpha + \alpha(2\beta A_0^2 \varepsilon t_1)^2 + 2\beta A_0^2 \xi^2} - 1\right] \tag{2.3}$$

Here, $\xi = x_1 - C_g t_1$, group velocity $C_g = \partial\omega/\partial k$, $\varepsilon = kA_0$. $x_1 = \varepsilon x$, $t_1 = \varepsilon t$, x represents the wave direction. A_0 is a parameter that describes the carrier wave amplitude. Under finite water depth, the parameters α and β are formulated as (Hu et al., 2015a):

$$\alpha = \frac{C_g^2}{2\omega} - \frac{\omega q \cosh^2 q}{k^2 \sinh 2q} + \frac{q \sinh q}{k \cosh q} C_g \tag{2.4}$$

$$\beta = \frac{\omega k^2}{16\sinh^4 q}(\cosh^4 q + 8 - 2\tanh^2 q) + \frac{\omega}{2\sinh^2 2q}\frac{(2\omega\cosh^2 q + kC_g)^2}{gh - C_g^2} \tag{2.5}$$

By performing derivations of the velocity potential and the