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Structural response of deck structures on the green water event caused by freak waves☆

Hao Qin[a,b], Wenyong Tang[a,b,*], Zhe Hu[a,b], Jinting Guo[c]

[a] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai Jiao Tong University, Shanghai 200240, China
[c] International Association of Ocean Engineers (IAOE), Houston 77042, United States

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ABSTRACT

Freak waves are huge and unexpected surface waves in the ocean which usually lead to severe destructions to ships and offshore structures. Green water is one of the most commonly observed phenomena when ships and marine structures encounter with freak waves. As a result, freak waves will likely to create significant wave impact on the deck structures. However, the existing researches on the interaction between freak waves and marine structures are still inadequate. In order to investigate the green water phenomenon caused by freak waves and the structural response of the deck, a 2-D numerical wave flume is built in which a nonlinear freak wave based on the Peregrine breather solution is generated. By setting an elastic bare deck horizontally in the flume, the fluid-structure interaction (FSI) is considered during the green water event. To approximate the complicated real decks, a deck model containing intermediate elastic supports are used. The simulation results include the snapshots of the entire green water process, the pressures of the fluid on the deck and the displacements of the elastic decks analyzed with the fast Fourier transformation (FFT) and the wavelet transformation method. By comparing the results of the rigid deck, the elastic bare deck and the elastic deck with intermediate elastic supports, advisable conclusions are drawn.

1. Introduction

Freak waves, which are also called rogue waves, giant waves or episodic waves, are type of waves that occur spontaneously in the ocean with huge wave heights. Draper (Draper, 1965) first proposed this concept in 1965. Because of the giant wave heights, accidents such as shipwrecks and offshore structure destructions caused by freak waves happened continuously in the recent decades (Kjeldsen, 2005). For example, a freak wave with a crest about 21 m hit the Ekofisk oil field in 1984, the wall structure on the lower deck of the 2–4 A platform was destroyed by the wave (Kjeldsen, 1984; Dysthe et al., 2008). 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). Existing researches mostly concentrate on the physical mechanisms of freak waves, experiment conductions and numerical simulations of motion responses of ships and marine structures. However, the fluid-structure interaction of freak wave with ships or offshore structures considering local hydroelastic structural response, such as green water induced by freak waves, still need more studies.

In order to study the green water phenomena caused by freak waves, a proper way of generating freak waves should be explained.

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* Corresponding author at: State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail address: wytang@sjtu.edu.cn (W. Tang).

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From the perspective of its physical mechanisms, freak wave formation models could be divided into two categories, the linear models and the nonlinear models. One of the most comprehensive linear model which have been deeply studied and successfully generated in numerical flumes is the superposition model (Fochesato et al., 2007; Zhao et al., 2010), which treats the freak wave as the superposition of a series of waves with different frequencies and phases. Although linear models provide us with a simple way of forming freak waves and explain the giant heights, transience and occasionality of freak waves properly, nonlinearity should be considered in freak wave models. The nonlinear Schrödinger (NLS) equation model that explains freak wave as driven by breather solutions which present time-spatial focusing effects (Peregrine, 1983), is commonly used to describe the modulation of wave envelop under water. One of the solutions named the Peregrine breather solution (Peregrine, 1983) is widely studied by researchers, which governs the 1st-order harmonic modulation that leads in surface expansion order. For example, Chabchoub et al. (2012a) 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 his 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. By using Darboux transformation, Chabchoub et al. (2012b) generated a series of freak waves from 2nd-order to 5th-order of NLS equation under deep water in a tank.

Since freak waves occur in the ocean unexpectedly and the significant wave height of the wave train is 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. From the description of witnesses (Graham, 2000) we know that when ships or offshore structures encounter with freak waves, a large amount of water would drop and spread upon the deck, which may leads to structure destructions. Therefore, researches on green water and wave impact caused be freak waves are necessary. Cox and Ortega (2002) conducted a small-scale laboratory experiment to quantify the transient wave overtopping on a deck. Greco et al. (2004) studied the whole process of wave overtopping and divided the whole process into several stages. 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 encounter with "freak waves" which were substituted by solitary waves with giant 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. Hu et al. (2014) calculated the structral response of a vertical beam under the impact of a freak wave based on the superposition model. However, few research on freak-wave-induced green water phenomenon, considering the nonlinear way of generating freak waves and hydroelastic effects of the deck, was conducted.

In this paper, a 2-D numerical wave flume is built which solves the incompressible Navier-Stokes equations and reconstructs the free surface by a VOF-Youngs method (Youngs, 1982). Simulations of the green water overtopping fixed decks which encounter with a freak wave based on the Peregrine breather solution are conducted, where fluid-structure interaction is considered. The snapshots of freak wave overtopping process are shown in figures. In order to reveal the hydroelastic effect of the deck, three simulations are conducted, regarding the deck as a rigid deck, an elastic bare deck and an elastic deck with intermediate elastic supports respectively. The intermediate supports may account for the influence of stiffeners or bulkheads beneath the deck. The fluid pressures on the decks and the displacement of the decks are obtained and further analyzed with the fast Fourier transformation. The differences among rigid deck, elastic bare deck and elastic deck with intermediate supports are compared and discussed.

The contents of this paper are organized as follows. Section 2 gives a brief introduction to the Peregrine breather solution, the numerical wave flume and the fluid-structure interaction method. In Section 3, the numerical settings and simulation conditions are explained. In Section 4, the green water phenomena caused by a freak wave are simulated on the rigid deck, the elastic bare deck and the elastic deck with intermediate supports respectively. Also, the results are summarized and compared. Finally, the conclusions are listed in section 5.

2. Numerical solution

2.1. Freak wave based on the Peregrine breather solution

In this section, the Peregrine breather solution is briefly introduced and the essential expressions are listed. Firstly, it should be noted that this freak wave model is applicable under assumptions that the viscosity and compressibility are omitted and the depth of water is finite.

The original Euler equation is usually developed by a multiple scale perturbation expansion (Mei, 1983), which divide the Euler equation 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