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Numerical study of nonlinear freak wave impact underneath a fixed horizontal deck in 2-D space

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ABSTRACT

Freak waves are extreme and unexpected surface waves with huge wave heights that may lead to severe damage to ships and offshore structures. However, few researches have been conducted to investigate the impact underneath fixed horizontal decks caused by freak waves. To study these phenomena, a 2-D numerical wave tank is built in which nonlinear freak waves based on the Peregrine breather solution are generated. As a validation, a regular-wave-induced underneath impact is simulated and compared to the existing experimental measurements. Then the nonlinear freak-wave-induced impact is investigate with different values of deck clearance above the mean free surface. In addition, a comparative simulation of a “large” regular wave based on the 2nd-order Stokes wave theory with the same crest height and wave length of the nonlinear freak wave is carried out to reveal the unique features of the nonlinear freak-wave-induced impact. By applying a fluid–structure interaction (FSI) algorithm in which the bottom deck and front side wall are simplified as Euler beams in 2-D and discretized by the finite element method (FEM), the hydroelastic effects are considered during the impact event. The vertical force acting underneath the bottom deck, the transversal force acting on the front side wall, the structural displacements of the elastic deck and wall are analyzed and discussed respectively, from which meaningful conclusions are drawn.

1. Introduction

Freak waves are waves of extremely large sizes, alternatively called the rogue waves or giant waves. Accidents such as shipwrecks and offshore structure destructions caused by freak waves have been reported occasionally for decades due to the giant wave heights [1]. For example, a freak wave with a crest over 21 m struck the Ekofisk oil field in 1984, the wall structure on the lower deck of the 2–4A platform was destroyed by the wave [2,3]. The tanker ‘World Glory’ encountered a freak wave which broke the tanker into two parts and led to the death of 22 of its crew members while traveling along the South African coast in 1968 [4]. However, existing researches mainly focused on the physical mechanisms of freak waves, experiment conductions and numerical simulations of motion responses of floaters, while investigations on the fluid–structure interaction between freak waves and ships or offshore structures are still inadequate.

Generally, the most widely used generation methods of freak waves can be divided into the linear superposition model and nonlinear model based on the solutions of the nonlinear Schrödinger equation (NLSE). The superposition model (or called the linear focusing) describes freak waves as the result of the superposition of a random wave train and a focusing wave train. Freak waves based on this model have been long studied and successfully generated [5–9]. Although superposition model is applicable in generating freak waves numerically and experimentally, many researchers argue that the freak waves should be explained in a nonlinear way. Slowly modulated weakly nonlinear Stokes wave is described by the NLSE [10], and one of the most widely-studied solution of the equation is the Peregrine breather solution [11,12]. Akhmediev et al. [13] proposed a method for finding the hierarchy of rational solutions of the self-focusing NLSE. Zakharov et al. [14] numerically simulated freak waves using the modulation instability of wave train and the evolution of the NLSE solitons respectively. Chabchoub et al. [15,16] generated freak waves in an experimental tank using the deep-water-based Peregrine breather solution of the NLSE. Onorato et al. [17] conducted sea-keeping tests using freak waves based on the Peregrine breather solution of the NLSE under the finite water depth in a laboratory. Didenkulova et al. [18]

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studied the properties of rogue waves in intermediate depth and found the Peregrine breather contained more individual waves in intermediate depth than in deep waters. Perić et al. [19] 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. [20] simulated Peregrine breather solution based freak waves in a numerical wave tank under finite water depth. He et al. [21] proposed a mechanism theory in generating high-order freak waves, and pointed out that high-order freak waves are with a larger wave height compared to the 1st-order freak waves. Chabchoub et al. [22] studied the high-order up to the 5th-order freak waves using the Darboux transformation, and generated a series of freak waves from 2nd-order to 5th-order of the NLSE under deep water.

Usually, the lower deck of offshore platforms are designed to be above the predicted maximum wave level. 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 crest, it is possible that deck structures of platforms such as gravity base structures (GBS) and semi-submersibles designed according to normal wave conditions may experience violent impact caused by freak waves. Also, for the GBS, the deck may suffer from a reduction of deck clearance above the mean free surface due to its own weight, foundation subsidence or reservoir compaction [23]. For floaters such as semi-submersibles, the same problem may happen because of a damaged condition, a failure in the ballast system, or an increased storage capacity requirement. The reduction of the deck clearance would surely increase the possibility of wave impact, especially when the deck structures meet with freak waves with extreme wave heights.

Concerning the wave impact upon structures, many works have been done in the recent 20 years. Wood and Peregrine [24] considered the wave impact on the underside of a projecting surface, in which a pressure-impulse approach was used. Baarholm and Faltinsen [25] proposed an approximation for impact on a fixed horizontal deck based on the Wagner's solution. Baarholm and Faltinsen [23] studied the regular wave impact underneath a horizontal deck in 2-D space experimentally and numerically using the BEM method. Based on previous works, Baarholm [26] carried out 3-D experiments to study the 3-D effects of wave impact underneath deck structures, besides, a theoretical method was presented by applying a 3-D correction of the von Karman approach. It was found that the 3-D effects would generally decrease the vertical impact force. Sulisz et al. [27] carried out experiments to study the wave impact on a horizontal deck, in which the elasticity of the deck was considered and the vibration of the deck during the wave impact was discussed in different stages. Lu et al. [28] studied the extreme wave impact on decks of offshore structures using the CFD method. The extreme wave was based on the New-Wave theory, and the wave load on a rigid deck structure as well as a bridge structure were reported. Scharnke and Hennig [29] investigated the vertical wave loading on a fixed platform deck. The analysis of study was focused on a comparison between short-crested and long-crested impacts and a comparison of the measurements to a simplified loading model.

On the global fluid–structure interaction between freak waves and offshore structures, researchers mainly focused on the forces acting on the rigid bodies and the motion responses of floaters. Sparboom et al. [30] studied the extreme wave loads on cylinders with different inclinations, recorded and analyzed the transient impulsive pressure. Clauss et al. [31] conducted the research on the problem of a semi-submersible effected by the "New Year Wave" with the solver WAMIT and TiMIT based on the potential theory, and obtained the loads and motions of the semi-submersible. El Moctar et al. [32] utilized the RANS equation solver COMET and finite element solver ANSYS to calculate the freak wave loads on a jack-up platform and the structure stress response of the jack-up platform. Zhao et al. [33] developed a numerical tool for modeling freak waves impact on a floating body, in which the freak wave was generated by the focusing wave theory. The results of distorted free surfaces and large amplitude body motions agreed well with the experimental data. Deng et al. [34] investigated the wave forces acting on a vertical truncated cylinder induced by a linear focused freak wave. Compared to the Morison results, larger force peaks and shallower force troughs were observed.

Although there are studies concerning the wave loads underneath fixed decks, deeper investigation on this issue is still in need for three reasons. Firstly, when studying the wave loads underneath decks, most of the existing researches only considered normal waves (or regular waves) rather than freak waves. However, as a kind of extremely huge and destructive wave, freak waves are more likely to induce much larger impact loads than normal waves. Therefore, the impact loads caused by freak waves and the unique features within this issue should be carefully studied from a structural safety point of view. Secondly, although there are researches on the interaction between freak waves and marine structures, most of them focused on the motions of floaters affected by freak waves. The impact loads underneath decks are seldom taken into account, which might be dangerous to platforms like GBS and semi-submersibles. Lastly, existing researches usually treated the decks as rigid bodies, however, the real deck structures are elastic bodies and the hydroelastic effects during the freak wave impact issue are significant. Therefore, investigations on the impact loads underneath deck structures induced by nonlinear freak waves and the hydroelastic effects during this event, are necessary.

In this paper, the impact loads caused by a nonlinear freak wave, as well as the hydroelastic effects when considering the deck structures as elastic bodies are studied numerically, which are the main purpose and highlights of our work. The nonlinear freak wave based on the Peregrine breather solution of the NLSE is generated in a self-developed numerical wave tank under 2-D flow conditions. The numerical wave tank solves the incompressible Navier–Stokes equations and reconstructs free surface using the VOF method [35,36]. The typical problem of a fixed horizontal deck slammed by a regular wave is simulated and compared with the experimental measurements by Baarholm and Faltinsen [23]. Then the freak-wave-induced impact on the same deck is studied in the same tank, with different values of deck clearances above the mean free surface. One of the most concerning question, which is "how does the hydrodynamics of the nonlinear freak wave influence the impact results compared with the ones of the regular wave with exactly the same crest height and wave length", is discussed by comparing the impact forces between the freak wave case and the regular wave case. To reveal the hydroelastic effects, the bottom deck and the front side wall are simplified as elastic Euler beams in 2-D. By using an implicit FSI algorithm, the displacements of the deck and the wall are calculated. In addition, the impact forces with/without considering the hydroelastic effects are compared and discussed.

2. Numerical method

2.1. Freak wave based on the Peregrine breather solution

In the recent years, the Peregrine breather solution is gradually accepted as a widely studied model for nonlinear freak waves. Based on the original Euler equation [37], a multiple scale perturbation expansion is used to divide the equation into a series of sub-equations. The 1st-order solution can be written as [20]:

$$\phi_1 = \phi_{10} - \frac{g \cosh Q}{2\omega \cosh q}(iAe^{i\psi} - i\bar{A}e^{-i\psi}) \tag{2.1}$$