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Freak wave forces on a vertical cylinder

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ABSTRACT

This study investigates the wave forces acting on a vertical truncated cylinder induced by freak waves. A series of freak wave trains were generated based on the New Year wave prototype in a wave flume. The inline forces and pitch moments on the fixed cylinder were measured and Morison predictions on them were also performed with different wave kinematic models. Compared with the Morison results, larger force peaks and shallower force troughs are observed in the measurements. Besides, the wave front steepness is found to have a closer relationship with the non-dimensional inline force than the conventional wave steepness. Wavelet transform-based analyses were also successfully performed to reveal the local characteristics of the incident waves, inline forces and transfer functions between them.

1. Introduction

Wave force is a conventional and at the same time very frontier problem. Numerous efforts have been conducted in order to assess the wave forces as accurate as possible over the recent decades. Yet, with the deepening awareness of wave environments, new technical challenges are constantly emerging. For instance, a typical giant asymmetric transient water wave, named as 'freak wave', has been receiving more and more attentions from offshore industry. These waves are always regarded as "the monsters of the deep", which appear surprisingly as "walls of water", or "holes in the sea", or several successive high waves ("three sisters") (Kharif and Pelinovsky, 2003), and disappear without a trace. Among them, the New Year wave is one representative freak wave, which attacked the Draupner Jacket platform located in the North Sea on January 1st, 1995, with a maximum wave height near 26 m (Haver and Anderson, 2000). In addition, freak waves are believed to be responsible for severe damages to offshore structures and ships (Bertotti and Cavaleri, 2008; Kharif and Pelinovsky, 2003; Kharif et al., 2009). It becomes obvious that the freak waves are real threats for marine structures such as wind turbine foundations, offshore platforms and floating vessels. To guarantee a safe and economic design, the interactions between freak waves and marine structures should be carefully examined.

Freak waves have been successfully generated in physical wave flumes and numerical wave tanks in many ingenious ways. One common approach is to focus all or part of wave component energy at a specific location at the same time by phase modulation (Cassidy, 1999; Kriebel and Alsina, 2000; Longuet-Higgins, 1974; Tromans et al., 1991). Moreover, in order to generate tailored design waves or to reproduce recorded freak wave trains, optimization schemes were proposed (Chaplin, 1996; Clauss, 2002; Schmittner et al., 2009). For example, Schmittner et al. (2009) presented a phase-amplitude iteration scheme for collecting shifts in time and location and successfully improved the initial wave trains based on the linear theory. With these modeling methods, it becomes possible and convenient to investigate the fully nonlinear interactions between freak waves and marine structures and the related nonlinear wave forces.

However, the majority of the studies on the wave forces are limited to moderate waves. Although many methods have been proposed to calculate the wave forces (Kriebel, 1998; MacCamy and Fuchs, 1954; Morison et al., 1950) and some attempts have also been made to predict the higher-order wave forces for the consideration of 'ringing' phenomenon (Chaplin et al., 1997; Faltinsen et al., 1995; Rainey, 1995), it remains questionable whether these available theories are still sufficient for the predictions of wave forces under freak waves. For example, Kim and Kim (2003) investigated the horizontal wave forces on a vertical truncated cylinder under freak waves and found that the forces are much larger than those of an equivalent-sized laboratory Stokes fifth-order wave. Pang et al. (2004) studied the wave loads on small diameter cylinder in freak waves using a BEM-based numerical wave tank and observed that the extreme loads are highly nonlinear. Ma et al. (2009)

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investigated the higher-harmonic forces due to wave focusing on a vertical cylinder and the results show that, with very steep wave crests, the wave force amplitudes at the fourth and fifth-order harmonics are significant. Zang et al. (2010) presented the wave forces acting on a bottom-founded vertical cylinder under the action of localized non-breaking and breaking wave groups. Li et al. (2012) and Li et al. (2014) experimentally investigated the interactions between multi-directional focused wave and a bottom-mounted vertical cylinder and demonstrated the effects of wave parameters on the wave run-up and wave force. Paulsen et al. (2014a) adopted an efficient domain decomposition strategy in the computations of wave forces on a vertical cylinder under phase-focused irregular waves. These researches provide us the general patterns of the nonlinear freak wave forces, but there is a long way to obtain a comprehensive understanding of the wave forces under such highly nonlinear waves. Furthermore, there are few researches on the wave forces on a vertical cylinder caused by the recorded famous New Year wave.

This paper presents a comprehensive analysis of the measured wave forces resulted from modeled New Year waves on a truncated vertical cylinder. The measured wave forces have been compared with Morison predictions based on modified stretching wave model and attentions are paid to large peaks and shallow troughs of the measured forces. Moreover, wavelet-based analyses were also conducted to study the local energy constructions of the incident waves and the related inline forces. The transfer functions between the inline forces and incident waves have been carefully examined.

2. Experimental set-up

The physical experiment was carried out in the wave flume of State Key Laboratory of Ocean Engineering (SKLOE) in Shanghai Jiao Tong University. The wave flume is 20.0 m long, 1.0 m wide and the water depth is $d = 0.9$ m. A flap paddle is equipped to generate various kinds of waves and an absorption wave beach is fixed downstream to eliminate wave reflection.

A sketch of the wave flume with a fixed cylinder is plotted in Fig. 1. To facilitate the study, a reference coordinate system was specified, with the origin located at the paddle position on the still water level and the x coordinate positive to the wave propagation direction. The reference point for the wave calibration and vertical cylinders is set at $x = 7.0$ m.

Given that the practical columnar structures in marine structures such as semi-submersibles and spars are with limited drafts, a truncated cylinder was selected and mounted stiffly below a rigid frame at $x = 7.0$ m. The diameter D and the draft d of the cylinder model are 0.1 m and 0.3 m, respectively. A six-component force/moment transducer was fixed between the cylinder and the rigid frame to measure the wave forces and moments. The force action point of the transducer is 0.29 m above the still water level. The natural period of the vertical cylinder is measured to be 0.09 s (11.11 Hz) through a knocking vibration test.

3. Wave environment and theoretical consideration

3.1. Wave environment

Freak waves were modeled and calibrated prior to the tests. To achieve different scattering parameters with a constant cylinder diameter, two scale ratio (1:100 and 1:150) were chosen to model the New Year wave based on the New Year wave prototype. Besides, the wave elevation values were artificially adjusted to 100%, 80%, 60% and 40% of original values for each scale ratio to examine the effects of wave steepness. Therefore, there are 8 different target waves categorized into two groups. To facilitate the analysis, a series of numbers were adopted to represent these different target waves. For example, A0 indicates the case with wave elevation values being 100% of the original values with scale ratio 1:100 and B0 denotes the case with wave elevation values being 100% of the original values with scale ratio 1:150.

The waves were generated with amplitude-phase iteration methods (Schmittner et al., 2009) as described below. The initial wave maker signals were determined by backwards transforming the target wave elevation to the wave maker location and superimposing the control signal of each wave component obtained through linear superposition. By comparing the measured waves with the target waves, phase and amplitude corrections were conducted for the wave maker signals. After several iterations, great improvements of the measured waves can be achieved. Fig. 2 shows the comparison between the measured freak wave trains and the target ones. Good agreements are observed, except that the maximum crest heights of A0, B0 and A1 did not reach the target values for nonlinear wave–wave interaction and possible wave breaking occurs before the focal position. However, it does not affect the findings in this study as all the wave parameters applied in the analyses of wave forces are based on the measured wave trains.

The definitions of local wave parameters of freak waves are given in Fig. 3. The wave height H is defined as the vertical distance between the wave crest and the preceding wave trough. A trough-to-trough period T_{tt} and a trough-to-crest period (crest rise time) T_{rise} are also employed to evaluate the local wave number k and the wave front steepness ε (Myrhaug and Kjeldsen, 1987). Table 1 shows the local wave parameters of measured freak waves. It is noted that the local wave length L results from the local wave number k based on the trough-to-trough period T_{tt}. The wave front steepness ε has similar meaning as wave steepness H/L, but focus more on the asymmetry and nonlinearity of local wave pattern. The wave front steepness ε is determined as

$$\varepsilon = \frac{\eta_c}{\frac{g}{2\pi} \cdot T_{rise} \cdot T_{tt}}. \quad (1)$$

It is shown that the trough-to-crest periods T_{rise} are smaller than half the corresponding trough-to-trough periods T_{tt} and the crest heights η_c are much larger than half the wave heights H. Therefore, the generated freak waves are of both horizontal and vertical asymmetry, leading to

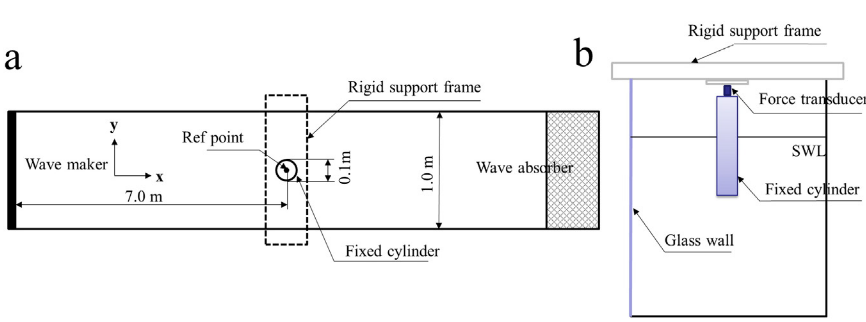

Fig. 1. Sketch of the wave flume experimental set-up. (a) Top view; (b) front view.