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An experimental study on deterministic freak waves: Generation, propagation and local energy

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ABSTRACT

An experimental investigation on deterministic freak waves is presented here. Four similar freak wave sequences with different wave steepness values were used as the target waves in the experiments. A phase–amplitude iteration method was adopted to generate these deterministic freak wave sequences in the wave flume. The results demonstrate that the phase iteration considerably improves the modeling in the first optimization and becomes less effective for subsequent optimizations. The method is more likely to achieve well-matching results for small steepness target waves through phase iterations. Wave speeds and wave energy distributions of analyzed freak waves were also investigated. Reasonable estimates of wave speeds were achieved by adopting trough-to-trough periods and wave heights of freak waves according to third-order Stokes wave theory. The quadratic phase couplings between the first-harmonic component and higher-harmonic components were significant.

1. Introduction

Freak waves are a frequent and serious hazard around the world and are believed to be the major culprits behind a large proportion of the destruction of offshore structures and ships (Bertotti and Cavaleri, 2008; Kharif and Pelinovsky, 2003; Kharif et al., 2009; Lemire, 2005). These waves are normally regarded as “the monsters of the deep” and appear surprisingly as “walls of water” and disappear without a trace. One such example, the New Year Wave, recorded at the Draupner platform, located in the North Sea on January 1st, 1995 (Haver and Anderson, 2000), is a well-known representative freak wave registration. Currently, there is no unified definition of freak waves, but one widely accepted definition regards a freak wave to be a wave of height exceeding at least twice the significant wave height (Kharif et al., 2009). Though the observations and registrations of freak waves are not rare (Kjeldsen, 2004), their physical mechanisms are still under discussion (Dysthe et al., 2008). Generating the recorded freak wave sequence in the laboratory is of great significance in achieving a better understanding of the wave formation mechanisms and studying the interactions between freak waves and structures.

The most common approach to generating freak waves is based on the dispersive focusing model (Dysthe et al., 2008; Li and Liu, 2015), which was first used to produce short groups of large waves at a specific position in a wave tank (Longuet-Higgins, 1974). On the basis of this model, Tromans et al. (1991) and Cassidy (1999) developed the NewWave theory and the constrained NewWave theory, respectively. Kriebel and Alsina (2000) introduced an efficient method by embedding a transient wave into a random wave. Numerous works have been conducted using the above-mentioned methods (see e.g. Bennett et al. (2013), Cui et al. (2012), Ning et al. (2009), Westphalen et al. (2012)). For the sake of generating tailored design wave sequences in extreme seas, Clauss (2002) proposed a novel phase optimization scheme with Sequential Quadratic Programming (SQP) and an improved Simplex method. In addition, modulational instability has been widely studied as well (Sulisz and Paprota, 2011; Toffoli et al., 2010). Modulational instability is believed to be responsible for the high probability of freak wave occurrence (Onorato et al., 2006; Onorato et al., 2001; Zakharov et al., 2006). In recent years, there have been some experimental investigations of Peregrine breather solution to demonstrate the effects of modulational instability in the formation of freak waves (e.g., Chabchoub et al., 2011; Deng et al., 2015; Onorato et al., 2013). However, freak waves generated using the Peregrine breather model are of single frequency of carrier wave, which does not accord with real sea conditions.

It is worth noting that generating deterministic wave sequences is of great significance, not only for investigating wave dynamics but also for studying the hydrodynamics of offshore structures. For this purpose, Liang et al. (2011) regenerated a single

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extreme wave in the numerical wave tank with the wavemaker signals determined by performing Fourier series expansion on the target wave train and calculating wavemaker amplitudes and phases corresponding to each wave component with a correspondent hydrodynamic transfer function. Chaplin (1996) proposed a phase iteration method to improve the phase distributions of the modeled waves. Schmittner et al. (2009) further developed this approach and presented a phase–amplitude iteration scheme for correcting shifts in time and location. The phase–amplitude iteration approach is intuitive and seems to be promising in generating deterministic wave sequences with various wave parameters. However, research regarding the optimization process and application scope of the phase–amplitude iteration method are lacking.

In this paper, the phase–amplitude iterations were applied in the experimental implementation of freak waves with different steepness values. The optimization process of freak wave generations is presented here. The wave speeds were measured experimentally and compared with the 3rd-order Stokes wave theory predictions. Moreover, the energy distributions of freak waves were analyzed with both Fast Fourier Transform (FFT) and Wavelet Transform (WT) methods.

2. Experimental set-up

A physical experiment was conducted in the wave flume of the State Key Laboratory of Ocean Engineering (SKLOE) in Shanghai Jiao Tong University. The wave flume is 20.0 m long and 1.0 m wide, with a standard water depth of 0.9 m. A flap-type wavemaker is equipped to generate various types of waves and an absorption wave beach stands at the downstream end of the flume to eliminate wave reflection. Fig. 1 shows the sketch of the test setup. The focal point was set 7.0 m away from the wavemaker position. To measure the wave evolution, three wave gauges were arranged along the centerline of the flume, i.e., 6 m, 7 m, and 8 m away from the wavemaker, respectively. The sampling frequency was set as 100 Hz and the sampling data length was no less than 60 s in the experiment. The wave gauges of resistance type were employed with a measuring error of less than 1.0 mm.

3. Wave parameters and optimization procedure

A freak wave sequence designed with the embedding model (Kriebel and Alsina, 2000) was selected as the original target wave. This target wave was derived from a JONSWAP spectrum (Hasselmann et al., 1973) with a significant wave height H_s=0.11 m, peak period T_p=1.7 s and peak enhancement factorγ=2.0. As the wave spectral energy of the frequency above 20 rad/s is negligible, the truncation frequency is 20 rad/s in this study. There was a total of 10.6% wave spectral energy coming into the transient wave part and the remaining wave energy was for the random wave part. The resultant maximum wave height, H_{max}, is 0.2577 m and the corresponding crest height, ζ_c, is 0.18 m, resulting in H_{max}/H_s=2.34 and $\zeta_c\ /H_s$=1.64. The parameters of the target wave are close to that of the New Year Wave at a 1:100 scale

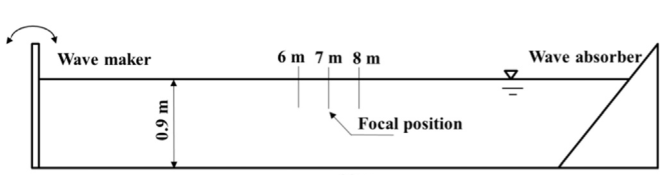

Fig. 1. Sketch of the experimental set-up.

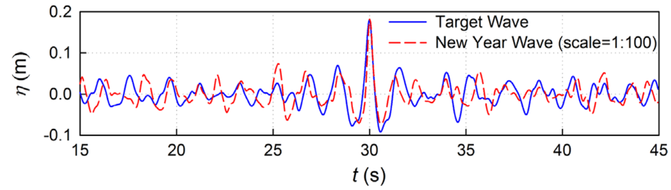

Fig. 2. Comparison of the selected target wave and the New Year Wave of scale 1:100.

(Fig. 2). To investigate the effects of wave steepness on the optimization implementation and the wave kinematics, wave elevation values of the above target wave were artificially adjusted to 40%, 60%, 80% and 100% of the original values, named Case A, Case B, Case C and Case D, respectively.

According to Longuet-Higgins (1952), the deterministic wave sequences at the target location x_c were divided into the combination of a series of regular waves as follows:

$$\eta(t)=\sum_{n=1}^{n=N} A_n\ \cos\left(\omega_n t+\theta_n\right) \tag{1}$$

where A_n, ω_n, and θ_n are the amplitude, frequency, and phase shift of the nth wave component, respectively. The equivalent form of the above equation is

$$\begin{aligned}\eta(t)&=\sum_{n=1}^{n=N}(A_n\ \cos\ \theta_n\ \cos\ \omega_n t-A_n\ \sin\ \theta_n\ \sin\ \omega_n t)\\&=\sum_{n=1}^{n=N}(b_n\ \cos\ \omega_n t+c_n\ \sin\ \omega_n t)\end{aligned} \tag{2}$$

in which

$$\begin{cases} b_n=A_n\ \cos\ \theta_n \\ c_n=-A_n\ \sin\ \theta_n \end{cases} \tag{3}$$

$$A_n=\sqrt{b_n^2+c_n^2} \tag{4}$$

To derive b_n and c_n, the Fourier series expansion was applied:

$$\begin{cases} b_n=\dfrac{2}{T}\int_0^T\eta(t)\cos\omega_n t dt=\dfrac{2}{N}\sum\limits_{i=1}^{M}\eta(t_i)\cos\omega_n t_i \\ c_n=\dfrac{2}{T}\int_0^T\eta(t)\sin\omega_n t dt=\dfrac{2}{N}\sum\limits_{i=1}^{M}\eta(t_i)\sin\omega_n t_i \end{cases} \quad n=0,1,2,\cdots,N;\quad c_0=0 \tag{5}$$

where ω_n=$n2\pi/(M\Delta t)$, M is the number of discrete points in the time series and the wave component number N must be theoretically equal to $M/2$.

After b_n and c_n are obtained, the amplitude and phase distributions of the deterministic wave sequence can be easily determined according to Eqs. (3) and (4). By substituting $\varepsilon_n-k_n x_c$ (k_n, is the wave number) for θ_n, we obtained

$$\eta(x_c,t)=\sum_{n=1}^{n=N} A_n\ \cos\left(k_n x_c-\omega_n t-\varepsilon_n\right) \tag{6}$$

By transforming backwards from the target location, the wave elevation at the paddle x=x_0 can be obtained as

$$\eta(x_0,t)=\sum_{n=1}^{n=N} A_n\ \cos\left(k_n x_0-\omega_n t-\varepsilon_n\right) \tag{7}$$

To implement the generation of a deterministic wave sequence in a wave flume, it is vital to determine the exact wavemaker displacement by which the water motion at the wavemaker boundary should be consistent with the initial conditions given by Eq. (7). In this study, the initial wavemaker signal was determined