Freak waves in three-dimensional random wave trains

Jinxuan Li, Shuxue Liu, Jiqing Yang
State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology
Dalian, China

ABSTRACT

A wave-basin experiment was conducted considering broad directional spreading in different water depth. Long-time surface elevation data were recorded. Freak waves generated by different mechanisms were observed and the effects of the directionality spreading on freak wave occurrence probability were investigated. The results showed that both modulation instability and linear directional focusing can generated the freak wave in multi-directional wave train. The directionality spreading had significant effects on freak wave occurrence probability. In relatively deep water, the waves with a narrow directional spreading range (less than 11°) and larger BFI values were unstable. The freak wave occurrence probability increased owing to the modulation instability. While, in shallow water depths or with wide directional spreading, freak waves occurrence probability decreased. This indicates that freak waves occur more easily in deep water when the wave directional spreading is narrower.

KEY WORDS: Freak wave; wave statistical property; multi-directional random wave.

INTRODUCTION

The freak waves have great wave height and are highly nonlinear, and are capable of causing serious damage to ships and offshore structures. Deeply understanding the mechanism of freak wave generation and the accurate prediction of the occurrence of freak waves, which are at the tail of the probability curve, is essential for the design of offshore structures.

In the past two decades, there has been increasing interest in the generation of freak waves. Several mechanisms have been proposed to explain the phenomenon — for example, wave focusing (Johannessen and Swan, 2001; Liu and Hong, 2005); modulation instability, or Benjamin-Feir instability (Janssen, 2003; Dysthe et al., 2008); and wave–current or wave–wind interaction (Hjelmervik and Trulsen, 2009; Onorato et al., 2011; Toffoli et al., 2011). Benjamin-Feir instability was thought to be the main mechanism in deep water unaffected by current and wind. Many studies have focused on the effects of B-F instability in freak wave generation (e.g. Clamond and Grue, 2002; Janssen, 2003; Li et al. 2013; Onorato et al., 2001, 2004, 2005; Shemer and Sergeeva, 2009; Toffoli et al., 2008). Onorato et al. (2001) studied freak wave generation in long-crested sea conditions initialized as a JONSWAP spectrum based on the cubic nonlinear Schrödinger equation. They found that the occurrence of freak waves increased with the Ursell number, the ratio of wave height to spectrum bandwidth (later called the Benjamin-Feir index (BFI) in Janssen, 2003). Toffoli et al. (2008) investigated freak waves using direct numerical simulation with Euler equations. Their results indicated that the distribution of larger waves is strongly dependent on the BFI. When the bandwidth of the wave spectrum is sufficiently narrow and the waves are sufficiently high, i.e. when BFI is sufficiently large, modulation instability occurs and waves are higher than that expected from second-order wave theory. The relationship between BFI and wave statistics was first experimentally verified by Onorato et al. (2004, 2005) who found experimental evidence that the tail of the probability density function for wave height is strongly dependent on the BFI. For a small BFI, the probability distributions are consistent with the Rayleigh distribution, but for a large BFI, Rayleigh distribution clearly underestimates the probability of large events.

The above studies were all focused on long-crested waves. However, the real ocean waves are short-crested waves. When more wave components in different directions coexist, more of them satisfy the conditions for resonance, and the quasi-resonant effect becomes no significant. If the wave directionality is sufficiently broad, the resonant interaction becomes dominant and the directional wave spectrum self-stabilizes (Young and Van Vledder, 1993). Recently, Waseda et al. (2009), Onorato et al. (2009) and Latheef and Swan (2013) performed experiments to investigate the effects of directional spreading of waves on statistical properties. Onorato et al. (2009) considered the different degrees of wave directionality, starting from long-crested waves up to directional distributions with a spread of ±30°. Their results showed that, for long-crested, steep and narrow-banded waves, second-order theory underestimated the probability of the occurrence of large waves. When directional effects are included, the departure from second-order theory becomes less accentuated.

In addition, focusing of the components from different direction can form a large wave. This is another important generation mechanism of freak wave — wave focusing. Johannessen and Swan (2001) and Liu...