Ocean Engineering 133 (2017) 262–270

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

# An experimental and numerical study on breather solutions for surface waves in the intermediate water depth

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ARTICLE INFO

*Keywords:*
Intermediate water depth
High-order spectral method
Kuznetsov-Ma breather solution
Modulational instability
Peregrine breather solution
Wave height
Wave steepness

ABSTRACT

A series of laboratory experiments related to Kuznetsov-Ma breather solution have been performed in a seakeeping wave tank with different initial wave steepness and intermediate water depths. Analysis of the experimental results reveals that the maximum wave height in Kuznetsov-Ma breather solution is normally accompanied with a large crest amplitude, which can be largely reduced with the decreasing water depth due to the slower modulational process and the limited length of wave tank, regardless of the initial nonlinearity. The laboratory observations can be accurately simulated by the high-order spectral model (HOS) if the initial Benjamin-Feir index is not very large as a result of weak nonlinearity and/or decreased water depth. Numerical studies also indicate that in the evolutionary process the amplitude of carrier wave will decrease sharply and a peak frequency downshifting can be detected. If the evolutionary time scale is long enough, the spectrum will eventually evolve into a continuous one with the energy relocated in the lower wave frequency part. For Peregrine breather solution that is a particular case of Kuznetsov-Ma solution, it is found that in some cases a specific phase shift of the initial condition can lead to a longer distance for the wave group to travel to achieve the first maximum amplitude and a larger amplification factor than that predicted by the theoretical solution.

## 1. Introduction

With the quick development of modern ocean engineering and the more frequent appearance of extreme weather conditions, more attention is paid to the safety of ships and marine structures encountering very large individual waves, because many vessels sunk or were seriously damaged during the period from 1969 to 1994, due to the sudden occurrence of rogue waves (Kharif et al., 2009).

Although a large number of observations of abnormal or rogue waves have been reported by the ship crews, the exact measurements, especially the corresponding records of wave series, are still very rare due to the very localized and time limited occurrence of such waves. One of the famous abnormal waves that has been recorded and widely researched is the “New Year Wave”, which was formed in a storm in the North Sea and hit the Draupner jacket platform on January 1st, 1995 (Taylor et al., 2006).

However, this measurement is only one single point registration of a real sea abnormal wave, and it is still unfeasible to directly figure out the spatial evolution in front of and behind the measure point even though a compromised assumption that the freak wave occurred in a long-crested or bi-directional sea state (Adcock et al., 2011) can be applied. As a result, the laboratory experiments have become an alternative to studying the complex dynamics of rogue waves.

With regard to the nonlinear features associated to water waves, the milestone work was made by Benjamin (1967) who firstly confirmed the existence of modulational instability or Benjamin-Feir instability (Benjamin and Feir, 1967) in the laboratory experiments. Later, Lake et al. (1977) found that the lower sideband amplitude can exceed that of the initial carrier wave and the evolution of non-breaking wave trains exhibits an approximate recurrence-type. A systematic study on the modulational instability was made by Tulin and Waseda (1999) in a large wave flume using wave trains with initially imposed sidebands. To further observe the characteristics of modulational instability in the later evolutionary stage, Hwung et al. (2007) conducted a series of experiments in a much longer wave flume with a length of 300 m.

In addition, the more realistic sea states, characterized by the JONSWAP wave spectrum, have been intensively studied by the wave tank experiments in the past decade (e.g., Onorato et al., 2006, 2009; Zhang et al., 2013), demonstrating that the nonlinear modulation can result in a high probability of appearance of abnormal waves in the

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http://dx.doi.org/10.1016/j.oceaneng.2017.01.030
Received 25 June 2016; Received in revised form 22 December 2016; Accepted 29 January 2017
Available online 20 February 2017
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long-crested sea state, which will be largely decreased by the directional spreading effect in the short-crested sea state. Statistical and spectral analyses of the laboratory experiments with various initial wave spectra illustrate that the spectral width can play an important role in the evolutionary process (Shemer et al., 2010). To better understand the dynamics of rogue waves, a series of observations in a wave tank related to breather solutions, even up to fifth-order (Chabchoub et al., 2012a), have been reported recently, confirming the existed forms of rogue waves with a water wall and/or deep hole (Chabchoub et al., 2012b).

Meanwhile, the various numerical methods, working as a complementary tool that is available to most researchers at very low cost, have been widely used to accelerate the investigation of nonlinear waves. For an ideal fluid the dynamics of surface gravity waves can be described by a set of nonlinear partial differential equations known as the Euler equations. Due to the complex nonlinearity, the Euler equation cannot be easily solved even though different numerical schemes such as the 2D conformal mapping method (Chalikov and Sheinin, 1996, Zakharov et al., 2002) or the high-order spectral method (West et al., 1987; Dommermuth and Yue, 1987) have been proposed and developed. Compared with the former method that is normally referred to as ChSh model, the latter one is an approximately fully nonlinear model if the order of nonlinearity is not large enough.

In order to further shed some light on the inside physics of the nonlinear water waves, several simpler models have been derived under some specified conditions, for example, the different forms of Zakharov's equation (Zakharov, 1968; Stiassnie and Shemer, 1984) and various versions of Dysthe equation (Dysthe, 1979; Trulsen and Dysthe, 1996). Among these simplified numerical models, the most attractive one is the nonlinear Schrödinger equation (Zakharov, 1968; Hasimoto and Ono, 1972) because of its considerable merits such as being integrable (Zakharov and Shabat, 1972). Consequently, many analytical solutions have been found and compared with the laboratory experiments, clearly indicating the related physics inside the phenomenon such as the travelling envelope soliton (Yuen and Lake, 1982; Slunyaev et al., 2013a).

Another class of important solutions is various breathers, one form of which is the Peregrine breather solution (Peregrine, 1983) that was first observed in a water wave tank by Chabchoub et al. (2011). Later, numerical simulations of Akhmediev breathers were performed by Slunyaev and Shrira (2013) by using Euler equations in a wide range of parameters. Slunyaev et al. (2013b) also simulated the rational breathers (and the Peregrine breather as a particular case) with the modified NLS equations and the HOS method, and compared them with the corresponding laboratory measurements. Due to the specific features, these breather solutions can be considered as the prototypes of rogue waves and have received intensive study recently (Clauss et al., 2011; Chabchoub et al., 2012c; Onorato et al., 2013; Shemer and Alperovich, 2013).

However, as presented and discussed in the former published works, these breather solutions reproduced in the wave tank are not fully consistent with the theoretical predictions. A certain degree of discrepancy can be detected, particularly after the formation of the maximum wave. In order to further explore the characteristics of the breather solutions, especially under different water depth conditions, a series of laboratory experiments related to Kuznetsov-Ma breather solutions (Kuznetsov, 1977; Ma, 1979) will be studied in this work. Moreover, since the NLS equation is only valid to a certain distance in the simulation of wave propagation (Trulsen and Stansberg, 2001; Zhang et al., 2014b, 2015a), the approximately fully nonlinear HOS model will be used to simulate these laboratory experiments and perform a further study on their evolutionary process.

## 2. Theory

### 2.1. High-order spectral method

In the case of irrotational motion of fluid that is considered to be homogeneous, inviscid and incompressible, the 2D flow can be described by a velocity potential $\phi\,(x, z, t)$, satisfying Laplace's equation within the domain. The governing equation and its boundary conditions are

$$\nabla^2\phi(x, z, t) = 0, \qquad -h \le z \le \eta(x, t), \tag{1}$$

$$\eta_t + \phi_x\eta_x - \phi_z = 0, \qquad z = \eta(x, t), \tag{2}$$

$$\phi_t + gz + \frac{1}{2}(\nabla\phi)^2 = 0, \qquad z = \eta(x, t), \tag{3}$$

$$\phi_z = 0, \qquad z = -h, \tag{4}$$

where $\eta(x, t)$ is the free surface displacement. The origin of the vertical coordinate $z$ is located at the mean free surface. In terms of the velocity potential $\psi(x, t) = \phi(x, \eta(x, t), t)$ evaluated at the free surface, the kinematic and dynamic boundary conditions can be rewritten as

$$\eta_t + \psi_x\eta_x - W(1 + \eta_x^2) = 0, \tag{5}$$

$$\psi_t + g\eta + \frac{1}{2}\psi_x^2 - \frac{1}{2}W^2(1 + \eta_x^2) = 0, \tag{6}$$

where $W(x, t)$ denotes the vertical velocity at the free surface

$$W = \phi_z|_{z=\eta(x,t)}. \tag{7}$$

In order to follow the time evolution of the surface elevation from Eqs. (5) and (6), a Dirichlet problem of Laplace's equation for $\phi\,(x, z, t)$ has to be solved first at each time step to obtain $W$.

It is well known that two slightly different versions of HOS method were simultaneously and independently proposed by West et al. (1987) and Dommermuth and Yue (1987). As summarized in Tanaka (2001a), the procedure to obtain $\phi$ is the same in both versions, but there exists an important difference in the way of calculating $W$. It has to be stressed again that in numerical scheme of HOS method, the Taylor series are normally truncated at some degree of nonlinearity, and that is why it is called an approximately fully nonlinear model.

Furthermore, comparison of these two methods has been presented by Clamond et al. (2006), whose results reveal that the formulation of Dommermuth and Yue does not converge when the amplitude is very high. Otherwise, it has been demonstrated in Bonnefoy et al. (2010) that the errors reported in Dommermuth and Yue can be drastically reduced and that convergence properties are conserved up to very high nonlinearity (close to wave breaking limit) by using West formalism with careful dealiasing. Based on the above discussions, the formulation proposed by West et al. (1987) is adopted for the present study (Toffoli et al., 2008, 2010; Slunyaev et al., 2014).

In order to be convenient to directly compare with the laboratory observations, a simple numerical wave tank is set up in the following section. The free surface boundary conditions expressed by Eqs. (5) and (6) are rewritten in the following form:

$$\eta_t - W^{(1)} = F, \tag{8}$$

$$\psi_t + g\eta = G, \tag{9}$$

where $W^{(1)}$ denotes the linear vertical velocity, and $F$ and $G$ are the nonlinear parts that can be further modified by a new adjustment scheme if the initial condition is complex such as in the case of JONSWAP sea state (Dommermuth, 2000; Ducrozet et al., 2007). In short, the linear part of the equations is analytically integrated while the nonlinear part of the system is computed numerically using a classical fourth-order Runge-Kutta method with an adaptive time step. Note that, the high frequency part in the system is very stiff to solve, the

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