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On the equivalence of unidirectional rogue waves detected in periodic simulations and reproduced in numerical wave tanks

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ABSTRACT

This paper deals with the reproduction of unidirectional extreme events in a numerical wave basin. From a rogue wave measurement at a given location, experiments or numerical simulations are conducted with the same wave profiles using reproduction procedures. Although it is recognized that many different physical mechanisms may be at play in freak wave formation, reproduction procedures generally use frequency focusing to generate these high waves. This paper intends to assess the validity of this approach. In particular, it will focus on the relationship between an accurate reproduction of the free surface elevation and the accuracy of the corresponding wave kinematics inside the fluid domain. A highly nonlinear model is used to compute the occurrence of unidirectional freak waves in large periodic domain, which are reproduced in a 2-D numerical wave tank and compared. The study presents an advanced reproduction procedure that deals with rogue waves embedded in an irregular sea state. It shows that, using the appropriate reproduction procedure, it is possible to accurately reproduce free surface elevation as well as kinematics induced by this extreme event.

1. Introduction

In the open ocean, a wide variety of sea conditions may be encountered. Marine structures must be designed to withstand, even the most extreme wave fields. In this context, the existence of freak or rogue waves is now acknowledged as a possible threat for large ships or any marine structure. The New Year's wave, observed in North Sea, is the first to have been monitored and reported (Haver, 2004). It has become a reference event for a large number of studies, representing a realistic extreme event for the analysis of the response of structures to such waves, e.g. see experiments in Clauss and Klein (2011). Note that other freak waves have been monitored and reported, see the review in Kharif et al. (2008) for instance.

Wave–structure interactions are typically analyzed through experiments or numerical simulations. However, it is not always obvious how to consider the interactions with rogue waves. One possible approach is to consider a given wave field that is known to produce extreme events (by means of focusing, Benjamin–Feir instability, see e.g. Bateman et al., 2012; Zhang et al., 2014; Toffoli et al., 2013). Otherwise, the study of these interactions usually relies on the reproduction of a given measured event at sea, usually time series obtained from a point sensor installed in the ocean. From these local measurements, a complete wave field is reconstructed to coincide with data at a given location. Procedures to accurately reproduce the measured wave profile have been developed, initially in the context of wave basins, but may also be applied to numerical wave tanks (NWTs). The simplest approach is the use of frequency focusing, assuming waves are linear and unidirectional; more complex procedures attempt to account for wave–wave interactions (see Fernández et al., 2014b for a review of classical methods for wave reproduction; and Trulsen, 2000; Slunyaev et al., 2014 for development of a promising new approach).

Note that some observations with spaceborne synthetic aperture radars (SARs) are now available, offering a directional information on the wave field. However, it is for now mainly used as a source of statistical information about the wave field, i.e. to determine directional wave spectra (see Li, 2010 for instance). To assess the accuracy of such a system in the description of 3-D free surface elevation in a given sea state and consequently use it to measure/detect extreme events, extensive validations are still needed.

Thus, classical reproduction algorithms always use the dispersive character of gravity waves to create the extreme events by spatio-temporal focusing in unidirectional wave field (with possible adjustments due to nonlinear effects). However, focusing (spatio-temporal or directional) is only one of several physical mechanisms that play a key role in the formation of rogue waves, see e.g. Kharif and Pelinovsky (2003) and Onorato et al. (2013).

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Others include non-linear wave interactions (modulational instabilities), wave current interactions, atmospheric forcing, etc.

This paper evaluates the validity of this approach (reproduction with focusing), and allows good reproduction of rogue waves with respect to free surface elevation as well as wave kinematics inside the fluid domain. This is a key point in the analysis of the interaction of these extreme waves with marine structures. The latter are up to now always based on 2-D (i.e. unidirectional) wave fields for simplicity of experimental or numerical set-up. Consequently, the present study is limited to unidirectional sea states. However, note that the directional spreading is important and essential to non-linear physics (including rogue waves), see e.g. Gramstad and Trulsen (2007), Toffoli et al. (2008), and Waseda et al. (2009).

As stated earlier, data collected about rogue waves are limited to time series of free surface elevation obtained from a sensor at a given location. Thus assessment of the accuracy of the reproduced event can only be based on these data. Consequently, we have chosen to adopt a numerical approach to treat this problem. However, freak waves exhibit large amplitudes, high steepness and short duration, making their simulation still challenging. Indeed, the use of time-domain highly nonlinear potential models appears to be the most suitable approach for studying such extreme events. Note that we limit our approach to unidirectional waves evolving in finite constant depth without wind or current.

The non-linear potential model chosen is based on the High-Order Spectral (HOS) method proposed by West et al. (1987) and Dommermuth and Yue (1987). This method has been validated on several test cases, which have demonstrated its efficiency and accuracy, making it suitable for large scale simulations. It has also been applied to modeling of freak waves in Ducrozet et al. (2007), allowing us access to all information required for the description of the original extreme events: free surface elevation, induced kinematics, etc. Several physical phenomena have been studied thanks to this highly nonlinear model, e.g. non-linear energy transfers (Tanaka, 2001), modulational instabilities (Fernandez et al., 2014a; Toffoli et al., 2010a), and bi-modal seas (Toffoli et al., 2010b) among others.

From the extracted temporal signal, a reproduction procedure is set up with a numerical wave tank. In this paper, we intend to reproduce the extreme event, embedded in an irregular wave field, which reflects the conditions under which actual rogue waves appear. The wavemaker motion is deduced using non-linear phase velocity (Madsen and Fuhrman, 2012) and possible iterations are conducted for correcting the remaining phase shift. The NWT used is also based on the HOS scheme, but adapted to take into account a wave generator, reflective walls and an absorbing beach, leading to the HOS-NWT model (Ducrozet et al., 2012b). This model has already been widely validated for free surface elevation prediction as well as wave induced kinematics, with several comparisons to experiments on different sea states: from regular unidirectional waves to directional irregular sea states. Consequently, comparisons of all physical features of the 'natural' freak wave and the reproduction will be available.

In Section 2, the nonlinear potential flow models will be briefly presented in their two configurations: periodic domain and NWT. In Section 3, the embedded reproduction procedure used is discussed and applied to the well-known New Year's wave for validation. In the last part, a large periodic domain is simulated thanks to the HOS model and different freak waves are detected in this configuration. From the corresponding wave signals, the reproduction procedure is applied and both extreme events in open periodic domain and in the wave basins are compared with specific attention paid to the pressure and velocity fields at the moment of focusing.

2. Nonlinear wave models

This section presents the non-linear wave models used in the following to simulate a rogue wave appearing in periodic (open) domain (HOS-ocean) and the NWT used for the reproduction (HOS-NWT). These are based on the HOS method proposed by West et al. (1987) and Dommermuth and Yue (1987). Both models use the same core but have different initial and boundary conditions. HOS-ocean computes the evolution of a given initial wave field in a large periodic domain while HOS-NWT simulations start from rest with the waves generated thanks to a wavemaker, propagated in the closed domain (reflective walls) and possibly absorbed. More details on both methods (detailed description, validation, etc.) can be found in Ducrozet et al. (2016) and Ducrozet et al. (2012b) for HOS-ocean and HOS-NWT respectively. Note that both models are now available as open source[1,2]. The methods are presented for the 2-D problem, but extension to 3-D is straightforward, see Ducrozet et al. (2016, 2012b).

2.1. Formulation

We consider a rectangular fluid domain D of horizontal dimension L_x and constant water depth h associated with a Cartesian coordinate system. Its origin O is located at one corner of the domain with Ox axis representing the horizontal axis and Oz the vertical axis oriented upward with $z=0$ located at the mean free surface. We are working under the potential flow theory (assuming the fluid to be incompressible and inviscid and the flow irrotational). Under these assumptions, the continuity equation reduces to the Laplace equation for the velocity potential ϕ.

Boundary conditions close the system of equations. Lateral boundary conditions are specific to the problem solved (open periodic domain in Section 2.2, NWT in Section 2.3). However, in both cases, in addition to bottom boundary condition, they allow us to define a spectral basis on which the velocity potential in the whole volume will be expanded. At the same time, surface quantities are also expressed on a spectral basis allowing the use of fast Fourier transforms (FFTs). $z = \eta(x, t)$ describes the free surface position, assuming no wave breaking occurs. We consider the non-linear free surface boundary conditions (kinematic and dynamic) which are written, following Zakharov (1968), using surface quantities η and $\tilde{\phi}(x, t) = \phi(x, z = \eta(x, t), t)$ the free surface velocity potential.

These non-linear free surface boundary conditions allow us to advance in time the two unknowns η and $\tilde{\phi}$, once the so-called HOS method evaluates the unknown vertical velocity. The HOS procedure relies on a series expansion in wave steepness ϵ up to the so-called HOS order M of the velocity potential. Expanding a Taylor series around $z=0$ and collecting terms at each order in wave steepness leads to a triangular system. A similar series expansion for the vertical velocity leads to another triangular system, which is solved iteratively.

The resulting numerical method is pseudo-spectral and exhibits very interesting convergence properties. Thus, this HOS model features high efficiency and accuracy compared to other advanced methods for wave propagation, see Ducrozet et al. (2012a).

2.2. HOS-ocean

HOS models have been widely used for the study of wave propagation in open domains starting from the original work of

[1] https://github.com/LHEEA/HOS-NWT/wiki.
[2] https://github.com/LHEEA/HOS-ocean/wiki.