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Numerical modelling of wind-modified focused waves in a numerical wave tank

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A R T I C L E I N F O

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A B S T R A C T

In this paper, we extend the non-breaking second-order corrected focused wave experimental results of Sriram et al. (2015) in a numerical wave tank based on HOS in the presence of wind. The wind is modelled using the modified Jeffrey's Sheltering Mechanism (Kharif et al., 2008). We take care to preserve the consistency of application of pressure terms in the hybrid Stokesian-HOS formulations when applying wind. We confirm the results of Kharif et al. (2008) i.e. the focusing points in presence of wind show an amplification of the measure wave heights although no discernible shifting of focusing location is observed. However, compared to Kharif et al. (2008), the sheltering mechanism is found to be very weak since it depends on exceedance of a threshold slope based on constant steepness or constant amplitude spectrum. The energy flux to local phase celerity (B_x) both in absence and presence of the aforementioned wind model for the detection of onset of wave breaking (Barthelemy et al., 2015b; Saket et al., 2017b) are reported. Moreover, in the absence of wind, if B_x is used as parameter the onset of wave breaking, then for intermediate water wave groups its threshold should be close to 0.9 (computations based on Kurnia and van Groesen (2014)).

1. Introduction

A reality for all the port facilities, ship and ocean structures is that they have to be designed for extreme wave loads due to their expected periodical exposure to the extreme wave events. As such, the investigation of the occurrence of extreme wave events is a topic of active research with multiple interesting facets and lines of inquiry. One of the many reasons for the occurence of extreme wave events may be due to the result of focusing on wave energy on a very narrow area of the sea surface. Recent advances in satellite imagery (Rosenthal and Lehner, 2008) and post-facto analysis of the numerous past disasters has confirmed that there is indeed a presence of very high steep waves occasionally emerging from the seas and then disappearing. Not only are they found in a natural sea state but also in shallow waters as has recently been confirmed (Nikolkina and Didenkulova, 2011).

This class of extreme wave events based on wave-wave interactions is typically referred to as a freak or rogue waves in the literature. These are waves or wave groups that may not necessarily be associated with rough weather conditions. However, some of these conditions can create a steep wave event of considerable elevation lasting for a very short duration. This sudden magnified elevation has led to many documented accidents. On the other hand, the steepness of the rogue wave amplifies the effect of nonlinearity in wave-structure interactions. Hence, a study of nonlinearity is pertinent in such cases (Kharif and Pelinovsky, 2003).

Nonlinearity in water waves can be classified in two forms-strong and weak. Strong nonlinearity in water waves leads to enhanced role of viscosity and is routinely associated with wave breaking. However, a great deal of water wave behaviour can be explained by weak form of nonlinear equations. In fact, weak nonlinearity typically, precludes strongly nonlinear behaviour (Rainey, 2007). The weakly nonlinear form of wave equations is based upon the representation of the solution as an asymptotically ordered series. The ordering is based upon a steepness parameter representative of the steepness of the physical wave. In such a scenario, the dominant low order solutions forces the high order solutions through a mode-coupling approach. In this framework of weak nonlinearity, freak or rogue wave mechanisms have been studied in this paper.

In general, for the safe and economic operation of coastal structures and various sea going vessels, these structures must be tested for the response under extreme waves, particularly the freak ones. Usually, this testing is to be done in a wave flume. This way, the concerned mechanism is isolated and simulated in the wave flume for a detailed study of the

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generated extreme waves and their effects. The mechanisms of such focusing can be of following type, viz. geometrical, spatio-temporal dispersion, bathymetry, wave-current interactions, wind effects, modulation instabilities, etc.(Kharif and Pelinovsky, 2003).

However, it must be realised that the generation of the extreme waves in the flume is not a trivial issue. Even in the absence of the structure, the generation and study of kinematics of these extreme waves is complex, due to the nonlinearity involved. Moreover, one has to wisely decide whether to simulate the regular wave conditions or random wave tests (with different wave components in a wave spectrum). The former doesn't necessarily represent the extreme wave events while the latter does but only if the test is long enough. This is because in the random case the extreme cases occur very rarely in the time series, meaning that realisation of the extreme events is possible only for a very long simulation duration. This requirement means that one should employ a combination of passive and active wave absorption control techniques to minimise reflection at the far walls away from the wavemaker in the wave flume (Grilli and Horrillo, 1997).

Among the many mechanisms for freak waves studied by various workers, the most common class of mechanisms studied is spatio-temporal dispersion (Kharif and Pelinovsky, 2003). This class aims to produce a localised focusing in the physical space and time. Three variants of this class have been reported by Chaplin (1996). viz. group celerity method, reverse dispersion method and phase speed/celerity method. Each of these variants have their merits and de-merits with respect to their effectiveness in the type of wave groups they form and are employed for. We refer the reader to Chaplin (1996) for a detailed review.

In this paper, however, we employ the third variant i.e. the phase speed method. Due to its simplicity and ease of replication, this method can be easily simulated in the wave flume. This method was first proposed by Longuet-Higgins, who specified a range of wave components (primary components) and synchronized their initial phases in such a way to produce a constructive interference at a given spatial location and a specified time. This constructive interference focuses the various components' energies, thus producing an extreme wave event. Subsequently, Rapp and Melville (1990) used this mechanism for their experimental investigation of breaking waves. Many other workers have used this mechanism for breaking process or its interactions in finite water depth (Kway et al., 1998; Adcock and Taylor, 2009; Li et al., 2015; Kharif and Pelinovsky, 2003) as well. For a recent review of breaking wave process with this mechanism, the reader is referred to Perlin et al. (2013).

Although the abovementioned mechanism is based upon a linear constructive interference, due to concentration of energy in the focused area, a local rise in the steepness is expected. This increase in turn accentuates the nonlinear interactions that were otherwise suppressed in the linear case. Baldock et al. (1996) have shown that the nonlinear interactions among the components will produce higher crests along with the underlying kinematics of crest steepening.

In general, the more the influence of the nonlinear interaction among the primary components, the greater is the generation and influence of the super-harmonic and sub-harmonic components in the final wave field (Longuet-Higgins, 1970; Longuet-Higgins and Stewart, 1964). The super-harmonic components (i.e. the high frequency components) will sharpen the crests while flattening the troughs in the wave field. On the other hand, sub-harmonic components (i.e. the low frequency ones) are responsible for the global perturbations in the mean water level. Hence, for producing focused wave packets wherein nonlinearity plays a major role, a correct reproduction of super and sub harmonics is pertinent. This is, however, easier said than done. A detailed review of the second-order wavemaker theory (Hughes, 1993) unequivocally finds that linear paddle displacement of the wavemaker in a wave flume, apart from generating the sub and super harmonic component, also generates a spurious free wave component (Hudspeth and Sulisz, 1991). Hence, the suppression of spurious free wave component should be effected by modifying the wavemaking signal (Schäffer, 1996). Due to the fact that linear wavemaking is dependent upon the linear dispersion relationship, the suppression signal has to be applied at higher orders.

Instead of laboratory experiments, it is also quite possible to simulate these extreme cases in a numerical wave tanks (NWT). The two main formulations in this regard have traditionally been the fully nonlinear potential theory (FNPT) and Navier-Stokes (NS) equations. The former is relatively computationally efficient than the latter, although the latter is quite well suited to breaking processes than the former. This has prompted studies that use hybrid coupling between the two wherein the computational efficiency of FNPT is exploited in areas away from breaking where NS equations are employed. Within the context of focused waves in NWTs, many studies can be cited (see Sriram et al. (2015) for a list). However, except for Sriram et al. (2015) all of them used linear control signals for the wavemaker and compared their results according to linear or second order results. The paddle motion in this paper is, however, based upon a second order corrected signal (Schäffer, 1996) as reported in Sriram et al. (2015). For the purpose of comparisons with the numerical model, we report the output of linear signals as well.

We simulate extreme wave events in NWTs wherein we employ an extension of a numerical model for surface waves, called High-Order Spectral (HOS) method (Dommermuth and Yue, 1987; West et al., 1987). This method relies upon weak asymptotically ordered series expansion of the wave field. It differs from the classical Stokes expansion in the sense that perturbations are performed in the local physical space as opposed to the functional space for Stokes expansion. This flexibility eases computations of arbitrary ordered expansions of the wave field. Moreover, the trial functions at each order of expansion are simply taken the same as basis functions of the fourier series. In this way, fast fourier transforms (Cooley and Tukey, 1965) can be deployed for computations, thus making large simulations computationally feasible with reasonable costs. However, a reformulation of the HOS method is required to extend its applicability to non-periodic boundary value problems like a numerical wave tank (NWT). For a discussion on the details of HOS method along with its extension to a numerical wave tank (NWT), the reader is referred to section 3. The results of the simulation have been obtained by deploying an open source computer code called HOS-NWT (Ducrozet et al., 2012). This code has been modified accordingly, for the purpose of this study.

Furthermore, following Sriram et al. (2015), we employ wavemaking signals developed by Schäffer (1996) for irregular waves in order to suppress the spurious free wave generation that pollute the nonlinear interaction among the primary components. Using the mechanical generation of water waves by a piston-type paddle in HOS-NWT along with these control signals to the wavemaker, we are able to maintain the one-to-one correspondence between the HOS-NWT results and laboratory experiments of Sriram et al. (2015). This allows us to extensively validate HOS-NWT with the non-breaking cases of Sriram et al. (2015) (henceforth, referred to as SR15).

Going further, we then simulate these non-breaking cases in HOS-NWT in presence of a wind model to see their evolution as a case of wind-wave interaction. This is in the same line of investigation as in Kharif et al. (2008). Therein, the authors tested a range of focused waves in a wave flume in the presence of wind. It was shown that Jeffrey's modified sheltering mechanism (Jeffreys, 1925) gave much better results in case of the growth of focused waves in Kharif et al. (2008). As such, this study also uses Jeffrey's modified sheltering mechanism as the wind model in the investigation of wind-wave interactions for focused waves. The point of difference between this study and Kharif et al. (2008) is the method of focusing. While Kharif et al. (2008) used the group celerity method for a chirped-type gaussian wave packet, this study uses a constant steepness spectrum with phase speed method for focusing (see section 5 for details).

Apart from this methodology, this study tries to answer three key questions. Firstly, the modifications in HOS-NWT theory are explored so as to order the pressure generated by Jeffrey's sheltering mechanism in a