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The evolution of free and bound waves during dispersive focusing in a numerical and physical flume

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ABSTRACT

Since the introduction of the NewWave theory (Lindgren, 1970), focused wave groups are used in physical and numerical studies to investigate the interaction of marine structures and ships with extreme waves. The propagation of such wave groups is associated with high order nonlinearities that can cause considerable deviations from linear and 2^{nd} order predictions. Consequently, nonlinear numerical models or laboratory tests are needed to accurately describe the evolution of focused wave groups. In the present study, we validate a widely used two-phase Reynolds Averaged Navier-Stokes (RANS) solver realised in OpenFOAM with experimental results for the propagation of steep focused wave groups, using a newly developed methodology based on the separation of harmonics. This approach allows for accurate focusing of wave groups and in-detail examination of the individual evolution of the high order terms, as well as identifying the source of discrepancies between experiments and numerical models. The wave groups comprise long-crested broadbanded Gaussian spectra of increasing steepness propagating in intermediate water depth. The contribution of the nonlinear harmonics to the crest height and overall shape of the wave are also discussed, together with the effect of nonlinear wave interactions on the free-wave spectrum. The rapid growth of 3^{rd} and 4^{th} harmonics near focusing as well as the evolution of the free-wave spectrum, cause departures of up to 29% and 22% from analytic linear and 2^{nd} order predictions. The present results demonstrate that RANS-VoF solvers constitute accurate models to propagate nearly breaking waves.

1. Introduction

The accurate definition of a design wave for offshore structures, vessels and coastal structures is vital for their survivability, preventing sea accidents with environmental consequences and human losses (Haver, 2000). For a sea state with a given spectrum, the average shape of the largest and steepest non-breaking wave crests can be represented by a theoretical wave form, which is the normalised autocorrelation function of a random ocean surface based on the underlying spectrum scaled by the crest amplitude (Tucker, 1999). When the distribution of the sea surface elevation follows a Gaussian process, this corresponds to the NewWave model, which has been traditionally used for offshore applications, but building on the deep water results, transient wave groups were also studied for intermediate and shallow water depth (Baldock and Swan, 1996). Recently, the validity of NewWave has been confirmed for the coastal zone as well (Whittaker et al., 2016; Whittaker et al., 2017) and the method was used to study wave - seawall interaction problems (Sun and Zhang, 2017). Assuming linearity by omitting nonlinear wave interactions and their effect on the underlying spectrum, a NewWave-type wave form is generated when all the components of a wave group come into phase (Tromans et al., 1991). This has been evidenced by a recent field study where the occurrence of extreme wave crests was found to be linked to the dispersive focusing of the most energetic wave components (Christou and Ewans, 2014). The theoretical background on the NewWave theory and its applications in coastal engineering are explained in more detail in the Appendix.

The majority of the studies regarding the evolution of unidirectional wave groups in experimental and numerical wave tanks (NWTs) demonstrated that dispersive focusing of unidirectional wave groups leads to a wave crest at focus, the shape and elevation of which is not predicted by either linear or 2^{nd} order wave theory (Baldock et al., 1996; Gibson and Swan, 2007; Johannessen and Swan, 2001; Johannessen and Swan, 2003; Shemer et al., 2007). This is an effect of high order nonlinearities in large transient waves, namely the bound and resonant nonlinearities (Gibson and Swan, 2007). Bound nonlinearities are caused by the emergence of nonlinear harmonics that are phase-locked to the

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wave group and they tend to sharpen the free surface profile. On the other hand, resonant interactions cause redistribution of energy within the wave spectrum by altering the phases and amplitudes of the linear components of the underlying spectrum and practically new free wave components are generated that satisfy the dispersion relation, as shown by Philips (Phillips, 1960). A noticeable effect of resonant interactions is the deterioration of the quality of focusing for increasing steepness of the wave group, manifested as downshifts of the spatial and temporal focus location (Baldock et al., 1996; Ning et al., 2008). The aforementioned bound and resonant nonlinearities have been shown to result in crest elevations higher than 2^{nd} order Stokes predictions for unidirectional focused wave groups in deep water (Johannessen and Swan, 2001; Johannessen and Swan, 2003), while for intermediate water depth they yield crest elevations lower than linear predictions (Katsardi and Swan, 2011).

It is worth mentioning that the exact resonant interactions cannot be realised in 1D (unidirectional) propagation, because the resonant conditions of the four-wave interaction, i.e. $k_1 + k_2 = k_3 + k_4$ and $\omega_1 + \omega_2 = \omega_3 + \omega_4$, where k_i and ω_i are the wavenumber and angular frequency of a wave component respectively, cannot be satisfied (Janssen, 2003). For 1D propagation, non-resonant interactions, which can evolve in short time scales, are of particular importance. Typical examples of such nonlinear effects include the instabilities in regular wave trains reported by Benjamin and Feir (1967) for narrow-banded spectra, also known as BF instabilities. For broadbanded spectra and long-term evolution of 100 T_p, where T_p is the peak period, resonant interactions tend to increase the bandwidth of the spectrum, as reported by Hasselmann (1962). Complementary to Hasselmann's observations, Gibson and Swan (2007) showed that for focused wave groups, changes to the wave spectrum similar to those of long-term evolution can occur rapidly and locally near the focal location within 3–5 wave cycles.

Consequently, the capacity of a NWT to simulate focused wave groups depends primarily on the accuracy of the numerical dispersion and the accurate calculation of wave-wave interactions. The former directly affects the quality and time of focusing and the latter the shape of the spectrum at focus. A NWT designed for steep waves should be able to account for higher than 2^{nd} order interactions and if wave breaking is involved, to provide the fully nonlinear solution of the problem. For industrial applications in the oil & gas and offshore renewable energy sectors, 3-Dimensional (3D) RANS solvers combined with surface capturing algorithms, like the Volume of Fluid (VoF) method (Hirt and Nichols, 1981), are the standard for wave-structure interaction problems examined with Computational Fluid Dynamics (CFD) tools. Good alternatives are nonlinear potential flow (NPF) solvers (e.g., Johannessen and Swan, 2003 and Ning et al., 2009) and Smoothed Particle Hydrodynamics (SPH) (e.g., Dao et al., 2001), but the latter are not broadly used in industry yet (Lin, 2008). The aforementioned fully nonlinear models provide the solution for the velocity potential and surface elevation, without any division in free and bound waves. On the contrary, weakly nonlinear wave models, solving for example the nonlinear Schrödinger equation (NLSE), yield the wave field as the variation of the free-wave regime and the bound waves calculated explicitly from former, but they have inherent limitations for studying fluid-structure interaction problems. Therefore, the use of CFD, SPH and NPF codes has gained ground in industry and research despite the high computational cost. This is especially the case for CFD and SPH, which unlike NPF, can also simulate breaking waves and green water effects.

A widely used and acknowledged open-source realisation of RANS models for industrial application is OpenFOAM, which comprises a CFD package for simulating continuous mechanics problems. Regarding the use of OpenFOAM in coastal and offshore engineering, recent research concerns the modelling of transient wave groups (Bredmose and Jacobsen, 2010; Chen et al., 2014; Higuera et al., 2015), but in most cases discrepancies with experimental results are reported, especially for steep wave groups. In previous studies, the reproduction of the steepest and highest NewWave-type focused wave group was limited mainly by the lack of an appropriate correction methodology for the input signal when a CFD model was used and to a lesser extent by the nonlinearity of the wave model when weakly nonlinear models were employed, e.g., Bateman et al. (2001), Katsardi and Swan (2011), Shemer et al. (2007). Here, we exploit the full capacity of the nonlinear solver to examine the spectral evolution by employing a highly controlled wave generation method (Stagonas et al., 2014) that guarantees accurate focusing of the wave group at a predetermined position in space and time in the NWT and simultaneously by conducting a thorough convergence study. The performance of a RANS/OpenFOAM NWT is compared with experimental measurements for a nearly breaking wave group based on a broadbanded Gaussian amplitude spectrum in intermediate water depth. The measured spectra are decomposed into their linearised part, quadratic sub- and super-harmonics, 3^{rd} and 4^{th} order harmonics and their propagation is examined separately. Such a detailed examination of the individual harmonics is useful for practical applications, such as overtopping (Orszaghova et al., 2014) and ringing (Fitzgerald et al., 2014). Wave groups of different steepness are employed to study the relative growth of the nonlinear harmonics.

In the remainder of the paper, the testing conditions and the focusing methodology are presented in Section 2 and the numerical solver is described in Section 3. In Section 4, the validation of the NWT is presented. Also, the spectral evolution and the contributions of high order harmonics to the crest elevation are discussed and compared with analytical solutions. The paper closes with concluding remarks and future work.

2. Wave focusing method and testing conditions

2.1. Generation of focused wave groups

The most challenging aspect of the accurate generation of focused wave groups is the appropriate selection of the amplitudes and phases of the wave components at the inlet. Previously, linear wave theory (Rapp and Melville, 1990), experimental observations (Baldock et al., 1996), Zakharov's equation (Shemer et al., 2007) and iterative techniques to calculate the required input phases (Chaplin, 1996) or both the phases and amplitudes (Schmittner et al., 2009) have been proposed. Other advanced methods employed NPF models (Fernández et al., 2014) and pseudo-third-order corrections (Alford and Maki, 2015). In general, the performance of these approaches reduces considerably as the nonlinearity of the wave group increases.

The new methodology for the highly accurate generation of focused waves (Stagonas et al., 2014) tackles the issues of previous techniques. The main difference with other methods is the use of linearised target spectra instead of the full target spectrum as the initial condition at the wave paddle and the utilisation of spectral/harmonic decomposition. The latter is applied on nonlinear wave records to separate the components of various harmonics corresponding to the orders of Stokes expansion. Johannessen and Swan (2003), among others, combined crest and trough focused waves to extract even and odd harmonics of the signal, but Stagonas et al. (2014) also added positive and negative slope focused waves to clearly separate 1^{st} (linearised part) from 3^{rd} and higher order components, and 2^{nd} sum from 2^{nd} difference terms, with a similar approach as that used for the harmonics of the forces on cylinders (Fitzgerald et al., 2014). The same approach is adopted here through the following application steps:

- The desired linearised target spectrum, focus point and time are selected and for the same amplitude spectrum, crest focused (CF), trough focused (TF), and positive and negative slope focused waves are generated.