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Focused wave evolution using linear and second order wavemaker theory

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ABSTRACT

In this paper, the evolution of focused waves using different paddle displacements (piston type) under laboratory conditions is presented. It is well known that in intermediate water depths, linear paddle displacements will generate spurious, free, sub and super harmonics. Thus, a second order correction to suppress these spurious free sub and super harmonics was used to generate the focused waves. The focused waves were generated in the laboratory using a linear superimposition principle, in which the wave paddle displacement is derived based on the sum of a number of sinusoidal components at discrete frequencies, whose phases are accordingly set to focus at a particular location. For this method of generation, the second order wave maker theory proposed by Schäffer [24] can be easily adopted and was used in the present study. Two different centre frequencies ($f_c = 0.68$ Hz and 1.08 Hz) with three different bandwidth ratios ($\Delta f/f_c = 0.5, 0.75$ and 1.0) were tested in a constant water depth, to consider both narrow and broadband spectra. These test cases correspond to wave focusing packets propagating in intermediate and deep water regions. Further, for each wave packet, two different amplitudes were considered in order to analyze non-breaking and breaking cases. Thus, by systematically generating the wave packets using the linear and second order paddle displacements, the analysis was carried out for the spectral and temporal evolution of selected long waves. The temporal evolution of the selected harmonics was analyzed using the Inverse Fast Fourier Transform (IFFT), to show the propagation of the spurious, free, long waves. Further, the variations in energy for the lower, higher and primary frequency ranges are reported for different wave paddle displacements. The analysis revealed that for the broadband spectrum the differences are more pronounced when using linear paddle displacements. We have also noticed a shift in focusing/breaking location and time (i.e. premature) due to the increase in crest height using linear displacements. The experiment data used in this paper has been provided as a supplementary, which can be used to validate the numerical models.

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1. Introduction

For many centuries, there are numerous reports on the mysterious surge of water that causes failure in offshore, ship and the violent waves that causes failure for coastal structures. Hence, the extreme events should also be taken into account for the design. Recent advances in satellite imagery and the analysis of numerous past disasters based on data from ships and offshore structures have shown that there is indeed a presence of very high steep waves that occasionally emerge from the seas and then disappear. These waves are also noticed in a natural sea state and very recently in shallow water depths [1].

Thus, in ocean and coastal engineering, the safe and economic design of any ocean going vehicle or any installation needs an accurate description of the interaction of these extreme waves with the structure. Even in the absence of the structure, the generation and the study of kinematics of these extreme waves is complex, due to the nonlinearity involved. Normally, a structure is tested in the laboratory for regular or random waves. But, regular wave tests will not represent the extreme events, whereas, random wave tests (having different wave components in the spectrum) only sometimes represent these extreme conditions, provided the tests are long enough. However, besides that these extreme cases occur only very rarely in a random time series, testing in a physical flume for a long time requires a good passive and active absorption control (i.e. beach at the other end of the flume and wave maker absorption), which itself is an active area of research since many decades.

Another method for extreme wave simulation is based on the nonlinear wave–wave interaction as first proposed by

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Longuet-Higgins [2]. In this method, a specified range of wave components (primary components) are generated and their phases are adjusted, in such a way that at a certain point in time the individual wave components are focussed at a specific location. Thus, a large wave height occurs due to constructive interference. This technique of the nonlinear wave–wave interaction has been used for the experimental investigation of the breaking wave process by Rapp and Melville [3]. Using the wave focusing mechanism, the breaking wave process or its interactions was also studied by many authors in finite water depth [4–10]. Recent reviews about the breaking wave process using the focusing mechanism are given in Perlin et al. [11]. Baldock et al. [12] showed that the nonlinear interaction of the different components will produce significant increase in both crest elevation as well as the underlying kinematics. They also showed that the nonlinear interaction is of 3rd order, and demonstrate that the linear and second order wave theories may underestimate both the maximum water surface elevation and the maximum horizontal velocity by 30–40%. Kit et al. [13] reported on the nonlinear wave evolution in shallow water wave groups and quoted that the influence of the spurious free components generated by the paddle motions are negligible. However the reported results are only for narrow banded spectra.

Instead of laboratory experiments one can also use numerical modelling to simulate these extreme cases. For the numerical models, normally called as numerical wave tanks (NWT), two general approaches to simulate the experimental wave tank exist, one using fully nonlinear potential flow theory for steep nonlinear waves until wave breaking and the other using Navier–Stokes equations, if the breaking process is under investigation. Many authors have used NWTs for focused wave simulations, like Fochesato et al. [14], Yan and Ma [15], Turnbull et al. [16], Ning et al. [17], Bai and Eatock Taylor [18], Chalikov [19], Chalikov and Babanin [20] and very recently, using hybrid coupling of the potential flow and NS equations [21]. In all those previous studies, the above authors either used wave paddle control signals based on linear wavemaker theory or they used a linear or second order solution as an initial condition for the generation of these waves.

In general, the nonlinear interaction of the primary components (the given wave frequency components) will produce super harmonic and sub harmonic components, as reported by Longuet-Higgins and Stewart [22]. The super harmonic terms are basically high frequency components that alter the local characteristics of the wave group (sharpening of wave crest and broadening of wave trough), whereas, the low frequency components (sub harmonics) correspond to global interactions (the perturbation of the mean water level). Hence, for producing the wave packets or groups, a correct reproduction of super and sub harmonics in the laboratory flume is mandatory. For this it is necessary to use second order wavemaker theory, because the linear paddle displacement does not correctly produce these lower and higher harmonic components (Barthel et al. [23] or Schäffer [24]). More details about the advantages and disadvantages of the second order wavemaker theory can be referred elsewhere, e.g. Hughes [25].

The evolution of focusing waves in intermediate water depths has been studied by Baldock and Swan [26]. Wherein, the authors used deepwater wave characteristics at the wave maker and allowed the waves to propagate in decreasing water depth. They demonstrated that as the water depth reduces, there is a significant redistribution of energy to the long wave components, or frequency-difference terms [22]. This is similar to the work carried out by Mansard et al. [27] or Daemrich and Götschenberg [28] who suggested that if the wave-induced kinematics are to be reliably predicted for shallower water depth, the second order frequency-difference terms should be included either using second order wave maker theory or by a self correcting algorithm. It should be noted that while using first order wavemaker theory (e.g. Hughes [25]) these sub and super harmonics are not provided and due to the mismatch of the water particle kinematics and the wave paddle velocity (piston type, most widely adopted), spurious, free, harmonics will also be generated apart from the actual sub and super harmonics. Thus, second order wave paddle displacement is required as argued by Schäffer [24] to remove the generated spurious free components. The coupling of the numerical model with the physical model using second order wavemaker theory has also been attempted by Yang et al. [29]. Very recently, Borthwick et al. [30] generated focusing waves in intermediate water depths using linear wavemaker theory and showed that the spurious free harmonics (or error waves as quoted by them) are passing either before or after the main focusing event and they do not influence the main waves. For their analysis they used separation of harmonics based on group inversion by examining the odd and even components of the velocities [31]. However, they failed to answer about the deviation of the sub and super harmonics generated by the linear wavemaker theory with the theoretical predictions. Further, the influence of the generated spurious free, sub and super harmonics or error waves on the shape of the resulting transient profile is still unknown. Particularly, if the shape of the profile changes those waves might play a major role in the interaction with a structure and the breaking process as well. Moreover, it is known that using linear paddle displacements, the bound components will automatically evolve, however the influence on the spectrum bandwidth is unclear. This paper is an attempt to answer these questions.

Based on the foregoing discussion, focusing waves will be generated using linear and second order paddle displacements for the corresponding input characteristics both in deep and intermediate water depths. Based on this the differences as well as the evolution of focusing waves using the different generation methods can be explicitly quantified. For the generation of focusing waves using second order wave maker theory the method provided by Schäffer [24] is adopted. The paper is organized as follows. Initially, the different methodologies for the generation of focused waves are reported, followed by a brief overview of the adopted wavemaker theory along with experimental test cases. The test cases cover a wide frequency range from narrow to broadband spectra, in both deep and intermediate water depths. The analysis of the experimental data has been carried out in the frequency domain as well as in the time domain in order to study the behaviour of the spurious free waves.

2. Methodology of generation

Extreme waves can occur due to four different processes, wave–current interaction, wave–bottom interaction, wave–wave interaction (i.e. linear superposition and phasing of different wave components) and more recently, wind-wave interaction [32]. In this paper, the extreme wave events based on the process of (non)linear superposition and phasing of different wave components (wave–wave interaction), also referred to as “wave focusing” is considered exclusively. As reported in Chaplin [33], three distinct generation approaches are available.

1. The group celerity method.
2. The reverse dispersion method.
3. The phase speed method.

In the group celerity method, the wave paddle displacement can be computed from the requirement that the instantaneous group celerity should at all times be what is needed to convey the wave energy to the focus point in the time remaining, before the appearance of the focused wave. Chaplin et al. [34] quoted that when reflections are large this method works successfully. In the reverse

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