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Linear irregular wave generation in a numerical wave tank

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ABSTRACT

In the design of any floating or fixed marine structure, it is vital to test models in order to understand the fluid/structure interaction involved. A relatively inexpensive method, compared to physical model testing, of achieving this is to numerically model the structure and the wave conditions in a numerical wave tank. In this paper, a methodology for accurately replicating measured ocean waves in a numerical model at full scale is detailed. A Fourier analysis of the measured record allows the wave to be defined as a summation of linear waves and, therefore, Airy's linear wave theory may be used to input the wave elevation and associated water particle velocities. Furthermore, a structure is introduced into the model to display the ability of the model to accurately predict wave–structure interaction. A case study of three individual measured waves, which are recorded at the Atlantic marine energy test site, off the west coast of Ireland, is also presented. The accuracy of the model to replicate the measured waves and perform wave–structure interaction is found to be very high. Additionally, the absolute water particle velocity profile below the wave from the numerical model is compared to a filtered analytical approximation of the measured wave at a number of time-steps and is in very good agreement.

1. Introduction

In real ocean conditions the waves are not linear or even regular in form. Therefore, it is necessary to develop a method of generating a wave which accurately represents real sea conditions. In general, when a measuring wave buoy records a wave, the wave energy spectrum is generated for that record and over time a catalogue of wave energy spectra are analysed for that site to formulate a single wave energy spectrum which is used to represent the wave climate of a given sea or ocean region. From this spectrum, a Fourier transform may be used to derive an irregular linear wave profile which represents typical waves at the location.

In this study, measured wave elevation records from a location are used and recreated. The main principle being used is the theory that real ocean waves are accurately represented by a linear irregular wave. However, these generated waves may not be an accurate representation of the typical wave climate but are, in fact, replications of real measured records. In other words, single samples are analysed and replicated and are not representative of the long-term wave climate. A major advantage of this is that extreme or exceptional wave conditions recorded at a location can be recreated accurately.

Various numerical modelling techniques, such as the boundary element method (BEM) [2,4,9,12,15,18], finite element method (FEM) [3] and finite volume method (FVM) [5,11,13,14,16,17], can be employed to represent linear irregular waves and nonlinear motions of floating bodies in water. A summary of selected relevant publications which explore wave generation and wave–structure interaction, particularly concerning irregular wave generation, are presented in Table 1. The commercial software packages used to implement the study are specified. However, where in-house software code was used, no software package is specified.

In recent years, a number of studies were performed using commercial software packages (see Table 1), which are based on the Reynolds averaged Navier–Stokes equations. For example, Lal and Elangovan [11] explored the CFD simulation of linear water waves for a flap-type wavemaker using the same finite volume package described in this study. However, the dimension of the model was taken as an experimental wave tank and simulations were only carried out for the shallow water case. Finnegan and Goggins [16] presented a methodology for developing an optimum numerical wave tank model which can accurately generate linear water waves and perform wave–structure interaction. In this methodology, the overall dimensions, the model mesh, the time-step and the method of wave energy dissipation at the end of the model are analysed and optimised. Yu and Li [17] used a Reynolds averaged Navier–Stokes based CFD method to explore the relative response of a two-body floating-point absorber in linear regular waves, in terms of its power generation capacity. Liang et al. [13] explored the

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Table 1
Summary of selected publications (including present study) detailing wave generation and wave–structure interaction.

Reference	Numerical method	Commercial software package	Reg/Irr waves	Wave generation method	Nonlinear waves	Wave–structure interaction
Kim et al. [1]	FDM	–	Reg, Irr	Flap-type wavemaker	√	–
Boo [2]	HOBEM	–	Reg, Irr	Numerical	√	√
Turnbull et al. [3]	FEM	–	Reg	Numerical	√	√
Koo and Kim [4]	BEM	–	Reg	Numerical	√	√
Park et al. [5]	FVM	–	Reg, Irr	Numerical	√	√
Wu and Hu [6]	FEM	–	Reg, Irr	Piston-type wavemaker	√	√
Hadzic et al. [7]	–	Comet	–	Numerical	√	√
Sriram et al. [8]	FEM	–	Reg, Irr	Piston-type wavemaker	√	–
Ning and Teng [9]	HOBEM	–	Reg, Irr	Numerical	√	–
Agamloh et al. [10]	–	Comet	Reg, Irr	Piston-type wavemaker	√	√
Lal and Elangovan [11]	FVM	ANSYS CFX	Reg	Flap-type wavemaker	–	–
Ning et al. [12]	HOBEM	–	Reg	Numerical	√	–
Liang et al. [13]	FVM	FLUENT	Irr	Piston-type wavemaker	√	–
Elangovan [14]	FVM	ANSYS CFX	Irr	Flap-type wavemaker	–	–
Yan and Lui [15]	HOBEM	–	Reg	Numerical	√	√
Finnegan and Goggins [16]	FVM	ANSYS CFX	Reg	Flap-type wavemaker	–	√
Yu and Li [17]	FVM	STAR-CCM+	Reg	Numerical	–	√
Present study	*FVM*	*ANSYS CFX*	*Irr*	*Numerical*	–	√

BEM: boundary element method, FDM: finite difference method, FEM: finite element method, FVM: finite volume method, HOBEM: higher-order boundary element method, Irr: irregular waves studied, Reg: regular waves studied.

use of a piston-type wavemaker to generate an irregular wave train using the finite volume method, using FLUENT, and compared the results to the results from that of an experimental wave tank. Elangovan [14] extended the work of Lal and Elangovan [11] to simulate irregular linear waves using a flap-type wavemaker in a wave tank, which is based on an actual experimental wave tank. The method is validated by comparing the output wave spectrum to the original. Agamloh et al. [10] used a commercial CFD software package to develop a 3-D numerical wave tank, which allowed fluid–structure interaction of a water wave and a cylindrical ocean wave energy device to be explored. Both the response of a single device and the response of an array of devices were investigated.

In this paper, a CFD numerical wave tank model, developed using the commercial finite volume method package ANSYS CFX, is presented for replicating measured real ocean waves at full scale. The fast Fourier transform is utilised in order to create an input wave, together with its associated water particle velocities, which replicates a measured wave record. The wave was recorded at the Atlantic marine energy test site (AMETS) [54.225 N, −9.991 W], as shown in Fig. 1. Three different wave records are replicated and compared with the measured wave in the time domain, as well as their corresponding wave energy spectra. Additionally, the absolute water particle velocity profile below the wave from the numerical model is compared to the filtered analytical approximation of the measured wave. Furthermore, a rectangular prism structure is introduced into the model in order to explore the interaction between a linear irregular ocean wave and a structure. The dynamic response of the structure to the linear irregular wave is compared with the analytical prediction, which is derived from a hydrodynamic analysis.

2. Methodology

In this section, the methodology for replicating a measured wave in a CFD model is described. Offshore ocean waves are irregular and random in nature with each different to the previous. For the most of the time, offshore ocean waves may be described as linear irregular waves and this is the type of wave which is being detailed in this study. It is acknowledged that when dealing with near-shore waves this is not always true, as a number of significant non-linearities are introduced due to the interaction of the wave with the coastline and the seabed. Similarly, there can be non-linearities associated with extreme wave conditions. However, these scenarios are outside the scope of this study.

The measured wave records, which are to be replicated in this analysis, have been recorded at the Atlantic marine energy test site (AMETS) off Belmullet, Co. Mayo, Ireland [19]. A map detailing the location of the wave data buoy at AMETS, which is located at 54.225 N, −9.991 W, is shown in Fig. 1. AMETS has been selected for the full-scale testing of pre-commercial wave energy devices. The site itself provides facility for the testing of near-shore, intermediate-water and offshore devices. It was selected principally due to its deep water with sandy seabed close to shore, the quality of its wave climate, the onshore infrastructure and the suitable grid connection. A Fugro Wavescan buoy is used to record the real-time wave data and is located approximately 3 km offshore in water depth of 50–100 m. The measured wave records are taken over a half hour time frame and three records are used in the analysis. Data recorded over 2 years at AMETS is used in the case study analysis discussed in Goggins and Finnegan [20].

The initial part of the study is to analytically describe the measured wave by using an irregular linear wave, which is comprised of a summation of a number of linear waves. This analytical approximation is then employed in the CFD model, which is implemented in the commercial software package ANSYS CFX [21]. The software uses a finite volume method in order to solve the Reynolds Averaged Navier–Strokes equations (RANSE), which accounts for turbulence and viscosity. Its governing equations are described in Section 2.1. ANSYS CFX offers increased user flexibility, compared to similar commercial codes, with a well-developed graphical user interface and the option of an expression language, along with user defined functions written in FORTRAN. Additionally, ANSYS CFX uses a node centred solver, which offers increased accuracy compared to more common cell centred solver. However, since the analysis is performed on an ANSYS academic licence, there are a number of limitations, including the maximum geometry dimension is 500 m and there is a node limit of 512,000 nodes, which is approximately 1.2×10^6 elements, which restricts the dimension of the fluid domain. In order to replicate the wave accurately at the desired location, an input wave with corresponding water particle velocities is derived and used as the input in the CFD model.

In order to validate the accuracy of the solution, the analytical wave and the output wave from the CFD model are compared in the time domain. In addition, the wave energy spectrum from the