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Investigation into wave basin calibration based on a focused wave approach

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ABSTRACT

The purpose of this paper is to present a detailed numerical investigation concerning the calibration of force controlled wave generation facilities. The methodology is presented for a 2-dimensional calibration; the findings being equally applicable to the calibration of 3-dimensional wave basins. State-of-the-art force controlled wavemaking facilities comprise sophisticated hardware, software and control systems, commonly incorporating active absorption mechanisms. Such facilities have the potential to reproduce ocean wave of exceptional quality, but poor understanding of accurate calibration processes often hinders full exploitation. A technique based upon the generation of focused wave events may offer a very accurate and time-efficient calibration. However, such a methodology may lead to erroneous results if not employed correctly. The theoretical and statistical analysis presented herein investigates the sensitivity of such method to a number of important parameters. The results obtained are directly applicable to a large number of hydrodynamic facilities.

1. Introduction

Tank testing is a key research and development tool in many fields of marine engineering. These include naval architecture, coastal engineering, the offshore oil and gas industry and more recently the marine renewable energy sector. Experimental work in these fields comprises, but is not limited to, wave breaking, extreme wave loadings and large amplitude motions of floating bodies. The complexity of these physical phenomena often means that their theoretical or numerical modelling is still challenging and experimental data are therefore required for design purposes or for validating the models. Tank testing makes it possible to obtain these experimental results in an accessible and controlled environment at only a fraction of the cost of sea trials.

An important aspect of tank testing is the control of the wave generation process. A large proportion of wave tank testing facilities are equipped with force controlled wavemakers of the type developed by the company Edinburgh Designs (www.edesign.co.uk). More than 85 wave basins across 23 countries are indeed fitted with Edinburgh Designs wave making apparatus which amount to over 1 500 wave paddles worldwide. The force control feature of this wave making technology allows active wave absorption and the generation of spectra of waves with a high degree of fidelity but it also means that the apparatus must be considered as a hydrodynamic feedback system. As a dynamic electromechanical device, the generation system will react differently to each input frequency. If left uncorrected the dynamic phenomena will result in unexpected wave generation that does not match the desired input from the user. However by identifying and subsequently correcting for the tank's dynamics, accurate and repeatable recreation of the desired sea state can be achieved. Such a tank is said to be calibrated, thus the process of identifying the proper correction factors is known as calibration. Because the underlying dynamics of each tank are a function of the entire system, the response of a particular tank is unique and requires a unique set of correction factors.

To some extent, the operation of force controlled wave machines can be derived theoretically. Spinneken and Swan (2009a) derived a theoretical relationship (also referred to as 'transfer function') between the input signal to the wave generation system and the resulting wave generated for wavemakers controlled in force-feedback, accounting for second order wave effects. The validity of their theoretical analysis was investigated in Spinneken and Swan (2009b), and an extension of their theory appropriate to the operation of 3D wave basins is presented in Spinneken and Swan (2012). In the context of these theoretical formulations, second-order wave effects include both second-order wave-wave interactions and second-order wave-structure interactions due to the presence of the wavemaker. These interaction models are developed as perturbation expansions of the potential flow governing equations,

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which are then truncated at the second-order of the expansion parameter (usually the wave steepness), and subsequently solved analytically. Even without taking into effect realistic wave tank effects such as transfer function discontinuities, this leads to very challenging analytical problems. To date, there is no consistent framework that addresses both second-order wavemaker effects and realistic tank effects.

A theoretical calibration function is a good starting point but it is often useful to refine it experimentally given that the theoretical models do not generally account for every single aspect of the complex electromechanical process of wave generation. The most common way to calibrate wave tanks is based on regular waves. In this method, one regular wave is produced in the tank at a time, and the tank output is compared with the desired user input to determine the appropriate correction factor. The process is then repeated for a range of frequencies. The regular wave method is highly accurate and generally easy to perform, but can be time-consuming to implement fully as the calibration is carried out for only one frequency component at a time. Compounding the problem, three or more iterations of the process may be necessary to determine the correction factors with a high degree of accuracy. In a three-dimensional wave basin the calibration must be performed separately over a range of directions.

A less time-consuming alternative to the regular wave approach is to generate a spectrum of waves at the desired calibration frequencies concurrently in the tank. The resulting sea state can then be compared with the desired spectrum, and correction factors for each frequency can be calculated simultaneously. Such a broadband approach reduces the total number of required runs significantly but can be affected by wave reflection. Sufficient time must pass to allow the generated waves to propagate to the measurement location. The amount of time required is dependent on the highest frequency component (which has the slowest velocity). At the same time, waves reflected from the edges of the tank will begin to interfere with measurement after a certain period. The time reflected waves take to return to the measurement location is dependent on the lowest frequency component (which has the fastest velocity). Thus the uncorrupted time period for a broadband approach is significantly shorter than that of the regular wave technique.

In an attempt to overcome the problems associated with wave propagation and reflection, Masterton and Swan (2008) proposed the use of a focused spectrum. In their approach, the component waves are 'focused' through phase modification so that they come into phase at the measurement location during the uncorrupted time period. This technique concentrates the wave energy around the focal point, ensuring that wave energy outside the uncorrupted region is minimal. The original purpose of the method described by Masterton and Swan (2008) was to calibrate the wave tank to accurately reproduce a particular type of focused event desired by the authors, and it was shown to be very effective at achieving this goal.

The present study was motivated by numerically investigating the use of this method to calibrate force controlled wavemakers for accurate reproduction of more generic sea states. This investigation highlighted cases where the technique may lead to erroneous results. This could happen for wet back wavemakers or when the wave tank has previously only been calibrated for a subset of its wave generation spectrum. Section 2 summarises the existing calibration methods, and further highlights the need for such procedures. Section 3 illustrates the potential pitfalls of the method with a clear example. The underlying reasons for those pitfalls are then described (section 3.2) and mitigations approaches are explored (section 3.3). Section 4 provides an in depth statistical analysis of numerical simulations designed to assess the calibration method's performance. To that end, formalised calibration metrics are first devised to quantitatively assess the success of the calibration procedure. Finally, section 5 concludes the present work and makes recommendations for improved wave tank calibrations.

In all the numerical simulations used in this study, wave propagation is modeled using linear theory. As a result, the findings may not be directly applicable to the generation of large focused wave groups or steep random sea states. However, steep wave group generation may still benefit from the methodologies outlined. Assuming an appropriately large distance between the wave group focus location and the wavemaker, the wave group is relatively dispersed at the wavemaker, where local nonlinearity is hence limited. The approach introduced here is likely to remain beneficial. For steep random sea states, nonlinearities will inevitably occur at the wavemaker location, and generation based upon second-order random wavemaker theory may be more suitable than an empirical calibration. While it is difficult to define an exact upper limit of linear theory in random sea states, a value of $\frac{1}{2} \cdot H_s \cdot k_p = 0.02$ (product of significant wave height H_s and wave number corresponding to peak period, k_p) can be taken as an approximate limit for linear theory to remain valid (Latheef and Swan, 2013). In terms of focused wave groups, the limit of validity depends on both the steepness of the event to be generated and the location at which the event is to be reproduced (distance from the wavemaker). Linear theory is generally applicable if $A \cdot k_p \leqslant 0.05$ (product of maximum event amplitude A and peak wave number k_p). Nevertheless, with a sufficient distance from the wavemaker, even large overturning or breaking wave groups may be dispersed and near-linear at the wavemaker.

2. Wave tank calibration

2.1. Definition of a tank transfer function

At this stage the concept of a tank calibration and a tank transfer function should be further clarified. For non-absorbing position-controlled wave machines a transfer function is simply represented by the well known wave-amplitude ratio, and extensive reference to this can be found in Havelock (1929), Biésel and Suquet (1954) and Ursell et al. (1960). It has long been established that a wavemaker produces both evanescent and progressive wave modes. The evanescent wave modes arise as a local effect in the proximity of the wavemaker, decay quickly with increasing distance from the wavemaker. In contrast, the progressive wave mode propagates into the wave flume or wave basin, and the model in the testing area is consequently only subjected to these latter modes.

The transfer function in position control solely addresses the relationship between the wave board displacement and the progressive wave. In a more general wave-body interaction context, the progressive wave may be regarded as the radiation damping, and this damping term must be in phase with the oscillator's velocity. In other words, the displacement of the wave board and the surface elevation due to the progressive wave (evaluated on the wave board) are 90° out of phase; this phase shift being frequency independent. In summary, the transfer function in position control is characterised by the wave-amplitude ratio and a 90° phase shift between the wave-board displacement and the progressive wave mode.

Considering the transfer function appropriate to force-controlled wave machines (as those developed by Edinburgh Designs), this incorporates the absorption mechanism, and directly relates to the hydrodynamic forces acting on the machine. In contrast to position control, the resulting transfer function is characterised by an amplitude *and* a phase relation. A detailed analysis of such a transfer function is outside the scope of the present work, and the reader is directed to Spinneken and Swan (2011, 2012). In the context of the present work, a 2-dimensional theoretical transfer function Spinneken and Swan (2011) will be used as a reference case within the analysis presented in sections 3 and 4.

2.2. The purposes of wave tank calibration

The exact purpose of a wave tank calibration somewhat depends on the user's testing strategy and environment. The focused wave tank calibration discussed herein may be used