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A laboratory investigation concerning the superharmonic free wave suppression in shallow and intermediate water conditions

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ABSTRACT

This paper concerns laboratory wavemaking in shallow and intermediate water conditions. A comparison is made between two wave generation techniques, a first based on controlling the wavemaker displacement, and a second based on controlling the wavemaker force. Nonlinear wave generation in position control is well understood, and many laboratories rely on established second-order or Stream-function inputs. In deep water, using flap-type wavemakers, a force-control approach based on a linear demand signal was recently shown to offer benefits in terms of wave quality. The shallow water operation of such force-control strategies is less certain, which motivates the present study.

To investigate the influence of the water depth on this type of control, a range of generation scenarios is considered, including small amplitude and large amplitude regular waves. Adopting both supporting calculations and experimental evidence, the work demonstrates that first-order force-based wave generation in shallow water suffers from similar limitations as first-order position control. This principally concerns the contamination of the testing area due to unwanted free waves, where the present focus is placed on the superharmonic range.

The main advance of the work lies in the solutions it offers to overcome this free wave contamination. A number of nonlinear wave solutions upon which force-based generation can be based are discussed, and a suitable methodology is proposed and validated for each case. The developed methodology allows for high quality wave generation, whilst maintaining the benefit of active wave absorption. The work is timely in the sense that is responds to two recent developments. First, the majority of wavemaking facilities commissioned over the past two decades are computer controlled, and active absorption has become commonplace. The work presented offers solutions highly relevant to such installations. Second, developments particularly in offshore wind, have seen many new structures placed in relatively shallow-water depth. It is essential that the model testing of such structures adequately accounts for the issues and solutions presented herein.

1. Introduction

The derivation of any wavemaker theory involves considering the motion of the wavemaker and its influence on the surrounding fluid. An ideal approach would be to design a wavemaker geometry and motion that match the desired fluid kinematics exactly. However, for practical purposes, wavemaker geometries generally consist of flat wavemakers, having a single translational or rotational degree of freedom. The mismatch between the ideal and the practical design leads to two principal issues:

(i) The mismatch between the wavemaker velocity and the fluid (wave) kinematics throughout the water column leads to the existence of evanescent wave modes. Fortunately, in the limit of linear waves, these modes are only significant in the vicinity of the wavemaker and do not propagate into the testing area. However, they must be understood if considering the applied fluid load on the wavemaker.

(ii) More importantly to nonlinear wavemaking research, a combination of the geometric mismatch and a mismatch in terms of the description of the harmonic content leads to the generation of spurious or unwanted free wave components. These components may arise both at low frequencies (subharmonics) and high frequencies (superharmonics). Given that these spurious components propagate freely, they inevitably contaminate the testing area.

To overcome (ii) above, a number of nonlinear wavemaking

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approaches have been proposed in the past. Traditional Stokes-type wavemaker theories rely on a perturbation expansion of the relevant boundary conditions. In addition to expanding the free-surface boundary conditions about the mean water level, the wavemaker displacement must be expanded about its mean position. A first-order Stokes-type solution to the wavemaking problem was presentfed by Havelock [1], and later validated experimentally by Ursell et al. [2]. At second order, wave-wave interactions give rise to both self-interactions and cross-interactions. These second-order interaction terms can occur as superharmonics and subharmonics. Ottesen-Hansen et al. [3] and Sand and Donslund [4] established that a second-order correction is required for the successful generation of long waves, particularly due to the importance of subharmonics. Sulisz and Hudspeth [5] developed a complete second-order solution for regular waves based on a matched eigenfunction methodology. The second-order formulation used within the present paper originates from the framework established by Schäffer [6], who combined much of the earlier work in a single consistent analytical formulation.

Goring and Raichlen [7] suggested that effective generation of long waves requires a different approach. Unlike Stokes-type expansions of the wavemaker displacement about its mean position, Goring and Raichlen [7] established a methodology where the wavemaker motion is considered relative to the generated wave kinematics. This approach was also demonstrated in the related development of several nonlinear wavemaker theories, including the Cnoidal approach by Goring [8].

In addition to accurate wave generation, active absorption is essential to any modern wavemaking apparatus. Wave energy is generally reflected from downstream beaches, and any test model placed within a laboratory wave flume or wave basin also reflects some wave energy back towards the wavemaker. The purpose of an absorbing wavemaker is to remove this unwanted reflected wave energy, hence maintaining an incident wave field of consistent quality. Research on active laboratory wave absorption led to a number of strategies, including: (i) position-controlled absorption techniques and (ii) force-controlled absorption techniques.

Position-controlled absorption was the first strategy to be developed, and is most commonly based on the water surface elevation recorded on the front face of the wavemaker feeding back into the system [9]. The body of work by Schäffer and Jakobsen [10,11] and Zhang and Schäffer [12] considers simultaneous nonlinear wave generation and active wave absorption. In doing so, Zhang and Schäffer [12] also demonstrated the operation of a Stream-function wavemaker theory is appropriate to both shallow and intermediate water conditions. This approach inherits from Stream-function wave theory its high performance for a wide range of conditions [13]. In particular, Stream-function wavemaker theory was shown to offer benefits over Cnoidal wavemaker theory in intermediate water, and to be more accurate than Stokes second-order wavemaker theory in deep water [12]. Most recently, Lykke Andersen et al. [14] considered the steps necessary to extend simultaneous generation and absorption to second order, and demonstrated the active absorption of highly nonlinear regular waves.

Salter [15] developed a force-controlled absorption technique, based upon the applied hydrodynamic force feeding back into the system. Salter [15] argued that a methodology based on force feedback allows for the determination of the average water conditions across the wavemaker front. In this context, it is also of critical importance that force sensors are not affected by the chemical conditions of the fluid and can be considered calibration free. Designing force-controlled laboratory wavemakers is not without challenges. To ensure that the fluid force is only recorded at the wavemaker front face, dry-backed or displacement-type wavemakers are required. A dry-backed operation is easily achieved for flap-type wavemakers, where a gusset is inserted between adjacent wavemakers or walls. For piston-type wavemakers, so called displacement-type constructions require a more elaborate design to ensure that no waves are generated at the wavemaker rear face. This type of wavemaker design leads to a slightly larger fluid gap under the piston, which may affect fluid leakage. For the purpose of the present work, an additional board was fitted to the front of the wavemaker, ensuring that this gap is minimised. Further detail concerning this gap is given in the discussion in Section 4.3.1.

Spinneken and Swan [16] derived an analytical second-order theory for actively absorbing force-controlled wavemakers; an accompanying experimental verification being presented in Spinneken and Swan [17]. Spinneken and Swan [16,17] also provided a correction force to cancel the spurious wave content at second order. However, they demonstrated that in many practical wave conditions a first-order force demand signal suffices, eliminating the need for a second-order demand. Spinneken and Swan [16,17] focused on flap-type wavemakers in deep-to-intermediate water conditions. In contrast, the present investigation concerns the shallow-to-intermediate water range, adopting piston-type wavemakers, and focusing on a regular wave analysis. The paper continues as follows. Section 2 provides the theoretical background and extends the mathematical formulation as required. Section 3 subsequently presents a brief theoretical comparison between position control and force control. A laboratory investigation in Section 4 demonstrates the problem of spurious wave contamination in wave flumes, and evaluates the practical success of a number of nonlinear wave generation approaches. Conclusions are finally drawn in Section 5.

2. Background

2.1. The wavemaking boundary value problem

Fig. 1 illustrates a piston-type wavemaker located in a two-dimensional wave flume. A Cartesian coordinate system (x, z) is aligned such that $x = 0$ defines the mean position of the wavemaker, and $z = 0$ defines the still water level in water of depth h. Waves generated by the wavemaker propagate into the positive $x-$ direction and the instantaneous surface elevation is defined by $\eta(x, t)$, where t denotes time. The wavemaker is defined by the distance d between the bed and the bottom of the wavemaker, with the horizontal time-varying position of the wavemaker being denoted as $X(t)$.

Assuming the flow to be inviscid and irrotational, a velocity potential ϕ may be introduced. This velocity potential must satisfy mass continuity throughout the fluid domain, which is commonly expressed through Laplace's equation as

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial z^2} = 0. \tag{1}$$

Furthermore, the wavemaking problem defined in Fig. 1 can be fully specified by the following boundary conditions:

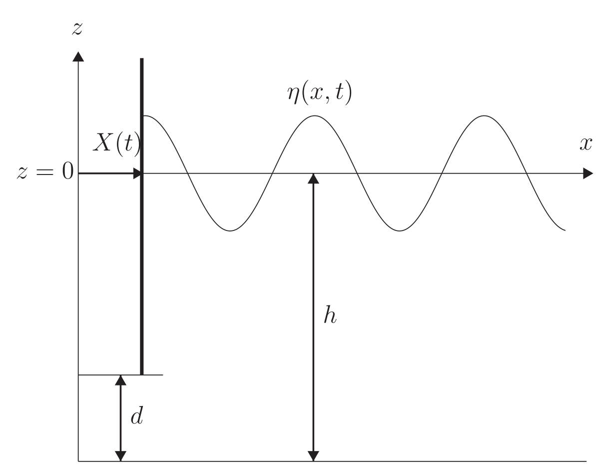

Fig. 1. Definition of a piston-type wavemaker.