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Linear parametric hydrodynamic models for ocean wave energy converters identified from numerical wave tank experiments

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ABSTRACT

Mathematical modelling of wave energy devices has many uses, including power production assessment, simulation of device motion and as a basis for model-based control design. Apart from computationally heavy approaches, such as those based on computational fluid dynamics (CFD) and smooth particle hydrodynamics (SPH), the vast majority of models employed in the simulation and analysis of wave energy converters (WECs) are based on boundary-element methods (BEMs). While BEM models have been shown to be useful, they have the inherent limitation that they are linearised around the still water level, with validity only on the immediate vicinity of this equilibrium point. In this paper, we develop a new modelling methodology, which combines the fidelity of CFD models with the computational attractiveness of BEM-type models. This flexible methodology can give representative linear models, or be extended into the nonlinear domain, as desired.

1. Introduction

Mathematical system modelling provides a possibility to determine an abstract description of a physical system, which can be easily subsequently manipulated, analysed and simulated on a computer. This can help to expedite the process of system design, while significantly reducing the cost of building physical prototypes at various scales. In addition, mathematical models are required as the fundamental building block upon which model-based control design is performed. However, if the analysis and results emanating from these models are to be meaningful, the models themselves must be a reasonably faithful representation of the original physical system.

There is a significant motivation to work with linear models. They are computationally simpler, obey superposition (divide and conquer) and lend themselves to a vast array of mathematical tools which can be used for their analysis and simulation. It is accepted practice in many disciplines, such as control engineering, that many systems are linearised around an operating point. In control systems, this is normally a reasonable assumption, since the usual control objective is to drive a system to a specific setpoint. However, in the contrasting case of wave energy, the objective is to drive the system as far away from equilibrium as possible. This is likely to result in the excitation of nonlinear dynamics, resulting in non-representative linear models.

Typically, linear hydrodynamic models based on boundary element methods are employed (Li and Yu, 2012; Maguire, 2011) for WECs, with hydrodynamic parameters determined from frequency-domain codes such as WAMIT or AQUAPLUS or, in the time domain using ACHIL-3D. These essentially follow a physical (first-principles) approach in parameterising Cummins equation, using finite element methods, where model-order reduction techniques (Taghipour et al., 2008) can be used to deliver a finite-order linear model. In some cases, such models can be extended to include some nonlinear effects such as viscous damping, for example using the Morison equation (Morison et al., 1950), where the viscous damping coefficient is determined based on historical experience. An alternative determination of the viscous damping coefficient is that by Bhinder et al. (2012), where CFD is used to evaluate the viscous force, to which a viscous damping constant is fitted. BEMs have also been used to parameterise nonlinear models (Gilloteaux, 2007; Gilloteaux et al., 2008), but require the recalculation of hydrodynamic parameters (on the instantaneous wetted surface) at each sampling instant, with a resulting high computational overhead.

An alternative modelling approach, popular in the systems and control community, is that of system identification, where models are determined from input/output data measured from the system under study (Ljung, 1999). Such methods are particularly useful where the system to be modelled is very complex and/or does not easily lend itself to first principles modelling. However, one major difficulty in system identification is ensuring that the input/output data used to determine the model is sufficiently representative of the system dynamics and, in particular, must cover the range of frequencies and amplitudes likely to be encountered during system operation. In the WEC case, such a range of excitation signals are not likely to be

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available in the open ocean (at least not in a reasonably short time frame) and there are difficulties in exactly enumerating the excitation experienced by the device, particularly for a directional device. In short, there is no external control of the excitation. One other possibility is to employ tank tests. However, in addition to the significant cost and the need for a physical prototype, there may be limitations on the range of excitation signals available and tank wall reflections may further limit the range and duration of viable tests.

One possibility for generating suitable input/output data is to use a numerical wave tank (NWT), implemented in CFD, which has the following advantages:

- Reflections from 'tank' walls can be effectively controlled.
- Can test the device at full scale, eliminating scaling effects.
- A wide variety of excitation signals, including incident waves *and* forces directly applied to the device, as well as free response tests, can be implemented.
- The device can be constrained to different modes of motion without requiring mechanical restraints which can add friction and alter the device dynamics.
- Signals can be passively measured without requiring physical sensor devices which can alter the device or fluid dynamics and are subject to measurement error, and most importantly.
- Specialist equipment, including a prototype WEC device, is not required.

Though CFD codes are relatively inexpensive (for example the open-source OpenFOAM code), they are computationally heavy and are best run on high-performance computers (HPCs). However, HPCs are now becoming quite cost effective.

Adopting a system identification approach also offers considerable flexibility in model parameterisation and the relationship to physical quantities and the desired complexity/fidelity trade-off. Regarding the connection with physical quantities, the following general classes are recognised:

- White-box, where each parameter represents a physical quantity.
- Grey-box (and the sub-classes of off-white, smoke-grey, steel-grey and slate-grey Ljung, 2008), with various levels of connection to the underlying hydrodynamical structure.
- Black-box, where the model simply reproduces the experimental output data, given the same stimulus, but the internal model structure bears no resemblance to the physical world.

White and grey box models present the significant benefit of a structure which is well related to physical aspects of the system and the model variables usually represent physical quantities. As the shade of grey gets darker, the connection with the physical world diminishes, until the only connection of black-box models with the physical world is the representation of the overall model input and output. For the current study, focus will be on grey-box modelling, as we try to retain the (physical) structure of a Cummins-type equation, while employing system identification techniques to get a good fit of the model to the NWT response data.

In this paper, we present a new methodology for the development of hydrodynamic models for WECs, outlined in Fig. 1. For this particular study, we will focus on the development of linear hydrodynamic models, in order to allow a comparison with linear models parameterised using BEM methods, and show the possibility to determine representative linear models valid for different wave heights and their interrelationship.

The remainder of the paper is laid out as follows: Section 2 describes the salient points of the numerical wave tank implementation, while Section 3 provides the linear WEC modelling background needed. Section 4 details the means by which the parameters of the linear hydrodynamic models are determined and Section 5 documents a case study showing the results of such a procedure for the case of a heaving buoy WEC. Finally, conclusions are drawn in Section 6.

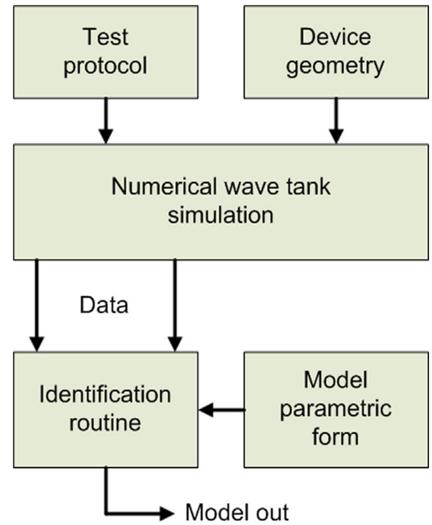

Fig. 1. Overview of modelling methodology.

2. Numerical wave tank

Numerical wave tanks (NWTs) have been used for many decades in ocean engineering to analyse fluid–structure interaction (Tanizawa, 2000). The fluid dynamics are governed by the transfer of mass, momentum and energy. These three processes are described by a set of nonlinear partial differential equations, known as the Navier–Stokes equations, detailed as follows:

1. Continuity equation:

$$\frac{\partial \rho}{\partial t}+\nabla \cdot (\rho \mathbf{u})=0. \tag{1}$$

2. Momentum equation:

$$\rho\frac{\partial \mathbf{u}}{\partial t}=\nabla \cdot \tau_{ij}. \tag{2}$$

3. Energy equation:

$$\rho\frac{\partial e}{\partial t}=\nabla \cdot (k\nabla T)-p\nabla \cdot \mathbf{u}+\tau_{ij}^{v}\frac{\delta u_i}{\delta x_j}. \tag{3}$$

where ρ is the fluid density, $\mathbf{u}$ is the velocity, e is the internal energy, T is the temperature, k is the thermal conductivity and τ_{ij} is the stress tensor comprising the pressure, $-p\delta_{ij}$, and viscous terms, τ_{ij}^{v}

$$\tau_{ij}^{v}=\mu\left\{\frac{\delta u_i}{\delta x_j}+\frac{\delta u_j}{\delta x_i}\right\}+\delta_{ij}\lambda\nabla \cdot \mathbf{u}. \tag{4}$$

where μ is the coefficient of viscosity, δ_{ij} is the Kronecker delta function and λ is the bulk viscosity.

The coupled continuity, momentum and energy equations, Eqs. (1)–(3), are indeterminate and require two more equations to obtain closure which are provided by the ideal gas laws

$$p=\rho RT, \tag{5}$$