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Non-linear numerical modeling and experimental testing of a point absorber wave energy converter

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ABSTRACT

A time domain model is applied to a three-dimensional point absorber wave energy converter. The dynamical properties of a semi-submerged hemisphere oscillating around a pivot point where the vertical height of this point is above the mean water level are investigated. The numerical model includes the calculation of the non-linear hydrostatic restoring moment by a cubic polynomial function fit to laboratory test results. Moreover, moments due to viscous drag are evaluated on the oscillating hemisphere considering the horizontal and vertical drag force components. The influence on the motions of this non-linear effect is investigated by a simplified formulation proportional to the quadratic velocity. Results from experiments are shown in order to validate the numerical calculations. All the experimental results are in good agreement with the linear potential theory as long as the waves are sufficiently mild i.e. $H/\lambda \leq 0.02$. For steep waves, $H/\lambda \geq 0.04$ however, the relative velocities between the body and the waves increase thus requiring inclusion of the non-linear hydrostatic restoring moment to effectively predict the dynamics of the wave energy converter. For operation of the device with a passively damping power take-off the moment due to viscous drag is found to be negligible.

1. Introduction

The dynamical behavior of wave energy converters (WEC′s) has been extensively investigated during the past years by means of analytical and numerical studies, including testing at laboratory scale and under real-sea conditions. Many concepts have been suggested namely the oscillating water-column principle, overtopping wave energy converters, point-absorber concepts and floating pitching devices. A comprehensive review of WEC systems can be found in Falnes (2007), Clement et al. (2002), and Falcao (2010). Examples of the state-of-the-art devices are provided in Neumann et al. (2008), http://www.wavedragon.net, http://www.wavestarenergy.com, http://www.weptos.com/. Point absorbers (PA) constitute an important class of wave energy converters particularly with regard to the relative simplicity of offshore deployments. This paper presents the results of a numerical and experimental study of a single Wavestar buoy (http://www.wavestarenergy.com).

For a single body device, maximum power capture in regular waves is known to occur when the PA is in a resonance condition (Falnes, 2002). The theoretical maximum power capture of an axisymmetric point absorber is reported in Budal and Falnes (1975), Evans (1976, 1981), and Mei (1976). Oscillating in resonance with the wave frequency will result in large motion amplitudes compared to the dimensions of the device. Advanced control strategies such as optimal phase or amplitude control (Falnes, 2002) are done to maximize power capture by encouraging resonance behavior. As a result, numerical models of WEC′s under advanced control must account for non-linear effects such as non-linear hydrodynamic forces that occur at large motion amplitudes.

Numerical models of WEC dynamics, which assume inviscid, irrotational and incompressible flow, normally use Boundary Element Methods (BEM) to estimate the frequency dependent hydrodynamic loads. Such models often exhibit high inaccuracy in high wave steepness. The effects of nonlinearities induced by viscous drag, kinematics or control strategies are typically assessed by corresponding time domain models. The present study is tied up to the development of such a technique which is also referred to as hybrid frequency–time domain modeling. The successful implementation of such models is reported in Taghipour et al. (2008), Kristiansen et al. (2005), Barbarit and Clement (2006), Backer (2008), and Alves (2011). Recently, Guerinel et al. (2011, 2013) presented a model for a cone and a hemispherical shaped WEC geometry which takes into account the hydrostatic and Froude–Krylov nonlinear effects by an integration over the

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instantaneous wetted surface, keeping the diffraction and radiation forces linear.

The first aim of this paper is to demonstrate the limitations of a linear fluid–structure assumption by means of experimental tests on a laboratory scaled Wavestar model (Ferri et al., 2013; Beatty et al., 2013; Zurkinden et al., 2013). Next, a relatively simple methodology is proposed which introduces a non-linear hydrostatic restoring moment in the WEC numerical model. An investigation of the effectiveness of the proposed methodology for improving accuracy in steep waves is presented. Based on experiments, the validity of the linear theory will be confirmed for mild waves i.e. $H/\lambda \leq 0.02$. For higher waves $H/\lambda \geq 0.04$ the deviation of the linear behavior will be presented by root-mean-square-errors elaborated on the peak values. When BEM is used to solve the flow problem around the geometry (Wamit Manual, 2012), the hydrodynamic loads are calculated in the frequency domain and linearized by assuming a constant equilibrium position, which could possibly introduce inaccuracy; however, the exact hydrodynamic coefficients would result if the instantaneous wetted surface of the float is considered. In case of the Wavestar model the wetted surface does not undergo large changes during the oscillations in waves, indicating that the linear assumption for the hydrodynamic coefficients is justified.

The second aim is to quantify the effect of a viscous drag on the WEC in waves. Hereby, the uncertainty lies in the assumption of the drag coefficients. In order to estimate these quantities experimental radiation tests were carried out (Ferri et al., 2013). The drag moment is then incorporated as a Morison term. The effect of Morison drag on the WEC dynamics are assessed.

At the core of the hybrid frequency–time domain model is an integro-differential equation, known as Cummins's (1962) equation, which has been formulated for the laboratory model. Two integration schemes will be presented, namely the direct computation of the convolution integral by a Taylor series expansion and the state-space approximation. The latter approach has been used by a number of researchers (Yu and Falnes, 1975; Kristiansen et al., 2005).

To summarize, the overall goal of this study is to develop a WEC numerical model by accounting for the most significant non-linear effects. The accuracy is tested by comparing the model results to experimental results from a laboratory scale 1:20 Wavestar device (http://www.wavestarenergy.com).

2. Description of the experimental setup

The physical model in the laboratory is shown in Fig. 1. The test setup consists of a hemispherical floating body connected to a lever arm. The device rotates in the pitch direction around a fixed point which is located 0.35 m above the mean water level. The laboratory device is similar to the well-known Wavestar float located in the Danish North Sea. The test setup is modeled with a scale of 1:20 compared to the prototype (Kramer et al., 2011). The geometrical dimensions are given in Table 1. Two-dimensional regular and irregular waves are considered propagating in the positive y-direction relative to (x, y, z)-coordinate system defined in Fig. 2. The water basin has a length of 15 m, a width of 8 m and a water depth of 0.65 m. The wave paddles are driven by a total of 15 hydraulic pistons moving in the horizontal direction only. The distance from the center of the float and the paddles is 7.5 m. After 10 m the waves reach the slope of the beach. The layout of the WEC in the wave tank is shown in Fig. 3. No active absorption is applied on the incoming waves thus a rather short duration of the time series has been chosen to avoid influences of any standing waves building up in the wave tank.

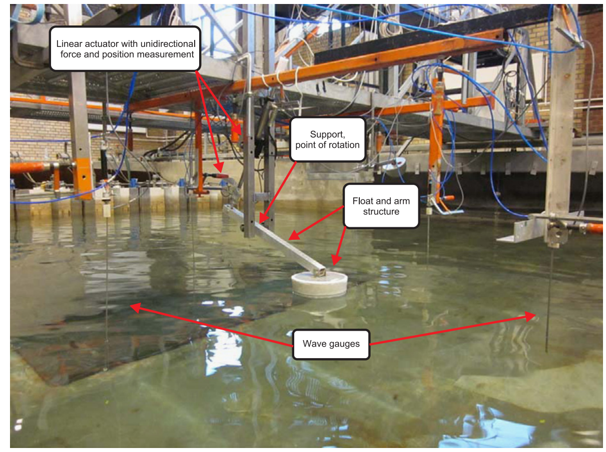

Fig. 1. Physical model in the laboratory—a small Wavestar device, model scale 1:20 to the prototype model.

Table 1
Numerical values of the laboratory model.

Description	Symbol	Value	Unit
Length of the float arm	L	0.680	m
Diameter of the float	d_o	0.254	m
Lever arm initial	l_c	0.200	m
Mass moment of Inertia	M	0.778	kg m^2
Hydrostatic stiffness	R	87.00	N m/m
Water depth	h	0.650	m
Draft	d	0.104	m
Wavelength	λ	*var.*	m
Natural period in pitch	T_n	0.79	s
PTO damping	c_c	1–15	N m s/rad
PTO stiffness	k_c	0	N m/rad

2.1. Data acquisition and laboratory PTO model

Translational force and displacement measurement systems are mounted on the device. The relative displacement between the fixed and movable arm is retained with a laser distance meter (DM), see Fig. 2. Both force and displacement signals were filtered with a 188 Hz analog low pass filter and recorded at a sample frequency of 1000 Hz through the use of an A/D converter. A Simulink program controls the power take-off (PTO) system. The program runs on a dedicated target PC. The control algorithm is programmed in Simulink and send to the target PC. The target computer logs and stores the acquired data and sends the force set-point back to the device.

The goal of the power take-off is to extract mechanical power from the WEC's capability to do work on an external load in any given sea-state. As it is well known (Falnes, 2002), adequate control of the external power take-off load is critical to the performance of a point-absorber. In addition, if non-linear friction effects are significant at model scale, the model scale WEC results cannot be usefully scaled up without scaling distortions tending to obscure the results. As a consequence, the laboratory PTO model in this work is designed to both allow for real-time control of the external load while minimizing the negative effects of friction. The PTO employs a force feedback controlled translational linear actuator based on the electromagnetic principle. A load cell provides the measured force exertion signal. The measured signal is then compared with the set-point generated by the target PC. The error is finally used in the PID controller to modulate the current absorbed by the linear generator. The load-cell combined with a velocity signal derived from a non-contacting laser displacement sensor signal allows for direct calculation of the