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Physical modelling of wave energy converters

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ABSTRACT

In guiding the progression and implementation of wave energy converters in a more effective and solid way, stepwise protocols have been recommended for assessing and validating their performance, feasibility, reliability and survivability during the devices' progression stages from the concepts to full-scale commercial devices. One important aspect is scale model testing in different development stages as a path to solve the most important problems and to build confidence in the device development. Particularly, in the early development stages of the wave energy converters, small scale models are often tested in well-controlled laboratory conditions in a manner that some dynamic effects can be isolated, hence the analysis and understanding of the dynamic process could be much simplified and specified. However, there is no theory or guideline developed for this scaling practice in explaining whether or not the scaling is correct and how the test data can be used. In this paper, a theoretical analysis to the requirements and an explanation to the feasibilities of physical modelling/scaling, and some important scaling issues on physical modelling of wave energy converters, are presented with an emphasis on the physical modelling and scaling of power take-off systems. This theoretical analysis can help to understand why and how a small scale model can be tested and how the test data can be used.

1. Introduction

Wave energy is a type of well-concentrated renewable energy when compared to other renewable energy resources, such as solar, wind etc., and its potentials are huge. IEA estimates the total wave energy is up to 80,000 TWh a year IEA-OES (2004), which is about 5 times of the worldwide electricity production 17,400 TWh in the year of 2004. It is now recognised that efficiently utilising wave energy may make significant contributions to achieve the target of green energy. For example, the World Energy Council has estimated that there may be 140–750 TWh/year of wave energy electricity production by the current technologies and designs of devices when they fully mature, and this figure could be as high as 2000 TWh/year if the potential improvements can be realised, see Jolly (2010).

A wave energy converter (WEC) is a device for extracting energy from waves and converting the extracted energy into useful energy. Most WECs may have two or more energy conversion stages. Essentially, the first conversion stage is the primary wave energy conversion in which the wave-excited components of the device or the water bodies in oscillating water columns/overtopping devices convert wave energy into mechanical or potential energy. In the second conversion stage, a power take-off system, such as hydraulic pump/motor, direct electrical generator, air turbine or water turbine (depending on the principle of the wave energy converter), is often applied to convert the mechanical/potential energy into useful energy, see Cruz (2008), and Salter et al. (2002). For an efficient wave energy conversion, a device is frequently designed to have large-amplitude motions in waves so that more wave energy can be converted into mechanical energy and thus extracted by the power take-off system. In many cases, the large-amplitude motions of the device and the power take-off (PTO) introduce significant nonlinearities in the dynamic systems of wave energy converters and create the difficulties for understanding and analysing them. Traditionally, those difficulties have led to extensive model tests in wave tanks and in seas during the development of a device, as suggested by the stepwise development procedures and protocols by Holmes and Nielsen (2010). In the stepwise procedure, different scale model tests are recommended in different stages as a path to solve the most important problems in the development stages and to build confidence in the device development. For instance, most of the well-progressed wave energy devices, such as Pelamis, Oyster, Wave Dragon and OE Buoy etc., have undergone significant wave tank tests and sea trials, from small scale models in early stages for feasibility testing, to large models for performance testing, and to larger sea-trial models for assessing the economic feasibility, and the reliability and survivability in real sea conditions.

In developing a wave energy converter (WEC), the important issues are the assessments of the device performances and its

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Nomenclature

A	regular wave amplitude/area
B	width of wave energy converter
b_{pto}, B_{pto}	(nonlinear) damping coefficient
$\vec{F}$	force vector
F_{pto}	force from power take-off system
F_P	average captured power function
F_r	Froude number
H	wave height
H_P	power capture response
g	gravitational acceleration
k_{pto}	stiffness from PTO
L	characteristic length
$\vec{n}$	normal vector
m	mass
m_{pto}	additional mass from PTO
P	power
p_0	atmospheric pressure
p, p'	pressure and non-dimensional pressure, respectively
q_p, q_w	flowrate through power take-off and driven by the interior water surface
R_e	Reynolds number
S_0	non-dimensional wetted surface
S	wetted surface
S_w	wave spectrum
T	wave period
U	characteristic velocity
u,v,w	velocity components in a Cartesian coordinate
u',v',w'	non-dimensional velocity components in a Cartesian coordinate
$\vec{v}$	velocity vector
V_0	volume of air chamber in calm water
W	capture width
$\vec{x}$	motion vector
γ	specific heat ratio of air
ρ	density of water
ε	scale factor (the ratio of the full-scale length over the scaled length)
μ	dynamic viscosity
ω	angular frequency

Superscripts/Subscripts

p	full scale (prototype)
m	model
L	large model
S	small model
$'$	denotation of non-dimensional parameter

wave power capture capacity from seas. Principally, this can be carried out either by a numerical analysis or a physical modelling. In this investigation, our focus is on physical modelling of wave energy converters.

It is well accepted that the stepwise development procedure/protocol is recommended by Holmes and Nielsen (2010) suggests that different scale models be tested for solving the most important problems in each development stage. This stepwise procedure shows the difficulties in wave energy development, and the uncertainties involved in the scale model tests. Those difficulties and uncertainties may be related to how well the physical modelling can be conducted and how the data be used.

Although the St. Denis-Pierson's superimposition method, St Denis and Pierson (1953) and the relevant principle and theory for scale model tests and the data utilisation have been developed and accepted for many years, see Chakrabarti (1998), Hughes (1994) and Vassalos (1999), it is basically only suitable for linear dynamic systems. This may be justified for the conventional ocean platforms because of its inherent small-amplitude motions in waves. For a nonlinear dynamic system, the scaling methods may be different. Recently, a review carried out by BMT (2000) has clearly indicated the scaling issues for floating platforms that if the dynamic system is nonlinear, its well-known response amplitude operators (RAOs) may not be meaningful as those frequently used in the linear dynamic system. In such a system, irregular wave tests may be conducted by scaling the relevant parameters of the specific waves, and the measured data must be scaled and used but in a limited manner. For wave energy converters, the nonlinear effects may be more evident, either from the designated large-amplitude motions of the device or from the nonlinear power take-off system or some other nonlinear sources. As proposed in Holmes and Nielsen (2010)), when an “appropriately large model” is used, the power matrix is suggested to be carried out in the accordingly scaled sea states. It can be seen that the scaling of the power matrix bears a similar principle to that shown in the literature (BMT 2000) for a nonlinear dynamic system.

The scaling in physical modelling is practically accepted in many cases, but the theory behind this is not well developed. For example, the Froude similarity is very preferable because it is widely applied and factually the relevant requirements can be easily satisfied for the reduced model. Another example is the dimensional analysis, which is very helpful in reducing the variables in test, and thus test numbers via the so-called non-dimensional numbers (Froude number and Reynolds number are the famous among those non-dimensional numbers), rather than the individual parameters. However, it is not clear so far why the physical modelling is correct or under what conditions the physical modelling can be correct or acceptable. To answer those questions, this investigation provides a theoretical analysis for the physical scaling of wave energy converters and an answer to the question why the physical modelling can be conducted and how the data can be used, and with an emphasis on the scaling of the power take-off systems for wave energy converters.

2. Similarities

It is generally known that for a physical modelling, relevant similarities must be satisfied to ensure the meaningful and useful scaling and modelling. For a meaningful physical modelling, geometrical similarity must be satisfied. That is, the scale model must be geometrically similar to the target of interest (prototype). If the physical modelling is made to be useful, for example, how to apply the data from a scaled model to the prototype, the important kinematical and dynamic similarities must be partially or fully satisfied, largely depending on the specific problems.

2.1. Geometrical similarity

A prerequisite of a meaningful physical modelling is the geometrical similarity. Geometrical similarity can be defined as all linear lengths of one object have a fixed scale factor to the corresponding linear lengths of the second object, see Hughes (1994). If a scale