

Numerical Modelling of a Surging Point Absorber Wave Energy Converter

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Abstract

This study presents numerical modelling of a WEC (wave energy converter) along with some details of the experimental setup. Issues related to the numerical modelling of the single DOF (degree-of-freedom) motion of a surging point absorber WEC are outlined and a comparison with experimental data is presented. A commercial CFD code Flow-3D is used for numerical modelling and the ability of the code to simulate free surface linear waves and wave structure interaction is evaluated.

The work is aimed at simulating a surging wave energy converter to achieve an optimized shape and to predict output power at a higher or full scale. The findings of this study may also serve as a reference point for the use of a commercial code such as Flow-3D for the simulation of such problems.

Keywords: CFD, Numerical modelling of Wave Energy Converter, Flow-3D, Surging Point absorber.

1 Introduction

Over the past three decades wave energy, as a renewable energy source, has received considerable interest from both research and industrial sectors. The recent quest to address global warming has made research in renewable energy inevitable and as a result, a great many prototypes have been proposed and are being tested both numerically and experimentally.

Research at Lancaster University has been mainly focused on the invention and development of novel point absorber WECs at model scale leading to better understanding of the theory and systematic design of

these devices [1-2]. Point absorbers, which were first investigated by [3-4], appear potentially more economical compared to other available wave energy converters.

However, a surging point absorber appears to have twice the output power compared to the heaving device as described in [4].

WRASPA (Wave-driven, Resonant, Arcuate action, Surging Point-Absorber) is a novel pitching surge WEC developed at Lancaster University and intended to be deployed at water depths of 20-50 meters. In this device, wave forces act on the face of a collector body carried on an arm which rotates about a fixed horizontal axis below sea level. The body, accordingly, oscillates at around about the frequency of the ocean swell, hence generating high power from a small and relatively cheap device. In storms the arm automatically moves to a position that minimises forces so ensuring its survival. The experimental and numerical results show that pitching-surge point-absorber WECs have the potential to generate high power from relatively small devices [5-9]. This paper will show recent results of an experiment as well as a numerical study of WRASPA.

Numerical study of a WEC has a potentially great impact on modifications of design; this perhaps being crucial during the early stages of model design. Several design configurations can be tested numerically at a much lower cost compared to an experimental setup. Major issues, however, related to numerical modelling of such devices include proper handling of the free-surface interface, wave-structure interaction and wave reflection at wall boundaries. A diagram showing the collector body which rotates around a specified pivot is shown in Fig. 1.

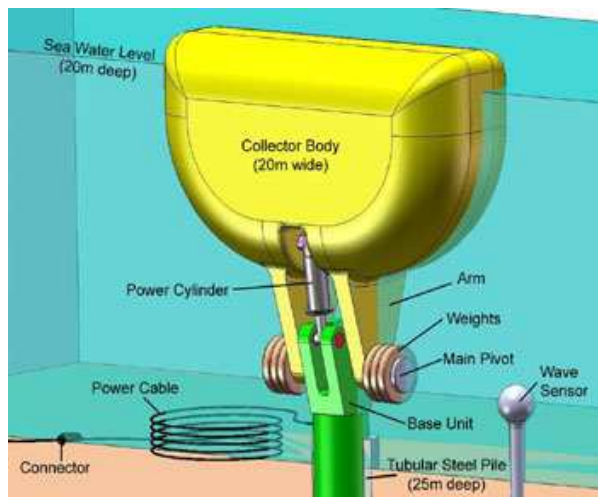


Figure 1: Collector body of WRASPA.

2 Wave Tank Experiments

Small scale ($1/100^{\text{th}}$ scale model) tank tests of WRASPA have been performed by the experimental project partner at Lancaster University UK. The model and apparatus used are shown in (Fig. 2). The experimental findings of both free and controlled motion of the device, in linear and non-linear waves, has led to an improved understanding of WRASPA's interaction with incoming waves.

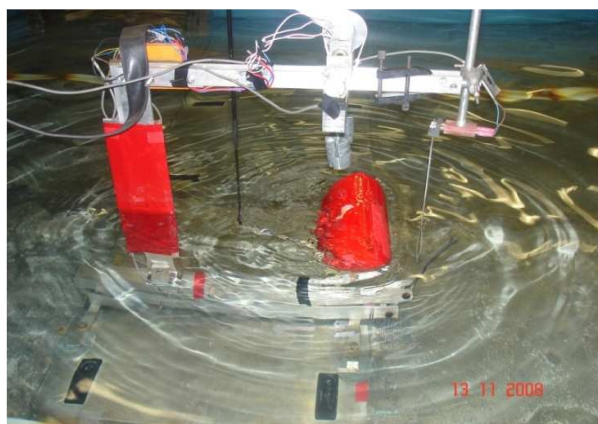


Figure 2: Experimental apparatus of $1/100^{\text{th}}$ scale model of WRASPA

A stepwise control system has also been devised for extracting optimum power from irregular waves [10]. Wave gauges have been used to monitor free surface elevation, and the required braking torque, based on automatic switching, has been used to supply the control torque. The power take off system matches the wave forces at various conditions in order to capture maximum power.

It is found that maximum power is obtained when the device is tuned according to the incoming wave swell. At this tuning the natural frequency of the device is adjusted to the incoming wave frequency. Decay

tests have been carried out to measure WRASPA's natural frequency.

The experimental study revealed that changing the freeboard or pivot depth controls the natural frequency of the device. Thus, this serves as an easy way of tuning the device to correspond with the desired frequency spectrum [10].

The collector body has a streamlined shape allowing large amplitude motion in order to extract energy from the waves [6-7]. The wave force vector on the collector and the pitch of the device are measured for various body immersions and pivot depths.

3 Numerical Modelling

Numerical modelling of WEC devices not only ensures that the current experimental results are validated but also provides an in-depth view of the underlying complex phenomenon of wave structure interaction. It also helps in predicting projected yields from a higher scale model that clearly offers huge advantages for experimental and development teams. Using numerical tools the design of a wave energy converter can be optimized to a higher standard providing improved maximum output power at a relatively lower cost.

Mathematically, the Navier-Stokes equations are used to describe the fluid flow and rigid body motion. This system of partial differential equations can be solved analytically but only for simple flow problems. However, for complex problems, algebraic approximations are needed.

In this paper, the presented numerical results are based on the use of a commercial CFD (computational fluid dynamics) package Flow-3D, a product of Flow Science Inc. In a preliminary analysis a number of commercial codes were considered for the purpose of modelling WRASPA, however, Flow-3D was found to be a good choice for this particular problem; as discussed in [11]. Flow-3D is based on the Reynolds Averaged Navier Stokes (RANS) Equations.

To capture the free-surface interface a technique named TruVOF is implemented within Flow-3D. This technique does not need extra cells at the free surface hence reducing computation time significantly.

Flow-3D uses a unique technique named FAVORTM to describe geometric objects in a computational domain which is based on the concept of area fraction (AF) and volume fraction (VF) on a rectangular structured mesh [12]. The FAVORTM technique works well with complex geometries by introducing the effects of AF and VF into the conservation equations of fluid flow. This technique has led to the successful development of a general moving object (GMO) capability which in principle permits the modelling of any type of rigid body motion (six degrees of freedom, fixed axis and fixed point) on a fixed-mesh.

A fixed axis dynamically coupled motion of WRASPA has been modelled by implementing this GMO capability of Flow-3D. The flow solver calculates the AF and VF at each time step to describe

accurately the object's position on a fixed-rectangular mesh. Hydraulic, gravitational, and control forces and torques are calculated and the equations of motion for the rigid body are solved explicitly for the translational and rotational velocities of moving objects under coupled motion. Further details of the mathematical model used within Flow-3D are given in the next subsection.

Equations of Motion for Moving Rigid Body in Flow-3d

For 6-DOF motion, the GMO model considers a moving body's centre of mass G as the base point. The equations of motion governing the two separate motions, namely translational and rotational, are [13]

$$\vec{F} = m \frac{d\vec{V}_G}{dt} \quad (1)$$

$$\vec{T}_G = [J] \cdot \frac{d\vec{\omega}}{dt} + \vec{\omega} \times ([J] \vec{\omega}) \quad (2)$$

Where F is the total force, m is rigid body's mass, V_G is mass centre velocity, T_G is the total torque about G and $[J]$ is moment of inertia tensor about G in a body fitted reference system. The total force and total torque are calculated as the sum of several components :

$$\vec{F} = \vec{F}_g + \vec{F}_h + \vec{F}_c \quad (3)$$

$$\vec{T}_G = \vec{T}_g + \vec{T}_h + \vec{T}_c \quad (4)$$

where $\vec{F}_g$ is the gravitational force, $\vec{F}_h$ is the hydraulic force due to the pressure field and wall shear forces on the moving object, $\vec{F}_c$ is the net control force prescribed to control or restrict the rigid body's motion. Similarly, $\vec{T}_G, \vec{T}_g, \vec{T}_h$ and $\vec{T}_c$ are, respectively, the total torque, gravitational torque, hydraulic torque and control torque about the mass centre.

Full details of the underlying conservation equations, integration schemes, approximations applied and mathematical model used for GMO are given in [14].

Simulation Setup in Flow-3d

The geometry file of the device was imported in STL format into the computational domain. It was observed that the geometry file and mesh structure can be modified independently reducing the problem setup time significantly. Three different mesh configurations were tested for mesh-independence and an optimum mesh was selected.

To add extra cells in a region of critical flow behavior, the option exists to use a nested mesh block. The mesh structure together with the boundary conditions used is shown in Fig. 3.

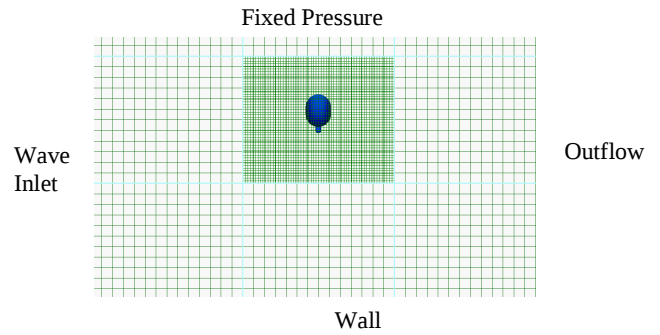


Figure 3: Side view of the computational domain showing mesh and boundary conditions.

The side wall boundaries in Fig. 3 were chosen to be symmetry boundaries. A linear wave boundary condition is set by prescribing velocity components using linear wave theory. The turbulence model used for the final simulations was the RNG (Renormalization group) model preferred by [14].

An implicit GMO model was used for all simulations. It was observed that the implicit method displayed high stability and good efficiency compared to the explicit model.

4 Results

A linear wave was modelled in the NWT (numerical wave tank) as part of a preliminary analysis and the resulting wave propagation studied. It is observed that Flow-3D's solver is quite robust for modelling water waves. The specification of the simulated wave is given below whereas the surface elevation of this wave at two different locations is presented in Fig. 4.

Wave amplitude = 0.15m, Time period = 4.2s, Water Depth = 1.5m, Tank Dimensions = (35m, 1.5m, 2.5m),

Computational Specifics = Intel(R) Core(TM)2 Duo CPU E6750@2.66GHz , 8GB of RAM.

Total Number of Cells = 793638, Smallest Cell Size = 5.4773E-02

Time taken by solver to compute a 20 seconds case = 2.030E+04(seconds) = 5.63 hr

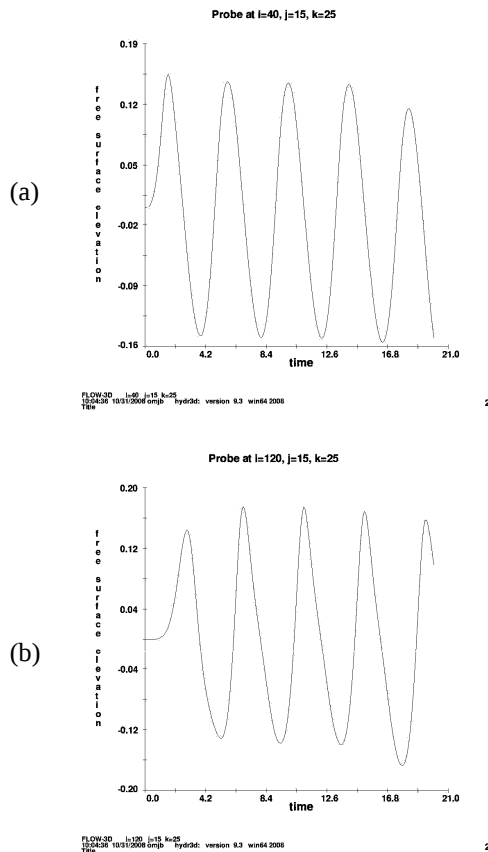


Figure 4: Surface elevation at (a) $x=2.1\text{m}$ (b) $x=6.5\text{m}$.

To measure the natural frequency of the device the decay test was setup. The decay test involved the pulling of the device from its resting vertical position (still water) towards one end, and then held for a few seconds until the disturbed free surface returns to its calm state. The device was then released and its damped oscillatory motion monitored. Experimental results of the decay test are validated by comparison with numerical results as plotted in Fig. 5.

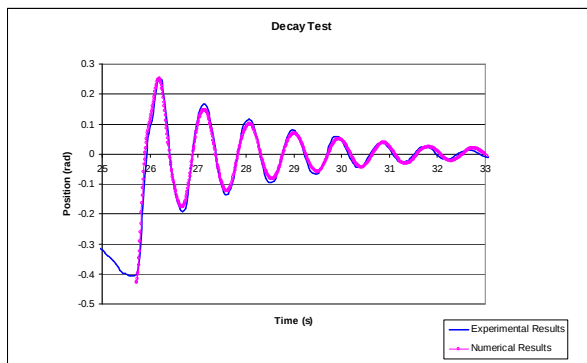


Figure 5: Comparison of experimental and numerical results of decay test.

To model the decay tests two separate simulations were set up. In the first simulation, the device was pulled towards the right end by 0.4 rad. This was achieved by prescribing a constant velocity. Then in the

second simulation, the coupled motion of the WRASPA device was modelled by using the results file of the first simulation as its initial conditions.

The pitch motion of the device for a range of linear waves was modelled and the results compared with the experimental data (Fig. 6~7).

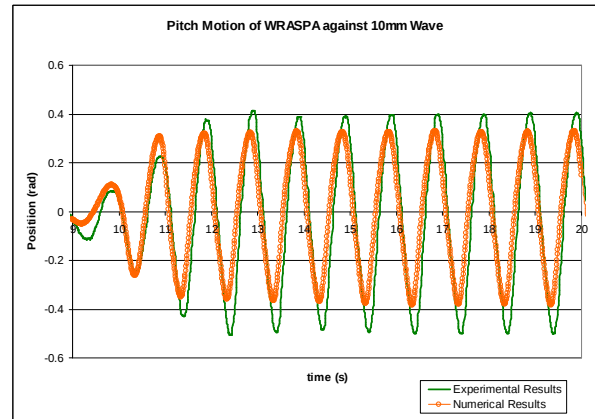


Figure 6: Pitch motion of WRASPA against linear wave of 10 mm Amplitude.

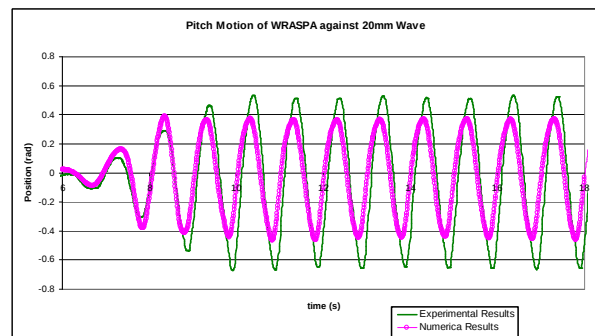


Figure 7: Pitch motion of WRASPA against linear wave of 20 mm Amplitude.

As part of the shape optimization process two collector shapes were numerically tested; depicted in Fig. 8.

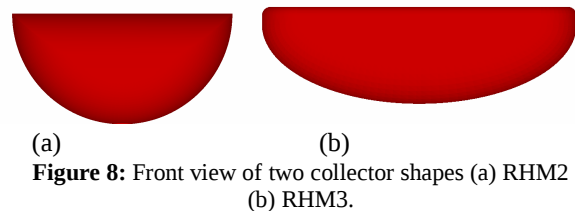


Figure 8: Front view of two collector shapes (a) RHM2 (b) RHM3.

A characterization test is conducted and the torque required to keep the device still against incident waves is measured. During these tests the device is held still against the incident waves while recording hydraulic torque exerted by incoming waves. The numerically measured torque (from characterization test) for both shapes is compared (Fig. 9) in order to distinguish an optimum shape. The simulated pitch motion of RHM3 is currently being analyzed experimentally.

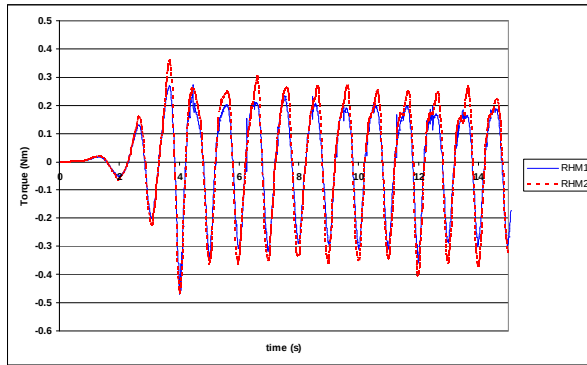
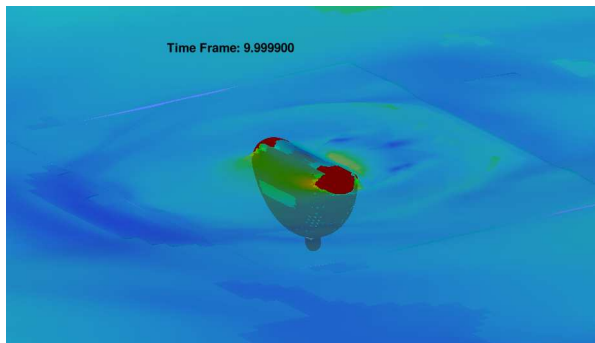


Figure 9: Numerical Results of time history of torque for shapes RHM2 and RHM3 from the characterization tests.

Visual comparison of experimental and numerical output is shown in (Fig. 10).



(a)



(b)

Figure 10: WRASPA in action (a) Experimental wave tank (b) Numerical wave tank.

The numerically modelled surging response of WRASPA to the incident waves at various instants is shown in Fig. 11. The colour contours in Fig. 11 refer to the velocity profile.

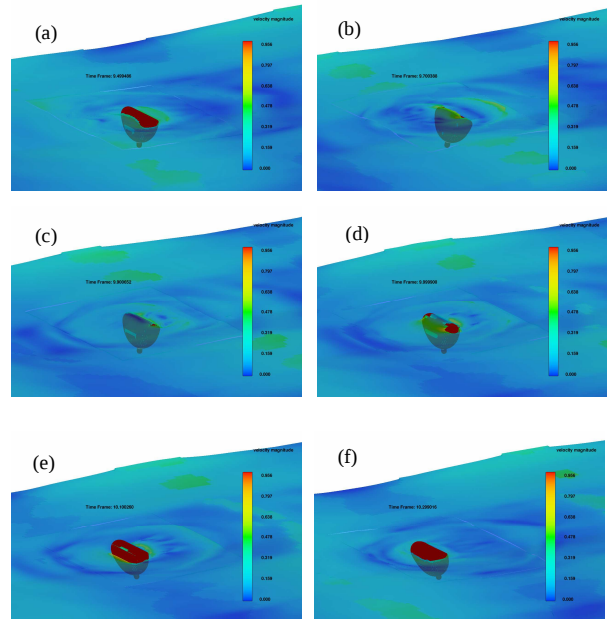


Figure 11: Wave interaction with WRASPA at various time instants.

5 Conclusions and Future Work

The numerical results of the decay tests are found to be in good agreement with the experimental data. However the free pitch motion of the device is underestimated by Flow-3D but is still in reasonable agreement. Numerically measured torque from the characterization test is being analyzed against experimental data and further work is required for shape optimization process for similar tests to be conducted against irregular incident waves. Further work will also involve an investigation of the pressure profile on the collector body in regular and irregular waves. Another important aspect which requires further investigation is the vorticity generation in the vicinity of the collector so as to improve the optimization of the collector shape. A final step of the further work would include prediction of power output using a full-scale model of the device.

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