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2D COUPLED CFD MODEL OF AN OSCILLATING WATER COLUMN USING PROTEUS

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ABSTRACT

Floating Oscillating Water Columns (OWC) are one of many potential Renewable Energy Devices under consideration as part of the global drive towards clean energy sources. In order to reach deployment, these devices first exist in the form of computational models. These models allow the devices to be tested under a range of conditions and mooring configurations. However, the design of systems often fails to account for the moorings at an early stage, which can result in disappointing performance at later stages of design and deployment.

In this study, Proteus is used to produce a 2D model of an OWC that demonstrates its effectiveness as a tool for modelling floating marine structures. The model solves the Reynolds Averaged Navier Stokes equations in the fluid domain, using a Volume of Fluid-Level Set approach for defining the air-water interface. Proteus is coupled with the Chrono library to solve the rigid body motions, and the response of the mooring lines. The model is validated against both experimental and other computational models. The effect of a mooring system is shown on the water column response.

This study provides a launch pad for more complex studies. Proteus has 3D modelling capabilities, and as a result, 3D OWC, other wave energy devices and floating wind turbines are all potential devices that Proteus has the capability to recreate in high fidelity models

1. INTRODUCTION

As the offshore renewable energy industry grows, developers are forced to widen the scope of sites with available resource worth harnessing. In practice, this means that developers are considering the need for deeper water sites to be considered. These deep sites mandate that devices float, and are constrained by mooring lines primarily for station keeping (and in some cases as an integral part of the power take off system).

During development, devices will usually be tested both computationally, and at model scale, due to the risk and cost of full scale testing, even for the smallest devices. In a sector with relatively little practical experience, these models are vital for the success of a device. A range of different modelling tools are used across the industry.

Proteus is an open source computational toolkit in active and ongoing development by the Engineering Research and Development Center (ERDC) of the US Army Corps of Engineers and HR Wallingford under a collaboration agreement. Proteus is designed to provide a multi-physics and multi-numerics modelling tool for continuum mechanics, which lends itself to modelling multi-phase flow problems, and fluid-structure interactions.

In this paper, a model of a 2D oscillating water column (OWC) is used to demonstrate the capabilities of Proteus as a modelling tool for floating renewable energy devices.

Section 2 gives a brief description of the Proteus model, and the most relevant components for this application. Section 3 details the model setup, and the device specifications. Section 4 details the validation work against computational and physical model testing. Section 5 then considers the impact of introducing a mooring system to the OWC, and exposing the device to regular waves.

2. PROTUES MODEL INFORMATION

Proteus is a computational fluid dynamics toolkit based on finite element analysis. The Proteus model can be considered as three major components for this application, the fluid domain, wave generation and body motion as described by de Lataillade [1] and Dimakopoulos [2].

2.1 FLUID DOMAIN

The fluid domain comprises both the air and water phases, with the velocity field determined by the incompressible Navier Stokes Equation:

$$\begin{cases} \rho\dot{\mathbf{u}} + \rho\mathbf{u}\cdot\nabla\mathbf{u} - \nabla\cdot\bar{\bar{\sigma}} = \rho g \\ \nabla\cdot\boldsymbol{u} = 0 \end{cases} \quad (1)$$

with fluid density ρ, fluid velocity vector $\mathbf{u}$, gravitational acceleration vector $\mathbf{g}$, and the Cauchy-Shwartz tensor $\bar{\bar{\sigma}} = -p\boldsymbol{I} + \mu\Delta\mathbf{u}$, with pressure p, and dynamic viscosity μ.
Implicit determination of the Fluid interface is performed using a coupled Volume of Fluid/Level Set (VOF/LS) approach [3]. This approach provides a sharp interface, and accurate determination of pressures at the surface, which is imperative for calculating hydrodynamic loads on floating structures.
The time-step of the simulation is controlled through the demands of the fluid domain using the Courant-Friedrichs-Lewy (CFL) condition:

$$CFL = \frac{u\Delta t}{\Delta x} \quad (2)$$

Where u is the fluid velocity, Δt is the time step, and Δx is the element length. The CFL for each cell is calculated, and constrained by reducing the time step, as this is easier than re-meshing. In this work, the CFL limit is 0.4.
The turbulence model used in Proteus can be chosen from a range of options. In this case, the $\kappa - \varepsilon$ model is used, however there are currently issues with the implementation.

2.2 WAVE GENERATION

Proteus uses the relaxation zone method to generate and absorb waves. Gradual diffusion of the boundary conditions is achieved through penalty terms in the momentum equations.
The waves generated in this case are regular monochromatic waves, using Fenton's approach, with eight Fourier components. [4]

2.3 BODY MOTIONS

Proteus utilises Project Chrono, a multi-body dynamics engine to simulate both rigid and flexible bodies. In the model presented in this paper, the device is modelled as a rigid body.
The hydrodynamic loading is calculated by taking the fluid stresses from the solution of the Navier-Stokes equation, and integrating them over the fluid-solid interface:

$$\boldsymbol{F_f} = \int_{\partial\Omega_{f\cap s}} \bar{\bar{\sigma}}\boldsymbol{n}\mathrm{d}\Gamma \quad (3)$$

$$\boldsymbol{M_f} = \int_{\partial\Omega_{f\cap s}} (x - r) \times (\bar{\bar{\sigma}}\boldsymbol{n})\mathrm{d}\Gamma \quad (4)$$

with fluid-solid boundary normal vector $\mathbf{n}$, a point on the boundary x, the position of the barycentre r, and the boundary Γ.
Mooring forces ($F_{mooring}$) are applied directly to the body, and are calculated depending on the nature of the mooring used.
Therefore the total forces on the device is given:

$$\boldsymbol{F}_{buoyancy} = m\mathbf{g} + \boldsymbol{F_f} + \boldsymbol{F}_{external} \quad (5)$$

where m is the body mass, and $\boldsymbol{F}_{external}$ are any other applied loads.
As the body moves, the mesh is deformed through the Lagrangian-Eulerian (ALE) method (or Mixed Interface-Tracking/Interface-Capturing Technique (MICTICT)). [5]

3. OSCILATING WATER COLUMN

The specifics of the OWC model used in this paper are derived from research by Uzair [6], who in turn based their computational model of a floating OWC on experimental testing performed by Faltinsen [7].
The 2D OWC consists of an open chamber bounded by a pair of caissons. In Proteus, the caissons are modelled as a single rigid body (even though the body is comprised of two shapes).
The dimensions are identical to those defined by Uzair (Figure 1), with the draft $d = 0.18$, the caisson width $L_{caisson} = 0.36$, the gap $L_{gap} = 0.18$ and water depth $h = 1.03$ retained. The corners are kept sharp as Uzair demonstrates that rounded corners make a minimal difference, and the resultant reduction in mesh elements aids the speed of the simulation.

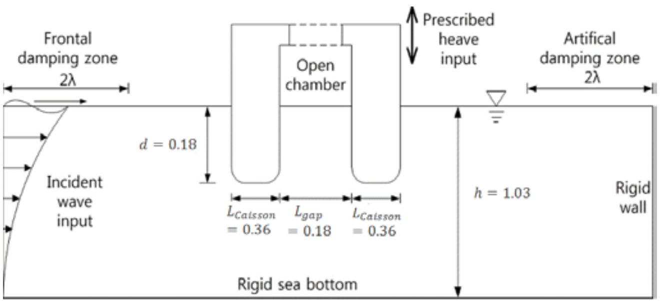

Figure 1 - OWC device geometry (adapted from Uzair [6])

Although unnecessary to consider in the forced oscillation case, the mass of the device needs to be defined for floating simulations. By considering other devices such as those in [8] and [9], and their approximate geometries and masses, a value for the mass of 100kg/m was determined.

The device is placed in a numerical wave tank, with dimensions dependent on the simulation:

- For forced oscillation simulations, the tank has absorption zones at either end of one metre, and two metres between the OWC and each absorption zone.
- For regular wave loading simulations, the generation zone has length equal to the wave's wavelength λ, absorption zone of length 2λ, and a spacing of 4λ between the device and absorption/generation zones. Proteus only requires a single wavelength for the wave generation relaxation zone, unlike Uzair's potential flow model.

The fluid domain is meshed with an unstructured triangular mesh, with maximum element length of 0.01m

4. VALIDATION

The Proteus model is validated against Uzair's potential flow model, and Faltinsen's experimental results. The forcing frequency and the water column amplitude are non-dimensionalised as equations 6 and 7 respectively:

$$\omega' = \frac{\omega^2 L_{gap}}{g} \quad (6)$$

$$\eta' = \frac{\eta_{water}}{\eta_{body}} \quad (7)$$

The OWC is forced to oscillate sinusoidally with amplitude 0.0025m for a duration of 60 seconds. A normalised frequency ranging from approximately 0.4 to 0.72 was designated as the range of interest, as excessive simulations along the tail of the data was deemed an inefficient use of computational time.

The resultant mean mid-column water level was calculated by tracking the flux through a slice at the base of the column. Then, by relating the flux $\bar{q}$ for the forcing frequency ω_f, the mean free surface $\bar{\eta}$ can be determined:

$$\frac{\bar{q}}{\omega_f L_{gap}} = \bar{\eta}\sin(\omega_f t) \quad (8)$$

Finally, the free surface height is corrected by the OWC position, as the height of the water column relative to the device is the relevant parameter for an OWC. This was performed through the use of the post-processing software, Paraview, through the python interface.

The resulting waveform of the water column height is then processed to find the peaks, troughs and resulting amplitudes, of which the root mean square value is taken as the response amplitude.

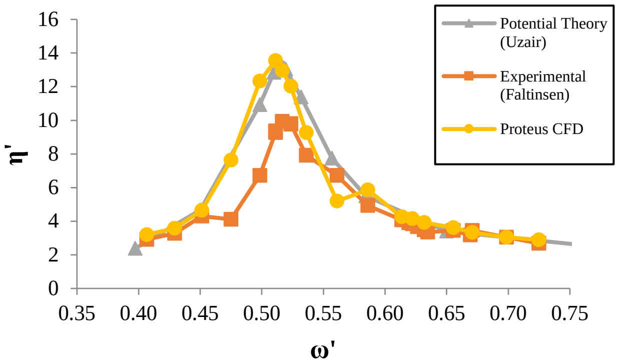

Figure 2 - Proteus CFD model validation against experimental and potential flow models

Proteus performs reasonably well, mirroring the performance of the potential flow model closely. While Uzair uses tuned damping coefficients to achieve increased agreement with Faltinsen's experimental results, the process is not rigorous, and may fail with these parameters on other models.

The simulation time ranged from 1 hour and 54 minutes to 2 hours and 50 minutes on a 36 node core on HR Wallingford's 'Hydra' high performance computing (HPC) cluster.

As potential flow models do not support turbulence models, this was identified as a more rigorous approach for the Proteus model to achieve results closer to the experimental.

However the current implementation of a single phase turbulence model is performing poorly, with excessive damping observed. The development of a 2-phase turbulence model is a development priority, with an approach similar to [10] to be taken.

5. MOORINGS

Simple springs are used for this initial investigation into moorings. This mimics a tension leg type mooring, in order to restrain the device movement. The parameters are chosen such that the design draft of the OWC is maintained under no wave loading. Fairleads are positioned at 0.18m either side of the centreline, with anchor points directly below. An initial extension is assumed of 0.01m, and from this the linear stiffness is determined such that the device sits at the draft at equilibrium. The damping coefficient is determined to achieve a damping ratio of one.
Waves of height 0.1m and the same range of frequencies are tested. (Figure 4).
The response of the OWC remains similar to that of the forced oscillations. A slight decrease in resonant frequency is observed, but this is too small to be significant.
As the assumption taken for the initial extension is significant, a range of initial extensions from 0.004m to 0.02m are trialled, at the peak wave excitation frequency identified as 0.5 from Figure 4. This then results in a different stiffness and damping coefficient. From these experiments a range of further results can be taken: Figure 6 shows the tensions in the mooring lines for the range of mooring stiffness; Figure 7 shows the device surge response; and Figure 8 shows the device heave response.

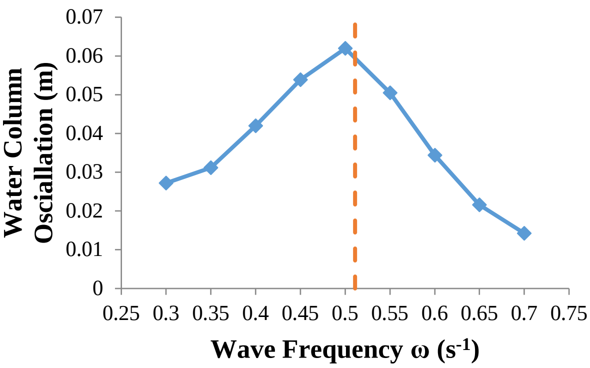

Figure 3 - OWC Response with simple spring moorings.

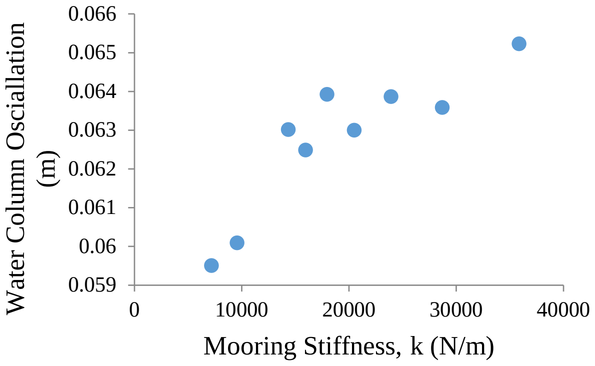

Figure 4 - OWC Response for different mooring stiffness

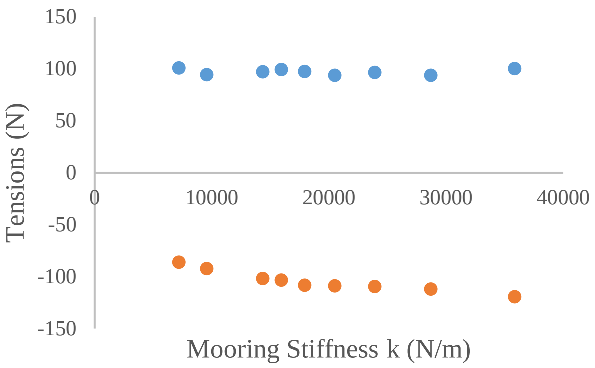

Figure 5 - Mooring tensions for different mooring stiffness

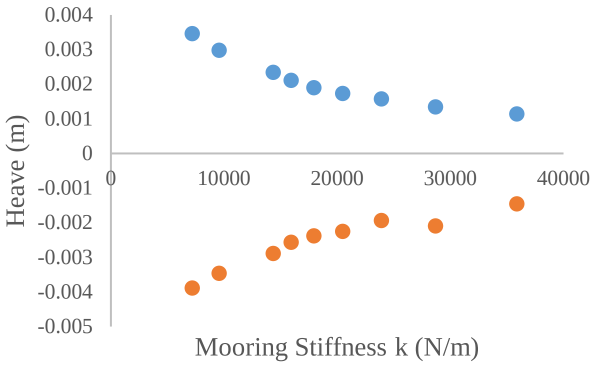

Figure 6 - Device heave response for different mooring stiffness

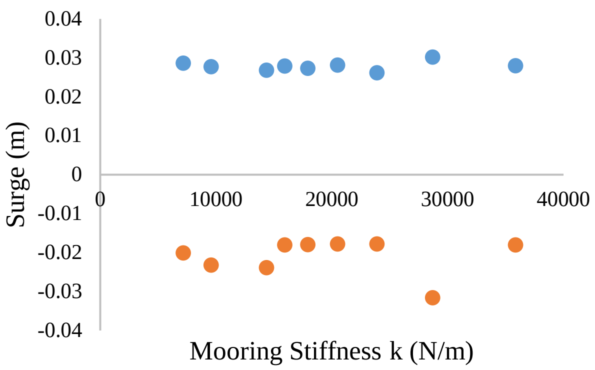

Figure 7 - Device surge response for different mooring stiffness

Whilst the OWC performance does vary with the stiffness of the moorings, it is less significant than it with the wave/oscillation frequency. The moorings behave as expected with a very small heave response, with a maximum 6% of peak water column oscillation. The surge response is much more compliant as expected with a TLP style mooring.
The heave compliance of the moorings is often used to counteract the tidal range in sites where an OWC would be installed. As a result, a tension leg mooring system (like which the simple springs mimic) would not usually be used in a site with significant tidal range. A Catenary mooring system is currently in development. In practice the stiffness of the mooring system would be limited by the material used.

6. CONCLUSIONS

This paper presents a 2D model of an OWC, which demonstrates the early potential of Proteus as a CFD modelling tool for floating offshore renewable energy devices. This is a work in progress on a rapidly developing software. Reasonable agreement was found with the potential flow model, with clear potential for further improvement identified.
Different mooring systems such as a fully dynamic catenary line is possible using Proteus and Chrono, and is scheduled for future work. Additionally, more complex wave regimes, with Proteus' fast random wave generation capabilities [10].
The fully coupled nature of Proteus as demonstrated in this paper indicates a useful design tool as models can be easily adapted, refined and perfected through a single interface.

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