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Modelling of fluid structure interactions in submerged flexible membranes for the Bombora wave energy converter

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Abstract

This paper presents a coupled Computational Fluid Dynamics and Fluid Structure Interaction model of the Bombora wave energy converter. The model consists of three components – the membrane, the power take off system (PTO), and the ocean – which are solved together to capture the device behaviour. The ocean (and waves) are solved using the volume-of-fluid method, the membrane is solved using a simplified Finite Element (FE) model, and the PTO is solved using a thermodynamic model of the ducting and turbine. OpenFOAM is used for the VoF models, extended by the `waves2Foam` toolbox. The membrane and PTO models are implemented from scratch as separate custom libraries, using OpenFOAM's base classes.

Comparison between the fully coupled inflation model and the uncoupled inflation model indicates that, as expected, the dynamic effects of the water cannot be ignored. It is expected that a combination of increased damping, and additional membrane mass may be able to account for a large part of the fluid loading. As a consequence of the different response times for each component of the model simulation run-times are excessive, and these simulations seek to quantify the certainty of some of the assumptions in the simplified models. However, future work will investigate alternative methods for coupling these models together.

Introduction

Development of renewable energy is essential given the need to reduce carbon emmissions to the atmosphere. While solar PV and wind power are relatively mature, they suffer from intermittent output (solar) and predictability (wind). Adding wave energy to the mix of renewables would alleviate this somewhat by diversifying the available sources. In contrast to solar and wind energy, wave energy is capable of 24h power production and can be reliably forecast a number of days in advance. Bombora Wave Energy has developed a novel concept for capturing wave energy. Their device consists of flexible membranes which use the force of incoming waves to drive air through a uni-directional air turbine to generate electrical energy, as shown in Figure 1. Each cell of the device is approximately 15 m long, with a chordlength of 5 m. The design water depths are between 5 and 15 m. Previous work has developed dynamic models for the power take off system (PTO), and the membrane(s)[5, 6].This paper modifies and extends this work to account for a change in the operation of the device, from a continuous membrane to a number of discrete membranes, in addition to extending the modelling to allow strongly-coupled simulations of the system to be undertaken.

The model consists of three components, the wave field, the membrane, and the power-take-off (PTO) system. The ocean and wave dynamics were modelled using a volume-of-fluid (VOF) approach, allowing for a moving deforming mesh. The membrane is modelled as a 3-dimensional tension membrane using triangular finite elements to determine the internal stresses and strains, while the PTO consists of a complete thermodynamic model of the air cells, ducting and turbine. All the models are implemented as custom code using the opensource CFD toolbox OpenFOAM [7]. Extensive use of OpenFOAM's mesh motion capabilities were used for the mesh deformation, while the `waves2Foam` toolbox was used for wave generation and absorption[4]. The system is solved as strongly coupled system using an iterative scheme.

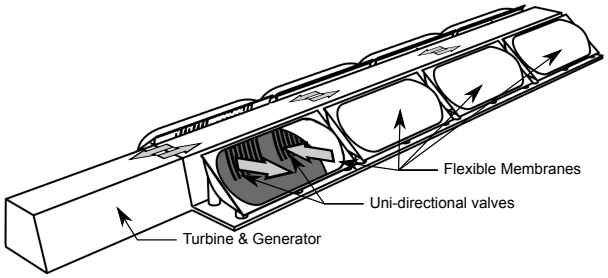

Figure 1: Bombora pilot-scale device

Background

A variety of wave energy converters exist in the literature and have been studied using analytical, numerical and experimental models. Numerical analysis techniques based on linear theory – frequency domain, time-domain, and spectral domain models – are well established, and give good results for a wide range of devices under various operating conditions [2]. Reasonably recently however more computationally intensive modelling techniques, such as Computational Fluid Dynamics, have become feasible [1, 3, 8, 10, 11]. The development of these models has been driven by the need to answer two key research questions, which are not readily answerable with linear models: behaviour of a device under the influence of large waves, or to investigate complex interactions of the device with the free-surface of the ocean. In contrast to Bombora's device, the wave energy converters in these studies are either entirely stationary (anchored OWCs), or rigid bodies (up to 6 degrees of freedom, depending on the device configuration). For the Bombora device, the research questions to be answered are similar but the motion of the membrane and the resulting stresses are key to developing an operational device, and present a much more difficult problem to solve.

Modelling

Membrane Model

The membrane is a key component of the Bombora device, and the deformation of the flexible membranes strongly influences the device behaviour. A key feature of membranes is their in-

ability to transmit forces other than those due to in-plane tensile stresses. Out of plane forces, compressive or bending stresses are not sustained in a static solution, while for a dynamic analysis these result in substantial deformation of the membrane. In the current modelling, the membrane's behaviour is modelled by direct integration of the forces acting on it. The membrane is discretised using a triangular mesh, with the resulting nodes forming discrete mass points on which the forces are applied. The internal stresses are calculated using a finite element approach with the element coordinates transformed into an element-local (2D) coordinate system. The element local coordinate system is aligned in the plane of the each triangular element, referenced to a particular point and edge. Using this coordinate system the local strains, and resulting stresses are determined using the strain-displacement matrix and are calculated relative to the unstressed reference orientation. These local stresses are used to determine internal stress acting on each node in the global-coordinate system after appropriate transformation. In addition to the internal stresses, the forces acting on the membrane are its self-weight, and the pressure forces from the ocean (p_{wave}), and the PTO (p_{PTO}). The resulting equation for each node point is:

$$\ddot{\mathbf{x}} = \frac{1}{m}\left(\mathbf{F}_{ext}(\mathbf{x}) - C\dot{\mathbf{x}} - \mathbf{F}_{int}(\mathbf{x})\right) \tag{1}$$

where, $\mathbf{x}$, $\dot{\mathbf{x}}$ and $\ddot{\mathbf{x}}$ are the mass-point dislplacement, velocity and acceleration; $\mathbf{F}_{ext}(\mathbf{x})$ and $\mathbf{F}_{int}(\mathbf{x})$ are the external and internal (stress) forces acting on the membrane; and C is a damping constant (Ns/m). In practice the membrane has negligle inertia compared to the fluid and the air in the PTO and Equation 1 can be simplified to

$$\dot{\mathbf{x}} = \frac{1}{C}\left(\mathbf{F}_{ext}(\mathbf{x}) - \mathbf{F}_{int}(\mathbf{x})\right) \tag{2}$$

This allows the membrane velocity to be directly calculated in each timestep and subsequently a reduction in the computational effort, and simulation time.

Fluid-Structure Coupling

The three components of the system are tightly coupled, and have very different inertias, and hence response times. This creates some modelling dificulties, and as such careful treatment of the coupling was required to allow for stable simulations. An initial displacement of the node points is calculated by time integrating Equation 2, however this is an over estimate of the actual displacement as the resulting change in the pressure of the fluid is ignored. To reach a stable solution, this displacement estimate is under-relaxed, before moving the mesh points in the fluid domain. This process is repeated within a timestep, until the final predicted membrane and fluid displacements agree to an acceptable tolerance. The complete algorithm is given in Figure 2. For the membrane, fluid and PTO system, an under-relaxation factor (β) in the order of 10^{-4} was required to reach a stable simulation. Correspondingly a large number of iterations (> 100) were required to reach convergence within each timestep.

Implementation

The membrane model and PTO model were implemented in C++, using OpenFOAM's native vector and scalar classes, using the in-built operators. Parallel partitioning for the fluid domain was performed using OpenFOAM's standard methods for decomposition and execution, while parallelisation of the membrane code was such that each membrane was solved on its own separate processor. The PTO model was also allocated a separate processor, and was responsible for transferring data to and from processors on which each membrane was solved. This partitioning allowed the simulation time to be reduced, compared with all membranes and the PTO model running on a single processor.

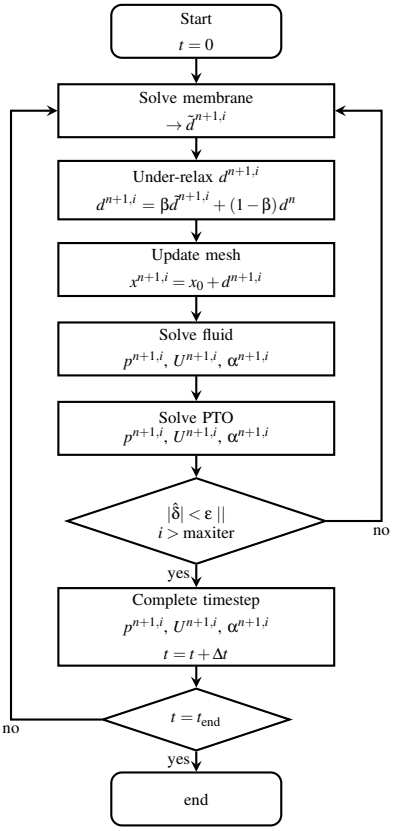

Figure 2: FSI coupling algorithm

A modular approach to the code was used, and allowed a simpler fluid model (hydrostatic only) to be used using the same underlying membrane and PTO code. A comparison between these codes is the first part of the results presented.

Results

Inflation test

The first case where the differences between the models is evident is for inflation of a single membrane with a 'constant pressure' PTO, and with no incident waves. For these cases, the membrane was initially in its equilibrium position (determined by a pre-cursor simulation), and the cell pressure behind the membrane was set to a constant uniform pressure, equal to the maximum expected operating pressure. The simulation domain is shown in Figure 3.

Figure 4 shows the internal cell volume versus time for the uncoupled membrane and the fully coupled fluid-membrane simulations for two different damping values (C). From this figure, it is clear that the artificial membrane damping, C, has a marked effect on the inflation results – the low damping case ($C = 1 \times 10^3$) is fully inflated within 1 s, whereas at the same instant the high damping case has only inflated to 65% of the maximum membrane cell volume.

In comparing the membrane only case to the fully coupled inflation case for the higher damping value ($C = 1 \times 10^4$), the inflation rates for each model are similar, with the fully coupled case inflating at a slightly lower rate.

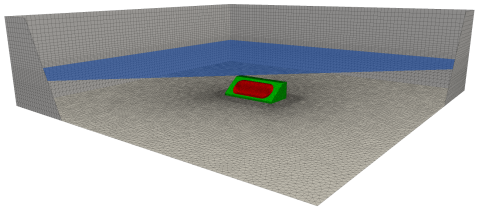

Figure 3: Domain used for inflation test

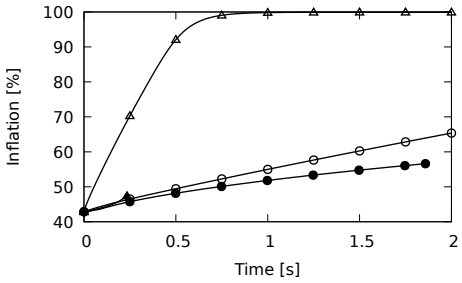

Figure 4: Comparison between membrane cell subject to hydrostatic loading, and the fully coupled simulation with no incident waves. △, ▲ have C = 1×10^3 Ns/m, and ○, ● have C = 1×10^4 Ns/m. Filled symbols indicate coupled simulations. Inflation is the % fullness of the membrane (0% indcates the membrane is resting on the floor). The membrane is initially at static equilibrium with $P_{\text{int}} = \rho g d_{\text{avg}}$

For the low damping fully coupled case, only a small amount of simulation time has completed (~ 0.24 s), but it is clear that the inflation rate does not follow the inflation of the uncoupled inflation model at all. Instead, the inflation rate matches the high damping simulations, at least for the period shown. The lower inflation rate for the coupled model is due to the additional mass and damping contributed by the water. The simulations are still at an early stage, but the result is useful, as it suggests that a (somewhat arbitrary) membrane damping of $C = 10^3$Ns/m, does not significantly affect the results.

Figure 5 shows the displacement of the membrane at different timesteps for the coupled and uncoupled inflation simulations. Again, as for Figure 4, similar deformations are observed for the uncoupled and coupled models. Figure 6 shows the displacement at $t = 0.2$ s, for the uncoupled and coupled models with low damping. Even after this short time, there is a substantial difference in the deformations predicted by the two models. Finally, Figure 7 shows contours of free surface elevation, and the radiated wave due to the membrane inflating.

Prescribed Sea-state simulations

The end goal of the simulation is to determine quantitatively the performance of the Bombora device under a given sea-state, representative of the location where the device will operate. The results from the static inflation tests suggest that completely coupled simulations of the device are likely to be infeasible for longer duration calculations (ie. in the order of 300s). However, an uncoupled model using an appropriate damping coefficient and mass may be sufficient to represent the effects of the ocean for design and performance assessment. In the uncoupled mode, the model uses the FE model for the membrane, the full thermodynamic model for the PTO and turbine, while the hydrodynamic forces from the ocean are due to the hydrostatic pressure beneath the wave only – calculated based on the wave height, and membrane position.

Taking advantage of this observation, it was possible to use the uncoupled model to predict the instantaneous power output of the device for a given sea-state, where this was simulated by superposition of the hydrostatic pressures of individual waves within a given spectra. Averaging of the data allowed the predicted power output of the device is able to be compared against the predicted power output calculated by linear modelling.

Figure 8 shows the comparison between the uncoupled, and linear modelling results. Due to limitations in transferring data between the different software the exact wave conditions could not be represented in both models. The same spectra, H_s, T_s and individual wave periods were used, while the random phase differed. From these results, the uncoupled model predicts approximately 25% less power than the linear model results. For this sea-state ($H_s = 1.25$, $T_s = 9.5$) non-linear effects are expected to hold, and the agreement is reasonable. For this set of parameters one of the key differences concerns the treatment of the membrane – the linear model assumes that the membrane shape is parabolic (with a simple scaling parameter), while the uncoupled model makes use of the full FE model of the membrane.

Discussion

The work presented here demonstrates that it is possible to model the coupled fluid-structure interaction of a light, flexible membrane under the influence of ocean waves. However, the large difference between the response times of the structure (membrane) and the fluid (water) make this technique extremely expensive in terms of the computational effort and wall time. The low-mass and high stiffness of the membrane relative to the water, require extremely small relaxation parameters (β in the order of 10^{-4} in Figure 2), and as a consequence a very large number of iterations to ensure convergence at each timestep. For the membrane itself small timesteps are required (independent of coupling), in order to resolve accurately its motion. These factors together mean that the required simulation wall times are long, even though parallelisation of the code is used where possible to speed-up the computations.

However, comparison of the coupled model and the uncoupled model with higher damping show reasonable agreement. This suggests that by judicious use of static CFD models and simplified uncoupled membrane/PTO models some of the research questions can be answered while avoiding the excessive simulation times required by a fully coupled FSI model. In particular the results indicate that the membrane behaviour can be made investigated using an uncouped model with an indicitive value of damping ($C \sim 10^4$). Future work will investigate whether more strongly coupled models (ie. using a single fluid/structure/PTO matrix) are able to reduce simulation runtimes.

Conclusions

The Bombora wave energy converter is a novel and promising method for renewable energy generation. However, its novelty also creates challenges in characterising its performance. A fully coupled Computational Fluid Dynamics-Fluid Structure Interaction model of the device has been developed to investigate and answer some of the questions that are traditionally considered out of the reach of the usual linear (potential flow) modelling of wave energy devices.

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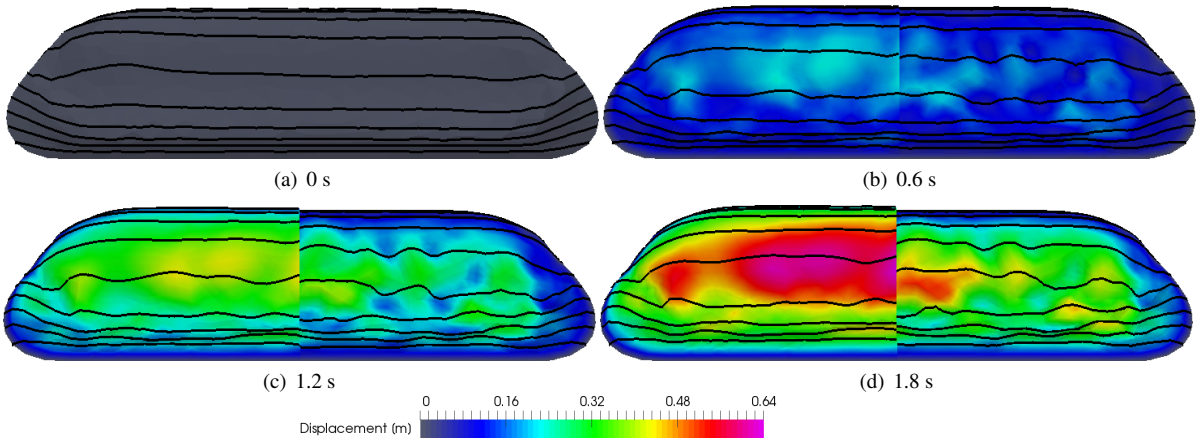

(a) 0 s (b) 0.6 s

(c) 1.2 s (d) 1.8 s

Figure 5: Comparison of inflation profiles between uncoupled (left) and coupled (right) models for the inflation tests with damping $C = 1 \times 10^4$ Ns/m. Images are coloured by displacement.

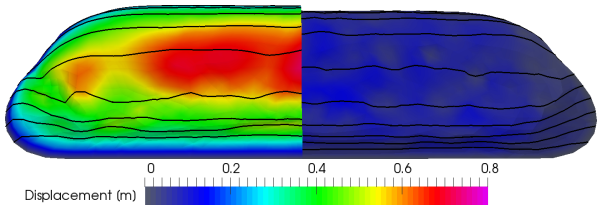

Figure 6: Comparison of inflation profiles between uncoupled (left) and coupled (right) models for inflation tests with damping $C = 1 \times 10^3$ Ns/m at 0.2 s.

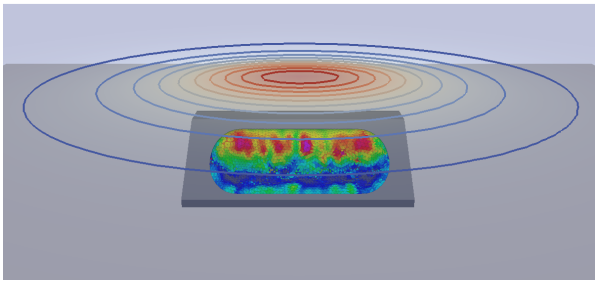

Figure 7: Contours of surface elevation, after 1.2 s. Membrane coloured by stress.

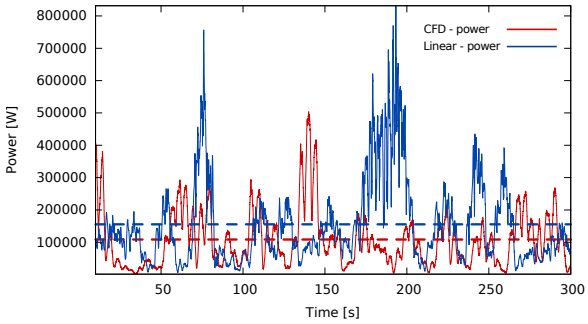

Figure 8: Comparison of linear and uncoupled model results. Average over the 300s is show as a dashed line for each model.

tional eResearch Collaboration Tools and Resources project (Nectar), and the Pawsey Supercomputing Centre with funding from the Australian Government and the Government of Western Australia.

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