COMPUTATION OF WAVE ENERGY DEVICE MOTIONS AND LOADS IN EXTREME SEA STATES (EXTENDED ABSTRACT)

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INTRODUCTION

Wave energy converters (WECs) are designed to maximize fluid-structure interactions between the device and the ocean wave environment in order to optimize energy production. As a result, the hydrodynamic loads that WECs experience during both normal operation and extreme conditions must be carefully considered during the device design process. Under most operational conditions, the relevant fluid-structure interactions can be modeled using common linear reduced-order numerical models and well-defined experimental methods. Conversely, under extreme conditions, WEC devices experience large amplitude motions, wave overtopping, wave slamming, and other physical phenomena that demand more complex modeling methods to deliver accurate predictions. Extreme conditions often determine the maximum design loads, and accordingly, the prediction of extreme loads is a critical step in the device design process. The inability to accurately determine device response in extreme seas has manifested itself in unexpected device failures [1]. The lack of certainty surrounding device loads will also lead to overdesign and must inflate the cost of wave energy.

The state of computational fluid dynamics (CFD) as practiced in the marine industry, has reached a point where fully nonlinear high amplitude waves may be simulated, in a statistically relevant way, with high fidelity. Although true simultaneous simulation of the smallest and highest frequency energy containing scales (sprays, ripples on larger waves, bubbly froth) can still not be feasibly done, the sensible effect of the smallest scales on large motions is dissipation. Due to the cascade of energy from larger, low frequency scales, to smaller high frequency scales, one only needs to simulate the larger scales of many such nonlinear motions to obtain accurate and useful fluid motion results. In fact, this dissipation may be reasonably represented, in CFD, by some combination of turbulence modeling and artificial diffusion. Thus, not true direct numerical simulation (DNS), but this approach is considered a best-design-feasible first-principals-based description of WEC motion. In these simulations the governing equations of motion are applied to both air and water fields, typically using a volume of fluid, level-set, or similar approach. Thus the detailed free surface wave-form and motion is resolved to a high degree of accuracy. The wind and water interaction with marine vessels is also simulated in a fully coupled fashion, by first-principals. For application to a WEC, mooring and power take-off device (PTO) must also be concurrently modeled.

RESULTS

The task of resolving the free ocean surface motion and coupled WEC motion has been demonstrated using the CFD software Star-CCM+ [2], applying a finite volume discretization with an overset mesh. The overset strategy facilitates the deduction of WEC motion, surface forces, and mooring loads with computational efficiency while allowing sufficient resolution and simulation of ocean waves. At this time, using CFD, the motion of a model WEC has been demonstrated in

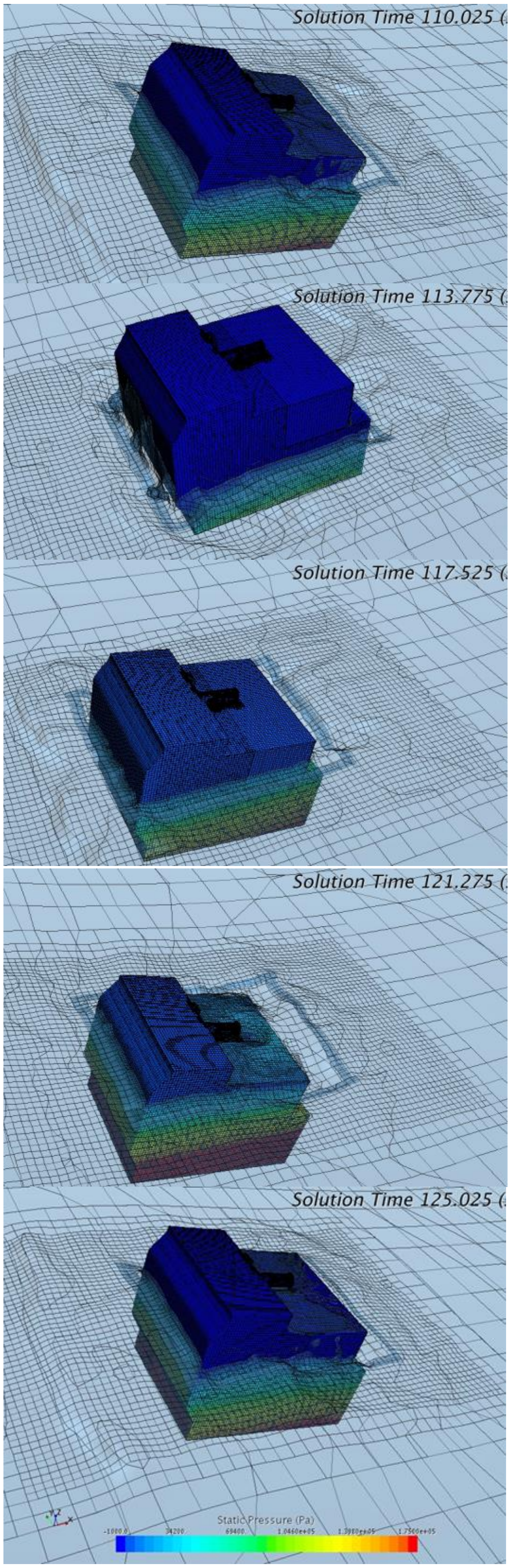

FIGURE 1: SNAPSHOTS FROM A SINGLE WAVE PERIOD OF BBDB SUBJECTED TO EXTREME SEA STATE.

moderately high sea states with a commensurate current and wind. Those states were specified to approximate a 100 year extreme for the Northern California coastal region. However, the mooring lines were modeled as elastic catenary lines, and thus they are relatively simplistic in comparison to the kinds of force and motion dependencies that one expects from a real mooring.

Sample results from this effort are shown in Figure 1. The motion of the WEC in high sea state is illustrated with a series of snapshots. The WEC body is colored by static pressure (which is gage zero at the undisturbed free surface) in Pa. The surface computational mesh on the body is also illustrated here. The gas-liquid free-surface interface is represented with a 50% by volume isosurface (based on the solution liquid volume fraction variable). The computational mesh resolution is also shown on the free surface. A cursory convergence study indicated this mesh was sufficient and asymptotic. However, further analysis is needed to quantify the discretization sufficiency for this state.

The WEC motion simulated in Figure 1 is at the demonstration level. The representative WEC is a full scale Backward Bent Ducted Buoy (BBDB, e.g. [3]) of notional design. Asymptotic discretization convergence practices were applied during this CFD modeling. However, physical experimental data was not available.

In Figure 2, a diagram from Weller [4] is shown. In the figure, a floating bobber is tethered by a cable in a wave tank. The cable is attached to a mass via pulleys in a fashion that should be easy to capture algebraically as an external force on the equations of motion for the bobber. Data from tests conducted by Weller are intended to be used for validation of numerical and other predictive tools. In Figure 4, a photograph of the bobber is presented (also [4]). Although not considered during this effort, the cable attachment, visible in Figure 4, may introduce unintended degrees of freedom. The bobber motion was modeled using the free-body motion solver packaged with StarCCM+ (same as applied for the BBDB). The cable force was determined algebraically using a *field function* [2]. Note that the cable was assumed to be inextensible, and the pulleys to be frictionless. A description of the assumed kinematics can be found in [5].

Waves were generated using the near focused wave modeling approach found in [6]. The near focused waves were captured in the StarCCM+ software by specification of an inflow boundary condition using *field functions* [2]. In order to verify the ability of the CFD software to reproduce the desired wave field, the wave form in the absence of the bobber, was generated on an asymptotically convergent grid. The CFD surface height history is presented along with the physically measured history in Figure 4. The wave form boundary condition was generated with 91 Fourier components using the first order approximation from [6]. This wave field was found to be in an asymptotic converged state on the given mesh. More details will be included with the final paper. The jaggedness of the CFD history is due to the formulation of the numerical probe. Clearly the wave forms (as seen in Figure 1) are smooth.

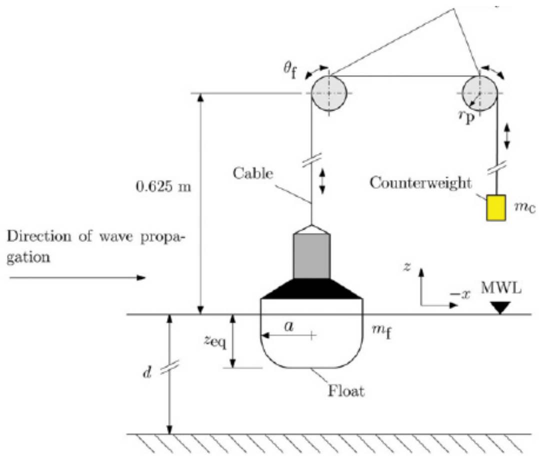

FIGURE 2: DIAGRAM OF BOBBER TEST [4]

FIGURE 3: PHOTOGRAPH FROM BOBBER TEST [4]

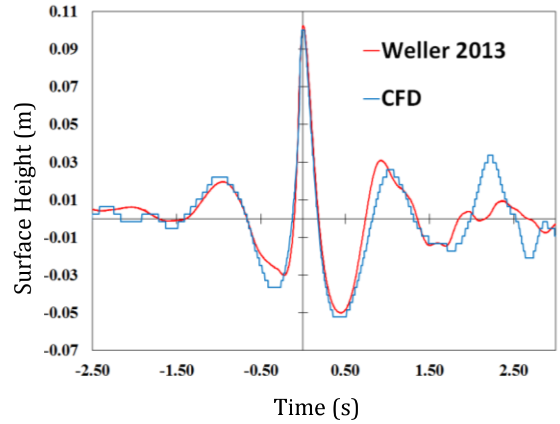

FIGURE 4: NEAR FOCUSED WAVE PROFILE.

In Figure 5, a phase plot of the motion of the model bobber and the measured bobber motion is shown. In this case, motion was computed in the presence of smooth regular waves. Again, the CFD results were determined to be asymptotically mesh and time-step convergent for this configuration. However, although the wave form was well captured, the CFD approach over predicts the motion of the bobber.

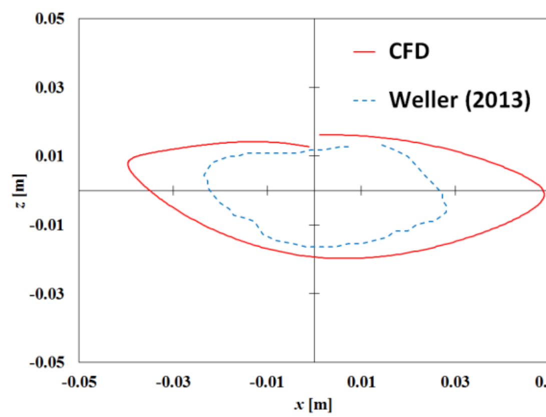

FIGURE 5: MOTION OF BOBBER UNDER INFLUENCE OF A REGULAR WAVE TRAIN.

The actual coupling of the bobber to the cable is pictured in Figure 3. This coupling may be more complex than assumed in the modeling effort. This might introduce significant degrees of freedom not captured in results pictured in Figure 5. Thus, although the work here does not convincingly reproduce accurate motions and loads, a potential modeling issue has been suggested. It is also noted that Westphalen et al. [5] have convincingly demonstrated a capability, using the CFD tool, StarCCM+, to accurately capture the motion of a similar bobber in similar near-focused wave conditions.

A final test case is that of a notional WEC PTO configuration. In this case, the hydrodynamic geometry is that of a spheroid of given mass and draft (the spheroid is approximately static at that draft). A second mass of undetermined geometry, given mass, and specified buoyancy is suspended beneath the spheroid. A pure damper couples the spheroid to the second mass. The second mass is moored to a fixed position by a pure spring. For this test case, all motions are restricted to the vertical direction.

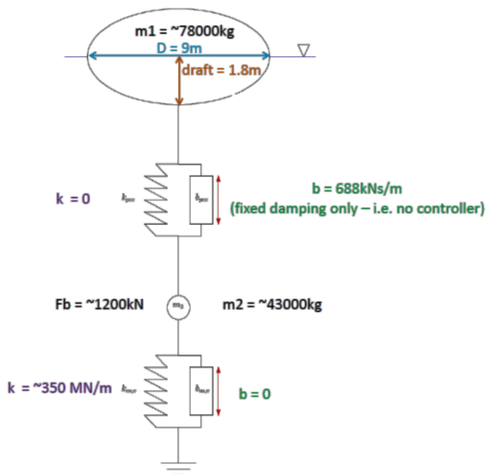

FIGURE 6: MODEL WEC PTO.

To approximate an extreme sea state, a JONSWAP spectrum based on 9 m significant wave height and 16 sec peak wave period was applied at the inlet boundary (see [2] for details of implementation). This wave spectrum is merely applied here as one that might be representative of an extreme condition on a notional device. Again the overset mesh approach was applied. Prior to CFD based solution of body motion, a background wave capturing mesh was determined to be convergent for the desired wave height and period. Then a convergence study was run on the motions of the test WEC PTO configuration. Some results from the study are pictured in Figures 7 and 8 and Table 1. In Figure 7, the computed heave force history due to wave WEC interaction is pictured. The heave motion is pictured in Figure 8. Results are tabulated in terms of root mean squared motion of the WEC for the first 15 seconds of simulation as well as the heave force time integration. This was done for several mesh densities. Note that seeds for the JONSWAP spectrum were frozen to facilitate convergence work.

One area of concern is the very large amplitude force excursions seen in the force histories pictured in Figure 7. These events appear to coincide with the notional WEC slamming into the free surface. It is clear that these events play a role in numerical convergence and the modeling of any real device in high sea states will require care and consideration in the capture of such events..

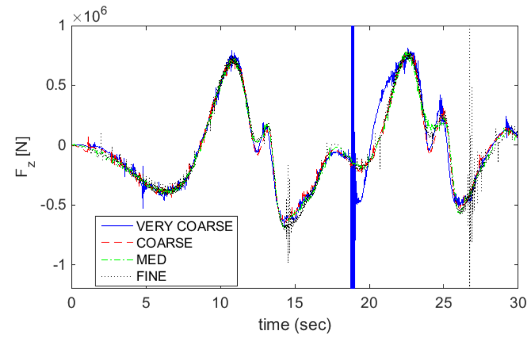

FIGURE 7: MODEL WEC PTO HEAVE FORCE (CONVERGENCE) PLOT.

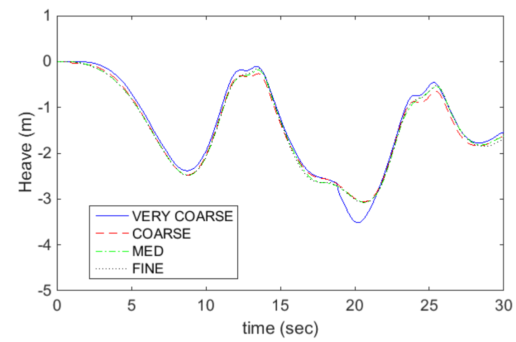

FIGURE 8: MODEL WEC PTO HEAVE MOTION (CONVERGENCE) PLOT.

TABLE 1: CONVERGENCE RESULTS FOR MODEL WEC PTO

MESH (cells)		0-15 sec rms $(z\text{-}z_{MEAN})$ (m)	$\int_0^{20sec} F_z dt$ (N-s)
Ocean (/10⁴)	WEC (/10³)		
7.08	7.34	0.8285	-3.210e6
12.8	14.5	0.8331	-2.061e6
256	222	0.8398	-2.074e6
1,780	1,700	0.8438	-1.986e6

CONCLUSIONS

The utility of finite-volume based CFD as implemented in a commercially available software package [2] as a tool for WEC simulation in extreme sea states has been demonstrated. Consistent with the findings of [5], the volume-of-fluid method coupled with a finite volume discretization is appropriate for computing motions and loads of a

WEC in extreme conditions. A critical issue, not addressed here, is determination of the needed fidelity of and the modeling of mooring and power-take-off components under extreme conditions and properly coupling this modeling to CFD. Modeling of more complex/representative configurations and rigorous convergence and validation studies are needed to appropriately quantify expected accuracy levels and determine best practices.

ACKNOWLEDGEMENTS

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