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Multi-Fidelity Framework for Modeling a Dual-Flap Oscillating Surge Wave Energy Converter

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Introduction

Wave energy is a promising high-density renewable energy resource that can effectively reduce dependence on fossil fuels and, thus, support mitigating the impacts of climate change. Its proximity to heavily populated coastal areas gives it specific advantages over other renewable energy resources such as wind and solar energy [1, 2]. Wave energy converters (WECs) have different designs and mechanisms to harvest power from ocean waves [3–6]. The oscillating surge wave energy converter (OSWEC) is one of the promising designs [7]. It is a single degree of freedom device hinged from the bottom to the seabed directly if deployed in shallow water or to a floating platform if deployed in deep water. Testing WECs at full-scale is challenging and costly. On the other hand, numerical simulations can provide an accurate alternative to assess the performance and optimize it. We introduce a multi-fidelity simulation framework to assess the performance of a full-scale dual-flap OSWEC and estimate its annual energy production. All numerical simulations were validated by experiments on 1:10 model performed in the Davidson Laboratory.

Results

Dual-flap OSWEC

The dimensions and mass properties of the full-scale and the scaled model of the dual-flap OSWEC are presented in Table 1. The dual-flap OSWEC was placed in the middle of the tank and the flaps were hinged to a box-shaped base with a height of 1.4 m, fixed to the tank floor as shown in Figure 1

Table 1: Dimensions and mass properties of full-scale and scaled-model flap

Parameters	Full-scale	1:10 scaled model
Width x height x thickness	12x7x2 m	1.2 x 0.7 x 0.2 m
Mass	35 tons	35 kg
Mass moment of inertia	10^3 ton $\cdot$ m^2	10 kg.m^2
Hinge depth from still water level	5.7 m	0.57 m
Center of gravity (CG) location from hinge	2.8 m (40%)	0.28 m (40%)
Flap draft	6 m (86%)	0.6 m (86%)
Distance between the flaps (hinge to hinge)	55 m	4.88 m

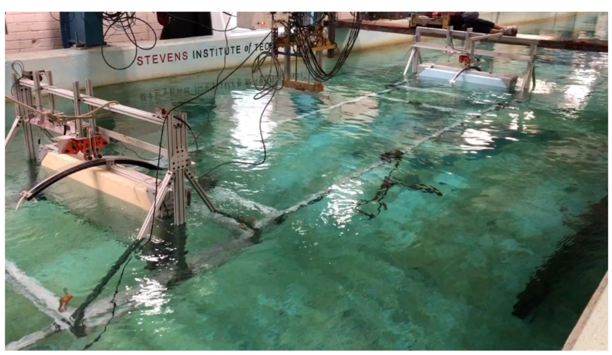

Figure 1: Picture of the dual-flap OSWEC as set in the experimental setup in the wave tank.

Numerical Modeling

Numerical simulations were conducted using ANSYS FLUENT and ANSYS AQWA. FLUENT uses the finite volume method to solve the governing equations of mass and momentum. In the high-fidelity (viscous) simulations, Fluent solves the Reynolds-averaged Navier–Stokes (RANS) equations, while in the medium-fidelity (inviscid) simulations it solves the Euler equations. AQWA assumes linear wave theory and solve the

Laplace equation along with unsteady Bernoulli equation to compute the torques acting on the OSWEC. Such simulations are referred to as low-fidelity simulations. The numerical domain was a mock-up of the geometry of the wave tank in Davidson Laboratory where the testing of the 1:10 scaled-model was performed except in length. Only a third of the length is simulated to reduce the computational cost.

Validation

The validation is based on comparing the responses from numerical simulations and experiments of the flaps and the values of the hydrodynamic coefficients (ω_n, I_a, and C_r). Figure 2 shows the high agreement between the experimental and high-fidelity numerical results in the first four cycles, the difference in the following cycles are most likely due to the the difference in the length of the numerical domain compared to the wave tank. Table 2 compares the hydrodynamic coefficients from the experiments and high-fidelity simulations. The error is less than 2% for the front flap and less than 4% to the back one proving the high accuracy in predicting the response by high-fidelity simulations. Moreover, wave excitation tests were performed covering a range of different wave frequencies and wave heights. An example is shown in Figure 3 for excitation under regular wave conditions of 3 s wave period and 0.08 m wave height. The results show a high agreement with an error less than 2% in the response amplitudes of the flaps. Considering these results, it is determined that high-fidelity simulations can predict the response accurately.

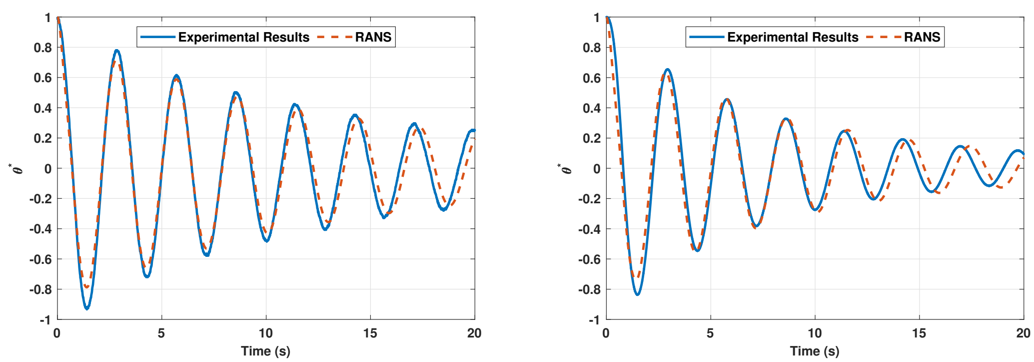

Figure 2: Comparison of measured and RANS simulated free responses of the front flap (left) and back flap (right). Responses were normalized with the initial displacement. It was noted during the experiments that the damping of the back flap was larger than the damping of the front flap. This difference was due to using different bearings with higher friction in the back flap. To represent this additional friction of the back flap in the simulations, we added a mechanical damping term to the equation of motion.

Table 2: Comparison between numerical and experimental values of hydrodynamic coefficients from the free decay tests

	Experiment (front)	Experiment (back)	RANS simulation (front)	RANS simulation (back)	Error (front) (%)	Error (back) (%)
ω_n	2.215 rad/s	2.218 rad/s	2.221 rad/s	2.182 rad/s	0.29	1.61
ζ	0.0395	0.0586	0.0400	0.0595	1.41	1.63
I_{added}	49.10 kg.m^2	48.92 kg.m^2	48.75 kg.m^2	50.87 kg.m^2	0.70	3.97
C_{rad}	10.34 Nm.s	15.32 Nm.s	10.45 Nm.s	15.82 Nm.s	1.1	3.3

Multi-fidelity Simulations

High-fidelity simulations are accurate, but computationally expensive. A lower fidelity model is needed for optimization purposes and evaluating the performance of WECs. We consider low-fidelity simulations with the assumption of linear wave theory using AQWA, and medium-fidelity simulations solving Euler equations for two different mesh sizes. To assess the accuracy of these models, a comparison of their predicted responses and the measured response from experiment is presented in Figure 4. The plots show that AQWA predictions have a large error, most likely due to the linear assumption and the underestimation of the damping

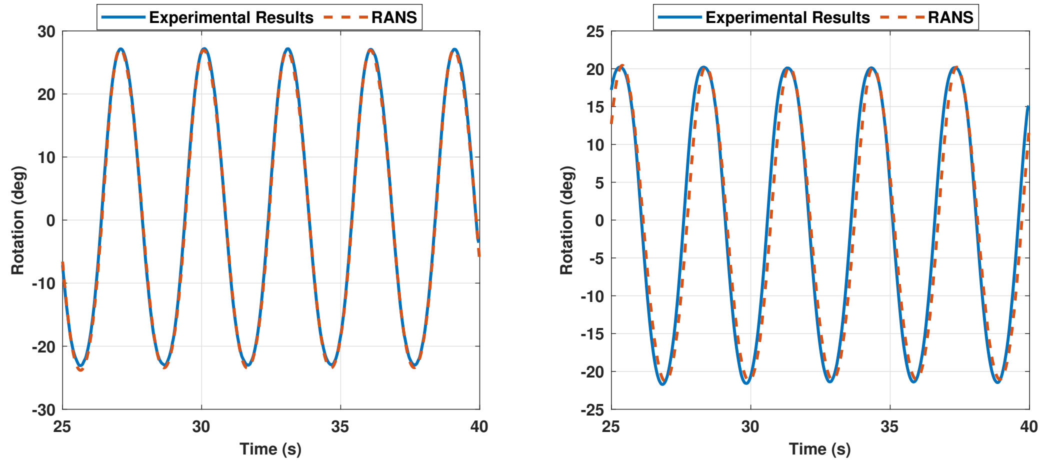

Figure 3: Comparison of experimental and RANS simulated time series of the front (left) and back (right) flaps when excited with a regular wave having a period of 3s and a height of 0.08m.

coefficients. On the other hand, the plots in Figure 5 show an acceptable prediction from the medium-fidelity simulations. Table 3 compares the required computational time to simulate 40 s from different fidelity simulations with the corresponding error percentage in the root mean square (RMS) of the responses. The results show a significant reduction in the computational time for medium-fidelity simulations with coarse mesh where the computational cost is reduced by 90% when compared with high-fidelity simulations with an error of only 11%.

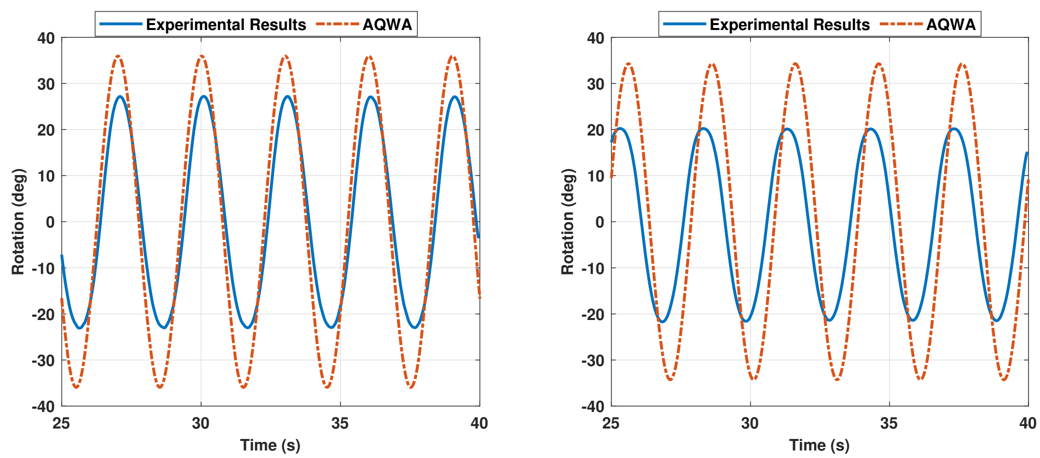

Figure 4: Comparison of the time series of the flaps responses as determined from AQWA simulations with the experiments under regular wave excitation with a period of 3s and a height 0.08m for front flap (left) and back flap taking into consideration additional mechanical damping (right).

Significance and impact

Balancing the computational cost and accuracy is important in the early phases of design and analysis of WECs. With the introduced framework of multi-fidelity simulations,it is possible to balance teh computational cost vs. acceptable error levels. The ability to reduce the cost by 90% is important for exploring different design configurations and power generation estimates under different sea states.

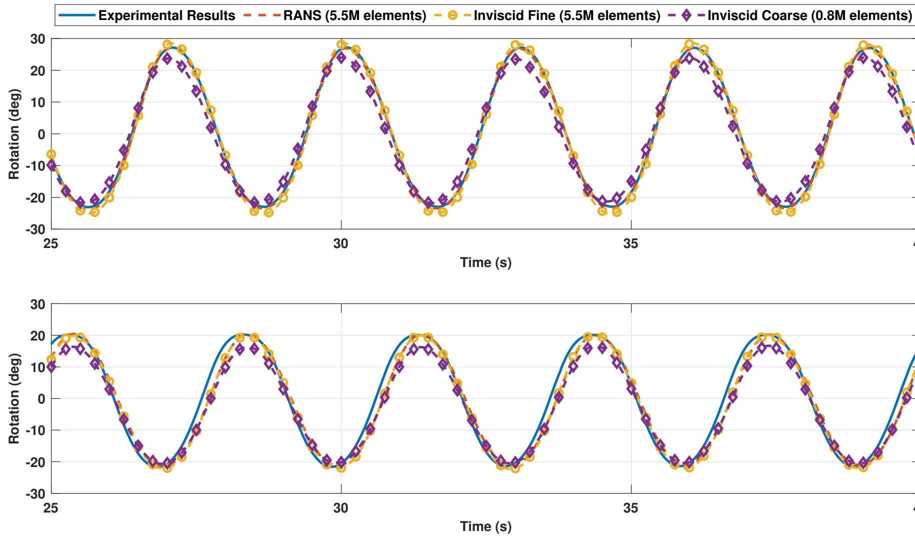

Figure 5: Comparison of simulated time series under regular wave forcing using a 3s wave period and 0.08m wave height obtained from different solvers and mesh resolutions for front flap (top) and back flap taking into consideration additional mechanical damping (bottom).

Table 3: Required time to compute 40s of the response and corresponding error relative to measured value at 0.08m wave height and 3s wave period (near the natural frequency)

	Computational time	Error (front) (%)	Error (back) (%)
RANS	72 hrs.	1.03	1.68
Inviscid (fine mesh)	57 hrs.	6.84	0.99
Inviscid (coarse mesh)	7 hrs.	10.36	10.93
AQWA	0.3 hrs.	52.75	80.65

Future Impact

The proposed design and framework will be applied to a a full scale dual-flap OSWEC to evaluate its performance and estimate annual energy production of such a framework in the Pac-Wave South site.

Publications

One paper that includes these results has been submitted to Renewable energy. A conference paper has been accepted for presentation at OCEANS 2023 - Gulf Coast Conference. Both papers acknowledge the Link Foundation support.

Link Foundation Impact

The Link Foundation fellowship has allowed me to dedicate my full-time effort to perform my doctoral research. Being awarded this prestigious fellowship will definitely add to my future career prospective. I am very grateful for being awarded this fellowship and look forward to applying my earned skills on different research topics in the field of ocean engineering.

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