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COMPARISON OF MODEL POWER PREDICTIONS TO DEPLOYMENT MEASUREMENTS

Kathleen A. Edwards, James Bretl, John Montgomery, Mike Mekhiche, and Bruce Downie
Ocean Power Technologies, Inc.
Pennington, NJ, USA

[1]Corresponding author: kedwards@oceanpowertech.com

ABSTRACT

OPT is presently validating output of a numerical modeling tool, STORM, against data collected during the ocean test of an autonomous PowerBuoy. While earlier comparisons of STORM to tank test results built confidence in the tool, in the present study significant differences are observed between the model and ocean test measurements. Such differences are attributed partially to real-world processes that were not included in the initial model, such as (a) friction upstream of the point at which power was measured, and (b) variability of real-world waves which may not be adequately described by height and period statistics when tabulating power output. Investigation into these processes continues; here we seek to provide an example of challenges in modeling real-world rather than idealized systems.

BACKGROUND

Ocean Power Technologies (OPT) develops heaving wave energy converters called PowerBuoys. The PowerBuoy® design process is described in [1]. Here the focus will be on autonomous PowerBuoys (APBs) intended to supply power to customer payloads. Compared to utility WECs, APBs are smaller in scale and unconnected to the power grid. OPT previously deployed an APB for 3 months off New Jersey for the LEAP project [2], and is presently refining the design of its structure and power takeoff (PTO) for upcoming deployments. The design refinement relies on power and load predictions from OPT's STORM tool (Simulink Target for Orcaflex Realtime Modeling), which has been validated against wave tank results for a variety of system geometries [3]. Figure 2 shows validation of STORM against wave tank test data for larger PowerBuoy prototype (PB150) geometry, described in more detail in [3]; while power is overpredicted at low sea states, model performance is judged acceptable for use in design. Compared to the APB geometry that is the focus here, PB150 is a larger system but with similar overall configuration (e.g. float, spar, and heave plate, Figure 1) for capturing power in heave.

Numerical WEC models are typically validated against tank test data instead of ocean deployments, since the former is more cost-effective. Tank testing is well-characterized: the tester can command selected sea states and confirm they are executed in the tank, for example specifying wave statistics like significant wave height (Hs) and average wave period (Ta). Such simplifications make it easy to obtain valuable information such as the device power matrix which in turn can be used to estimate power performance at any site with a known wave climate.

However, tank simplifications necessarily decrease the realism of results. Real wave conditions may be complex: instead of a single-peak spectrum, multiple wave sources may be present (swell and wind waves). Energy at the latter short periods may be closer to the natural resonance of smaller APBs, and thus affect the power performance. WEC tank tests often employ simple parameterizations of sea state, such as Hs and Ta, but spectral shape may also vary and influence WEC power output [4]. Further, full-size mechanical components must be selected for many aspects (e.g. cost, off-the-shelf availability, and life) that result in performance differences from scale models used in tank tests. Full-size component performance may not be known when the scale model is built; for example, PTO friction is difficult to measure due to its non-linear dependence on PTO motion and the physical challenges of testing an assembled WEC. If friction is unknown, it is difficult to represent in a model.

These challenges are illustrated by OPT's effort to reproduce ocean test results using the

STORM model, which has required addressing issues that could be ignored in prior tank test comparisons. It is hoped that results are relevant for other efforts to develop WEC performance models, such as WEC-Sim [5], WaveDyn [6], and Inwave [7].

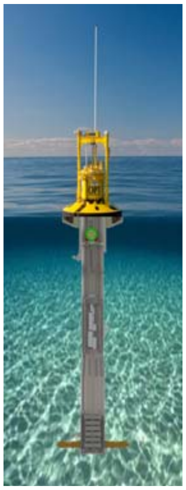


FIGURE 1: SCHEMATIC OF APB CONSISTING OF SURFACE FLOAT, SPAR CONTAINING POWER TAKEOFF, AND HEAVE PLATE CONSTRAINING SPAR MOTION

	Period (s)					
Height (m)	4	5	6	7	8	9
5						
4						1.03
3				1.17		1.01
2		0.84		1.02		1.05
1		0.79		1.02		0.96

FIGURE 2: RATIO OF TANK TEST TO STORM MECHANICAL POWER VS. SEA STATE (HS, TA) FROM PRIOR PB150 GEOMETRY STUDY [3]

APPROACH

Data from Ocean Test

In August 2011, OPT conducted a 3-month APB deployment off the New Jersey. The LEAP project (Littoral Expeditionary Autonomous PowerBuoy) extended offshore coverage of a coastal radar network via a radar antenna atop the APB, which used power generated by the APB.

The APB contained sensors to measure system health and behavior and power flow. Here the focus will be mechanical power at the input to the generator (Figure 3), estimated from the product of the commanded damping value, β_{PTO}, and the square of PTO velocity measured by the encoder. A constant PTO damping value was applied throughout much of the deployment; only data from those periods is included in the analysis here. Power captured by the APB is reduced by several sources of frictional losses prior to the generator input. Approximate values of these friction terms were estimated prior to deployment, but also indicate measurement challenges:

- Horizontal pusher tests of PTO prior to insertion in the APB accounted for linear and rotary systems (Figure 3) as well as generator bearings and indicated ~400 Ns/m frictional damping and ~200N constant frictional loss.
- Sealing elements friction of ~350N was estimated based on a pusher test; results varied with seal temperature.
- Neither test was configured to account for stiction; additional friction due to known lateral loading; float bearing friction; or changes in friction over time due to wear.
- Due to these lessons learned, OPT is presently iterating the design of systems in Figure 3 to reduce friction.

During the ocean test, measurements were collected relevant to various operational and performance aspects of the APB. To record wave information, an Acoustic Doppler Current Profiler (ADCP) was deployed adjacent to the APB. The software WavesMon [8] was used to obtain hourly estimate of wave statistics including Hs and Ta. Mechanical power was averaged within bins of Hs and Ta then tabulated to obtain a power matrix.

As stated previously, a height/period description does not capture spectral shape, e.g. multiple peaks. In the simulations described in the next section, a Bretschneider one-peak shape was assumed [9]. One measure of its adequacy is the ratio of Tp (peak wave period) to Ta, which is expected to be constant (1.29) for a Bretschneider spectrum; during the 3-month deployment, 17% of the measurements had a ratio exceeding 2. The limitations of a simple Hs/Ta description of sea state may account for high scatter of power measurements within sea state bins (Figure 4), and motivate continuing investigations into the effect of spectral shape on power output, which will be carried out with spectral measurements collected by the ADCP.

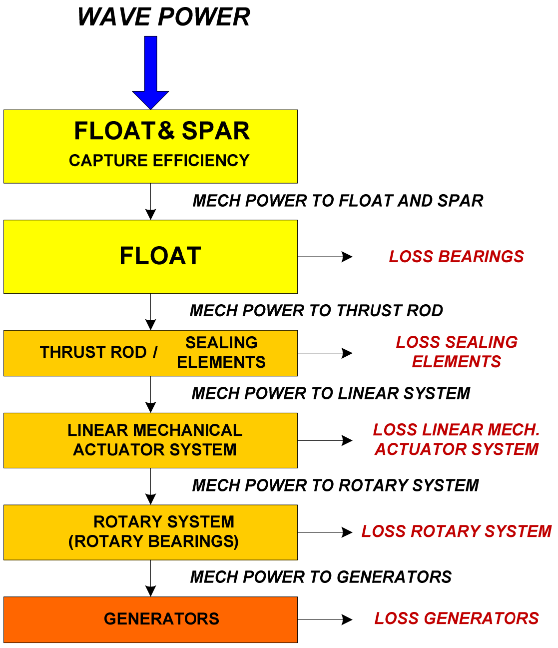
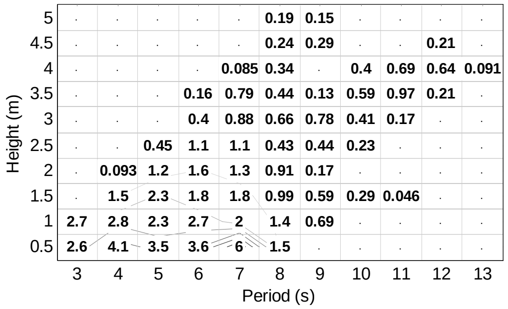


FIGURE 3: SCHEMATIC OF POWER FLOW FROM WAVES TO GENERATOR INPUT.



Height (m) \ Period (s)	3	4	5	6	7	8	9	10	11	12	13
5	·	·	·	·	·	0.19	0.15	·	·	·	·
4.5	·	·	·	·	·	0.24	0.29	·	·	0.21	·
4	·	·	·	·	0.085	0.34	·	0.4	0.69	0.64	0.091
3.5	·	·	·	0.16	0.79	0.44	0.13	0.59	0.97	0.21	·
3	·	·	·	0.4	0.88	0.66	0.78	0.41	0.17	·	·
2.5	·	·	0.45	1.1	1.1	0.43	0.44	0.23	·	·	·
2	·	0.093	1.2	1.6	1.3	0.91	0.17	·	·	·	·
1.5	·	1.5	2.3	1.8	1.8	0.99	0.59	0.29	0.046	·	·
1	2.7	2.8	2.3	2.7	2	1.4	0.69	·	·	·	·
0.5	2.6	4.1	3.5	3.6	6	1.5	·	·	·	·	·

FIGURE 4: SCATTER OF POWER MEASUREMENTS WITHIN SEA STATE BINS. VALUES ARE MAX-MIN RANGE WITHIN BIN, DIVIDED BY BIN AVERAGE. MECHANICAL POWER IS MEASURED AT INPUT TO GENERATOR.

STORM Simulations

APB behavior in different sea states was simulated using OPT's STORM modeling tool [3], which incorporates two commercial software packages: OrcaFlex to simulate interactions of the APB geometry with waves and Simulink to represent the behavior of the PTO. While a range of spectral shapes can be simulated, simulations to date have used a spectra equivalent to a Bretschneider. PTO constraints on force and velocity were represented in the model.

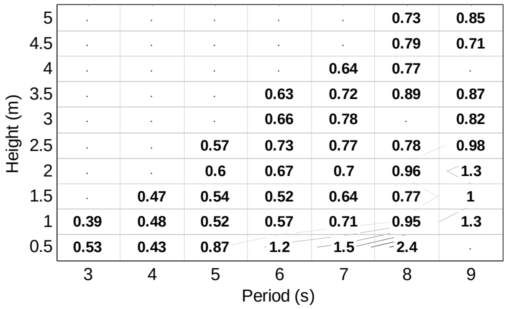
Across all sea states, the same resistive damping value, β_{PTO}, was applied, as was done during the ocean test since pre-deployment studies had shown limited overall advantage in optimizing β_{PTO} in each sea state. Simulations were performed in all sea states; results were time-averaged, and binned vs. Hs and Ta to obtain a mechanical power matrix. A key appeal of this statistical description is that power performance can be estimated for any site with a known wave climate. To compare STORM results to ocean test measurements, the simple metric used here will be the ratio of ocean test to simulated sea-state average mechanical power.

RESULTS

As stated earlier, measured mechanical power did not include frictional losses upstream of the generator (Figure 3). These losses were not accounted for in the initial model study, which substantially over-predicted power output (ratios less than 1 in Figure 5). This was puzzling given prior satisfactory comparison to tank results (Figure 2 and [3]), and suggested model setup may have neglected real-world physical processes.

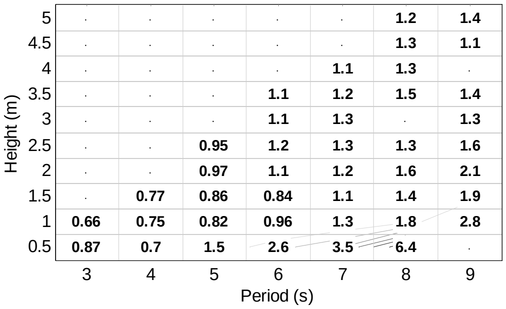
The first step toward increasing model fidelity was to include a linear frictional damping, β_{fr}, intended to represent losses upstream of the generator. When that resulted in limited improvement, a constant frictional loss term *F* was also incorporated. Since total upstream frictional losses (Figure 3) were not measured, a range of β_{fr} and *F* values were simulated to determine their effect on the power ratio. The best combination of the two frictional terms exceeded the limited friction measurements described previously, and indeed may partially compensate for other yet-unknown errors in model physics. The adjustment reduced STORM over-prediction in low sea states, bringing it closer to ocean test measurements, but introduced underprediction in high sea states (Figure 6). While low sea states are common and improvement there is welcome, at present the model performance is outside the desired range (within 10-20% of measurements).

For this reason, the implementation of STORM will continue to be refined. Results presented here highlight challenges of modeling a complex system and its surrounding environment.



Height (m) \ Period (s)	3	4	5	6	7	8	9
5	·	·	·	·	·	0.73	0.85
4.5	·	·	·	·	·	0.79	0.71
4	·	·	·	·	0.64	0.77	·
3.5	·	·	·	0.63	0.72	0.89	0.87
3	·	·	·	0.66	0.78	·	0.82
2.5	·	·	0.57	0.73	0.77	0.78	0.98
2	·	·	0.6	0.67	0.7	0.96	1.3
1.5	·	0.47	0.54	0.52	0.64	0.77	1
1	0.39	0.48	0.52	0.57	0.71	0.95	1.3
0.5	0.53	0.43	0.87	1.2	1.5	2.4	·

FIGURE 5: RATIO OF OCEAN TEST TO STORM MECHANICAL POWER VS. SEA STATE. NO FRICTIONAL DAMPING OR CONSTANT FRICTION FORCE.



Height (m)	3	4	5	6	7	8	9
5	.	.	.	.	.	1.2	1.4
4.5	.	.	.	.	.	1.3	1.1
4	.	.	.	.	1.1	1.3	.
3.5	.	.	.	1.1	1.2	1.5	1.4
3	.	.	.	1.1	1.3	.	1.3
2.5	.	.	0.95	1.2	1.3	1.3	1.6
2	.	.	0.97	1.1	1.2	1.6	2.1
1.5	.	0.77	0.86	0.84	1.1	1.4	1.9
1	0.66	0.75	0.82	0.96	1.3	1.8	2.8
0.5	0.87	0.7	1.5	2.6	3.5	6.4	.

FIGURE 6: RATIO OF OCEAN TEST TO STORM MECHANICAL POWER VS. SEA STATE. FRICTIONAL DAMPING AND CONSTANT FRICTION FORCE INLCUDED.

DISCUSSION

Comparing STORM output to ocean test measurements has proved more challenging than prior tank comparisons, suggesting real-world factors that were not previously considered. The first factor below received preliminary investigation here, while others are the source of ongoing assessment:

- Friction upstream of the location where mechanical friction was measured on the APB, namely at the generator input. This friction is difficult to characterize, though OPT is addressing this in a separate study.
- Real-world waves may not be adequately described by Hs and Ta when estimating APB power output. OPT is in the process of assessing whether measured spectra result in significantly (>10%) different time-averaged power output than idealized spectra. A candidate approach to reduce spectral complexity is to filter out long periods (swell), since the APB is not expected to respond to them.

The STORM validation and improvement effort is ongoing, and indicates challenges inherent in modeling real-world WECs which may not emerge in studies relying only on simulations or wave tank test data.

CONCLUSIONS

Prior studies showed satisfactory comparison of STORM to controlled tank measurements. However an initial comparison to ocean test measurements showed systematic over-prediction, suggesting a need for the model to incorporate additional real-world processes. A preliminary investigation of friction resulted in improved model performance, but the model will continue to be refined. Future work will include the effect of measured vs. idealized spectra on power output.

ACKNOWLEDGEMENTS

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