THE DEPLOYMENT OF THE PB-3-50-A1 POWERBUOY®: POWER PREDICTION AND MEASUREMENT COMPARISON

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ABSTRACT

In August 2015, Ocean Power Technologies (OPT) deployed the PB-3-50-A1 PowerBuoy® off the coast of New Jersey. After commissioning, the buoy operated for a cumulative period of 108 days and generated more than 1.3 MWh of electrical energy. One goal of the deployment was to validate OPT's modeling tools which are used to predict power output. In a prior deployment, simulations using realistic rather than idealized spectra produced more accurate power predictions. This finding was further investigated for the present deployment using power and wave measurements collected during the A1 (short for PB-3-50-A1) deployment. Since wave spectra are not available until recovery, remote measurements were used. Comparison of these results with the actual power output of the buoy indicated that simulations using Bretschneider-based wave spectra over-predict the amount of power while if realistic spectra are used, the power predictions appear to provide a reasonable match to the measured power. These findings will be finalized when local spectra measurements are substituted. Based on these results, OPT is investigating approaches to upgrade and streamline its standard power prediction approach.

INTRODUCTION

OPT is a leading player in the design and development of systems converting ocean-wave energy into electricity. For wave-energy conversion, OPT utilizes its proprietary dual-point absorber configuration known as the PowerBuoy [1]. The PowerBuoy has a float and a spar in a relative translational heave motion induced by ocean waves. This motion is converted to electrical energy using the buoy power take-off (PTO) system.

A class of the OPT PowerBuoys developed specifically for supplying power to customer payloads independently from the utility grid, is known as the Autonomous PowerBuoys (APBs). APBs have many desirable features; for example, they are smaller in size, capable of being deployed in shallower seas, easier to deploy and retrieve using standard marine equipment, and require simpler mooring systems, while providing persistent and sufficient electric power for a wide range of sensor suites as well as data processing and real time communication and transmittal.

In 2011, OPT deployed an APB off the coast of New Jersey for 3 months under a project known as Littoral Expeditionary Autonomous PowerBuoy (LEAP) [2]. The power measurements made during the LEAP deployment were compared to the simulation model predictions and the results were reported in [3]. Since that deployment, OPT has been working on refining the design of the LEAP buoy to improve various facets of the system performance, cost and manufacturability toward its full commercialization.

The OPT A1, is a prototype which shares the body and mechanical structure of the LEAP buoy but is equipped with the OPT next generation PTO. The A1 buoy, shown in Figure 1, was deployed in August 2015 off the coast of New Jersey to test the new PTO design in actual ocean wave conditions, identify any design modification requirements, and verify the overall power generation capabilities of the A1 with its new PTO. Generated power was supplied to a demonstration payload (MetOcean measurement package). In addition, OPT has deployed a TRIAXYS wave buoy made by AXYS Technologies next to the A1. From spectral wave measurements, the TRIAXYS calculates the wave significant height (H_s) and average period (T_a). Only these statistics are transmitted in real time; the full wave spectra are retrieved upon recovering the TRIAXYS memory card.

Noteworthy is that, in the literature pertaining to wave energy convertors, many authors instead use the energy period T_e, which can be used to directly estimate the power of waves. However, for two practical reasons, OPT has decided to continue using T_a: (1) the possibility of reusing available legacy code and (2) direct availability of T_a within NDBC and TRIAXYS data. Properly speaking, when T_e is not provided by a source, one has to directly calculate it using the wave spectra. A detailed discussion of the subject can be found in [4].

While the A1 is operating, numerous parameters of the system are measured and then recorded by the onboard computer and transmitted to OPT's servers at its headquarters in Pennington, NJ. Among those parameters are the instantaneous PTO position, velocity, and overall distance travelled as well as the peak and average generated and excess powers. Off-line, these performance indicators are compared with those calculated using numerical simulation models developed in OrcaFlex software package. Some aspects of the system dynamics which cannot be properly modeled in OrcaFlex directly are modeled using an OPT proprietary tool called Simulink Target for OrcaFlex Real-Time Modeling (STORM), which helps generate a dynamically linked library directly usable by OrcaFlex. STORM setup and validation is described in [5].

For the present study, the hydrodynamics parameters of the model were set using the experience acquired with a dynamics model of the LEAP buoy. As discussed in [3], the system Coulomb friction and viscous damping are difficult to directly measure. They are also difficult to properly implement in OrcaFlex. Due to the reduction in friction and increased efficiency in the A1 PTO design relative to the LEAP buoy, however, these effects are expected to be less prominent.

To conduct an OrcaFlex simulation, in addition to the hydrodynamics parameters, the sea state at which the buoy is operating must be specified, for any given period of time. That information can be extracted from the TRIAXYS wave statistics, the wave spectra measurements available from a U.S. National Data Buoy Center (NDBC) buoy—known as NDBC 44091—deployed 48 km from the A1 deployment site, or both. The NDBC 44091 buoy is farther than is desirable; so results will be recalculated when the TRIAXYS wave spectra are recovered, but the data are useful for a first consideration of the effect of realistic spectra on predicted power output.

Wave spectra can be used to generate a time history of sea elevation. Depending on the phase differences of the constituent frequencies, the time history of the sea elevation changes, and so does the simulated response of the system. Consequently, it is the statistical properties of the system actual response and performance indicators that can be compared with those of the OrcaFlex model.

Two sets of simulations have been conducted: one assuming a Bretschneider distribution [6] with H_s and T_a data provided by the TRIAXYS buoy located at the A1 site, and the other using the spectral data from NDBC 44091. It should be noted that the Bretschneider spectrum is widely used, but other idealized spectra may better represent a particular site.

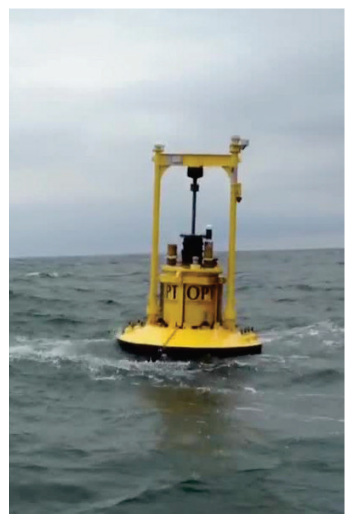

FIGURE 1. THE OPT A1 POWERBUOY OFF THE COAST OF NEW JERSEY SHOWN DURING A PRE-SCHEDULED VISUAL INSPECTION IN NOVEMBER 2015

In this paper, we will report on the data collected from the A1 buoy and compare them with the results of the two sets of simulations conducted under the wave statistics at the deployment site as determined by the TRIAXYS buoy and the wave spectra reported by NDBC 44091. Moreover, some metrics for the performance of the A1 buoy to date are provided.

POWER GENERATION METHOD

As mentioned in Introduction, the A1 PowerBuoy generates electrical power using the translational motion of the float with respect to the spar. This is performed by converting this motion to rotational and thus turning the shaft of a generator. The generator drive amplifier is then programmed in such a way that the generator will apply an active damping torque dependent on the PTO speed. This torque will result in the application of a force on the translational system which is ideally linearly related to the PTO speed, v_{PTO}. This linearity constant is denoted by β_{PTO}. Therefore, the effective mechanical power delivered to the shaft of the generator will be $\beta_{PTO} v_{PTO}^2$ except for when the force computed exceeds a predetermined design threshold, in which case the generator torque command is limited to a corresponding torque limit. To enforce the force limit and other similar nuances in the OrcaFlex simulations, a model of the PTO created with STORM is used.

The optimal value of β_{PTO} for each sea state can be determined based on the results of simulation studies conducted beforehand for a wide range of physically possible sea states (H_s and T_a) assuming Bretschneider distributions. However, due to practical considerations, a fixed optimal damping value is determined for each candidate deployment site based on the above-mentioned simulation studies and the average wave climate of the particular site.

RESULTS

Here we mainly focus on the actual and predicted power generated by the A1 buoy. The former values are calculated from the deployment data, while the latter are obtained from the two sets of simulations.

The Actual Power Generated

The energy generated in the buoy supplies the buoy hotel load supporting its operation and recharges the buoy batteries. The excess power is dissipated in a resistive element of the buoy's power system (dump load resistor). In the A1 deployment, the power delivered to the dump load is the power available to customer payload, which is in addition to the power consumed by the demonstration payload, a MetOcean package.

TABLE 1. THE GENERATED AND EXCESS TOTAL ELECTRICAL ENERGY AND AVERAGE POWER

Measurement	Avg. Power (W)	Total Energy (kWh)
Generated	481	1,314
Excess	359	887

The total energy and the average power generated and dissipated by the buoy as of 12 January 2016 are reported in Table 1.

Other Performance Metrics

Various operation metrics are summarized in Table 2. The approximately 1.5 million PTO cycles have been calculated using a peak-over-threshold (POT) analysis of the velocity data. For a cycle to be counted, the PTO velocity has to up-cross the set threshold of 0.1 m/s. This means that low velocity cycles that strain the system very little are not counted, but neither are the cycles whereby the PTO moves down fast and comes back up slowly. Moreover, as seen in Tables 1 and 2, as of 12 January 2016, the buoy has generated more than 1.3 MWh of energy, out of which 887 kWh were available for additional payload.

TABLE 2. VARIOUS OPERATION METRICS OF THE A1, AS OF 12 JANUARY 2016

Metric	Ocean Test
Days of Operation	108
Energy Generated (MWh)	1.3
PTO Cycles (Vel. POT 0.1 m/s)	1,493,372

Comparing Predicted and Generated Power

Power predictions of two sets of simulation models have been compared with the power actually generated by the buoy during operation in the ocean. The simulations were conducted in OrcaFlex and using the OPT STORM models of the A1 PTO. As explained in Introduction, the wave conditions in the two sets of simulations were set to represent the Bretschneider distribution of the H_s and T_a provided by the TRIAXYS deployed by OPT next to the A1 and the wave spectra provided by NDBC 44091. Because the generator subsystem of the PTO cannot be modeled in OrcaFlex, an OPT proprietary generator loss model fine-tuned for the A1 system, was used to estimate the amount of the electrical energy generated by the A1 buoy.

The results showed that the simulations that use the TRIAXYS-calculated H_s and T_a to drive the dynamics of the buoy generally over-predict the amount of generated power. The simulations pertaining to the wave spectra at NDBC 44091, too, appear to over-predict the power most of the time; however, as seen in Figure 2, there are numerous occasions whereby these results follow the actual electrical power very well. The data points in the figure have been color mapped based on how much the ratio of NDBC H_s to TRIAXYS H_s is larger than one. Values are zero when H_s is the same.

Interestingly, the occasions of almost-perfect match between predicted and measured power seem to coincide with occasions of the H_s estimated by TRIAXYS closely matching that provided by NDBC 44091. One explanation for this observation may be that, on these occasions, the wave spectra at the A1 site are very similar to those at NDBC 44091, a hypothesis that can be verified after

TRIAXYS is retrieved, and its data are downloaded. At that point, a new set of simulations will be run with the TRIAXYS wave spectral data to verify the findings. They are consistent with a prior model-measurement comparison for LEAP [3], which found that using measured rather than ideal spectra improved the accuracy of power predictions significantly, especially in low sea states, as well as with prior investigations into the sensitivity of WEC power output to spectral shape [7].

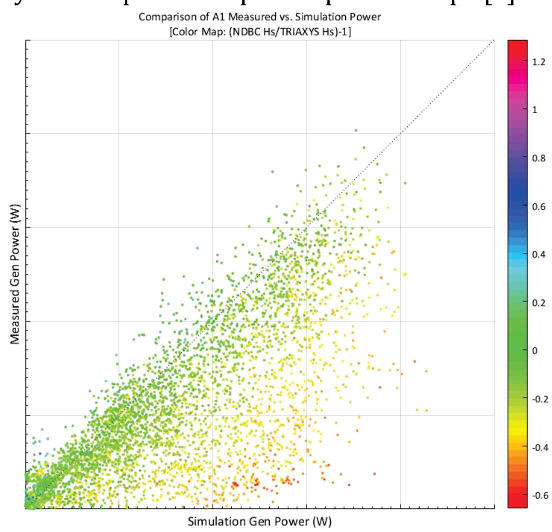

FIGURE 2: MEASURED VS. SIMULATED GENERATOR POWER DURING THE A1 DEPLOYMENT. PERFECT MATCH WOULD FALL ON DIAGONAL LINE. COLOR SCALE INDICATES SIMILARITY OF NDBC AND TRIAXYS WAVE STATISTICS.

CONCLUSIONS

OPT deployed an autonomous PowerBuoy called PB3-50-A1 off the New Jersey shore in August 2015. Since its commissioning, as of 12 January 2016, the buoy has been operational for 108 days and generated more than 1.3 MWh of electrical energy over this time period.

Two sets of simulations were performed using the OrcaFlex dynamics model of system, in which the dynamics of the PTO was modeled using the OPT STORM tool. In one set of the simulations, the H_s and T_a estimated by a TRIAXYS buoy deployed at the A1 site were used to create idealized wave spectra based on the Bretschneider distribution. In the other, the wave spectra provided by an NDBC buoy located at some 48 km away from the A1 site were utilized to drive the buoy dynamics.

The simulation results were then processed to predict the amount of electrical power to be generated by the buoy based on a loss model of the generation system. Comparison of these results with the actual power output of the buoy indicated that simulations using Bretschneider-based wave spectra over-predict the amount of power. Moreover, it suggested that, if the site actual wave spectra used, the power predictions provide a reasonable match to the measured power. This insight is driving pertinent changes in OPT's power prediction approach.

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