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OCEAN POWER TECHNOLOGIES POWERBUOY®: SYSTEM-LEVEL DESIGN, DEVELOPMENT AND VALIDATION METHODOLOGY

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ABSTRACT

In this paper the authors will describe a system-level, multi-physics based development of PowerBuoy® products at Ocean Power Technologies (OPT). The PowerBuoy is a moored system which extracts useful electrical power from waves. Different PowerBuoy solutions have been developed for different markets (grid-connected systems vs. smaller autonomous systems) and/or different customer applications.

The PowerBuoy design approach focuses on clarification of operational requirements at the onset of the effort. An iterative closed-loop process optimizes various aspects of the system. The goal is a solution that addresses all Key Performance Parameters while minimizing life cycle cost. This paper will outline the PowerBuoy design process, which consists of the following steps, illustrated by examples from recent development efforts.

INTRODUCTION

Over the last half a century, a variety of geopolitical and socio-economic drivers have emphasized the need for the development and maturation of new and renewable energy resources at the global scale. Attaining a reduction of and soon thereafter full independence from fossil fuels is critical for sustainable economic growth and safeguarding the environment for future generations, as well as for mid- to long-term national security.

In renewable energy, much of the technology development effort and focus over the last two decades has been on solar and wind power. While the pursuit of these technologies is necessary, it is not sufficient due to the limitations of each technology, such as intermittent supply or a restricted number of suitable development locations. It is the authors' view that all renewable energy sources must be exploited concurrently and used simultaneously to ensure a continuous and sustained supply that leverages their complementarity with respect to each other.

Leveraging ocean waves to generate electric power is an emerging technology that offers tremendous potential but has not been fully exploited as of yet. OPT has dedicated the 17 years of its existence and continues to do so, to the design, development, fabrication and testing of associated systems and devices dubbed the PowerBuoy.

As shown in the schematic in Figure 1, the PowerBuoy is a floating power generation system which captures energy from waves. A mooring keeps the PowerBuoy on station in the ocean. At the surface, a float moves in response to ocean waves along a spar with a reduced response to waves due to a heave plate at its base. Relative motion between the float and spar drives a push rod into the spar. A mechanical actuator converts the linear motion into a rotary action that drives a vector-controlled electric generator, which in turn outputs a three phase wild voltage and wild frequency AC power. A state of the art power management and conditioning system converts and conditions the AC power into high quality DC power. An advanced Energy Storage System (ESS) utilizing state of the art battery and ultra-capacitor technology is then used to remove the transient nature of the power. Depending on the PowerBuoy type and size, the DC power may or may not be converted back into constant voltage and constant frequency AC power.

As a result, the PowerBuoy system supplies a steady and transient-free, high quality power to all loads, including the electrical grid. Integrated into the device are a variety of sensors that are used for the overall control of the system as well as for continuous monitoring and diagnosis, allowing for a proactive system management. OPT's SCADA encompasses the acquisition of sensor data as well as its processing, storage and transmission to shore stations via a variety of communication means to include High Frequency, Satellite, WiFi and others.

In order to maximize wave energy capture and hence the electric power output, OPT has developed proprietary Advanced Control algorithms [1] that allow for dynamic control of the generator back torque based on the characteristics of the surrounding waves (wave height and period). Such algorithms allow for the PowerBuoy control system to dynamically and proactively adjust the system closer to resonance whereby the amount of energy extracted from the waves is maximal, given system limitations.

Of critical importance is the power conversion efficiency. In the PowerBuoy system, five such conversions take place: - Hydraulic to Mechanical power, - Linear Mechanical power to Rotational mechanical power, - Rotational Mechanical power to wild Frequency, wild voltage AC power, - Electrical AC to Electrical DC, and then – Electrical DC back to constant voltage and constant frequency AC power. Each conversion has its own efficiency and losses, which contribute to the overall system efficiency. By working to reduce/eliminate such losses, and hence maximize the overall system efficiency, OPT's goal is to further viably commercialize the PowerBuoy technology.

The PowerBuoy system requires careful design of its electrical and mechanical sub-systems as well as its hydrodynamics. This requires a multi-physics based solution with a closed loop design and optimization process in order to achieve a cost competitive and commercially sound product. In the design process, OPT seeks to avoid the classic silo-driven development philosophy where components and subsystems are engineered within different departments using isolated tools/model environments. This approach is rejected because it leads to costly and complex issues when individual elements of the system are consolidated in the final stages of the development process, severely reducing the likelihood of a cost-effective and high performance, reliable, and durable system solution. Since the PowerBuoy is complex and requires the input of multiple disciplines in its design, the design process must be highly coordinated with coherent development flowand concurrent engineering interaction and collaboration. Further, integrated modeling and analysis tools that simultaneously account for (a) the various component and subsystem interfaces as well as (b) the subtle dynamics of the multi-physics systems are a fundamental pre-requisite for the design and development effort to succeed.

OPT seeks a system solution that satisfies all operational requirements simultaneously while remaining within a pre-established set of boundaries that enforce a compromise between competing drivers such as cost, performance, reliability, maintainability and life. When an approach such as the above is well implemented and validated, it allows for an effective and thorough investigation of a multi-dimensional design space that ultimately ensures the system's cost and performance converge, resulting in a lower overall Levelized Cost of Energy (LCOE), a standard metric for comparing the costs of renewable technologies and to assess their commercial viability.

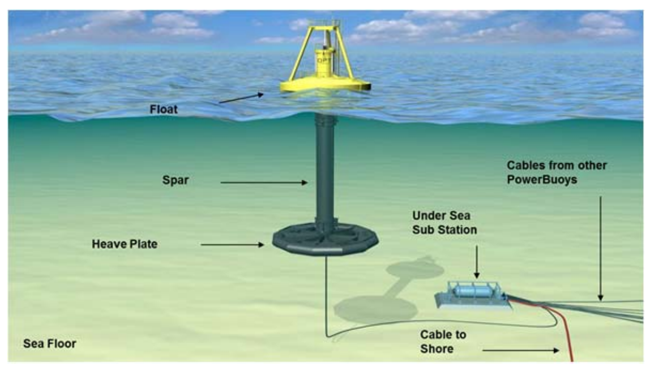

FIGURE 1: EXAMPLE OF OPT POWERBUOY SYSTEM

The following sections provide design and optimization examples derived from OPT's systems approach to developing PowerBuoy solutions. The examples are chosen to illustrate the process, rather than providing detailed case studies.

EXAMPLES OF DESIGN AND DEVELOPMENT ACTIVITIES BASED ON THE SYSTEMS PARADIGM

Requirements drive the generation of initial concepts

The fundamental basis for a sound PowerBuoy development effort is a clear and concise understanding of the anticipated application for the system solution to be developed. Initial requirements for technical performance include targets for output power, efficiency, operating voltages and currents, mechanical and electrical interfaces, data monitoring and acquisition. As well, physical parameters such as weight and volume must also be carefully defined and integrated in the design process.

Additional considerations include environmental conditions: water depth and seabed slope, incident wave power and site MetOcean conditions that drive operational and survivability conditions, which in turn define an important portion of the design trade space and strongly affect the system hydro-mechanical and mooring design. Further, deployment logistics, in-situ product support, and the overall maintainability and life cycle management strategy of the device must also be understood at the onset of the effort. Additionally, cost metrics must be defined that provide a benchmark and a goal for the development team to achieve. Such metrics encompass initial estimates for both capital and operational costs (CAPEX and OPEX).

Several approaches can be taken in order to define the above requirements; customer-provided specification document(s) is usually the preferred method. However, it is seldom the case that an end-user can clearly articulate their specific needs in the form of a design requirements document. Hence, the development team usually combines (a) direct interaction with the end-user with (b) a market research effort and (c) their own technical expertise to establish a baseline system specification that is then reviewed with all stakeholders, including customers and end-users and updated accordingly. During the development activity of the final system solution, the requirements document will continue to be updated utilizing a configuration management process that ensures all reviews and approvals are attained in order to safeguard the integrity of the technical solution and customer/application objectives.

Once the requirements document is released, the development team proceeds with the generation of several initial system concepts that attempt to respond to the various competing and antagonistic specifications. Through an iterative and phased design process known as the Stage Gate Process [2], the initial concepts will undergo a set of design trades studies in order to rapidly down-select the top two or three concepts that have the highest potential of meeting application requirements at the lowest risks possible. The Stage Gate Process has been shown to be an effective tool in developing system solutions that provide an optimum between technical performance and cost and hence in achieving the most competitive LCOE. This result is achieved by methodical retiring and mitigation of technical risks as the design evolves through the various Gates.

Concept evaluation

Once several design concepts are generated based on the power and site requirements, each concept undergoes preliminary modeling to determine output power and design loads. The initial trade studies are completed utilizing OPT's proprietary modeling tools developed over a period of 15 years and corroborated with test data collected from both reduced scale and full scale PowerBuoys. Modeling may include parameter sweeps which vary the system's geometry, such as float diameter or spar length. Model studies take advantage of applicable existing MetOcean data for candidate deployment sites.

In-house OPT models are used for power output. OPT has both time- and frequency-domain codes for simulating the candidate design's interaction with the waves, including its output power. Simulations are performed at different sea states and combined to give the annual average power as well as PTO loads. For a given sea state, the PowerBuoy's output is largely a function of the geometry of the float, the PTO's force and stroke limits, and the mooring mechanism for the static component of the system: the spar.

The commercial package OrcaFlex is used for preliminary load analysis. For load studies, the hydrodynamic properties of a candidate device are first obtained from the commercial package WAMIT. The WAMIT frequency dependent added mass and damping coefficients are assigned to the float modeled in OrcaFlex. The mooring model includes specification of mooring properties. Simulations are run in survival wave conditions for a sufficiently long duration for extreme load estimation [3]. Simulation results include structural loads such as those between the float and spar.

To further extend OrcaFlex for PowerBuoy-specific applications, in-house code is coupled with OrcaFlex. Due to the many limitations of such models in steep seas, the resulting loads are understood to be a preliminary placeholder that will be replaced with more accurate estimates (from wave tank tests) later in the design process. However the OrcaFlex loads are useful for trading off concepts in terms of their load, as well as for incorporating models of the PTO; as such commercial modeling tools are refined, OPT will continue to monitor the literature.

Given the proposed overall shape of a given concept, its structure is designed and preliminary load analysis is performed. Candidate moorings are generated given the site conditions and dimensions of the concept. It is necessary to iterate the concept geometry to obtain acceptable power and load results. For the PowerBuoy and other wave energy converters, the cost of energy correlates directly with the design load of the structure, mooring, and Power Take Off (PTO), as well as with the PTO power rating and conversion processes.

As an example of the outcome of the concept generation process, Figure 2 shows a case from the PowerBuoy design history which led to three distinct mooring systems and three distinct float concepts, which produced markedly different hydrodynamic behavior of the system.

		Float		
		Symmetric	Cylinder w/Plate	Rhombus
Mooring	Monopile	The broad test goals were to evaluate the coupled performance metrics of 3 floats and 3 mooring configuations. * Float power performance * Float load/power shedding vs. draft * Mooring and float loads * Mooring power performance		
	Gimbal			
	TLP			

FIGURE 2: EXAMPLE OF INITIAL CONCEPTUAL POWERBUOY CONFIGURATIONS AND GOALS OF TESTS

In this particular design case, the three concepts combined three mooring topologies with three float shapes and designs, which then underwent subsequent investigation.

In general, this step of the development effort seeks to carry-out a trade study that relatively compares these float-mooring combinations such those shown in Figure 2, based on the following criteria:

- Float power performance: Amount of wave energy captured by the float and transmitted to the PTO. Figure 3 gives an example comparison of annual average power for competing float concepts at candidate deployment sites.
- The amount of mechanical stress that the design must survive, generated by the hydrodynamic loading in both operational and survival conditions, including hydrostatic loads during short-term submergence in large waves. Figure 4 shows an example close-up of a load time series used to estimate design values. Both simulated and wave tank test measured values are shown; after tuning the model hydrodynamic parameters to match the measurements, the resulting tuned model could be used for more accurate load studies.
- The performance of the mooring topology in terms of stabilizing the spar section of the PowerBuoy so to allow for a maximum relative motion between the float and the spar, leading to a maximized energy transfer and conversion.

			Float		
			Symmetric	Cylinder w/Plate	Rhombus
Mooring	Monopile	Site A	40-90	90-140	110-160
		Site B	70-120	90-140	130-180
		Site C	90-140	120-190	180-250

FIGURE 3: EXAMPLE OF MODELED ANNUAL AVERAGE POWER (KW) FOR A CANDIDATE DESIGN IN 3 DEPLOYMENT SITES OF INTEREST

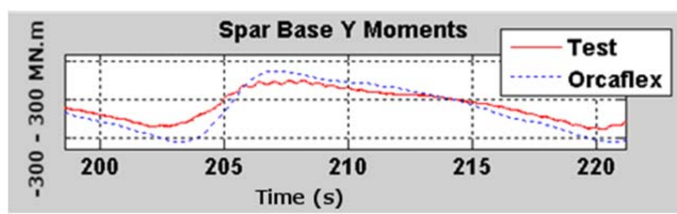

FIGURE 4: EXAMPLE OF ORCAFLEX MODELING OF SPAR LOADS

Wave tank testing to identify best concept

Following the initial modeling effort, the next level in the down-select process involves testing reduced scale models in a wave tank. Figure 5 shows an example reduced-scale model from a prior OPT tank test [1]. Tests include operational testing of a model with a working PTO to measure generated power across a wide range of sea states, as well as testing of a smaller model in representative 100-year wave conditions to measure survival loads, which are calculated following [3]. In both cases, the models are significantly smaller than the full-scale PowerBuoy (typical ratios are 1:20 to 1:40), necessitated by the height of the waves that can be produced in the tank as well as the tank depth.

OPT's experience is that this reduced-scale-model range allows for meaningful data to be collected and then correlated with the performance of the full scale systems via Froude scaling.

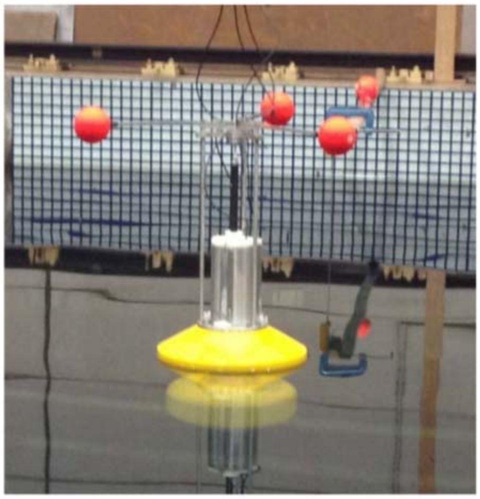

FIGURE 5: EXAMPLE OF OPT REDUCED SCALE MODEL USED IN OPERATIONAL WAVE TANK TESTS [1]. YELLOW FLOAT AND SILVER SPAR ARE VISIBLE ABOVE WATERLINE. RED BALLS ARE USED TO TRACK MOTIONS. BLACK WIRES COMMUNICATE MEASUREMENTS FROM AND CONTROL COMMANDS TO A WORKING PTO INSIDE THE SPAR.

The general approach to tank test design is as follows:

- Determine a systematic way to replicate the site wave environment in the tank
- Over a testing program, test a succession of increasingly complex reduce-scale models to understand the impact of the various system parameters under consideration
- Carry out the appropriate parameter adjustments in order to capture the design metrics of interest
- Evaluate the reduced scale model performance in terms of power and loads over the test space, namely different sea states and different parameter settings.
- Use the results to validate the numerical modeling tools described above.
- Using these model tools, make predictions for cases not tested, such as other sea states or water depths, as required by the application of the final system solution.

This approach maximizes the value of the wave tank tests, mitigates risks (technical, cost and schedule) early on in the development process and hence ensures a viable approach is selected at the onset of the project.

Figure 6 shows an example of tuning a model against wave tank measurements in order to improve model fidelity for a candidate concept with a Tension Leg Platform (TLP) mooring. Careful perturbations of the hydrodynamic coefficients in OrcaFlex were required in order to match measured motions and certain loads measured in the tank. These coefficients could then be used in subsequent model studies of the concept.

In Figure 7, OrcaFlex simulations of loads for a concept with a different mooring (monopile, or a rigid connection to the seabed) was compared to wave tank test measurements. The agreement between the two sets of data is good for all the time series except during slam events, which are not comprehensively simulated in OrcaFlex.

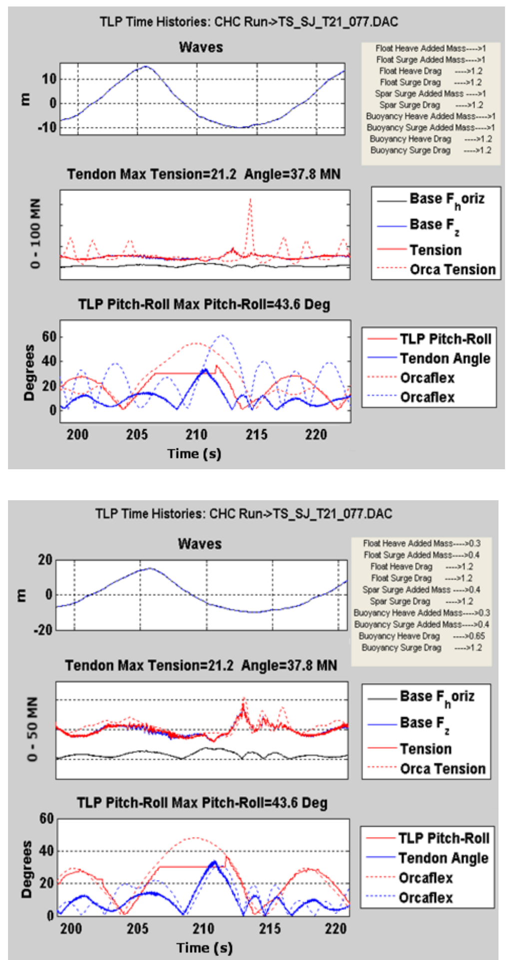

FIGURE 6: EXAMPLE COMPARISON OF CONVENTIONAL (TOP) AND TUNED HYDRODYNAMIC COEFFICIENTS (BOTTOM) USED IN ORCAFLEX (DASHED) TO SIMULATE LOADS. TANK MEASUREMENTS (SOLID) SHOWN FOR COMPARISON. ONLY SHORT PERIOD OF TOTAL TEST TIME IS SHOWN.

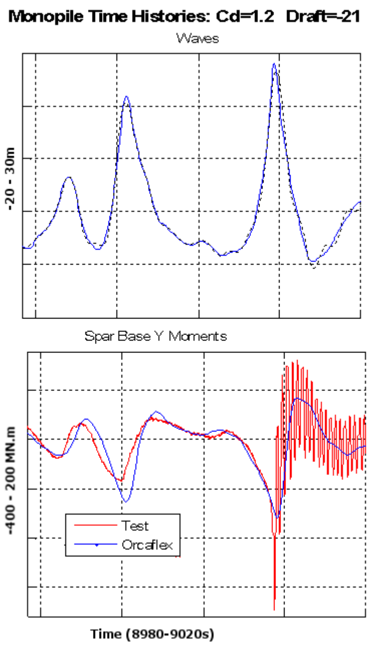

FIGURE 7: EXAMPLE COMPARISON OF ORCAFLEX SIMULATION AND WAVE TANK MEASUREMENTS DURING A SLAM EVENT. TOP: SEA SURFACE ELEVATION. BOTTOM: MOMENT AT SPAR BASE.

Similar model/data analysis was performed for all candidate concepts that were considered in this past design effort. The coefficients determined from the above approach were implemented in the various OrcaFlex models.

Using the tuned coefficients in OrcaFlex, Figure 8 shows an example of how load predictions are used to assess predicted loads for different mooring types (monopile, gimbal, and TLP) at different wave periods. The concepts were tested in the wave tank. Subsequent model-data comparisons found that:

- In high sea states, OrcaFlex under-predicted loads for the monopile and gimbal moorings but over-predicted loads for the TLP.
- In intermediate sea states, OrcaFlex marginally over-predicted loads.
- In low sea states, OrcaFlex greatly over-predicted loads.
- These results can be brought closer in lined with test results by adjusting hydrodynamic coefficients based on Keulegan-Carpenter number [4] or similar treatment.
- As expected, perturbations in the hydrodynamic coefficients can have a strong impact on simulated dynamics and loads, making it essential to validate the coefficients in the wave tank. It can therefore be assumed that similar perturbations in inertia and buoyancy can lead to similar effects.
- Based on measurements with operational models (larger-scale models with working PTOs), OrcaFlex generally predicts fatigue loads within 10% (see Figure 9).

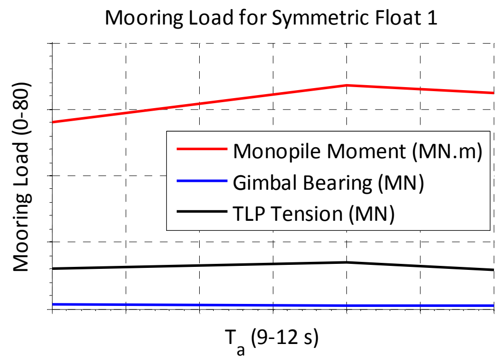

FIGURE 8: PREDICTED ORCAFLEX LOADS FOR SURVIVAL CONDITIONS OF DIFFERENT WAVE PERIODS

		Float					
		Symmetric		Cylinder w/Plate		Rhombus	
Mooring	Monopile Moment (MN.m)	90-100%	60-70%	90-100%	90-100%	60-70%	70-80%
	Gimbal Bearing (MN)	90-100%	160-170%				
	TLP Tension (MN)	120-130%	80-90%	100-110%	100-110%	90-100%	60-70%
		7	12	7	12	7	12
		T_a (s)		T_a (s)		T_a (s)	

FIGURE 9: FOR HS=5.5M, COMPARISON OF OPERATIONAL ORCAFLEX LOADS TO TEST RESULTS FOR CONCEPTS WITH DIFFERENT MOORINGS

Leveraging the wave tank test results and the parameter tuning that was carried out to corroborate the various OrcaFlex tools, a set of models was constructed for each of the concepts to perform power generation prediction by including a representation of the PTO. An example of using a series of tuned OrcaFlex models in power prediction is shown in Figure 10. Results can be used to compare different concept designs.

		Symmetric					Cylinder w/Plate					Rhombus				
H_s (m)	5.5				500-600	420-500				750-1000	510-600				550-750	550-750
	3.5			180-270		120-210			380-470		200-210			280-370		180-210
	2			50-100					150-160					80-140		
	1	5-30	5-30	5-30			15-55	15-55	30-40			5-30	5-30	5-30		
		5	6	7	9	12	5	6	7	9	12	5	6	7	9	12
		T_a (s)					T_a (s)					T_a (s)				

FIGURE 10: FOR DIFFERENT CANDIDATE DESIGNS, POWER PREDICTION AT DIFFERENT SEA STATES OR COMBINATION OF SIGNIFICANT WAVE HEIGHT (HS) AND AVERAGE WAVE PERIOD (TA).

Example down-selection decision

Based upon the above testing and associated modeling efforts, Figure 11 provides a summary of the pros and cons of the candidate float-mooring concepts, and how they can be used to down-select a final geometry. Using Site C as the deployment site of reference, the two highest average power output options (Figure 3) are Rhombus float-monopile (approximately 180kW to 250 kW) and Rhombus float-TLP (approximately 150kW to 200kW).

Considering that the Rhombus float is the best float option, the choice then becomes the mooring system: Monopile vs. TLP. Although a direct comparison of the mooring loads is not possible between the two systems dues to their fundamental differences, the evidence suggests that the peak TLP loads are relatively easier for the structural design to accommodate in comparison with the survival moments associated with the monopile. The concept design tradeoff has revealed a choice between the reduced loadings of the TLP vs. the increased power output of the monopile.

	Rhombus
Monopile	Pro Highest power configuration of all cases studied; 600-610 kW mechanical power Best agreement between predicted and measured Con Large float size Estimated base moments (-5.5m survival) 550-750 MN.m @ 40m depth 750-1000 MN.m @ 50m depth Float moment: 40-100 MN.m
TLP	Pro Second highest power studied Avoid base moment load Con Large float size High tether loads (15-60 MN) @ maximum operating sea state

FIGURE 11: SUMMARY OF PROS AND CONS OF CANDIDATE CONCEPT DESIGNS

PTO design process

Once the overall hydrodynamic structure and associated mooring system have been finalized, the next step in the design process is the development of the PTO.

For its utility products, OPT's approach is to develop a single PTO platform which can meet the needs of a variety of customers and sites. At the start of PTO design, a specification is generated which details the functions that the PTO should meet. Based on experience with earlier designs, an initial solution is generated then undergoes optimization to reduce cost, increase efficiency and reliability.

The PTO is responsible for all electromechanical and electrical power conversion and conditioning functions. The PTO design loading requirements are developed using OPT's proprietary modeling tools as calibrated using the previously collected wave tank test data in combination with the projected performance of the selected float and mooring system. Such requirements as PTO force and PTO operational duty cycle are used to then carry-out a thorough trade study involving a variety of potential PTO topologies. Careful considerations are given to infrequent high operating conditions versus predominant lower operating conditions. The incremental power contributed in high but rare operating conditions (storms) is carefully weighed against associated cost and complexity of the PTO design.

Various PTO concepts and topologies are considered such as rack and pinion, belt drive, linear motor, or hydraulic PTO systems. Various trade metrics are defined in order to effectively cover the trade space. Such metrics include: power density, weight, size, efficiency, modularity, scalability, reliability, redundancy, manufacturability, and simplicity of integration within the rest of the system.

The technical approach focuses on PTO designs that convert the wave induced float motion into a higher velocity mechanical motion prior to conversion into electrical power. The motivation behind this approach is that higher velocity (i.e. frequency) electromechanical power conversion enables the reduction in size and weight of the actual actuators (both mechanical motion converters and generators weight and size are inversely proportional to their fundamental operating velocity and frequency), as well as the increase of their conversion efficiency, and hence making it feasible to utilize off-the-shelf components. In turn, this results in increased power density, lower overall PTO cost, and consequently an improved cost competitiveness of the generated electricity. Additionally, smaller PTO size and weight enables the use of a smaller diameter spar, and reducing the drag force on the moorings, while simplifying the PTO's mechanical assembly interfaces onto the spar.

Example of generation of PTO concepts

To illustrate the PTO design process, the following example describes a case from OPT's history in which two PTO concepts were compared and down-selected.

The first concept was a Rack and Pinion PTO. Several aspects were investigated and analyzed. These technologies include rack and pinion actuator options, input rod and associated cabling, speed increaser and others.

The second concept was a Belt Drive System PTO technology. It consists of a double sided belt connected to the float which engages a rack that is fixed relative to the spar. This technology allows the PTO to be internal or external to the PowerBuoy and provide the following advantages:

- Eliminates the need for an input rod and associated seals
- Increases the number of rack options
- Eases the tolerance requirement for PTO alignment
- Eliminates the need for lubrication
- Reduces the size of the PTO

Several key aspects of the Belt Drive System PTO were investigated to include: Belt drive, rack options, rotary bearings, and gimbal system.

Several vendors were approached during the development effort in order to validate and/or modify the assumed subsystem and component design. Further, quotes were obtained and used as part of the performance metrics comparison.

Figure 12 summarizes the conclusions drawn from the PTO trade study and development effort. A check mark signifies the component is compatible with the PTO system and an X means it is not.

The final selected PTO was configuration RP#2, namely a rack and pinion with a fixed input rod. The resulting system was built, tested and validated for final ocean deployment.

		RP#1 Adjustable input rod	RP#2 Fixed input rod	Belt #1 External rack on spar	Inte
		Option?	Option?	Option?	
Input Rod	Fixed Input Rod	✗	✓	✗	
	Wire Rope Adjustable Input Rod	✓	✗	✗	
Speed Increaser	Gearbox	✓	✓	✓	
	Beltbox	✓	✓	✓	
	Chain drive	✓	✓	✓	
Brakes	External linear brake	✓	✓	✓	
	Rotary spar to sheave	✓	✗	✗	
	Internal linear rod lock	✓	✓	✗	
	Internal rotary pinion caliper brake	✓	✓	✓	
Locking Mechanism	Latch	✓	✓	✓	
	Shear pin	✓	✓	✓	
Pinion	Vendor 1	✓	✓	✓	
	Vendor 2	✓	✓	✓	
Wire Rope	Vendor 1	✓	✗	✗	
	Vendor 2	✓	✗	✗	

FIGURE 12: PTO CONFIGURATION AND COMPONENT COMPARISON MATRIX

Lab and field testing of the PTO

Upon design completion, the components, the subsystems and the PTO system undergo a thorough test regimen prior to ocean deployment. Each component and subsystem is tested to its full rated capability in order to validate it meets all its prescribed requirements. Then, the PTO is fully integrated and undergoes a set of functional tests followed by an endurance test.

Endurance testing is performed in a back-to-back setup where an existing PTO configured as a driver ("pusher") is programmed to simulate a variety of sea states expected to occur in the deployment site(s) of interest. The goal is to capture the varying wave frequencies and amplitudes that might be expected to occur in the real ocean during a long deployment at a chosen site. The full frequency range is important since different mechanical resonances might be excited, and affect component wear and overall system operation. The PTO endurance test lasts about 300 hours, during which it is thermally cycled. Various measurements such as temperature, vibration, currents, voltages, power, efficiency, battery state of charge, velocity, force are collected in order to monitor system health and provide a dataset for analysis.

Example of PTO component and subsystem testing

To illustrate the PTO testing process, an example is drawn from OPT's history.

- Generator and drive testing: This was completed in a back to back setting as shown in Figure 13. In addition to power output and thermal performance, BEMF (Ke) and Torque (Kt) constants were measured at various temperatures to confirm subsystem performance meets all requirements.

- Active Front End (AFE) Inverter subsystem test: The AFE fulfils the critical function of PowerBuoy grid connection. This test is designed to validate the system interfaces (High Voltage DC bus within the system and AC voltage on the Utility grid) are designed and implemented properly. Further, the effort also focuses on ensuring the controls are setup correctly (software, Firmware and Hardware) for the AFE subsystem to perform such tasks as pre-charge, synchronization and bidirectional power transfer (see Figure 14)

- The PTO endurance test was completed successfully (see Figure 15). Various sea states were programmed into the test setup utilizing 4 different waveforms representing sea states with an average wave period of 5, 7, 9, and 13 seconds. These realistic test profiles were repeated every 5 minutes over a 5- week/230-hour total test period. During the entirety of this critical test, continuous data collection was active and parameters such as vibration and efficiency were collected. Further, remote access to the system controller was also performed to ensure OPT's PB.Vue™ Human-Machine Interface (HMI) proper operation and to validate the remote control and software upload and download. Additionally, the High Frequency, WiFi and Satellite communication capability of the system was tested and validated.

- Mechanical to Electrical power conversion efficiency: The PTO measured efficiency exceeded baseline requirements (see Figure 16). When compared to OPT's previous PTO generation, this new PTO has demonstrated an increase of 5 to 10 percentage points (power dependent) in efficiency. Further, when compared to hydraulic based PTO design, this measured efficient is 2X better.

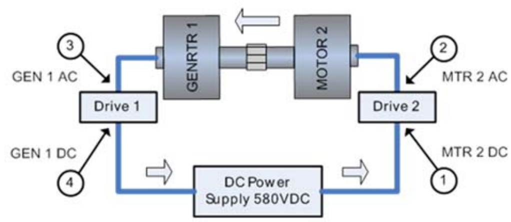

FIGURE 13: SETUP FOR BACK-TO-BACK TESTING OF GENERATOR-DRIVE

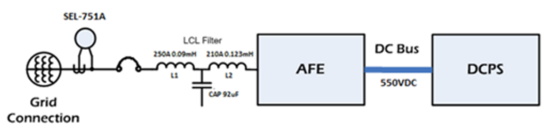

FIGURE 14: AFE SUBSYSTEM TEST SETUP

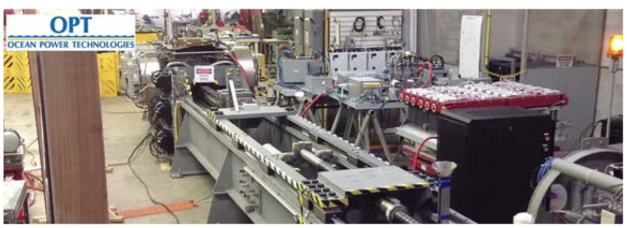

FIGURE 15: PTO ENDURANCE TEST SETUP AT OPT

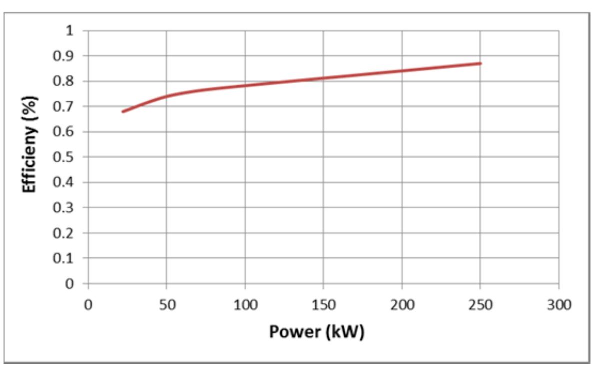

FIGURE 16: MEASURED MECHANICAL TO ELECTRICAL PTO EFFICIENCY

CONCLUSION

This paper attempted to address the complex multi-discipline and concurrent engineering process required to successfully design, develop, test and validate such Wave Energy Converters as OPT's PowerBuoy. In addition to the description of the overall approach, specific design and trade study examples were provided. Further, lessons learned and system test data were provided and discussed.

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