An Innovative Tool for Hydrodynamics Modeling and Control Development for Wave Energy Converters

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For an ocean wave energy converter (WEC) to capture wave energy efficiently, generator controls need to be optimized for a wide range of sea-state operating conditions. Wave energy researchers need a reliable method of simulating variable sea-state loading on a device in order to measure the overall performance of a given control algorithm. Researchers at Oregon State University have developed a rotary testbed that simulates forces generated by stochastic sea-states on a WEC. The testbed has two coupled motors, one of which performs the hydrodynamic force modeling, and the other is used to develop and test generator control algorithms. The tool is compact, inexpensive, and easily programmed. Theory and hardware results are presented.

Nomenclature

A_b	Added buoy mass
α	Motor rotational speed
C_a	Added mass coefficient
C_d	Drag coefficient, linear case
c_b	Buoy hydrodynamic dampening
$\bar{c}$	Structural dampening per unit length
D	Buoy diameter
E	Young's modulus
F_e	Excitation force
f	Fraction of the total virtual mass
I	Second moment of cross-sectional area with respect to bending axis
k_b	Restoring force constant
k_t	Fixed motor parameter constant
l	Length of buoy
m_b	Buoy mass
$\bar{m}_o$	Actual mass per unit length
ω	Wave angular frequency
φ	Wave phase shift
P	Motor power
ρ	Fluid density
Z	Maximum wave height amplitude
z_b	Vertical position of the buoy
z_w	Vertical position of the water surface at the buoy
τ	Motor torque

Introduction

Due to the rising cost and limited supply of fossil fuel energy, nations are becoming increasingly interested in developing clean, renewable energy technologies. Technologies harnessing ocean tidal, saline, and thermal energy are deployed around the world, however the kinetic energy available for extraction from wave motion is substantial. According to the Electric Power Research Institute (EPRI), the total available incident wave energy flux is estimated at 2,300 TWh per year in the U.S. alone.[4]

Compared to other established energy conversion technologies like wind and solar, wave energy technologies are still relatively new. Researchers at Oregon State University's Wallace Energy Systems and Renewables Facility (WESRF) are pursuing a novel wave energy converter (WEC) device in the form of a linear generator buoy. The linear generator buoy prototype contains inductive windings coiled around a central magnetic shaft which is tension moored to the sea floor via a long cable. As the buoy rises and falls due to passing waves, the relative motion between the magnetic shaft and the inductive windings creates an electric current, which can then be regulated onto the power grid.[1]

For WEC devices such as the linear generator to capture wave energy efficiently, generator controls need to be optimized for a wide range of sea state operating conditions. Developers need a reliable method of simulating stochastic sea state loading in order to measure the overall performance of a given control algorithm.

WESRF has developed a rotary testbed that simulates forces generated by a range of programmable sea states. The rotary testbed is comprised of two coupled motors, one of which performs the hydrodynamic force modeling, and the other which is used to develop and test generator control algorithms. The testbed design allows complete user control of the motor wave and load generator simulator; all hydrodynamic and generator control algorithms are programmed in standard C code and easily modifiable.

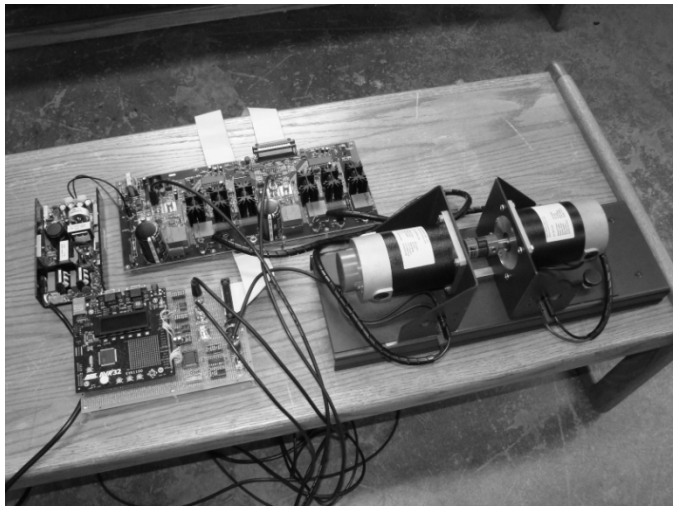

Figure 1. WESRF rotary testbed prototype.

The testbed consists of two directly coupled DC motors, a digital signal processor (DSP), a master control board (MCB), a motor drive board (MDB) and a computer interface. The first motor provides shaft torque and models the cyclic hydrodynamic forces of the ocean waves while the second simulates a WEC linear generator. The DSP board is used to measure motor currents and rotational speed, while the MCB receives feedback from a proportional integral (PI) controller to minimize simulation errors and sends pulse-width modulated (PWM) control signals to the MDB based on the desired sea state. An overview of the system is shown below in Figure 2.

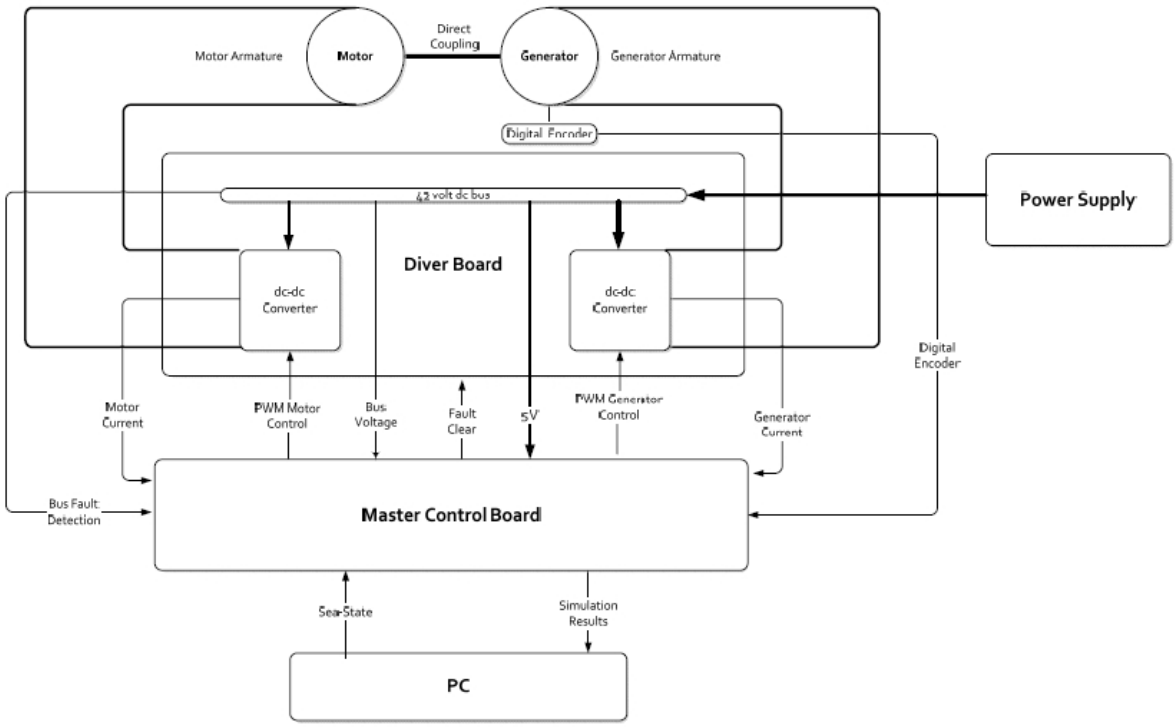

Figure 2. Rotary testbed block diagram.

The complete system allows the user to select from a variety of sea states through a computer interface and observe results in real time. By connecting the generator to a known electrical load and analyzing the generator power output over time, the user can effectively test the efficiency of a particular control algorithm for a given sea state.

The testbed is compact, inexpensive and preferred for small-scale testing as mechanical handling, control, and position sensing are more easily accomplished and verified.

Modeling

The rotary testbed software uses two common mathematical models to simulate forces generated by ocean waves. The first model is a sea state model which is used to simulate ocean wave heights based on physical data collected from offshore buoys. Results from the sea state model are delivered to a hydrodynamic model which determines the forces generated by the waves

using known buoy hydrodynamic coefficients. Numerical force results are then passed back to the onboard motor controller. Both models assume a single degree of freedom and are intended to serve as first order approximations of WEC physical behavior. Figure 3 below illustrates the simulation process in further detail.

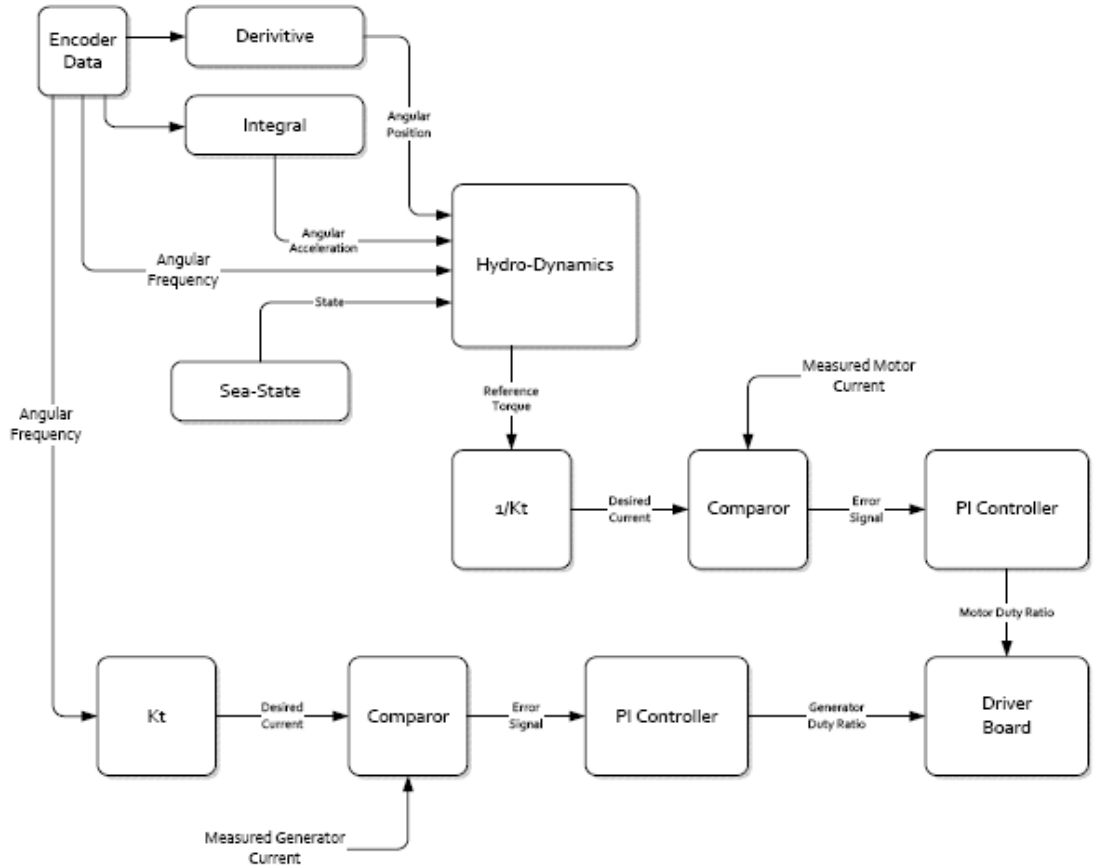

Figure 3. Control system overview.

Sea state model

The sea state model used to simulate the position of the buoy over time is a linear superposition of sinusoidal waveforms, as given in Equation 1:

$$z_w(t) = Z_1 \cos(\omega_1 t + \varphi_1) + Z_2 \cos(\omega_2 t + \varphi_2) + Z_3 \cos(\omega_3 t + \varphi_3) \qquad (1)$$

where z_w represents wave height, $Z_{1,2,3}$ maximum wave amplitudes, $\omega_{1,2,3}$ wave angular frequencies and $\varphi_{1,2,3}$ wave phase shifts. Using physical wave data obtained from National Buoy Data Center (NBDC) buoys located off the Oregon coast, typical wave parameter values for each sea state (i.e., World Meteorological Organization sea states 1 through 4) were determined by averaging over a wide distribution.[5]

Parameter values remain fixed for a given sea state, resulting in wave profiles that are more pseudorandom rather than truly stochastic. In the future, more advanced sea state models (i.e., models with multiple degrees of freedom and fewer fixed parameters) can be developed by the research team and easily implemented in the simulation software.

Hydrodynamic model

The software uses a linear Morrison model to iteratively determine the forces produced by a given sea state on a simulated buoy with known hydrodynamic coefficients. The Morrison model can be expressed mathematically as a differential equation in terms of only one time-dependent scalar coordinate which uniquely describes the buoy's position.[2] The excitation force depends on the incident wave and the hydrodynamic characteristics of the floating object:

$$F_e = m_b\,\ddot{z}_w + c_b\dot{z}_w + k_b z_w \qquad (2)$$

where z_w is the vertical position of the water surface at the buoy, m_b is the mass, c_b is the linear damping coefficient, k_b is the water plane stiffness, and F_e is the excitation force.

The second governing equation is the dynamic response of the buoy from the excitation force and any applied generator force:

$$F_e + F_{gen} = (m_b + A_b)\ddot{z}_b + c_b\dot{z}_b + k_b z_b \qquad (3)$$

where z_b is the vertical position of the buoy and A_b is the added mass.[3]

Values for coefficients m_b, A_b, c_b and k_b were determined empirically from OSU's 1 kW buoy prototype based on the following hydrodynamic equations as given in Wilson[2]:

$$m_b + A_b = \left(\bar{m}_o + C_a\,\rho\frac{\pi}{4}D^2\right)fl \qquad (4)$$

$$c_b = \bar{c}l + C_d\rho\, l\,\frac{D}{2} \qquad (5)$$

$$k_b = 192\,\frac{E\,I}{l^3} \qquad (6)$$

where $\bar{m}_o$ is the actual mass per unit length, C_a the added mass coefficient, ρ fluid density of sea water, D the buoy diameter, f the fraction of the total virtual mass, l the length of the buoy, $\bar{c}$ the structural dampening per unit length, C_d the drag coefficient for a linear case, E Young's modulus, and I the second moment of cross-sectional area with respect to the bending axis.

Finally, motor torque and power production are calculated using the following standard DC machine equations:

$$\tau = k_t\,I \qquad (7)$$
$$P = \tau\alpha \qquad (8)$$

where τ represents torque, k_t is a fixed parameter based on motor hardware, I is machine current, P is power, and α is the rotational speed of the motor.

Hardware

The rotary testbed consists of the following primary hardware components:

- DC Motor which simulates ocean conditions: 42 Volt, 200 Watt, four pole, brush type motor, with a max speed of 4700 RPM under no load conditions.
- DC Generator which simulates the OSU energy extraction buoy: 42 Volt, 200 Watt, four pole, brush type motor, with a max speed of 4700 RPM under no load conditions.
- Digital encoder attached to the generator: allows the measurement of the generator rotor position and the motor rotor position.
- Motor Driver Board: performs buffering and level shifting of the PWM signals from the master control board to drive the motor and generator and Monitors the motor and generator for fault conditions.
- Master Control Board (MCB): mainly consists of the AVR EVK 1100. The MCB generates the control signals to the motor drive board based on sea state, current motor/generator conditions, and hydrodynamics.
- Personal Computer: runs the rotational test beds user interface which provides the ability to program the current sea state. The simulation results can be displayed and evaluated.
- Power Supply: supplies the rotary test bed with the 42 Volts required by the motor driver board.

Results

The testbed capability to send specific motor torque reference signals to the PI controller and receive accurate generator torque responses was verified by running the test bed under a variety of sea states.

Using a digital encoder, physical rotation and angular frequency of the motor generator shafts were measured. These data were then both integrated and differentiated to produce motor/generator shaft position and motor/generator shaft angular acceleration. The testbed software then applied these parameters and the user defined sea state in Equation 3 to determine the correct motor torque reference signal that accurately simulates wave/buoy conditions.

Figure 4 on the following page shows typical reference and response torques for the rotary system during general sea state conditions. The plotted motor and generator torque curves tightly overlap and measurements indicate that generator response torque is within 1-2% of the motor reference torque.

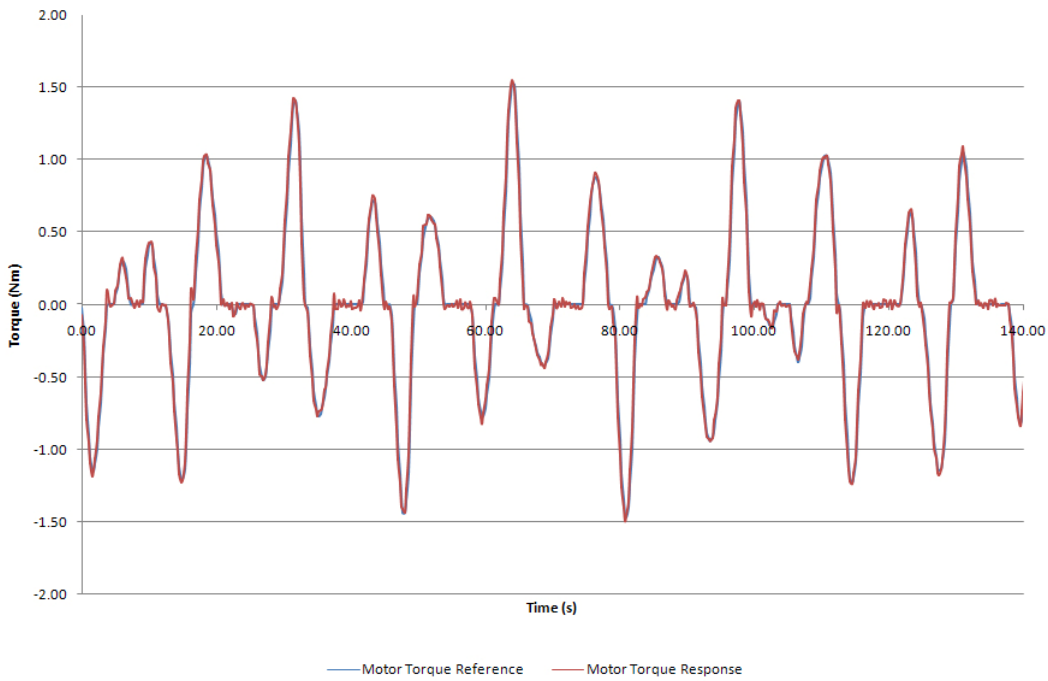

Figure 4. Rotary testbed motor and torque response.

After torque production capabilities were verified, the next important step was to verify the testbed capability to accurately simulate changing wave conditions and also measure the generator power output to ensure values match real world results. For example, during calm conditions, the rotary generator should experience 1-2 meter wave heights.

Using data obtained from the testbed and Equations 7 and 8, numerical results for such a sea state were tabulated. Graphical results are shown on the next page in Figure 5.

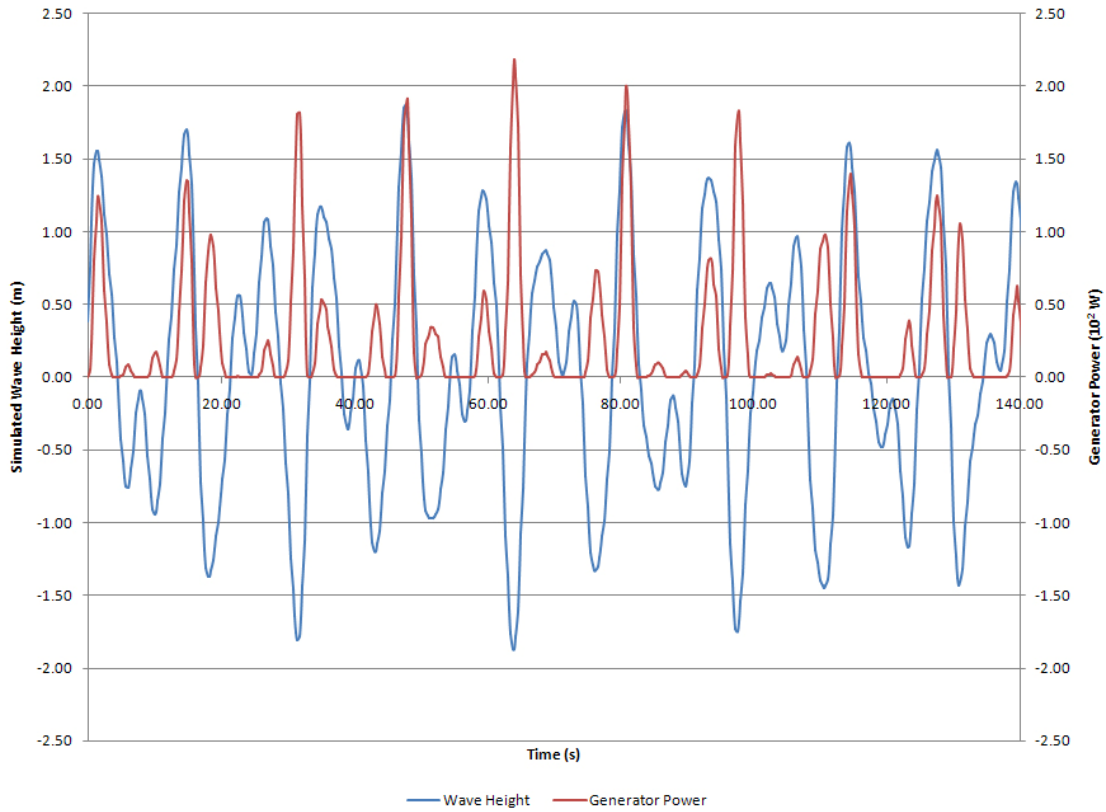

Figure 5. Rotary testbed wave height and generator power results for an arbitrary sea state.

The vertical plot axes are scaled to show the wave height and power output results simultaneously. As expected, the simulated wave heights are within acceptable bounds for a calm sea state, and the generator power output is phase shifted slightly due to system dampening. As mentioned previously, the generator power output is rated at 200 Watts. As the simulated wave height oscillates, output power ranges from zero to slightly approximately rated power.

Conclusion

The WESRF rotary testbed is a robust, custom tool that allows researchers and developers to accurately simulate a wide variety of user-defined wave conditions on a small-scale generator in a safe laboratory environment. The design allows full user control of the motor wave and load generator simulator and enables extensive testing and development of optimal WEC generator control algorithms. The application for this type of control system is so unique that very few similar systems exist. Although the testbed is designed to simulate ocean waves, in the future the testbed could be used to model wind conditions and test wind generator control algorithms with only minor software modifications.

Acknowledgments

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