SIMULATION OF AN AXISYMMETRIC, PNEUMATIC-PTO WEC IN OPERATIONAL AND SURVIVAL CONDITIONS FOR MODEL-BASED DESIGN

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INTRODUCTION

The Healy buoy-inertia tube wave energy converter (WEC) is under development using a scale-up approach incorporating numerical modeling and wave tank testing. This paper provides an overview of the Healy WEC and describes numerical analysis conducted to guide the design of the WEC and its mooring system.

The WEC designed by Healy Wave Energy, LLC consists of a buoy rigidly connected to a long, vertical inertia tube which is open at the top and bottom (see Fig. 1). A piston-rod assembly is enclosed and connected to the power take-off (PTO) mechanism. Due to inertia of water within the tube, relative motion between the piston and buoy-inertia tube structure drives the PTO. The PTO consists of an air compressor, a dynamic pressure regulator, and a turbine connected to a generator. The developer claims the following:

A. *Low-pressure double-acting pneumatic piston.* One-way valves rectify airflow.

B. *Rolling diaphragms* completed over 71 million cycles without failure before fatigue test was stopped (equivalent to 15 years at a 6 sec. period).

C. *High-efficiency unidirectional air turbine.* Air driven by the piston through the turbine is sealed from both water and atmospheric air.

D. *Variable-ballasted piston with inertia tube* provides large reaction mass.

E. *Low-impact-force end-stop feature* reduces fluid loading on piston when approaching end stops by allowing fluid flow around piston.

Nonlinear numerical models of the device were developed. These models were used to analyze the system in operational and extreme conditions and to design a mooring system that accommodated the following objectives:

- Provide adequate safety factors in mooring.
- Reduce maximum loads on the device.
- Keep footprint within a 350 m permitted site.
- Minimize effect of mooring on power take-off.
- Reduce pitching of WEC.

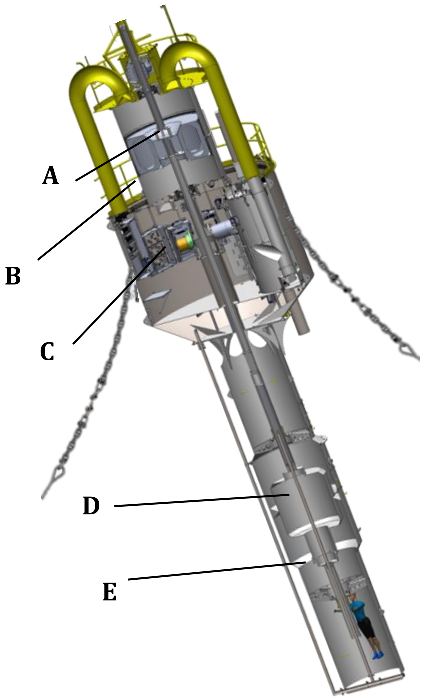

FIGURE 1. SCHEMATIC OF THE HEALY WEC.

A design-of-experiments approach was used to identify designs that met these objectives.

NUMERICAL MODELING

Numerical models of the Healy WEC were developed in both WEC-Sim (Yu et al., 2014) and OrcaFlex (Orcina Ltd., 2016). Both models include mooring dynamics and nonlinear hydrodynamics, but use different methods. The WEC-Sim model includes a detailed model of the PTO pneumatics. This model was used to compute linearized PTO coefficients that were used in the OrcaFlex model.

WEC-Sim Model

Hydrodynamics

The dynamic system was modeled in WEC-Sim, an open-source wave energy modeling software project sponsored by the Department of Energy. Frequency dependent hydrodynamic coefficients (added mass, diffraction and radiation) were calculated using the open-source Boundary Element Method (BEM) solver Nemoh (Ecole Centrale de Nantes, 2016). The BEM assumes potential flow (no viscosity or vorticity in the fluid). This assumption is clearly violated at the openings of the inertia tube and in the interaction of the piston with the walls of the inertia tube. Thus, Computational Fluid Dynamics (CFD) implemented in OpenFOAM was used to estimate linear and quadratic dissipation coefficients associated with the motion of the piston, as well as a modified coefficient of added mass for the piston in heave. Furthermore, in moderate and extreme sea states the Reynolds numbers associated with the flow around the device are sufficiently large to ensure separation. Thus, quadratic drag was applied to these bodies as per Morison et al. (1950). Coupled mooring dynamics were simulated using MoorDyn (Hall and A. Goupee, 2015). Validation of the WEC-Sim hydrodynamic model was established by wave tank tests of a 1/9.4 Froude-scaled model (Dewhurst et al., 2016).

Operational control of the piston motion relative to the buoy is achieved by a hydraulic brake acting on the shaft. The hydraulic pressure is dictated by a simulated Programmable Logic Controller (PLC). Since applying the brake creates an extremely stiff numerical system, a variable time step solver (MATLAB's ode45) is employed.

Coupled Pneumatic PTO Model

The force between the buoy and piston is given by

$$F = -A_c(P_u - P_d) + F_{stops} + F_{brake}.$$

Here A_c is the cross-sectional area of the piston, P_u and P_d are the pressures in the upper and lower portions of the compressor chamber, respectively, and F_{stops} is the sum of the hydrodynamic and mechanical force applied by the piston stops. F_{brake} is the force applied by the hydraulic brake.

The PTO system is represented as a series of control volumes (A-E in.) For each control volume, mass and momentum conservation are used to determine instantaneous pressure, density, and airflow in and out of the control volume.

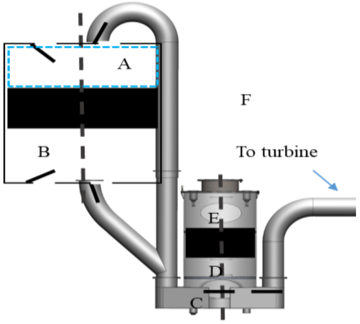

FIGURE 2. PNEUMATIC PTO SYSTEM. EACH ZONE (A-F) REPRESENTS A CONTROL VOLUME IN WHICH MASS AND MOMENTUM OF AIR IS CONSERVED. SEPERATING ZONES D AND E IS A DYNAMIC PISTON INTENDED TO ACT AS A PRESURE REGULATOR. ZONE F IS THE ENGINE ROOM WHICH CONSTITUTES A LOW PRESSURE ACCUMULATOR.

By way of example, the governing equations for control volume **A** (outlined in dashed blue) are:

$$\dot{\rho_A} = \frac{\rho_A(A_C\dot{y} - u_{out}A_v) + \rho_o u_{in} A_v}{V_o + yA_c}$$

$$P_A = P_o\,(\rho_A/\rho_o)^\gamma$$

$$\dot{u}_{out} = \frac{P_A - P_C}{\rho_A S_{out}} - \frac{u_{out}|u_{out}|}{2S_{out}}.$$

$$\dot{u}_{in} = \frac{P_o - P_A}{\rho_o S_{in}} - \frac{u_{in}|u_{in}|}{2S_{in}}.$$

Here V_o is the control volume at equilibrium, ρ is the density of the air, and S is the nominal length of the accelerating streamline. P_A and P_C are the absolute pressure in volumes A and C, respectively, and P_o is atmospheric pressure. A value of γ=1.67 was used to represent humid air at approximately 20^o C. u is the instantaneous fluid velocity through each one-way valve, which is assumed to be uniform across the area of the valves, A_v. The flow through the turbine is computed as a function of instantaneous gage pressure, based on information from the turbine manufacturer.

The variable ballast tank (Figure 1, D) is treated in the same manner as volumes **A** and **B** in Figure 2, except that the lower volume is filled with incompressible seawater and the piston is replaced with a massless air-water interface. Sloshing in the tank is ignored.

OrcaFlex Model

The Healy WEC and mooring system were modeled in the commercial software OrcaFlex™ (Orcina Ltd., 2016) to assess the device's response to extreme sea states and to investigate the effects of various mooring configurations. Whereas WEC-Sim is developed based on linear potential flow theory (with some nonlinear effects), OrcaFlex is conducive to a nonlinear approach that accounts for the large changes in position, orientation, and submerged volume experienced by the device. OrcaFlex is particularly well suited to analyzing axisymmetric shapes whose diameter is small compared to the length of the design wave, such as the Healy WEC.

Radiation damping in heave and pitch were included by setting pitch and heave damping (relative to fluid velocity) results from potential flow theory interpolated to the peak wave frequency. The heave excitation force was set in a similar manner.

ANALYSIS—DESIGN OF (NUMERICAL) EXPERIMENTS

The test location is the University of New Hampshire (UNH) Center for Ocean Renewable Energy (CORE) site south of the Isles of Shoals, NH. A preliminary mooring system, consisting of anchors, chain, rope, and associated hardware, was designed by (Dewhurst et al., 2016). The goal of the present analysis is to design a mooring system sufficient for holding the WEC on station and minimizing pitching while also minimizing interference with its energy absorption function and fitting within the permitted test site (350 m by 340 m).

Operational and Extreme Sea state Identification

Historical wave data from CDIP site 160 (Jeffrey's Ledge) for the years 2008-2015 were used to calculate representative and extreme sea states.

Calculation of Representative Irregular Wave States

The representative Irregular Wave States (IWSs) for computing the ACE metric were derived using methodology similar to that used by the U.S. DOE Wave Energy Prize (2016). *K-means* clustering analysis was used to group historical wave data into six different wave regimes, each of which was represented by a single IWS. The resulting Irregular Wave States are given in Table 1, along with the probability of occurrence associated with each regime. IWS 4 and 6 were discarded due to their low probability of occurrence.

TABLE 1. IRREGULAR WAVE STATES USED TO COMPUTE THE REPRESENTATIVE POWER CAPTURE OF THE HWEC IN THE GULF OF MAINE

	T_{pk}, s	SWH, m	Probability
1	4.4	1.0	0.22
2	6.4	1.4	0.24
3	8.4	1.0	0.25
4	9.5	3.4	0.05
5	10.6	1.1	0.17
6	13.4	1.3	0.07
		Sum:	1.0

Extreme Sea state Identification

Principal component analysis was used to calculate 50-year return period extreme sea states, as described in (Eckert-Gallup et al., 2016) and as implemented in the Wave-Energy-Converter Design Response Toolkit (Coe et al., 2016). The computed 50-year return period contour (dashed red line) is shown in Figure 3. The historical observations of peak period and significant wave height are shown as circles colored by significant wave height.

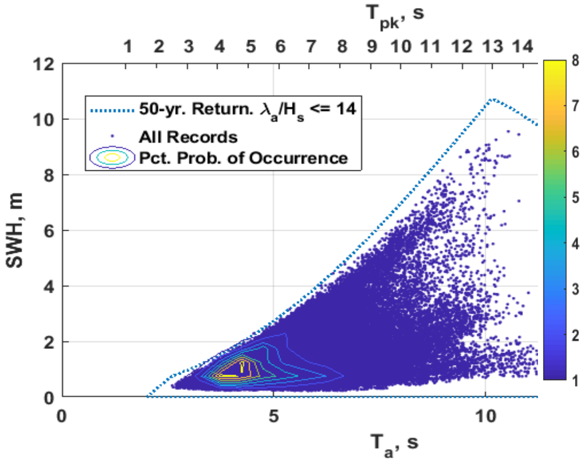

FIGURE 3. SIGNIFICANT WAVE HEIGHT AND MEAN WAVE PERIOD: HISTORICAL DATA FROM JEFFREY'S LEDGE, NH. DASHED BLUE LINE SHOWS THE 50-YEAR RETURN PERIOD CONTOUR COMPUTED USING PRINCIPAL COMPONENT ANALYSIS, LIMITED TO THE STEEPNESS AT WHICH WAVES GENERALLY BREAK.

Design of Experiments Setup

A design-of-experiments approach was used to assess the impact of various mooring system parameters on the maximum expected mooring tensions and on the estimated annual energy absorption. A fractional factorial experiment was chosen for efficiency. A resolution of IV was specified, meaning that no two-factor interactions were aliased with any main effects. See, e.g. (Oehlert, 2010). A Franklin-Bailey algorithm was used to find generators for the smallest two-level fractional-factorial design. This resulted in a 2^{6-1} fractional factorial experiment. Each of the 32 designs was run with two different random wave seeds so that the uncertainty due to wave seeding could be estimated.

Early numerical experiments yielded several key results:

1. Mooring floats and a bridle system were critical to improving pitch stability.
2. Mooring floats were essential for mitigating the effect of the mooring system on power absorption.
3. Filling the ballast tank during extreme events had a minimal effect on improving pitch stability. Consequently, the tank can be emptied during extreme events, significantly reducing the necessary holding force of the hydraulic brake.
4. The stiffness of the mooring line was strongly correlated with the maximum forces that the mooring exerted on the device. Using Nylon line greatly reduced mooring loads compared to Spectra® or Amsteel®.

Building on these results, the factors selected for the final numerical experiment were:

- Bridle length
- Bottom chain mass/length
- Mooring pretension
- Mooring line length
- Mooring line stiffness (EA)
- Bridle chain

The mooring footprint was constrained to fit in a 350 m square test site. Thus, increased length of the synthetic mooring line length corresponded to decreased length of chain on the seafloor.

For each factor, low (-1) and high (1) levels were chosen to span the range of reasonable design values. Each design was simulated in sea states shown in Table 1. Weighting the energy production in each IWS by the probability of occurrence yielded a representative annual energy production for each design. Each design was also simulated in a 50-year storm.

Maximum expected pitch angles during a three-hour storm were calculated assuming a Rayleigh distribution. Most-likely maximum values of mooring tensions and loads exerted on the device during a three-hour storm were computed using a. Peaks-Over-Threshold (POT) method assuming a Generalized Pareto Distribution. A *declustering* algorithm was applied, with a period equal to the zero-crossing period of the ocean sea state. The threshold was selected using a *Mean Residual Life* analysis. To estimate the simulation time required to produce valid estimates of extreme values, a convergence test was applied using three-hour simulations of several designs. Results are shown in Figure 4.

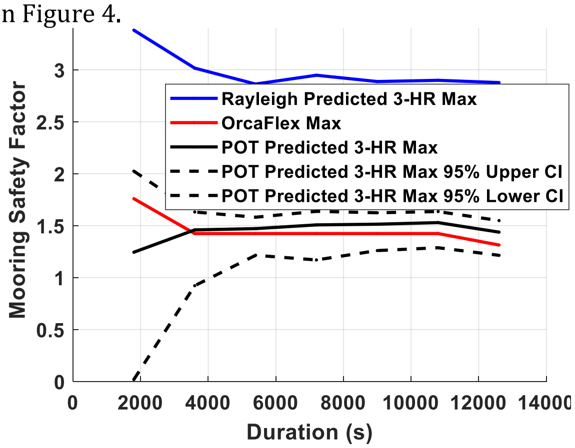

FIGURE 4. PREDICTED SAFETY FACTOR USING VARIOUS STATISTICAL METHODS AS A FUNCTION OF SIMULATION LENGTH. THE SOLID BLACK LINE SHOWS RESULTS OF POT METHOD. DASHED LINES SHOW THE 95% CONFIDENCE INTERVALS OF THIS METHOD. THE ACTUAL PEAKS RECORDED IN THE ORCAFLEX SIMULATION ARE SHOWN IN RED. FOR COMPARISON, A 3-HR. PEAK IS ALSO COMPUTED USING A RAYLEIGH DISTRIBUTION (SOLID BLUE LINE).

Design of Experiments Results

The design-of-experiments approach yields the estimated effect of each design factor on each objective function of interest. For example, Figure 5 shows the effect of each design parameter on the WEC's pitch safety factor in extreme conditions.

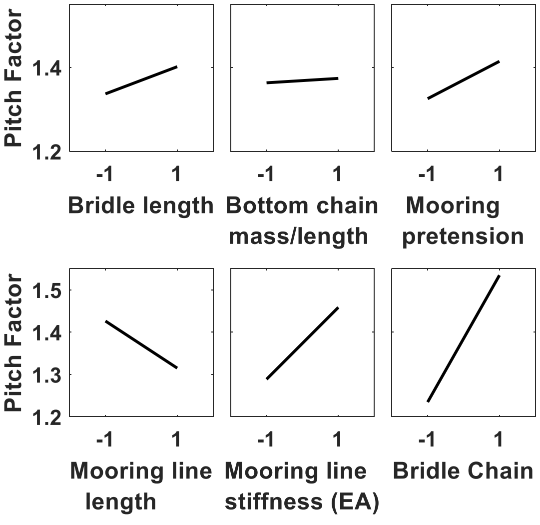

FIGURE 5. MEAN EFFECT OF FACTOR LEVELS ON MAXIMUM PITCH AMPLITUDE IN A 3-HOUR LONG 50-YEAR STORM WITH PEAK PERIOD OF 13 S AND A SIGNIFICANT WAVE HEIGHT OF 10.7 M.

Figure 5 shows that the pitch safety factor can be increased by using chain in the lower bridle segment and by decreasing the mooring line length.

Increasing the stiffness of the line also increases the pitch safety factor, but an increased line stiffness was found to significantly increase the loads on the WEC. Such trade-offs between objectives were examined using scatter plots like Figure 6, which shows the pitch safety factor versus the mooring safety factor for each design.

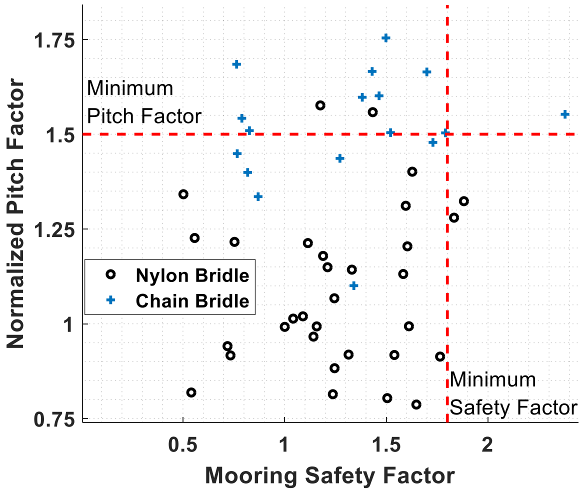

FIGURE 6. PITCH SAFETY FACTOR VERSUS MOORING LINE SAFETY FACTOR FOR ALL DESIGNS. MINIMUM MOORING SAFETY FACTOR IS FROM AMERICAN BUREAU OF SHIPPING (ABS). PITCH FACTOR IS FROM DEVELOPER. DESIGN(S) IN THE UPPER RIGHT-HAND QUADRANT ARE ACCEPTABLE.

FUTURE WORK

The 49 ton prototype device is under construction in Clearwater, Florida. It will be deployed at the University of New Hampshire Center for Ocean Renewable Energy Open-ocean Test Site starting in 2018 for a long-term test of its power production and longevity.

The prototype deployment will include a two-week observation of wave and current forcing, device motions, mooring tensions, and power absorption. This will provide the opportunity for a model validation study.

CONCLUSION

Modified state-of-the-art tools were employed to model a WEC with a pneumatic PTO in operational and survival conditions. Models were employed in a design framework to efficiently analyze the effects of a large number of design variables for the mooring. Results provided in this paper showed that, for WEC in question, using a bridle system with mooring floats and a small angle from horizontal reduced the pitching in extreme storms and improved power take-off. The use of Nylon rope compared to high-stiffness line was found to significantly reduce loads on the WEC while maintaining acceptable safety factors. In general, this model-based design approach was successful in identifying mooring designs with acceptable safety factors that mitigated the effect of the mooring on power production and fit within the footprint prescribed by the test site dimensions. However, there appears to be a necessary compromise between improving the pitch behavior of the device and reducing the loads on the WEC. Sea trials of the 49 ton WEC in 2018 will provide validation data for a code-to-code comparison of the numerical methods presented.

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