EE0000955 MOD 5 –

M2.1.3 Report – WEC engineering design and numerical simulation

Project Title: National Marine Renewable Energy Center Upgrades

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Background

The Laboratory Upgrade Point Absorber (LUPA) is designed to provide the broader wave energy community with an open-source WEC that is well validated, modular, and accessible for experimental and numerical testing. Experimental testing of wave energy converters is an important step to validate and calibrate numerical models, but it is time and resource intensive. The LUPA device was designed to reduce these barriers and help accelerate innovation in wave energy technology. The LUPA acts as a platform for experimental validation of hydrodynamic models, control systems, power take off designs, and hull and heave plate geometries. This report details the motivation, engineering design, testing, results, and future work of the Lab Upgrade Point Absorber.

Upgrade

Introduction

The Laboratory Upgrade Point Absorber (LUPA) is a two-body point absorber wave energy converter (WEC) specifically designed to be a research platform for fundamental and applied work on hydrodynamics, controls, system integration and optimization. The LUPA provides an extremely valuable upgrade to the current open-source WECs as it was designed with an active and controllable power-take-off (PTO) and generator. It is truly an open-source device, meaning all the data, designs, models, and materials will be available to the public. The time, capital, and knowledge needed to build a tank-scaled WEC is an often-cited barrier to advancing the wave energy industry; the LUPA reduces these barriers by providing a validated, ready-to-use WEC for researchers, industry and technology developers.

The concept for LUPA was developed in 2020 with the goal of creating a WEC with an active PTO. Initial designs and iterations occurred throughout 2021. Several webinars and design meetings were held in 2021 to solicit feedback from experts in the industry, national labs and federal experts to improve the design and add features recommended by future users. Numerical modeling was completed throughout 2021-2022 to inform the initial design and provide predictions of WEC movement and power produced. Dry tests on the PTO were conducted in spring 2022 to physically test the generator and sensors, and improve the user interface for the active control. The construction of LUPA was completed in the summer of 2022 and experimental testing began in September 2022 and ended in January 2023.

LUPA Engineering Design

One major goal for this infrastructure upgrade was to design and build a tank scale wave energy converter with an active power take off system. Additional goals include:

- Develop an open-source WEC with a high level of accessibility for future users.
- Design modular systems for future users including: three PTO configurations, easy modification of heave plate and hull geometries, modification of mooring lines, space for additional sensors, and user defined fields in the control interface.
- Transform the WEC into three fundamentally different WEC concepts by changing the number of bodies and degrees of freedom.
- Maintain a high level of documentation in the design process and testing procedures to share lessons learnt.

The LUPA is a two-body point absorber wave energy converter with a buoyancy driven float and a spar that acts as a reactionary body. The SolidWorks design rendering and physical device are shown in Figure 1 with labels noting the major components. The motor/generator is mounted on the float along with the sensors and power electronics. The sensors onboard LUPA and deployed in the tank are shown in The specifications are listed in Table 1; the scale was determined by scaling the depth from the PacWave South wave energy test site off the coast of Newport, Oregon, USA to the depth in the Large Wave Flume (LWF) at the O.H. Hinsdale Wave Research Laboratory in Corvallis, OR, USA.

Table 1. LUPA Specifications

Specification	Value	Units
Scale	1/20	m/m
Float Diameter	1	m
Total height	3.7	m
PTO Stroke Length	0.5	m
Mass	424	kg
Motor Continuous Torque	46	Nm
Water Depth	2.7	m

Table 2.

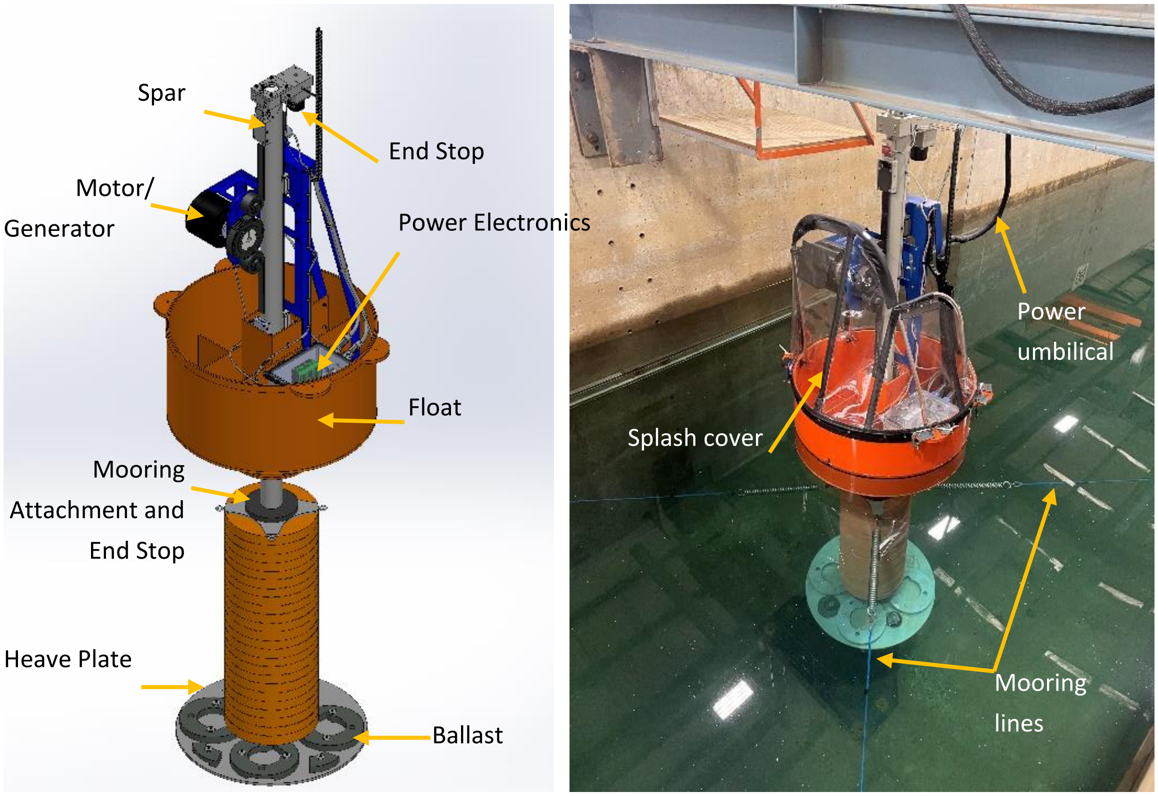

Figure 1. (Left) LUPA SOLIDWORKS rendering. (Right) LUPA deployed in the Large Wave Flume with the splash cover and mooring lines installed.

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Table 2. LUPA Sensors

Sensor Name	Parameter Measured	Units
Draw Wire	Relative motion between spar and float	Meters
Temperature Sensor	Temperature of motor and motor drive	Degrees Celsius
Load Cell	Force in the PTO	Newtons
Vertical Reference Unit	Hull angle of rotation, angular velocity, and translational accelerations	Degrees, degrees/second, m/seconds^2
Motor Encoder	Motor position	Radians
Motor Drive	Motor current	Amps
Wave Gage	Free surface	Meters
Load Cell	Mooring line force	Newtons
String Pot	Relative motion of spar	Meters

The LUPA has three modes of operation that vary the number of bodies and degrees of freedom and therefore the complexity; these include *'one body heave only'*, *'two body heave only'*, and *'two bodies six degrees of freedom (DOF)'*. The '*one body heave only'* mode replicates common surface following single body WEC systems. In this mode, the LUPA spar is locked so only the float moves, and only in heave (vertical). The '*two body heave only'* mode increases the complexity and allows both the float and spar to move, but both bodies are restricted to heaving. The '*two body six DOF'* mode replicates many common commercial WEC archetypes and allows the LUPA to translate and rotate in all six directions (surge, sway, heave, roll, pitch, and yaw). In this mode, LUPA has taut mooring lines connected to the spar. Switching between modes is a simple process of removing mechanical locks. These modes are visualized in Figure 2. LUPA Modes of Operation

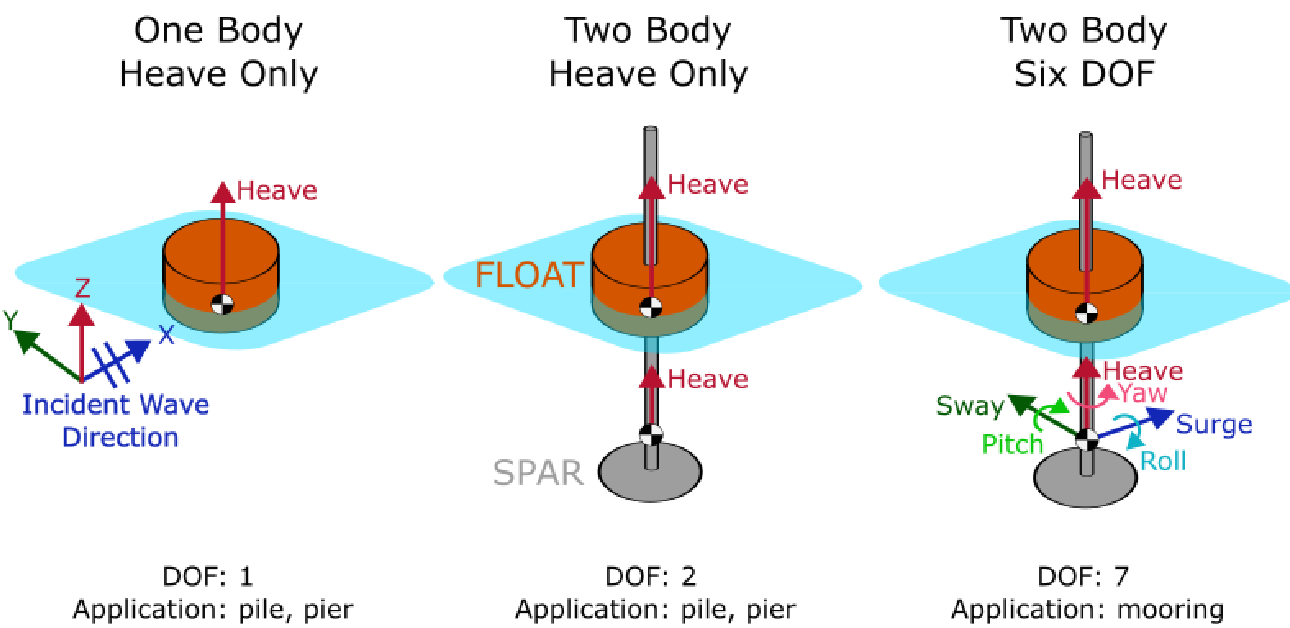

Figure 2. LUPA Modes of Operation

Results

The LUPA underwent a rigorous iterative testing process of numerical, dry and west physical testing. As lessons were learnt from individual testing campaigns, these were documented, and knowledge transferred to other testing efforts.

Numerical Modeling

Numerical modeling of LUPA was completed in WEC-Sim for all three modes of operation. WEC-Sim is a , a time domain solver for wave energy converters which reports forces on the WEC and power generated from the PTO (Ogden et al., 2022). A damping optimization was performed by running 672 wave cases, sweeping the possible range of regular wave periods and PTO damping coefficients. The results for the 'two-body heave only' mode are shown in Figure 3, indicating the optimal values of the damping coefficients for each regular wave period. As shown, the LUPA two body heave only mode has a resonant period of about 2 seconds with an optimal damping coefficient of 6000 Ns/m.

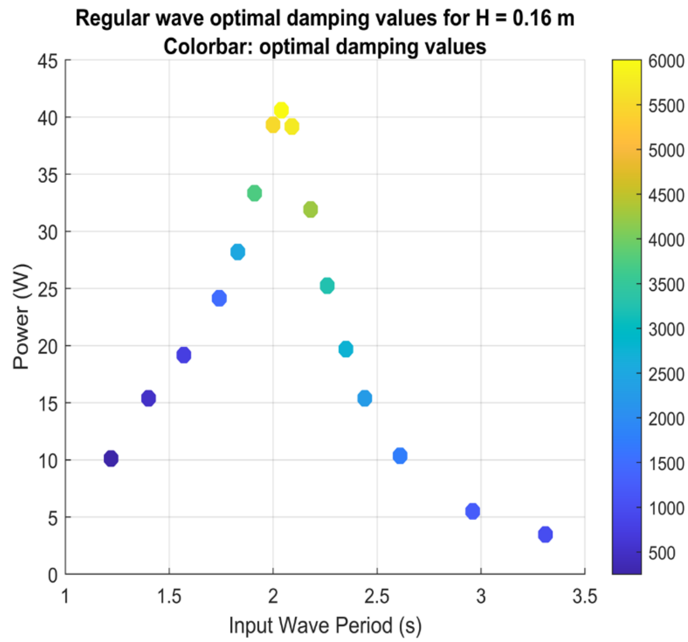

Figure 3. Numerical damping optimization for the two-body heave only mode of operation.

Dry Experimental Testing

The LUPA underwent both dry and wet tests at the O.H. Hinsdale Wave Laboratory. The dry tests include rigging the power take off on an external frame to test the motor and sensors in the system. Other dry testing included swing tests to experimentally find the moments of inertia of the spar and float, and locate the center of gravity on each body. The setup for the testing the PTO is shown in Figure 4; as well as the user interface used to actuate the motor and collect data.

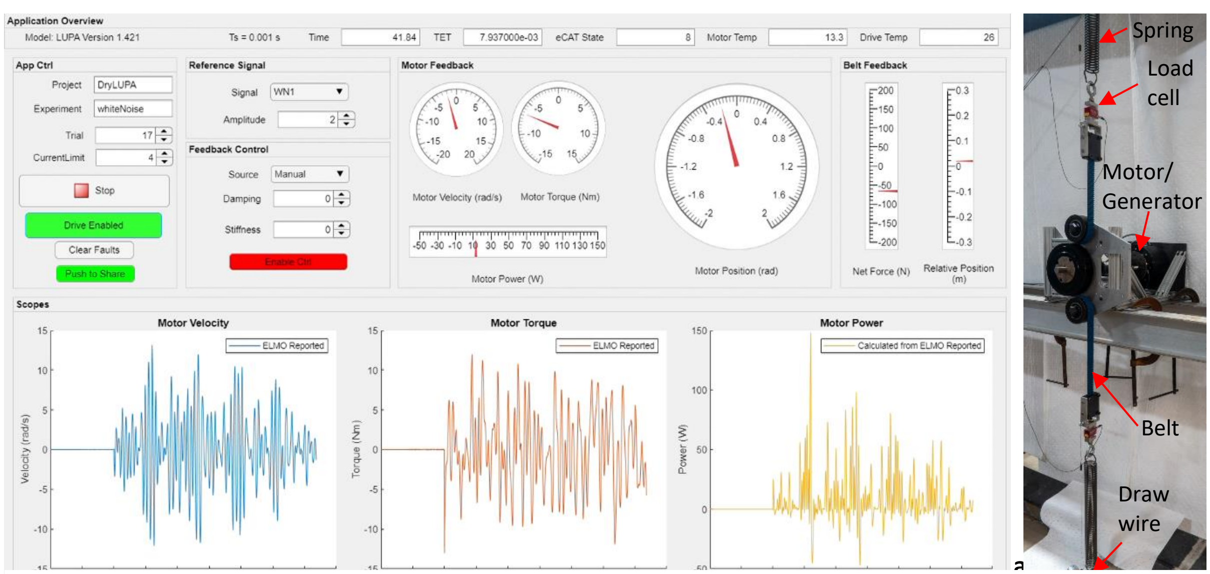

Figure 4: Dry experimental test rig and control system graphical user interface

The dry testing of the PTO was used to test the control input to the motor/generator, and evaluate the mechanical to electrical conversion. Figure 6 shows a section of the time series data produced from a test with a 2 second sine wave input into the motor. The power in the belt represents mechanical power and the motor power represents the electrical power. This data shows the effect of gravity on a vertical PTO as well as time delays between the mechanical and electrical systems. The dry testing provided an invaluable time to test the system in a controlled environment without the complexity of being in water.

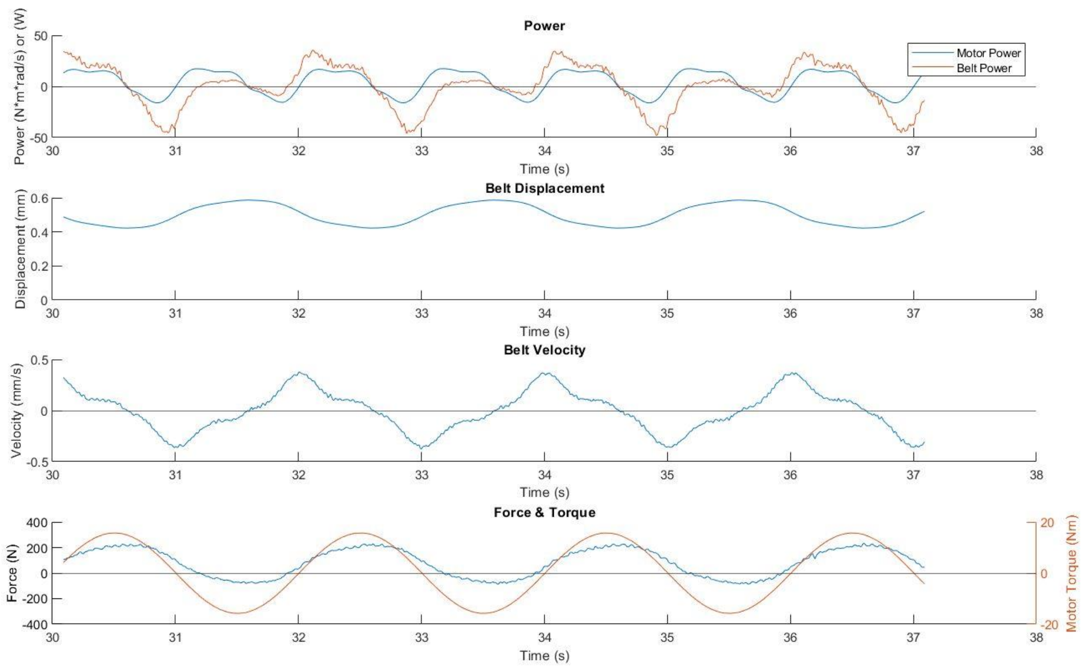

Figure 6. Dry test plot of power, belt displacement, belt velocity, and force & torque.

Wet Experimental Testing

The wet tests included no-wave and wave conditions to perform a system-identification; the details and purposes are shown in Table 3 below. These tests were completed in the Large Wave Flume at a depth of 2.7 meters.

The LUPA wet testing performed a system identification that included free decay, forced oscillations, and regular wave cases. These tests established working procedures for deploying and installing LUPA and developed a testing procedure for running waves and implementing controls. The limitations of the PTO controls were determined for each mode of operation through free decay and forced oscillation tests.

Table 3. Wet Tests

Test	Conditions	Purpose
Free Decay – Float Heave Only	Still water, 1-13 Amp inputs to motor	Find limitations in motor input
Forced Oscillation – Float Heave Only	Still water, motor inputs from 2.5-12 Amps: sine wave (0.5-3.5s), chirp signal, white noise	Find limitations in motor input, find resonant frequency of float.
Free Decay – Float and Spar Heave Only	Still water, 1-12 Amp inputs to motor	Test mooring and buoyancy restoring stiffness. Test end stops.
Forced Oscillation – Float and Spar Heave Only	Still water, motor inputs from 2.5-12 Amps: sine wave (0.5-3.5s), chirp signal	Find limitations in motor input, find resonant frequency.
Waves – All Modes of Operation	Regular waves (1.5-3.5s) for all three modes, Random (PM, chirp, pink noise) for float heave and two body 6 DOF	Perform damping optimization, find RAO curves, compare power curves, and perform control experiments.

Numerical WEC-Sim modeling was also completed to compare the damping optimization of the PTO as well as the Response Amplitude Operators (RAOs). The wave tests provided an experimental version of the PTO damping optimization by sweeping damping coefficients across each wave period. The optimization results are shown in Figure 7 with the normalized power reported for the optimal damping coefficient. These results aide modelers and future users of LUPA by providing the optimal power take off conditions across the relevant wave conditions.

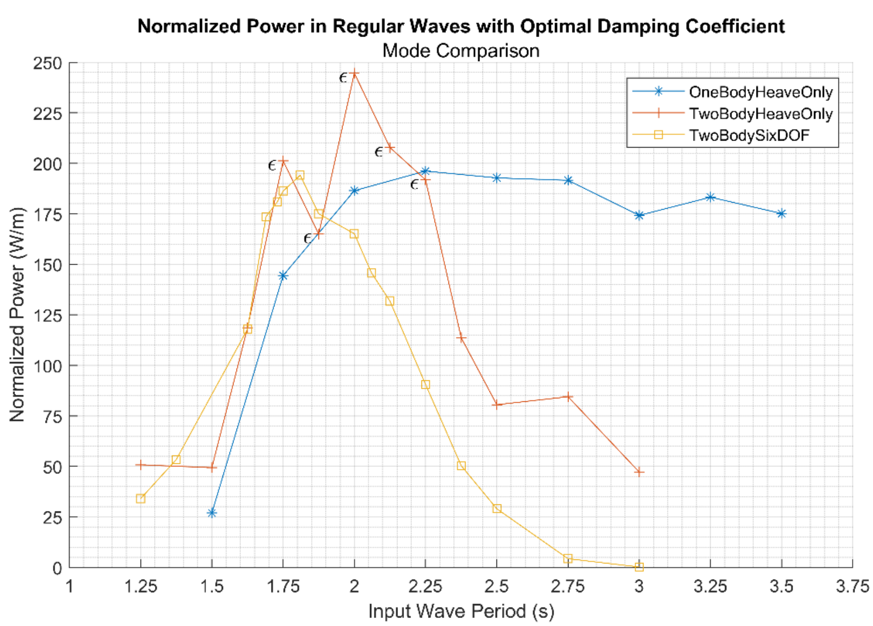

Figure 7. Experimental damping optimization for all three modes of operation. The values marked by an epsilon are biased by the limitations set by users in the controls.

Supporting Documentation

The open-source nature of LUPA is supported by public platforms for greater accessibility of data, media, and models. Note that these resources are still in development, but the following sources will point to resources on LUPA:

- Website serving as a central location for information supported on GitHub: https://pmec-osu.github.io/LUPA/
- Data from testing: https://mhkdr.openei.org/
- Photos and videos from testing: https://vimeo.com/user164791676

Future Work

The LUPA has great potential to serve researchers for years to come. It is currently being used to study the following topics:

- Degree of freedom effects on wave energy converter power production
- Stiffness and damping control effects
- WEC hydrodynamics for AUV docking and recharging.
- Optimization example in WecOptTool.
- Reduced order modeling of wave energy converters
- Non-linear wave structure interactions
- WEC power dynamics in remote microgrids
- Power integration into the Oregon State University campus grid

The LUPA is available for collaboration to support the advancement of marine renewable energy.

References

Ogden, D., Ruehl, K., Yu, Y. H., Keester, A., Forbush, D., Leon, J., & Tom, N. (2022). Review of WEC-Sim Development and Applications. *International Marine Energy Journal*, *5*(3), 293–303. https://doi.org/10.36688/imej.5.293-303