Degrees of freedom effects on a laboratory scale WEC point absorber

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Abstract—**There are many archetypes of wave energy converters (WEC) that vary widely in operating principles, geometry, controls, number of bodies, and degrees of freedom (DOF). Fundamental WEC research often simplifies this complexity by reducing the number of floating bodies and restricting motions to the dominant degree of freedom. This paper presents the effects of increasing the number of bodies and degrees of freedom of a WEC on body response, power take-off controls, and power capture. The results are from physical experiments with a 1 meter diameter model of the open-source laboratory upgrade point absorber (LUPA). LUPA is a two-body point absorber WEC with a buoyancy-driven float and a reactionary spar with a large heave plate. It can be transformed between a one-body heave-only, two-body heave-only, and a two-body 6 DOF device without changing the geometries, controls, or mooring lines. Results show that adding a secondary submerged body to a point absorber causes power capture to decrease by up to 76% at longer periods. It is also demonstrated that constraining a two-body point absorber to heave motions can be a good power capture approximation for a six-DOF moored two-body point absorber with slight shifts in the resonant period. A discussion on the uncertainty of frequently used metrics in wave energy literature is included with a special focus on uncertainty in wave energy experimental testing.**

Keywords—**degrees of freedom, number of bodies, laboratory testing, point absorber**

I. INTRODUCTION

RENWABLE energy technologies are poised to alleviate many of the world's most pressing challenges related to climate change, energy demand, and environmental injustice due to their low greenhouse gas emissions and ability to be distributed widely geographically [1]. Their technological development, political support, and social acceptance are catalysts for making that a reality [1]. For populations near the coast, a wave energy converter (WEC) could offer energy resiliency by converting the power in ocean waves to mechanical or electrical power. There is a large resource potential in ocean waves and with more development, WECs could become a substantial source of low emission power [2].

There are dozens of WEC designs in development with many technical challenges to overcome such as improving energy efficiency and structural reliability [3], [4]. The designs vary widely in operating principle, number of bodies, degrees of freedom, geometry, and controls. Due to this complexity, it is often necessary to make assumptions in numerical and experimental studies that simplify body motions and controls and neglect real phenomena in numerical studies such as friction and mooring lines. Interest in WECs with multiple floating bodies is due to the ability to tune the resonant frequency and increase power capture by adding additional submerged bodies [5]. The resonant frequency refers to the incident wave frequency that captures the most power; it can also be represented in the time domain as resonant period and will be referred to as such in this paper.

The first objective of this paper is to compare the body response and power capture between a one-body floating WEC and a two-body floating WEC that are both constrained to heave-only, via experiments that optimize the power take off damping coefficient. The second

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objective is to analyse the effect of increasing the degrees of freedom of a two-body WEC from heave-only to a moored, six degrees of freedom system. A discussion on friction and mooring effects, as well as uncertainty, is also included.

II. Literature review

Among the many WEC designs, the point absorber is promising due to its easy fabrication and installation and wave-direction independence [6]. A point absorber WEC is designed to be small in comparison to the incident wavelength. The more common design includes a floating body on the surface of the ocean to generate power from motion induced by a wave, but the design can also be fully submerged underwater. This floating body, or float, generates power via a power take-off (PTO) by the relative motion between itself and another object. The float can be attached to a rigid structure (e.g. piling or seafloor), a mooring line, or another floating body. The attachment of two floating bodies refers to a two-body point absorber (or self-reacting point absorber). The second floating body, the spar, is relatively stationary in the water when compared to the motion of the float due to the presence of a heave plate. Spars have most of their volume submerged underwater and are also referred to in the literature as a submerged body or reactionary body. This paper focuses on the effects of increasing the number of bodies and degrees of freedom of a point absorber.

Engstrom et al. (2011) [5] performed a numerical study with mechanical-electrical conversion considerations between a one-body point absorber and a two-body point absorber that showed a 200% increase in capture width ratio at the resonant period when the submerged second body is placed far below the floating body. Their work used a constant PTO damping coefficient throughout the study and limited the motions to vertical only (heave). Bozzi et al. (2013) numerically compared the power capture in Italian seas of a floating buoy WEC and the same buoy with a secondary, deeply submerged spherical body and found that the capture width ratio can improve by 20% by adding a second body and the resonant frequency decreased into a more typical sea state frequency [7]. Their study assumed heave motions only and indicated mooring lines are a necessary future improvement. This concept of adding mass with a second body to decrease the resonant frequency is given by (1)

$$\omega = \sqrt{\frac{\rho \cdot g \cdot A + K}{m + m_a}} \tag{1}$$

where m is the total mass of the WEC, m_a is the total added mass of the bodies at the frequency of the incident wave, ρ is the density of seawater, g is gravity, A is the waterplane area of the bodies at rest, and K is mooring lines stiffness. The added mass from the second body increases inertia in the system and decreases the resonant frequency into more energetic wave frequencies since point absorbers typically have high resonant frequencies at the edge of ocean wave frequencies [7].

Al Shami et al. (2019) [8] found that increasing the number of submerged bodies of a point absorber from two to four increases the average captured power by 26% and reduces the resonant frequency of the device, but only for submerged spheres. They found that submerged cylinders have too much drag and decreased power capture with an increasing number of submerged bodies. Their study also used only one PTO damping coefficient across all tests.

Beatty et al. (2015) [9] performed an experimental and numerical comparison of two self-reacting point absorbers with the same float shape and different reacting submerged body shapes with impedance matching control. They constrained the WECs to heave-only motion and concluded that a reactionary body with a large heave plate has a higher resonant frequency and may be better suited for reactive control schemes to increase power capture. The Reference Model 3 project [10] conducted three experimental tests of a two-body point absorber: 1) with no PTO and locked bodies, 2) with a PTO and constrained to heave motion, and 3) with a PTO in a moored setup. They reported the average power output across different wave periods and PTO damping coefficients, but the confidence in the applied damping was limited due to the nature of the non-linear hydraulic piston used to represent the PTO. While this body of work provides promise for two-body WECs, the research on them is not as rigorous as with one-body WECs, and lacks experimental studies due to the complex nature of increasing the degrees of freedom [11].

III. Methods

A. Power capture

Velocity proportional damping is a control method for WECs where the damping force is caused by mechanical or electrical means in the PTO. The linear damping force in a PTO is calculated by (2)

$$F_{lin} = C_{PTO} \cdot V_{rel} \tag{2}$$

with V_{rel} being the relative velocity between the float and a reference (the spar, either fixed or floating) and C_{PTO} being the PTO damping coefficient. For optimum power absorption in regular waves C_{PTO} depends on the wave period and the hydrodynamics of a WEC. The linear mechanical power is calculated by (3).

$$P_{lin} = F_{lin} \cdot V_{rel} = C_{PTO} \cdot {V_{rel}}^2 \tag{3}$$

The PTO damping coefficient directly affects the body velocities as more damping to the system reduces the relative velocity, hence there is a balance between PTO damping and relative velocity that maximizes power. To find this optimum C_{PTO} value for each period and WEC, an exhaustive search was completed by running a range of regular wave periods and sweeping damping coefficients across each wave period. The damping coefficient that captured the largest average power over the time series was deemed the "optimal" value for each wave period.

In a motor/generator the linear PTO damping coefficient is converted to rotational torque applied in opposition to the measured motion through a sprocket which turns the shaft of the motor/generator. The torque, τ, commanded by the motor/generator is calculated by (4)

$$\tau = C_{PTO} \cdot r^2 \cdot \omega \quad (4)$$

where r is the sprocket radius and ω is the angular velocity of the motor shaft measured by an encoder in the motor. The rotational power, P_{rot}, captured is found by (5).

$$P_{rot} = \tau \cdot \omega \quad (5)$$

Although P_{lin} and P_{rot} are similar, they are not equal due to frictional losses in mechanical connections. The electrical power captured was not reported in the current setup, but future work aims to collect that information. This paper uses P_{rot} as it is closer to the electrical power output of the device.

The data were filtered by removing the first and last 60 seconds of data from the wavemaker wave ramp and ramp down. The first wave of each damping value was also removed due to transient behavior in the motor/generator. The power captured is averaged over 19 waves and normalized by the measured incident wave height squared, as P_{rot}/H^2, where H is the average wave height measured by the wave gages offshore of the WEC. It is good practice to normalize by wave height as there is natural variation in the measured wave height.

B. WEC specifications

This paper performs a case study on the Laboratory Upgrade Point Absorber (LUPA), which is an open-source wave energy converter designed to be a research platform for fundamental work in controls, geometry, mooring, and more. It was designed to be highly modular with configurable float and spar geometries, interchangeable gear ratios and control schemes in the PTO, interchangeable mooring setups, and space for new research ideas. Information about LUPA can be found at [12], [13] including pictures, videos, control codes, numerical models, CAD models, webinars, and more .

Fig. 1 details the major components in LUPA and shows it deployed for testing. The physical specifications are in Table I. The LUPA can transition between three configurations with varying number of bodies and degrees of freedom: 1) one-body heave-only, 2) two-body heave-only, and 3) two-body six degrees of freedom. Fig. 2 shows the three configurations and the degrees of freedom they are allowed.

LUPA has an actively controlled PTO designed to minimize friction and mechanical backlash. It was designed as a 1:25 scale device based on the PacWave WEC test site [14] off the coast of Newport, OR, USA, and for testing in the O.H. Hinsdale Wave Research Laboratory in Corvallis, OR, USA. Bosma et al. [15] provides the

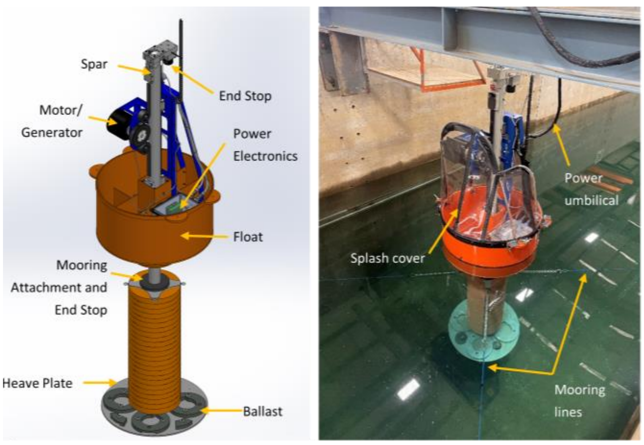

Fig. 1. (Left) Computer rendering of the LUPA in SOLIDWORKS. (Right) LUPA deployed in the Large Wave Flume.

TABLE I
DEVICE SPECIFICATIONS

Parameter	Value	Unit
Float mass	248.72	kg
Float diameter	1.0	m
Float draft	0.44	m
Spar mass	175.54	kg
Spar heave plate diameter	0.90	m
Spar draft	2.05	m
PTO stroke length	0.5	m

TABLE II
TANK SPECIFICATIONS

Parameter	Value	Unit
Length	104	m
Width	3.7	m
Height	4.6	m
Maximum water depth	2.7	m
Wave period range	0.8-12	s

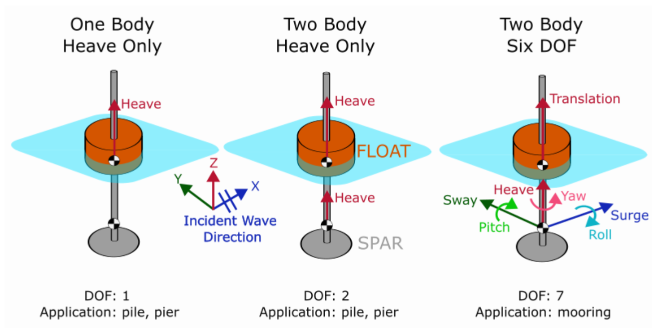

Fig. 2. Configurations of the LUPA WEC. The white and black circles represent the center of mass of each body. The spar is locked in place for the one-body heave-only and cannot move. Both of the two-body configurations have mooring lines as a restoring force to the spar and to provide station keeping.

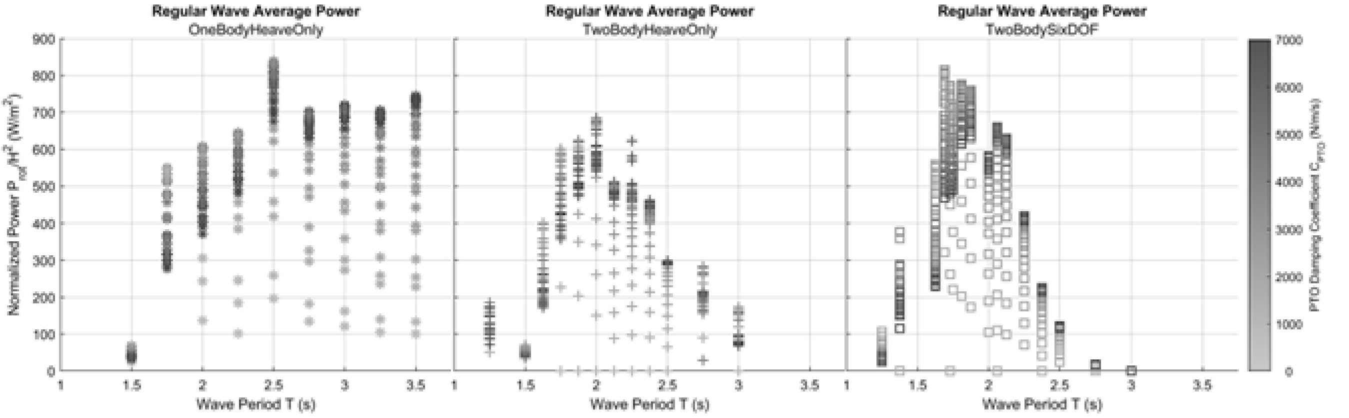

Fig. 3. PTO damping coefficient exhaustive search results. The average power is normalized by the measured wave height squared. Throughout the paper, the plot symbols are consistent for each configuration: stars (*) for one-body heave-only, plus sign (+) for two-body heave-only, and squares (□) for the two-body six degrees of freedom.

engineering details for the design of the LUPA. The motor drive reports torque, the motor encoder reports speed, a draw wire reports relative motion between the spar and float, and an inertial measurement unit in the float reports translational accelerations of the WEC, rotations, and angular velocities. The spar is positively buoyant and pretensioned mooring lines provide the restoring force for the two-body heave-only and two-body six-DOF configurations. There are four mooring lines spaced 90 degrees apart, with an axial stiffness of 963 N/m and an average axial pretension of 284 N.

To ensure a comparable study, each configuration in this study underwent a PTO damping coefficient exhaustive search across a range of regular wave periods from 1.25 to 3 s at model scale (6.25-15 s prototype scale). The wave height was 0.2 m for the one-body heave-only and the two-body heave-only, and 0.15 m for the two-body six-DOF configuration to ensure the device's survivability and mooring lines. For linear wave theory assumptions, the wave height difference in the tests has no effect. In reality, non-linear processes in the WEC may be affected by this change in incoming wave height and therefore all results are normalized by the incoming wave height. In total, 40 PTO damping values were tested from 0 N/m/s up to 7000 N/m/s, changed in real-time via a Speedgoat machine and MATLAB/Simulink Real-Time system. Higher damping values are desired to show the full sweep of damping effects, but mechanical/electrical resonance was present beyond 7000 N/m/s. Future work aims to solve this limit.

C. *Large Wave Flume specifications*

The Large Wave Flume (LWF) at Oregon State University in Corvallis, OR, USA was used for testing. The tank specifications are given in Table II [16]. A string pot reports the displacement of the spar in the two-body heave-only configuration. There are two wave gages offshore of the LUPA and two onshore of the LUPA reporting the wave surface elevation. A 1:12 beach slope is employed to break the waves and reduce reflection effects.

IV. Results

1) *Damping results for each configuration*

The results of each configuration are shown in Fig. 3 with the average rotational power captured on the y-axis normalized by the measured wave height squared. The color bar shows the PTO damping coefficient, C_{PTO}, and the x-axis is the incident regular wave period.

The one-body heave-only reacts very differently to C_{PTO} values for low periods compared to high periods. At 1.5 s, the damping value has nearly no effect as power capture is low regardless. At high periods, such as 3.5 s, the higher C_{PTO} (6,000 N/m/s), the more power captured generally. For wave periods between 2-2.75 s the optimum C_{PTO} value is around 3,500 N/m/s because the high damping values cause such a dramatic decrease in relative velocity. There is no clear resonant period present when a C_{PTO} exhaustive search is employed as the float is a wave follower and continued to oscillate with longer wave periods and higher damping.

The two-body heave-only configuration (Fig. 3 middle plot) has a clear resonant period at 2 s with a C_{PTO} of 2,800 N/m/s. Between 2.125 s and 2.5 s, the higher end of the tested damping values (6,000 N/m/s) is better for power capture, but the opposite is true for periods less than 1.625 s which has an optimal C_{PTO} value around 1,000 N/m/s. These results show that choosing a single PTO damping coefficient can lead to biased results in power capture across periods and incorrect findings for resonant periods.

The rightmost plot in Fig. 3 shows the PTO damping coefficient exhaustive search results for the two-body six degrees of freedom LUPA. The resonant period is 1.81 s with a C_{PTO} of 2400 N/m/s. The periods below the resonant frequency have optimal damping coefficients in the lower range, about 1,400 N/m/s. And power drops off rapidly when the damping coefficient is increased. This is due to the float and spar 'locking' together, causing the relative velocity to decrease. As the damping coefficient goes to infinity, there is more force applied in the PTO and the relative velocity goes to zero. On the contrary, for periods between 2-3 s, the LUPA power capture increases as C_{PTO} increases to 7000 N/m/s. The relative velocity between the

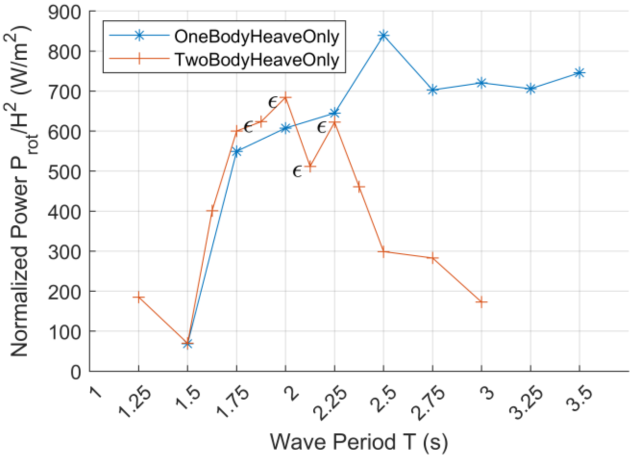

Fig. 4. Normalized average power comparison between one-body heave-only and two-body heave-only. The epsilon value represents conditions that were affected by the motor current limit.

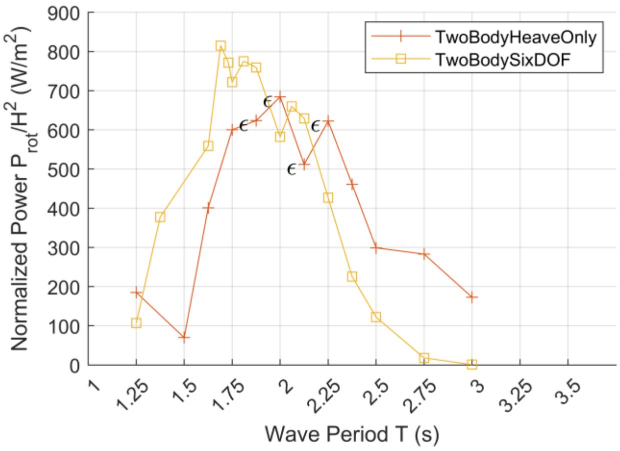

Fig. 5. Normalized average power comparison between two-body heave-only and two-body six-DOF. The epsilon value represents conditions that were affected by the motor current limit.

float and the spar does not decrease as rapidly in higher periods as compared to lower periods.

2) Number of bodies power capture

The optimum PTO damping coefficient was determined for each period from the value that captured the maximum average power. The results for the one-body heave-only and two-body heave-only are in Fig. 4 showing the average power capture at the optimum PTO damping coefficient. There is a current limit on the motor and conditions that hit this limit are indicated with an epsilon (ε) which only affected the two-body heave-only configuration. This limit protects the motor/generator and if the limit was set higher, the power capture may have been greater. Future experiments and numerical work aim to improve this data.

The one-body heave-only and two-body heave-only

Fig. 4. Normalized average power comparison between one-body heave-only and two-body heave-only. The epsilon value represents conditions that were affected by the motor current limit.

behave very similarly for lower wave incident periods between 1.5 s and 2 s. They had similar optimal PTO damping coefficients with the two-body heave-only having slightly greater coefficients at these periods. For periods above the resonant period (2 s) of the two-body heave-only configuration, the power capture reduces significantly as compared to the one-body heave-only. At 3 seconds, the power capture is reduced by 76% from the one-body to two-body configuration. This is due to the decrease in the relative velocity of the two bodies at higher periods caused by the hydrodynamics of the spar with mooring lines, irrespective of the damping coefficient.

3) Degrees of freedom power capture

The power capture comparison between the two-body heave-only WEC to the two-body six-DOF WEC is shown in Fig. 5. The average PTO mechanical power resonant period of the two-body heave-only WEC is near 2 s. Increasing the degrees of freedom of this WEC to a floating, moored 6 DOF WEC caused the resonant period to shift to a lower period, 1.81 s. The LUPA had little to no roll, yaw, or sway movements in the six-DOF configuration; there was considerable pitching at lower periods and significant surging at higher periods.

For periods below the resonant period of a two-body heave-only WEC, the six-DOF configuration has greater power capture. This is likely caused by the ability of the WEC to pitch and capture the heave and surge energy of the incoming wave. Overall, the two-body heave-only configuration does well at predicting power capture for two-body six degrees of freedom WEC. It underpredicts at low periods and overpredicts at high periods, shifting the entire power capture curve to higher periods.

V. DISCUSSION

The influence of the PTO damping coefficient is more complex than a single optimal value representing the maximum power capture. This study showed that using a single PTO damping coefficient to evaluate power or body motions creates bias by favoring either periods below the resonant period with a 'low' damping value or periods above the resonant period with a 'high' damping value.

It is hypothesized that the hydrodynamic added mass of the spar would have increased power at the resonant period without the motor current limit. This would be consistent with the previous literature on additional

Fig. 5. Normalized average power comparison between two-body heave-only and two-body six-DOF. The epsilon value represents conditions that were affected by the motor current limit.

submerged bodies that claims power capture is improved by increasing hydrodynamic added mass. The previous literature, however, fails to make their studies comparable since a single PTO damping coefficient was chosen which produces bias results on one side of the resonant period of the WEC.

The effects of mooring lines and friction are a real and important aspect of analyzing the power capture of a WEC. The two-body heave-only configuration was constrained with High Density Polyethylene (HDPE) linear bearings between the spar and the aluminum skewer spanning the entire height of the Large Wave

Flume. Marine-grade grease was used in this connection to reduce friction, but it was not eliminated. The absence of this friction force in the six-DOF configuration may have also been responsible for the increase of power over most of the incident wave periods when compared to the two-body heave-only configuration.

The PTO belt-pulley system connects the float and spar which inherently has friction in the bearings, but they are also connected through a greased linear ball bearing carriage. Friction in the PTO connection is common for any size WEC that has mechanical to electrical conversions. Both major sources of friction in LUPA are lubricated with fluids which can be modeled as velocity-dependent viscous friction damping. The lubricant fluid properties also change over time and across temperatures, causing more uncertainty in friction effects. Friction effects are captured by this experimental testing and future work on uncertainty in friction would benefit WEC numerical models which traditionally assume friction is negligible.

The mooring lines in this study were taut due to the physical size constraints and safety concerns in the Large Wave Flume. They were necessary to provide a restoring force in heave to the spar due to the small surface piercing area of the spar at the water surface and its inability to return to a neutral buoyancy position on its own. The mooring pretension also helped overcome the friction between the spar and the skewer which otherwise would have caused the spar to settle in inconsistent vertical locations and change the PTO stroke length. Without the mooring lines providing heave restoring force, the two-body heave-only configuration would have been dominated by friction effects; initial trials without the mooring lines caused unpredictable motions of the spar and frequent end-stop collisions resulting in reduced relative velocity and power capture. These findings can help inform numerical studies by highlighting the influences of real phenomena like friction, end stops, and mooring lines.

Comparing the effects of adding bodies and degrees of freedom provides a solid fundamental understanding, but in reality, the deployment type and location of these three WECs may be vastly different. The purpose of a spar in a point absorber is to provide more added mass, but this is mostly in the context of deep water deployments where the sea floor is far away from the surface buoy. The spar provides a relatively stationary object for the float to react against to capture power, while the mooring lines are station keeping and stabilizing the spar. A single body point absorber with only a float might be more suitable connected to a pier, piling, platform, or moored in shallow water where a spar may not be necessary and more power can be captured at higher periods. There are cost-benefit analyses that each designer must make to weigh the power capture of each configuration, the energy available in different deployment locations, and the cost of complexity as it pertains to the number of bodies and degrees of freedom.

VI. Conclusion

This paper investigates the effects of increasing the number of bodies and degrees of freedom of a point absorber WEC. This was done through experimental testing of the Laboratory Upgrade Point Absorber (LUPA) in regular waves. An exhaustive search was performed for the power take-off damping coefficient and average power was analyzed across a range of operational wave periods.

This study finds that using a single PTO damping coefficient causes biased results of body motions and power capture and conducting an exhaustive search allows for fair comparative studies. The addition of a second submerged body to provide more added mass was shown to have similar power capture as the one-body heave-only WEC up to the resonant period of the two-body WEC. For periods above the resonant period, the power capture rapidly decays for the two-body WEC, up to 76% lower power capture than the one-body WEC. This study also finds that a two-body heave-only WEC does well at estimating the power capture for a six degrees of freedom moored two-body WEC. The six degrees of freedom configuration had a slightly lower resonant period, shifting the whole power curve to lower periods.

As indicated throughout the paper, there are many opportunities and challenges for future work. Improving the data acquisition of the power stages in the PTO would allow a comparison between the linear mechanical power, rotational mechanical power, and electrical power captured by LUPA. This dataset would provide a baseline for advanced studies and analyzing effects of friction throughout the PTO. Numerical models of LUPA have already been developed and can be improved upon by tuning the viscous drag and viscous friction coefficients from experimental data. Numerical models of LUPA employing an exhaustive PTO search can also provide information that the motor/generator current limit prevented in experimental testing. Testing in regular waves has its limitations for practical use in real ocean conditions and therefore future work includes analyzing the irregular wave data from LUPA with a similar study.

LUPA will also be used for uncertainty quantification of widely reported WEC performance metrics (capture width, efficiency, etc). Both aleatoric and epistemic uncertainties will be quantified with suggestions for reducing them and providing a standard methodology for doing so. Aleatoric refers to inherent randomness in the system; for WECs, this would be the actual wave height or period of the incident wave in a tank or open water. Epistemic uncertainty is the uncertainty related to missing information; for WECs, this could be the accuracy of a sensor measuring power or velocities, or assuming drag and friction are negligible. The combination of these uncertainties contributes to the uncertainty of performance metrics presented in the literature such as normalized power and capture width.

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