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Numerical Simulation of a Wave-Powered Autonomous Underwater Vehicle Charging System

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Abstract

Wave energy converters (WECs) hold immense potential to provide electrical power for various applications, from grid connections to remote sensors. One possibility within the "Powering the Blue Economy" initiative is generating power for Autonomous Underwater Vehicles (AUVs). This can be achieved either through wave-powered charging stations or by integrating WECs directly into the AUV design. The latter approach was employed in developing the Platypus Prowler WEC, a WEC/AUV design created for the DOE/NOAA Ocean Observing Prize contest. This system features a module that functions as a WEC when the AUV is oriented vertically (bow up), converting mechanical energy into electrical energy via a drivetrain and generator. The WEC design includes three paddle arms that fold down during transit and extend out in charging mode. These arms capture wave energy by oscillating due to variations in net buoyant force and fluid loadings from the wave field. To evaluate and optimize the performance of this system, numerical simulations using WEC-Sim were conducted. WEC-Sim employs the Morison load approach to model the interaction between the WEC and dynamic waves, and the Boundary Element Model (BEM) approach to calculate hydrodynamic response coefficients through a discretized panel mesh. This enables the calculation of added mass, excitation, and radiation forces. Initially, system loading, and power output capabilities were analyzed to optimize PTO damping. Following this, the system's performance was assessed across various wave periods and heights to determine its capture width under different wave conditions. This provides valuable insights into the potential of WECs to effectively harness wave energy for AUV charging.

Keywords: Wave Energy Converter, Autonomous Underwater Vehicle, AUV charging, Numerical Simulation, WEC-Sim, Hydrodynamic Response

1. Introduction

Wave Energy Converters (WECs) harness the potential and kinetic energy available within a wavefield and typically convert it into electrical energy. There are numerous WEC design types currently under development for various applications. These designs can be classified into three main categories [1]:

a. **Overtopping WECs**: These systems collect water above the mean waterline, converting the resulting potential energy into electricity.
b. **Oscillating Water Column WECs**: These WECs use wave motions to force air through bi-directional wind turbines, generating power.
c. **Oscillating Body WECs**: In these systems, waves move all or part of the WEC, and these motions form the basis for power production.

Oscillating body WECs are the primary design type currently being developed. These systems can be designed to function as standalone power plants capable of generating several kilowatts of power from a single WEC [1]. They are also being designed for use within wave energy farms and for "Powering the Blue Economy" applications, which support offshore power needs not connected to the main power grid, often with relatively modest power requirements [2].

The conversion of mechanical power to electrical power within oscillating body WECs can be achieved through various mechanisms, including hydraulics, pneumatics, linear induction, and rotating motors/generators [3]. This paper presents the numerical modeling of an oscillating body WEC using WEC-Sim. It then details the tuning of PTO damping and numerical simulation results focused on the relationship between power production and wave period/height. Finally, conclusions and planned future work are provided.

2. Numerical Simulation Development

The main objective of developing this numerical modeling effort is to accurately simulate the proposed WEC under wave conditions like those expected at its intended deployment site. The freely available software tool WEC-Sim [4], co-developed by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratory, was used in this study. This section presents summaries of the system design and WEC-Sim numerical modeling.

WEC-Sim models the complex interactions between wave dynamics, WEC structures, and power generation systems. The foundational modeling principles employed by WEC-Sim to compute the time-domain behavior of a WEC are centered around the hydrodynamic coefficient matrices created by a Boundary Element Model (BEM), which, for the results in this paper, was Capytaine [6]. These matrices serve as the basis for computing the hydrodynamic forces acting on each rigid body, subsequently enabling the determination of the accelerations for each of these bodies. These coefficients are leveraged to solve Cummins' Equation in six degrees of freedom (6 DOF), which is used to ascertain the WEC's accelerations [4]:

$$m\ddot{x}(t) = f_r(t) + f_{rad}(t) + f_{ect}(t) + f_v(t) + f_{moor}(t)$$

where $\ddot{x}$ represents the translational and rotational accelerations of the system, $f_{rad}(t)$ is the force vector due to wave radiation and added mass, $f_{ect}(t)$ is the wave excitation and diffraction force vector, $f_v(t)$ is the viscous force vector, $f_{moor}(t)$ is the mooring force vector (not used in this study), and $f_r(t)$ is the hydrodynamic restoring force vector. All the forces and $\ddot{x}$ are presented as column vectors with six elements, where the first three relate to linear directions (x, y, z), and the remaining three pertain to rotational axes about (x, y, z).

The rotational Power Take-Off (PTO) system employed in the WEC harnesses the rotational motion of its paddles to generate electrical power from ocean waves. As waves interact with the WEC, the paddles pivot and rotate, transferring mechanical energy to the PTO mechanism. The rotational (PTO) systems were integrated into the WEC model, with each PTO positioned around the circumference of the main hull (Figure 1).


Figure 1: Dual modes of the Platypus Prowler WEC

3. Description

This Autonomous Underwater Vehicle (AUV) has a module just aft of the nose that acts as a WEC when the system is oriented vertically (nose up). To achieve this, three paddles that are folded down along the side of the system during transit that extend outwards when the system is vertical and harvesting power. When vertical, a bladder expands to supply a buoyant force at the outermost portion of each paddle, inducing fluctuating torques and angular velocities on each arm relative to the main AUV body. This mechanical energy is converted to electrical energy using a drivetrain and generator within the energy module. In this current configuration, a gear system is used to transfer mechanical torque in one direction (when a paddle is rising) to the generator and rotate freely when the paddle is falling. Fig. 1 illustrates the dual modes of the Platypus Prowler WEC, including its streamlined transit configuration and its power-harvesting configuration.

4. WEC Design

This WEC is made up of a cylinder with a length of 48 in and a diameter of 8 inches. The pivot point is 2 inches from the capped end, with that cylindrical section having a mass of 32 kg. The center of buoyancy is 24 inches aft from the point where the paddles pivot, and the center of mass is 1 inch aft, ensuring the cylinder floats upright.

The paddle profile is 1 inch thick in the uninflated state. A bladder inflates to a half-sphere with a diameter of 10 inches during the recharge phase, which is the phase that is numerically simulated in this paper. The entire paddle assembly has a mass of 3.1 kg, with the center of mass located 15 inches from the pivot point illustrated in Figure 2.

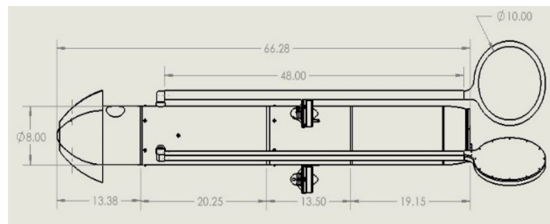

Figure 2: Geometrical Parameters of platypus Prowler WEC

5. Numeric Simulation Development

The geometry of the Wave Energy Converter was designed using SolidWorks. This design incorporates four distinct bodies: one central main hull and three accompanying paddles. The reference point for this geometry is defined at the coordinates [0, 0, 0], which correspond to the center of the main hull and the free water surface. This origin serves as the focal point for the entire structure, ensuring all measurements utilize a common reference point.

Each of the three paddles is created separately and is hinged at the radius of the main hull. They are evenly spaced at angles of 120 degrees, forming a symmetrical and balanced configuration around the main hull.

Capytaine was used to calculate hydrodynamic coefficients for the multiple bodies simultaneously including wave diffraction and wave reflection coefficients. The same coordinate system was used to compute the hydrodynamic coefficients by placing the bodies at the same coordinates as were in SolidWorks. Mesh was created in Capytaine, and boundary element analysis was conducted. The hydrodynamic coefficients were calculated using a mesh with 152,640 elements. The paddles have their centers of mass positioned at calculated coordinates that reflect their respective configurations: (0.4826, 0, 0) m for the first paddle, and (-0.2413, 0.4178, 0) m for second paddle and (-0.2413, -0.418, 0) m for the third. The results were saved in .nc format and then transformed using BEMIO so that they can be read by WEC-Sim.

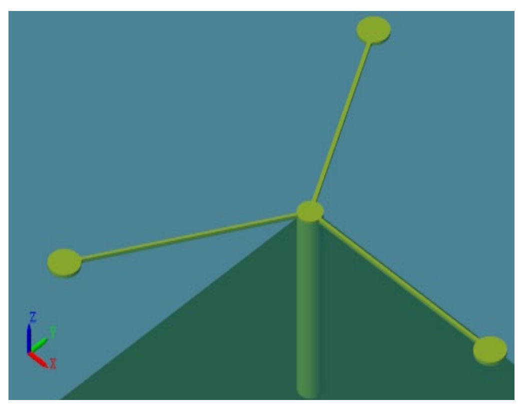

Figure 3: Numerically simulation of platypus Prowler WEC

For the simulations presented in this paper, the hull of the WEC is assumed to be stationary. This simplification is deliberately introduced to isolate the effects of the flap motion on power production. By fixing the hull, it removes the influence of the hull's mass, inertia, and any potential interactions with the waves. This allows us to focus solely on the energy extracted by the power take-off (PTO) system from the rotational motion of the flaps, establishing a clean baseline for evaluating the relationship between wave conditions and power generation independent of the hull properties.

The simulation is designed using the Simulink model file. The simulation parameters are initialized through a simulationClass object, with the simulation mode set to 'normal' and the SimMechanics Explorer enabled. This provides the necessary input for the hydrodynamic interaction within the simulation. The system comprises a central hull and three flaps, each modeled by separate bodyClass objects. The central hull's hydrodynamic data is sourced from 'hydroData/full_body.h5', and its geometry is defined by 'geometry/main1.stl'. The hull is assigned a mass of 32 kg and an inertia tensor of [0.17, 4.05, 4.05] kg.m^2, with an initial displacement set to the origin [0, 0, 0] m. The body is fixed in place by a constraint located at [0, 0, 0] m, which does not allow the main hull to move. Each paddle (Paddles1, 2, and 3) is also initialized with hydrodynamic data from 'hydroData/full_body.h5' but with different geometry files: 'geometry/pp1.stl', 'geometry/pp2.stl', and 'geometry/pp3.stl' respectively. All paddles have a mass of 3.1 kg and an inertia tensor of [0.01, 1.02, 1.03] kg.m^2, with initial displacements set to [0, 0, 0] m.

The simulation includes detailed configurations for the Power Take-Off (PTO) mechanisms, essential for converting mechanical energy from the paddles into electrical energy. Each paddle is equipped with a PTO: PTO 1, associated with Paddle1, has a tunable damping coefficient, located at [0.1016, 0, 0] meters, PTO 2, linked to Paddle2, shares the same damping values, positioned at [-0.0508, 0.0879, 0] meters, PTO 3, corresponding to Paddle3, is similarly configured with the same damping, located at [-0.0508, -0.0879, 0] meters. The PTO coordinates are assigned to position the system along the circumference of the main hull, corresponding to the locations where the paddles are hinged. The torque generated by the PTO system is calculated as the product of the flap's rotational velocity relative to the WEC hull and the PTO damping coefficient. The expression for the PTO torque is given by:

$$\tau = -C_{PTO}\omega$$

where τ is the torque exerted by the PTO (Nm), C_{PTO} is the PTO damping coefficient (N·m·s/rad) and ω is the angular velocity of the flap (rad/s).

6. Results

An iterative process is used to help select an appropriate damping coefficient for produce near maximum power in modest waves assuming a simple damping type PTO is used. To do this, multiple damping coefficients are evaluated, and Figure 4 demonstrates the resulting average power output from the simulated WEC. The WEC is simulated for wave conditions where the wave height is 0.5 meters, and the wave period is 5 seconds. As the damping coefficient increases from 500 to 900 (N.m.s/rad), generated power monotonically increases, from 35 watts to nearly 40 watts. However, as the damping coefficient increases beyond 1000 (N.m.s/rad), the power output decreases, dropping to 36 watts at a damping coefficient of 1400 (N.m.s/rad). This behavior indicates that there is an optimal damping coefficient for this device and operating conditions between 900 and 1000 (N.m.s/rad), which maximizes the energy capture from the waves. Therefore, a damping coefficient of 950 (N.m.s/rad) is used when running the simulations used to produce the results shown in the remainder of this paper.

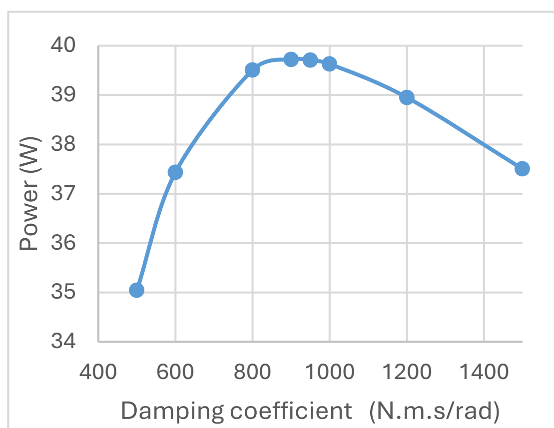

Figure 4: Power output of the WEC vs damping coefficient

To evaluate WEC performance under a range of operating conditions numerical simulations were performed over a range of wave periods and wave heights. Numerical simulations performed during the WEC-sim based analysis of the WEC include wave fields defined using simple sinusoidal waves. The study analyzes wave heights ranging from 0.5 m to 2.0 m, in 0.5 m increments, with corresponding wave periods of 5 to 11 seconds. Figure 5 illustrates the relationship between wave height (in meters) and wave period (in seconds), highlighting the average power output (in watts). The x-axis represents the wave period, ranging from 5 to 12 seconds, while the y-axis depicts wave height, extending from 0.5 to 2.0 meters. The color gradient on the right side indicates power output, with shades transitioning from blue, signifying lower power outputs around 42 W, to red, representing higher outputs that can reach up to 317 W. The visualization reveals a clear trend: for a larger wave height having smaller wave period the average power increases.

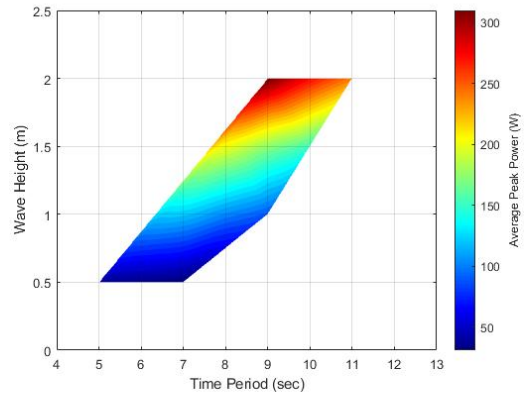

Figure 5. Relationship between wave height and wave Period for Power produced.

Figure 6 shows the efficiency of a Wave Energy Converter (WEC) as a function of varying wave heights and periods. The wave heights range from 0.5 m to 2.0 m, in 0.5 m increments, with corresponding wave periods of 5 to 11 seconds. Efficiency η is calculated using the formula:

$$\eta = \frac{\bar{P}_{mech}}{\bar{P}_{wave} B}$$

where $\bar{P}_{mech}$ is the mean power output of the WEC, $\bar{P}_{wave}$ is the incident wave power per unit width, and B is the width of the WEC. Here, $B = 2.8m$ is calculated as twice the radial distance from the center of the AUV hull to the tip of a paddle. Since the simulations were run using a single sinusoidal wave the mean incident wave power $\bar{P}_{wave}$ is determined by[7]:

$$\bar{P}_{wave} = \frac{\rho g H_s^2 C_g}{16\pi}$$

where H_s is the Significant wave height and C_g is the group velocity. The x-axis represents the wave period, ranging from 5 to 12 seconds, while the y-axis indicates the wave height, spanning from 0.5 to 2.0 meters. The efficiency of the WEC is illustrated through a color gradient on the right side, with blue representing lower efficiency and red indicating higher efficiency. This gradient shows that the efficiency of the WEC decreases with both greater wave heights and longer wave periods. The maximum efficiency is 2.5% for the smallest wave height of 0.5m and a period of 5 sec.

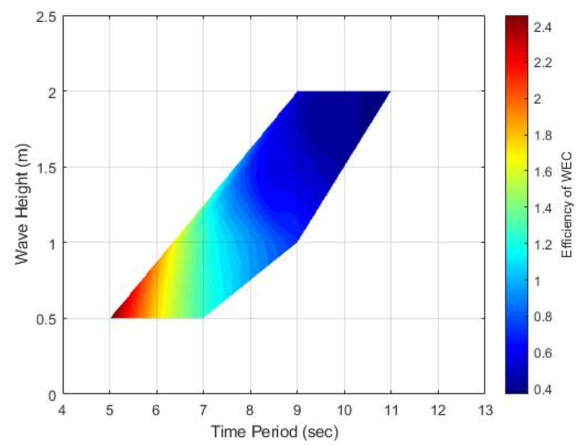

Figure 6. Relationship between wave height and wave Period for WEC Efficiency

7. Conclusion

The Platypus Prowler WEC is a new technology for use in harnessing wave energy to power an Autonomous Underwater Vehicle (AUV). The detailed numerical model was developed in WEC-Sim, with hydrodynamic coefficients calculated in Capytaine using a 152,640-element mesh. After PTO coefficient tuning, mean power production was evaluated for wave heights from 0.5 to 2.0 m and wave periods from 5 to 7 seconds for the case when the main body (hull) of the WEC was held stationary, setting a baseline for comparison where different mass and damping values are compared. For these conditions and system configurations, a maximum time averaged power of 317 Watts was calculated for a wave height of 2.0 m and wave period of 8 seconds and a maximum efficiency of 2.5% was calculated for a wave height of 0.5 meters and period of 5 seconds. These calculations assume that power is produced during both the upward and downward strokes of all three paddles and 100% efficiency when converting this mechanical energy to electrical energy.

Future work includes allowing the main body (hull) to move in all 6-DOF, modifying the PTO models to simulate one-way (upstroke) power production with all three paddles attached via a clutch to a single generator, and evaluating the prototype design in a wider range of wave conditions.

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