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TAGUCHI-BASED SENSITIVITY ANALYSIS OF HYDRODYNAMIC AND POWER TAKE-OFF DESIGN PARAMETERS FOR OSCILLATING SURGE WAVE ENERGY CONVERTERS

Md Riasat Morshed Khan* **and Danesh Tafti**

Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24060

ABSTRACT

Oscillating Surge Wave Energy Converter (OSWEC) devices are currently at a critical juncture in the process of full-scale technology implementation. While their governing hydrodynamic laws and theoretical energy extraction limits are well-defined, their design parameters are yet to be finalized. One key reason is that wave energy converters are highly coupled systems, involving both hydrodynamic and control systems, making it a highly iterative design problem. This is why sensitivity analyses are particularly insightful for both hydrodynamic and control engineers. While similar sensitivity analysis studies exist for Point Absorbers, the hydrodynamic field for OSWECs is significantly different. In our study, we applied the Taguchi method—a design of experiment approach—to explore our design parameters, including device mass, flap geometrical shape, and the damping and stiffness of the Power Take-off (PTO) systems. With the help of the Taguchi method, the full design space of 256 cases was reduced to 16 cases for a particular monochromatic wave condition that represented the whole design array well. The frequency-domain hydrodynamic solver is based on linear potential flow theory using the Boundary Element Method (BEM) solver Capytaine, while the time-domain calculations were performed by WECSim, which solves the Cummins equation. The study concludes that PTO damping has the most significant impact on the mechanical power extraction. This study has the potential to be extended to irregular, panchromatic wave conditions and full-scale OSWEC applications.

KEY WORDS: Oscillating Surge Wave Energy Converters, Design of Experiments, Taguchi Method, Power Take-off system, Sensitivity Analysis, Capytaine, WECSim

1. INTRODUCTION

According to studies, the wave energy resource in the United States alone is 2600 TWh/year [1]. Thus increasing efforts are being made to harness this power. Among Wave Energy Converter (WEC) devices, Oscillating Surge Wave Energy Converter (OSWEC) technology has begun to gain momentum due to its superior power capture ability, even in shallow waters, compared to other available technologies, such as Point Absorbers (PAs) [2]. PAs have been extensively investigated in recent years, leading to established design parameters for devices like LUPA [3], WaveBot [4], and so on. However, PAs are often susceptible to control strategies that require matching the natural frequency of the device, which is not the case for OSWECs. For OSWECs,

Table 1 Parameter Definition

Density (kg/m^3)	Stiffness (N-m/rad)	Damping (N-ms/rad)	Geometry
100	10	10	1
200	100	100	2
300	200	200	3
400	300	300	4

*mdriasatmorshed@vt.edu

it is more crucial to consider the converter holistically, focusing on its physical characteristics, which influence its hydrodynamic properties and control techniques.

In this study, we selected key parameters, including flap shape, flap density, and Power-Takeoff (PTO) stiffness and damping, which essentially functions as a proportional-integral (PI) controller. We employed the Design of Experiments (DoE) method, specifically the Taguchi Method, to reduce the number of experiments needed to evaluate the sensitivity of these parameters on the extraction of mechanical power. The Taguchi DoE concept has previously been applied by to examine point absorbers [5].

We considered a 1/12th scale OSWEC with dimensions of 0.2m x 1.2m x 0.8m in the *x*-, *y*-, and *z*- directions, respectively, with a freeboard of 0.1m. Moreover, the center of rotation is located at (0, 0, -0.57) m. To ensure realistic conditions, we selected a wave case that corresponds to the appropriately scaled conditions of the PacWave South site, where the maximum occurrence wave height is 0.145m, and the wave period is 1.31 seconds. It was suggested that increasing the difference between the top and bottom widths of the flap enhances power extraction [6]. Accordingly, we decreased the bottom and increased the top side of the flap, keeping the area and volume constant, with a step of 0.2m in the *y*- direction. **Fig. 1** represents our design space for the OSWEC shape parameters. The range for both stiffness and damping values is from 10 Nm/rad to 300 Nm/rad, and the density of the flap varies from 100 kg/m³ to 400 kg/m³. Table 1 above represents all the parameters and specifications of the design space.

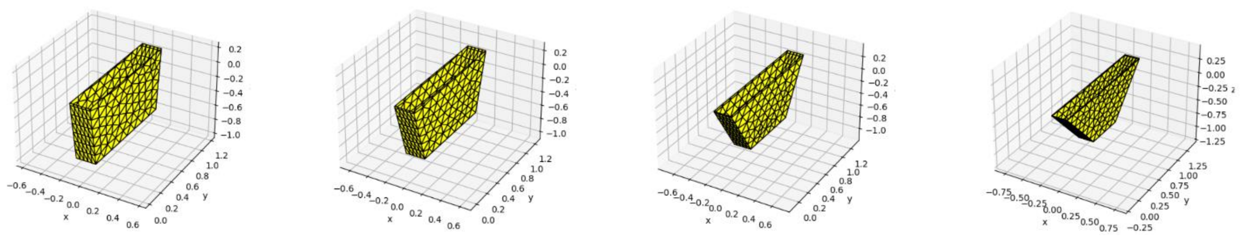

Fig. 1 Concerned Array of Geometry with Varying Top and Bottom Width

2. METHOD

The Taguchi method, a type of design of experiments (DoE) approach from applied statistics, focuses on analyzing key parameters. It reduces the number of experiments required to explore the full design space by creating a smaller design space that accurately represents the full factorial design. In Taguchi terminology, the choices for each parameter are called levels, and in this study, we have four parameters with four levels each. As a result, the total number of experiments amount to 256, with each experiment consisting of a combination of the four options from each parameter.

The Taguchi method emphasizes that each level of every parameter should appear an equal number of times in the representative array of experiments, while minimizing the repetition of parameter-level combinations. This is achieved using the Taguchi Orthogonal Table, a reduced experimental configuration table based on the levels and parameters, that is shown in Table 2. To generate our orthogonal array, we utilized MATLAB code developed by Chixin Xiao [7], based on the work of [8]. Each row in this table represents a combination of all levels and parameters, and each corresponding simulation is conducted to assess the average mechanical power output. To find the sensitivity of power output on any of 4 parameters, a mean power is calculated for each value of the parameter. For example, to obtain the sensitivity of PTO damping on mechanical power extraction, we look for the cases where 10 Nms/rad appear. Then we take the mean of the values which indicate the effect 10 Nms/rad damping value. Similarly, we look for 100 Nms/rad, 200 Nms/rad, and 300 Nms/rad. Finally, we plot them as the PTO Damping Effect as can be seen in Fig. 2. We calculated the effect of density, PTO stiffness, geometrical shape in a similar manner.

Each simulation consists of two phases: a frequency domain solver and a time domain solver. The frequency domain hydrodynamic analysis is carried out using Capytaine, an open-source Python-based Boundary Element Method (BEM) Potential Flow solver. The time domain calculations are then handled by another open-source package called WECSim, a MATLAB-Simulink-based multibody dynamics solver. To transfer the data between the frequency and time domains, we used the BEMIO module, which was developed by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories.

3. RESULTS

The output, along with the input parameters, from all the sixteen experiments are tabulated in Table 2. Fig. 2 presents the trends for each of the input parameters over their respective range.

Table 2 Average Mechanical Power Output for Taguchi Design Space

Cases	Density (kg/m^3)	Stiffness (Nm/rad)	Damping (Nsm/rad)	Geometry	CG (m)	Moment of Inertia (kg-m^2)	Mass (kg)	Power (W)
1	100	10	10	1	-0.30	6.66×2.18×4.74	19.2	-2.76
2	100	100	100	2	-0.28	3.38×1.08×2.43	19.2	-17.93
3	100	200	200	3	-0.26	3.55×1.05×2.62	19.2	-24.47
4	100	300	300	4	-0.23	3.82×1.00×2.94	19.2	-27.04
5	200	10	100	3	-0.26	7.09×2.1×5.25	38.4	-16.83
6	200	100	200	4	-0.23	7.64×2.01×5.89	38.4	-23.78
7	200	200	300	1	-0.30	6.66×2.18×4.74	38.4	-25.66
8	200	300	10	2	-0.28	6.77×2.16×4.86	38.4	-2.84
9	300	10	200	1	-0.30	9.98×3.26×7.1	57.6	-24.02
10	300	100	300	2	-0.28	10.15×3.24×7.30	57.6	-25.34
11	300	200	10	3	-0.26	10.64×3.15×7.87	57.6	-2.54
12	300	300	100	4	-0.23	11.46×3.01×8.83	57.6	-17.17
13	400	10	300	3	-0.26	14.18×4.2×10.50	76.8	-24.83
14	400	100	10	4	-0.23	15.27×4.01×11.78	76.8	-2.25
15	400	200	100	1	-0.30	13.31×4.35×9.47	76.8	-17.16
16	400	300	200	2	-0.28	13.53×4.31×9.73	76.8	-23.62

While running the simulations, we ensured that the rotation angle for the converter remained well within 30 degrees. In all cases, the angular displacement ranged from 7 degrees to 9 degrees, which fulfills the condition for the applicability of linear potential flow theory.

The frequency-domain to time-domain conversion includes checks for the stability and accuracy of the numerical solution in the time-domain. This involves crosschecking whether the excitation impulse response function and the radiation impulse response function tend toward zero within a specific timeframe. Moreover, the normalized radiation damping should tend toward zero within a specific timeframe, and the normalized added mass should tend toward a constant value. All of these checkpoints are ensured before carrying out the time-domain calculation.

From **Fig. 2**, we can clearly see that the effect of PTO stiffness, flap density, and geometrical shape has minimal impact on mechanical power extraction compared to the PTO damping value. While PTO stiffness shows a slight increasing trend and density a decreasing one, the changes are minimal. Extrapolating the trend for damping values, it can be safely assumed that the optimum value could be reached with a slight increase in damping. This kind of trend is typically observed when sweeping across a range of damping values.

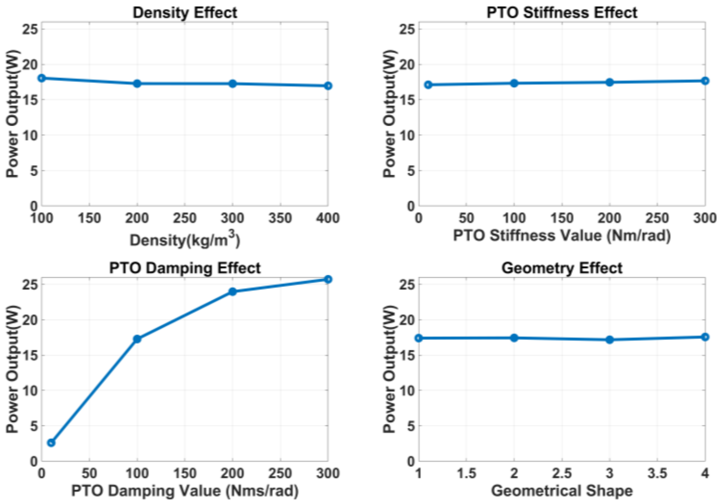

Fig. 2 Effect of the Parameters on Mechanical Power Extraction

4. DISCUSSION

As pointed out in the results, the pitch angle of the converter is relatively small, which fulfills the linearized assumptions, such as linear hydrostatic force and linear Froude-Krylov force, which apply only when the angular amplitude is small. Because if the rotation angle is relatively large, the wetted surface area increases significantly which turns the linearized hydrostatic force into a non-linear one. The Froude-Krylov force also changes significantly which must be recalculated with respect to time.

The impedance matching condition for optimal PTO performance, which is a combination of PTO stiffness and damping values for a specific wave condition and geometry, is a well-established concept among WEC designers [9]. However, our study aims to provide a clearer understanding of the interplay between these parameters and their inertial properties, such as shape and mass. It is important to note that similar studies on point absorbers found PTO stiffness to be the dominant parameter, whereas we found that PTO damping dictates power extraction capacity [5].

The conclusion of Liu et al. [6] where they found that changing the top and bottom width extracted more power did not exactly match with ours. This could be because their study included more parameters such as center of rotation, height of the flap and different wave conditions while also ignoring PTO stiffness.

5. CONCLUSIONS

In our study, we found that the mechanical power extracted from the device was most sensitive to PTO damping, while deviations from a rectangular geometry had little effect. Although PTO stiffness and density showed a general increasing trend, their impact on harnessing mechanical power was not substantial. Moreover, the minimal hydrodynamic benefits of these flap bodies may not justify the increased manufacturing complexity and potential structural compromises, making them less viable for practical applications.

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