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Simulation Based Design of a Small-scale Point Absorber Type Wave Energy Converter with Improved Performance for Sri Lankan Power Generation Applications

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Abstract: As a solution to the world energy crisis, which is becoming more alarming at present than ever before, people are moving towards greener or renewable energy sources. Among various renewable energy sources, ocean wave energy has gained a significant attention for quite some time, leading to the development of many different techniques. However, still most of these designs have not become commercially viable, mainly due to shortcomings in the designs and the low efficiency of Wave Energy Converters (WECs). Accordingly, the aim of this research was to design a point absorber type WEC to extract energy of ocean waves more efficiently. In this research, design of a WEC having a small-scale capacity of 1 kW having a buoy and a flap was optimised to harvest the maximum possible amount of energy from the sea waves, while complying with marine design standards and Sri Lankan local wave conditions. Extensive numerical simulations were done using the open-source software DualSPHysics leading to the selection of the best suitable flap design, which is of a rectangular shape with perpendicular fins to harvest energy at a peak efficiency of 88% and with improved hydrodynamics. The experimental validation of this has to be done in the future to validate the simulation results. With such further improvements, it can be expected that this WEC design will be a useful benchmarking study for the stakeholders who wish to design WECs for Sri Lankan wave energy conditions aiming to generate renewable energy.

Keywords: Efficiency of WEC, Ocean Wave Energy, Renewable Energy, Smoothed Particle Hydrodynamics, Wave Energy Converter

1. Introduction

Global electricity generation is gradually increasing and is expected to reach nearly 30,000 TWh by 2025 and approximately 40,000 TWh by 2040 [1]. Due to the depletion of crude oil based resources, more contribution from renewable energy sources is needed, highlighting the necessity to explore new generation greener power sources like wave energy [1]. Wave energy can be harnessed from the natural motion of ocean waves, which is a significant source of energy that can be captured to generate electricity with an annual global potential of about 30,000 TWh of electricity [2]. WECs are expected to become a more important source of clean, renewable energy [3]. However, due to several techno-commercial challenges, WECs have not still become commercially available. For instance, the harsh marine environment can cause wear and corrosion, reducing WEC lifespan and increasing maintenance costs. Despite these challenges, wave energy holds a great potential as a renewable and abundant power source, especially for coastal areas. With the involvement of advanced numerical modelling and simulation tools suitable design and technological improvements should be undertaken effectively to reduce the overall performance, efficiency and design cost.

In this context, the main objective of this research was to carry out the mechanical design and hydrodynamic optimisation of the key components of a small-scale flap-type oscillating wave surge converter with one degree of freedom (DOF), rated at 1 kW, selected as a practical demonstrator capacity that matches the order of nearshore wave-energy availability and enables scalable development for Sri Lankan coastal applications.

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2. Literature Review

Sea waves, generated by wind blowing across the ocean's surface, possess significantly higher energy density and availability compared to wind itself [4]. This makes them a promising renewable energy resource. However, harvesting wave energy remains a complex challenge, primarily due to the dynamic and harsh marine environment. To design an efficient WEC, it is essential to first understand the fundamental behaviour of sea waves. While wave energy is transmitted in the direction of wave propagation, individual water particles follow an oscillatory circular motion. A large portion of this energy is lost after the wave breaks, due to factors such as surface tension, turbulence, and viscous forces [5]. Therefore, capturing wave energy before the wave breaks is critical to maximizing efficiency [5].

Beyond these natural losses, additional energy dissipation occurs within the WEC system itself due to viscous drag, mechanical friction, pretension in structural elements, and generator inefficiencies [6]. These internal losses further complicate the challenge of effective energy conversion.

To address these challenges, various types of WECs have been developed that aim to convert either the potential or kinetic energy of sea waves into usable electrical energy. These include oscillating water columns (OWCs), point absorbers, overtopping devices (OTDs), and oscillating wave surge converters (OWSCs) [7]. Depending on the water depth at the deployment site, WECs can be classified as onshore, nearshore (depth < 20 m), or offshore (depth > 20 m) systems [8].

Despite considerable innovation, many WEC designs have experienced limited success due to high costs, technical limitations, or reliability issues, where reliability refers to the ability of a device to operate continuously in the sea without frequent breakdowns or damage. For example, the Pelamis WEC was discontinued due to high installation and maintenance costs [9], [10], [11]. The OSPREY device suffered structural damage during transport and deployment. Similarly, Tapchan, Kvaerner Brug, and Oceanlinx faced failures under storm conditions, while CETO6 and Anaconda encountered various technical obstacles [9], [10], [11]. Overall, the operational efficiency of existing WECs still ranges widely from as low as 3% up to 50% in ideal conditions [12].

Among the available designs, oscillating body-type converters have demonstrated relatively higher efficiency, owing to their compact interaction area with waves. In contrast, overtopping devices with larger surface widths offer more consistent performance regardless of wave intensity. Oscillating water columns and body-based systems show improved efficiency with stronger wave environments. However, performance metrics from simulations or lab-scale models often overestimate real-world outcomes due to unmodeled losses [5].

A key technical problem for both oscillating body and water column systems is the conversion of low-velocity bidirectional motion into unidirectional rotational motion for power extraction. Oscillating water columns typically use air turbines, whereas oscillating body systems may utilize hydraulic drives, mechanical systems, gas accumulators, or direct drive linear generators as shown in Figure 1. Among the available Power Take Off (PTO) systems, direct drive linear generators offer the highest efficiency (~95%), followed by mechanical drives (90%), water systems (85%), hydraulic (65%), and air turbines (55%) [5]. Despite this, mechanical drives are often preferred due to their practical balance of efficiency, reliability, and integration ease [5].

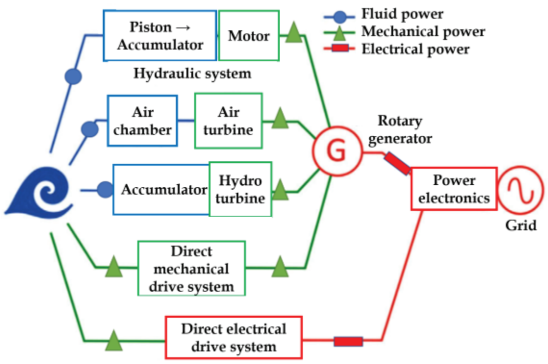


Figure 1- Power take-off systems for WECs [5]

The efficiency of different WEC types varies significantly. Oscillating water column systems typically achieve 20% to 45%, overtopping devices range from 4% to 23%, while bottom-fixed oscillating flap systems offer the highest efficiency, reaching 25% to 65% [13]. These figures indicate that bottom-fixed oscillating flap-type point absorbers are among the most efficient WEC designs currently available. However, despite their promising performance, the overall energy conversion efficiency remains low due to the presence of multiple stages of energy transformation, each introducing its own losses. The primary bottleneck lies in the initial conversion of wave energy into mechanical energy [11]. In contrast, the PTO and electrical energy conversion stages have high efficiencies of around 80 to 85% [11]. To address this gap, it is essential to enhance the hydrodynamic performance of WECs at the early energy capture stage. This should be supported by the optimisation of mechanical components, power electronics, and control systems, tailored to the specific wave conditions at the deployment site [6].

3. Methodology

Design of the WEC was started by doing a background study on the types of WECs available and their efficiencies, hydrodynamic performance, and maintainability. Then, key design specifications were developed, followed by conceptual design and detail design. The following sections present key information on each of these stages.

3.1. Key Design Specifications Involved in the Design Process

Table 1 presents the key design specifications that guided the conceptual and detail design phases of the proposed WEC system. These specifications were selected based on performance, site conditions, and operational requirements to ensure optimal efficiency and practical feasibility. A 1 kW rated capacity was adopted because Sri Lanka's nearshore wave climate can support small-scale energy capture, while larger-capacity devices would demand substantially higher structural strength, fabrication capability, and more complex seabed fixing and installation logistics that are difficult and costly under local mechanical fabrication and deployment constraints [14].

3.2. Conceptual Design

In determining the most suitable concept for the WEC, seven different conceptual designs which are having higher efficiency and easier maintainability were found based on a functional analysis. Out of the generated concepts, a weighted decision matrix was used to select the most suitable design. Based on the criteria of ease of operation and maintenance, durability, energy efficiency, hydrodynamic performance, ease of fabrication and transportability, fabrication cost, environmental impact, and ergonomics, selected the "oscillating body flap type WEC with 1 DOF and with structure fixed to seabed". This selected best conceptual design is shown in Figure 2. The device is fixed to the seabed to provide stability against wave-induced loads. A flywheel is incorporated to smooth the fluctuating mechanical input from the waves by temporarily storing kinetic energy during high-energy periods and releasing it during low-energy periods, thereby ensuring a stable and continuous power output. The generated electricity is transmitted to the shore via subsea cables for end use.

Table 1- Key design specifications

Specification	Description
Power output capacity	1 kW
WEC type	Bottom-fixed oscillating body flap type with 1 DOF
Wave condition	Average wave height: 0.36 m; Wave period: 12 s (Sri Lankan coastal data)
PTO	Bevel gear drive + step-up gear system + flywheel for stable output

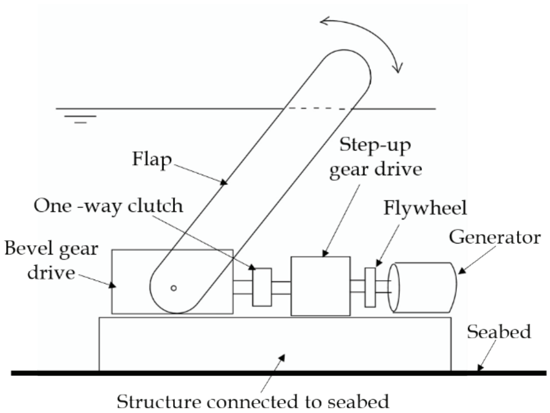


Figure 2- Conceptual design of the 1 DOF oscillating body flap type WEC with structure fixed to seabed

3.3. Fundamental Formulations Used in WEC Designing

The wave energy comprises two forms: kinetic energy and potential energy [15]. In the deep sea, where waves are less disturbed and experience minimal breakage, wave energy is primarily potential energy. In shallow seas, waves are more disturbed and break due to obstacles, resulting in a mix of both kinetic and potential energy [15]. The efficiency or the capture width ratio (η) of a WEC is given by the Equation …(**1**), where 'P_{abs}' is the power absorbed by the WEC, 'P_w' is the power transported by wave per meter of wave front and 'B' is the width of the wave [5].

$$\eta = \frac{P_{abs}}{P_w B} \qquad \ldots(1)$$

The mechanical energy (E_m) associated with a surface wave can be expressed as the sum of instantaneous potential energy ($E_{p(t)}$) and kinetic energy ($E_{k(t)}$) components [13]. For a loss-free propagating wave, the mean values of these two components are equal, and the total wave energy for a sinusoidal wave can be estimated using Equation …(**2**) [13].

$$E_k(t) = E_p(t) = \frac{E_m}{2}$$

$$= \frac{P_{abs}}{P_w B} \qquad \ldots(2)$$

When the depth of the water is considered infinite, the speed of the energy propagation (V_g) can be given by the Equation …(**3**), where 'g' is the gravity and 'T' is the period of sinusoidal wave [13].

$$V_g(T) = \frac{gT}{4\pi} \qquad \ldots(3)$$

Therefore, the power per meter of a sinusoidal wave (P_w) can be given as in Equation …(**4**), where 'ρ_w' is the density of water and 'H' is the height from the crest to trough of the wave [13].

$$P_w = E_m V_g = \frac{\rho_w g^2 H^2 T}{32\pi}$$

$$= 980 H^2 T \ (W/m) \qquad \ldots(4)$$

When the spectral nature of ocean swell is considered, sea waves are recognized to be more complex than simple unidirectional and monochromatic waves, as they comprise a range of frequencies; in this case, 'H_s' represents the significant wave height and 'T_e' is the energy period. Then the power per unit length of wave is given by the Equation …(**5**) [13], [16].

$$P_w = \frac{\rho_w g^2 {H_s}^2 T_e}{64\pi}$$

$$\approx 490 {H_s}^2 T_e \left(\frac{W}{m}\right) \qquad \ldots(5)$$

4. Results of Numerical Modelling and Simulation Setup

4.1. Hydrodynamic Performance Optimisation Using Numerical Modelling and Simulation

To enhance the overall efficiency, improving shapes and sizes of components of a WEC which interacts with the sea water under different wave conditions is critical. For such hydrodynamic performance optimisations, various numerical modelling tools and techniques can be applied such as the Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES), and meshfree methods such as the Smoothed Particle Hydrodynamics (SPH), and Reynolds-Averaged Navier-Stokes Equation (RANSE) [17]. In this work, SPH was chosen as the modelling method and the state of the art SPH-based open-source hydrodynamic modelling software DualSPHysics was used for the simulations, mainly considering the higher capabilities of modelling sea waves and interactions with oscillating bodies to predict forces and power output [17], [18].

Accordingly, as presented in Figure 3, five different flap designs were used in the study where the flap design 01 was a basic rectangular bottom-hinged flap, used as the reference. The flap design 02 has perpendicular horizontal fins on wave-contacting surfaces aimed to increase the surface area in contact with the wave. The flap design 03 has downward-angled fins, the flap design 04 has two crossed rows of perpendicular fins on the wave-contacting surfaces, and the flap design 05 has perpendicular horizontal fins along with extended bordering to further increase interaction with wave energy.

In this process, the wave tank geometry and the flaps were first modelled using 3-D modelling software: SOLIDWORKS and were later imported to the DualSPHysics software, which is an open source SPH-based software dedicated to hydrodynamic studies [18]. Accordingly, the flaps were set to interact with waves generated in a wave tank as shown in Figure 4, to identify the best flap design with the highest hydrodynamic performance and energy absorption efficiency.

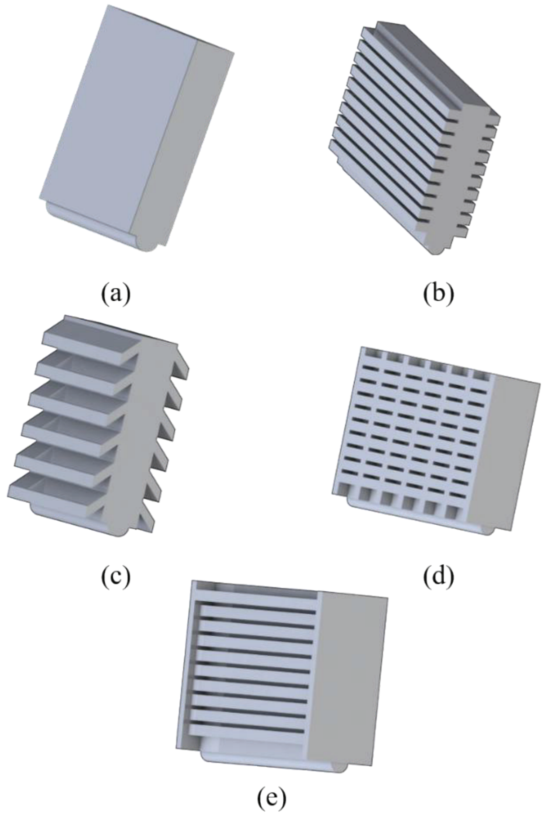


Figure 3- Flap designs: (a) Flap design 01- rectangular flap design, (b) Flap design 02- rectangular flap with perpendicular horizontal fins design, (c) Flap design 03- rectangular flap with downward angled fins design, (d) Flap design 04- rectangular flap with crossed fins design, (e) Flap design 05- rectangular flap with horizontal and bordering fins design

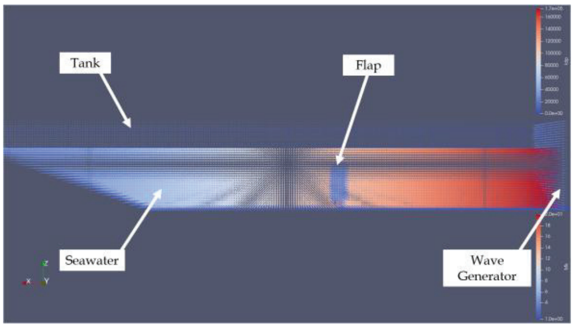


Figure 4- Arrangement of the flaps in the wave tank modelled using the DualSPHysics software

To reduce the computational time while maintaining acceptable prediction accuracy, the flap width was limited to 1 m, and the SPH particle spacing (numerical gap between water particles) in the wave tank was set to 0.05 m. The choice of a 1 m flap width is consistent with the Sri Lankan nearshore wave climate; for the average Galle sea state (wave height ≈ 0.36 m and period ≈ 12 s), the theoretical incident wave power is approximately 1.52 kW per metre of wave crest, which is comparable to the selected 1 kW device scale. Therefore, all flap designs were evaluated using the same 1 m width to allow a consistent comparison under identical geometry and boundary conditions. For the comparative simulations, regular waves with an amplitude of 0.15 m and a period of 2 s were generated as a scaled representation of low-energy wave scenarios that can occur during calmer periods along the Galle coast [14]. Table 4 summarises the critical parameters used in setting up the model. Accordingly, the performance of these flap designs were studied under the same wave conditions with identical height and wave period and the results are presented in Figure 5 and Figure 6.

4.2. Simulation Results Analysis for the Selection of the Best Flap Design

The simulation was performed using the DualSPHysics software, which was selected due to its considerable accuracy and calculation time. To determine the best flap design for the WEC, five different flap designs were simulated under the same wave condition using a wave with 0.15 m height and a period of 2 seconds which is shown in Table 2. The first design was inspired by an already available flap design from the oyster WEC, which was simulated using a low height and lower period wave condition to reduce the computational time. The second design was an improvement on the first design, with perpendicular fins added to the flap's wave-contacting surfaces. The perpendicular fins were angled downward toward the seabed in the third design. The fourth design included two crossed rows of perpendicular fins, and in the fifth design, horizontal and bordering fins were added to the flap.

Figure 5 and Figure 6 present the wave-induced horizontal force and the corresponding flap velocity for all five designs under the same regular wave input. The responses are periodic and comparable in phase, confirming that differences in absorbed power arise mainly from the flap-surface modifications rather than changes in the imposed wave condition. In particular, flap design 02 consistently exhibits the highest force and velocity peaks, which explains its superior absorbed power and efficiency reported in Table 3. The peak energy captured by each design was measured and compared with the peak efficiency values reported in the literature for the conventional rectangular flap design. The results confirmed that the peak efficiency of the rectangular flap design (design 01) was consistent with the literature review findings. According to the results, the rectangular flap with perpendicular fin design (design 02) had the highest efficiency of around 88% under the uniform wave conditions (ideal conditions), as shown in Table 2. This flap design 02 was found to be the best flap design for the wave energy converter according to the results mentioned in the Table 3.

Table 2- Parameters used for the DualSPHysics simulation

Data	Value
H (Wave height)	0.15 m
T (Wave period)	2 sec
Power Available in the Wave under these conditions	44.1 W

Table 3- Calculation of power extracted and efficiency by different flap designs

No.	Type of Flap	Peak Force (N)	Peak Velocity (m/s)	Absorbed Power (W)	Efficiency of Extraction
1	Rectangular Flap	2.33E+02	1.11E-01	25.86	59%
2	Rectangular Flap with Perpendicular Fins	3.27E+02	1.19E-01	38.91	88%
3	Rectangular Flap with Downward Angled Fins	2.94E+02	1.12E-01	32.93	75%
4	Rectangular Flap with Crossed Fins	3.03E+02	1.16E-01	35.15	80%
5	Rectangular Flap with Horizontal and Bordering Fins	3.05E+02	1.12E-01	34.16	77%

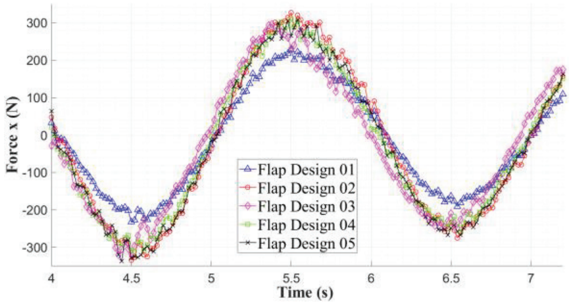


Figure 5- Force vs time for different flap designs

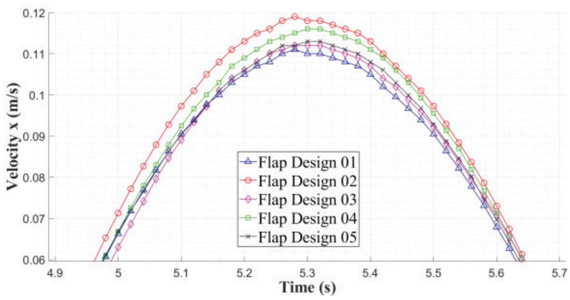


Figure 6- Velocity vs time for different flap designs

4.3. Estimation of the Incident Power of the Waves Interacting with the WEC

In order for the wave energy converter (WEC) to have a high plant factor throughout its operational life, there should be 1 kW of power available at the end of the generator after the final conversion of energy. Therefore, to determine the power that the incident wave should possess to produce a 1 kW output at the WEC as per Figure 7, the efficiency values of each energy conversion process should be considered. Accordingly, the efficiency values of the required generator and the gear mechanism were found to be in the range of 85% through a market research [19]. The chosen flap design (design 02) was found to have an efficiency of around 88% through SPH simulation. Based on these values, it was calculated that 1.48 kW of energy is required in the incident wave to generate 1 kW of power out of the WEC, by accounting the combined losses.

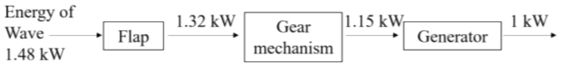


Figure 7- Energy required at the flap by the incident wave

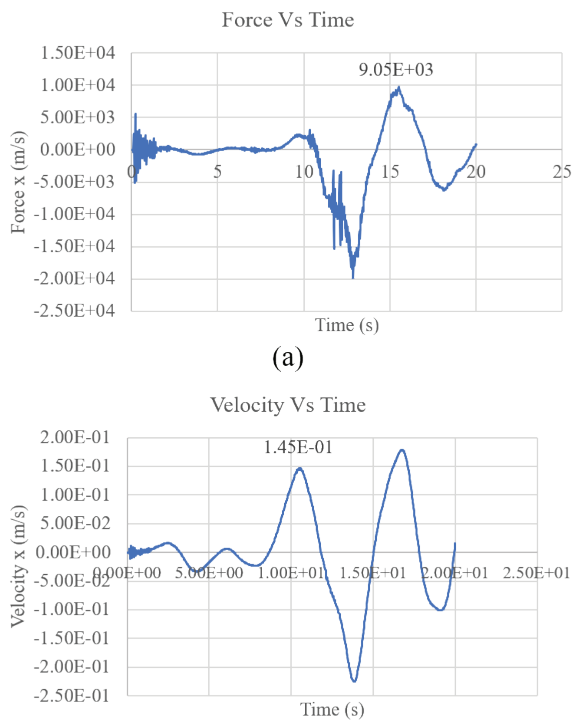
4.4. Initial Calculation to Select Suitable Location for the Deployment

A suitable location for deploying the designed wave energy converter (WEC) was selected based on typical wave conditions in the Sri Lankan coastal region near Galle. The site has an average wave height of 0.36 m and a wave period of 12 seconds [14], which corresponds to an incident wave energy of approximately 1.5 kW. To evaluate the performance of the most efficient flap configuration (design 02: rectangular flap with perpendicular fins), a numerical simulation was conducted using DualSPHysics software under these real wave conditions. The simulation results, presented in Figure 8 and Table 4, show that the selected flap design could extract approximately 1.31 kW of energy from the wave, indicating high efficiency and suitability for deployment at the selected coastal site.

Table 4- Simulated results and calculated data under actual wave condition in WEC deployment

Data	Value
H (Wave height)	0.36 m
T (Wave period)	12 sec
Force at the centre of gravity of flap	9050 N
Torque at the shaft of flap	3801 Nm
Velocity of the flap at centre of gravity	0.145 m/s
Angular velocity of the shaft of flap from simulation	0.345 rad/s
Power available in the wave	1.52 kW
Extracted power of flap design 02	1.31 kW

After simulating the wave conditions and the performance of the chosen flap design, it was found that, under the simulated wave conditions, the force acting at the center of gravity of the flap reached 9050 N, resulting in a torque of 3801 Nm at the flap's shaft. The corresponding angular velocity at the shaft was calculated to be 0.345 rad/s. This torque and angular speed combination delivered an input power of approximately 1.31 kW to the step-up gear drive. These results confirm that the generator can operate safely and efficiently, maintaining the required rotational speed and torque throughout the full wave cycle, including peak conditions. Therefore, the analysis validates the WEC's performance at the selected location and supports its feasibility for practical deployment to meet local renewable energy demands.



(a)

(b)

Figure 8- Simulation data for flap design 02 under real wave conditions of deployment area: (a) Force Vs time plot, (b) Velocity Vs time plot

5. Mechanical Design of the Key Components of the WEC

5.1. Solid Model of the WEC

The solid model of the wave energy converter, shown in Figure 9, provides a detailed isometric view, illustrating the arrangement and interaction of components such as the flap, generator, bevel gear drive, step-up gear train, shaft couplings, bearings, and oil seals. Figure 10 highlights the bevel gear drive designed to convert the oscillatory motion of the flap into unidirectional rotary motion using one-way bearings and bevel gears.

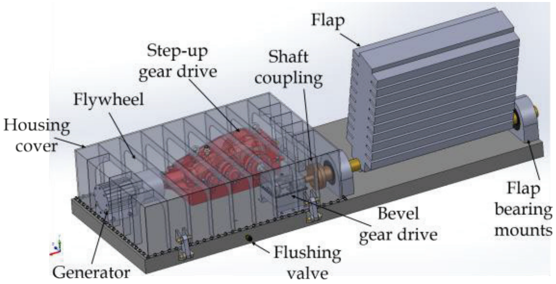


Figure 9- Isometric view of the wave energy converter's solid model

5.2. Bevel Gear Drive

In the oscillating flap type wave energy converter (WEC), energy is harnessed by capturing the oscillatory motion of water particles through the flap's oscillation in response to incoming waves. Directly translating this motion into electrical energy is impractical. Therefore, the system converts the oscillatory motion into unidirectional rotary motion using a specially engineered bevel gear drive with one-way clutch bearings, as shown in Figure 9 and Figure 10.

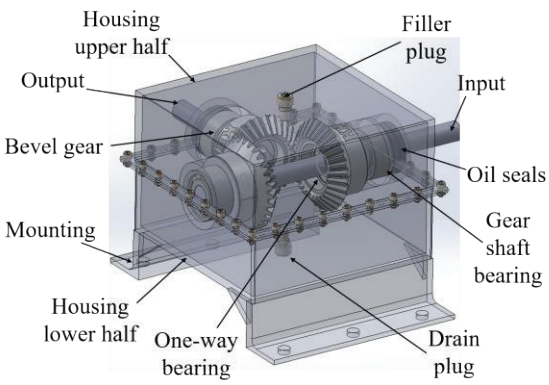


Figure 10- Designed bevel gear drive to achieve one directional rotation

5.3. Step-up Gear Drive

In the wave energy converter (WEC) system, the bevel gear drive alone cannot operate the generator effectively because the flap's oscillatory motion is approximately 2.5 rpm, while the generator requires around 500 rpm for efficient electricity generation. To bridge this gap, a step-up gear drive with a gear ratio of 1:200, shown in Figure 10, has been integrated into the system. This gear drive increases the rotational speed to the necessary levels, ensuring optimal and consistent generator operation.

5.4. Flywheel

In the wave energy converter (WEC) system, the oscillatory motion of the flaps is successfully converted into single-direction rotary motion, reaching the required 500 rpm. However, at the extreme points of the flap's motion, the velocity drops to zero, causing fluctuations in the generator's speed and output current. To address this, a flywheel, shown in Figure 9, is incorporated into the system. The flywheel stores excess energy during high-velocity periods and releases it when the flap's motion decelerates, ensuring smoother and more stable generator operation and minimizing fluctuations in speed and electrical output.

5.5. Housing Cover of the WEC

In the WEC, a critical challenge was the increased drag forces on the step-up gear drive shaft when its rotation speed reaches approximately 500 rpm due to the direct contact with seawater. To address this, all WEC components were enclosed within a housing as shown in Figure 11, which protects them from direct seawater contact and reduces drag forces. The housing includes a drain plug with a one-way valve and a top plug with another one-way valve to remove any trapped water. These features ensure the WEC components' durability and functionality. During maintenance, the housing cover's removal can be challenging due to ocean wave motion. To ease this, as shown in Figure 11, mounting hinges were incorporated into the cover, allowing it to be moved like a door when disengaged from the securing bolts, facilitating easy access to internal components and efficient reattachment post-maintenance.

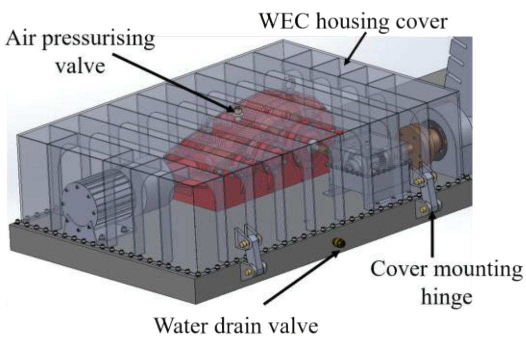


Figure 11- Housing cover mounting hinges

6. Conclusion

This study focused on addressing the least efficient stage in wave energy conversion, which is the transformation of wave energy into absorbed mechanical energy and has been identified as a critical bottleneck in conventional WEC systems [6]. To overcome this, a 1 kW bottom-fixed, oscillating flap-type WEC with perpendicular fins was designed and optimized to enhance hydrodynamic energy capture.

Using DualSPHysics simulations, the selected flap design demonstrated an energy extraction of approximately 1.31 kW under average wave conditions representative of Sri Lanka's southern coastline. These results highlight a significant improvement over traditional configurations and confirm that the device can meet its target output when paired with appropriately selected power take-off components, including a step-up gear and generator.

The project successfully achieved its primary research objective of enhancing WEC efficiency through structural and hydrodynamic optimization. The proposed design offers a promising solution for small-scale wave energy harvesting in coastal regions and contributes to the broader goal of promoting clean, renewable energy adoption.

Future work will focus on experimental validation and practical deployment. This includes mechanical testing of fasteners under cyclic loading, designing a stable seabed anchoring system, and fabricating a physical prototype for wave tank testing. Upon successful validation, the WEC will be deployed in real sea conditions for performance assessment and iterative improvement. These steps are essential to bridging the gap between simulation and real-world application, ultimately enabling reliable and efficient wave energy extraction for practical use.

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