Sustainable Energy Harvesting Mechanism for an Unmanned Underwater Vehicle

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Abstract. Increased demand for clean energy solutions along the coast led to this research work, which will attempt to design a small wave energy conversion system to produce electricity from ocean surface motion. Literature on wave behavior, marine energy systems, and the coastal conditions in Tamil Nadu was reviewed initially to determine primary design considerations. On this basis, three wing configurations were designed to transform wave-induced motion into rotational energy. These configurations were analyzed using static structural analysis in ANSYS, considering stress distribution and deformations due to wave and hydrostatic pressure. The most efficient design was incorporated into a mechanical setup that transforms wave energy into rotary motion and then into electrical energy. To project real-world performance, the entire system was simulated and modelled in MATLAB Simulink so that voltage and current output can be predicted based on real ocean wave conditions. The simulation confirmed that the chosen design is mechanically sound and capable of generating detectable electric output, proving the viability of micro-scale wave energy harvesting for coastal applications.

1 Introduction

Wave energy is a very promising renewable energy source, especially in coastal areas where wave action is steady and plentiful. Much research over the last two decades has gone into the development of technologies capable of converting this energy into usable forms. Equipment like point absorbers, oscillating water columns, and overtopping converters has been widely investigated. But most of these systems are either too large in scale, too costly to deploy, or too mechanically sophisticated to be practicable for small-scale or local applications. Over the last few years, however, there has been a turn toward smaller, modular energy harvesters that are capable of operation in lower-energy wave conditions normally encountered along Tamil Nadu-style coasts. Simulation software like ANSYS and Simulink has also simplified the assessment of structural and energy efficiency in a virtual environment, prior to development in the physical realm. This research investigates one such modular design involving a wing-based system intended for the efficient utilization of surface wave motion and the generation of usable electrical energy.

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By bringing mechanical innovation to the table and simulation-led design, the research work hopes to be part of the expanding niche of micro-scale marine energy solutions.

Although there are many wave energy technologies, they are usually designed for large offshore installations and are unsuitable for areas with moderate wave activity, such as Tamil Nadu. Current devices either need deep water, high wave intensity, or advanced anchoring systems, which are not practical for local or near-shore installation. In addition, very few designs are scalable for small-scale energy applications, e.g., powering sensors, navigation buoys, or coastal monitoring systems. Under these conditions, the solution has to be low cost, low mass, and robust—one that performs well under benign or moderate ocean states. The advancements in this area notwithstanding, there is a lack of miniature energy harvesting devices that are easy to produce, structurally stable, and optimized for dynamic ocean surface parameters. For this reason, there is a demand for an appliance that can satisfy these conditions without sacrificing the generation of a quantifiable and reliable electrical output. This research work fills that void by examining the efficiency of various wing geometries optimized specifically for harnessing wave motion as energy and assessing their viability through simulation and system modeling.

To overcome the shortcomings of current wave energy devices in near-shore, moderate-wave conditions, and this study suggests a compact energy harvesting system using an oscillating wing mechanism. Three different wing designs were envisioned to engage with surface waves and create rotational motion at their root, where they are mechanically anchored. This rotational energy is subsequently converted into electrical energy using a mechanical linkage attached to a small generator. To determine the optimal configuration, structural analysis with ANSYS was done to analyse stress and deformation under wave and hydrostatic pressure environments. This optimal-performing wing configuration was then integrated into a full system model, which was simulated in MATLAB Simulink to predict electrical output in voltage and current. The originality of this work is the integration of structural optimization, mechanical-to-electrical energy conversion, and system-level simulation, all specifically for low-energy, near-shore environments. In contrast to conventional large-scale converters, this is lightweight, modular, and simpler to prototype using existing prototyping facilities. The findings indicate that the system is structurally feasible as well as capable of generating usable electrical power in a coastal setting, and thus it is a candidate for future marine energy uses.

2 Review of literature

A literature review is a critical appraisal of the previous work published in the literature about the topic of the investigation. Literature reviews are secondary sources and do not report new or original experimental work. The worldwide requirement for renewable energy has boosted the interest in wave energy as a steady and persistent source, particularly for island and coastal communities. Although large wave energy converters (WECs) have been well researched, their deployment in moderate wave climates is still not prevalent because of cost, scalability, and mechanical complexity concerns. This review discusses recent studies aiming at compact, structurally efficient, and effective wave energy devices, especially using wing-based mechanisms for motion-energy conversion. Structural analysis, hydrodynamic behavior, simulation techniques, and field adaptability have been reviewed for 15 published journal articles dated between 2023 and 2024.

2.1 Structural and mechanical design considerations

Several studies have envisioned novel wave energy harvester structures based on mechanical or biological concepts. Yang et al. (2024) conceived a jellyfish-inspired TENG that exhibited improved energy yield under wave excitation, indicating the promise of biomimicry in the realm of fluid-structure interaction [1]. Zhang et al. (2024) also investigated multi-dimensional vibration control using integrated decoupled power take-offs for floating platforms [2], shedding light on how structure decoupling enhances efficiency and resistance to fatigue issues of great significance for wing-based converters.

Mechanical integrity is at the heart of WEC design, and structural analysis through finite element analysis (FEA) has become increasingly important. For instance, Zhao et al. (2024) provided a hydrodynamic and mechanical analysis of an oscillating component platform, which emphasized the significance of moment transfer and distributed load modeling [3]. In our application, wing structures fixed to floating bodies through connecting rods are under sophisticated loads such as torque, shear, and hydrostatic pressure. In addition to structural decoupling strategies, mechanical modulation techniques have also been explored to enhance energy capture efficiency in marine environments. Zou et al. (2024) demonstrated that mechanical modulation-based wave energy harvesters can effectively regulate motion transmission and improve energy extraction stability for self-powered monitoring systems [4].

2.2 Hydrodynamic behavior and flow interaction

It is necessary to know how the ocean engages with energy-harvesting surfaces to achieve optimum power output while maintaining structural integrity. Wei et al. (2024) investigated heave-hinge wave energy converters in different sea conditions and offered effective modeling methods for pressure distribution and dynamic loading [5]. Similarly, Sun et al. (2024) presented a hybrid pendular-translational nanogenerator that is tailored for water wave motion, where the importance of integrated motion modes for energy absorption was highlighted [6].

These studies are in accordance with our simulation-based methodology of testing various wing configurations, under hydrodynamic loading conditions such as slamming forces and changing wave heights, modeled in ANSYS and subsequently validated in Simulink. Zhao et al.'s (2024) work on omnidirectional pendulum harvesters [7] also emphasizes the benefit of capturing motion in more than one direction, adding weight to the utility of flexible, multi-axial wing designs. Furthermore, hybrid environmental loading conditions have been shown to influence the dynamic response of marine energy devices. Shi et al. (2024) investigated coupled wind–wave energy converters and highlighted the role of buoy mass tuning and dynamic response optimization in stabilizing energy extraction under fluctuating ocean states [8].

2.3 Motion-to-energy conversion mechanisms

Whereas most studies focus on energy capture, fewer investigate the mechanical conversion path in detail. Martínez de Alegría et al. (2024) surveyed wireless power transfer systems for unmanned underwater vehicles (UUVs), highlighting the requirement for autonomous charging in deep-sea environments [9]. Our research advances this idea by developing a mechanism that taps surface wave-induced wing motion to produce rotational torque, which is subsequently converted into electrical power using an enclosed generator.

Zhao et al. (2024) and Petikidis & Papadakis (2024) made contributions to this field with their research exploring flapping foil dynamics and ways in which those can be optimally tuned towards continuous mechanical energy transfer [10]. Their outcomes attest to the viability of wing-based systems as a means of steady torque creation, particularly in conjunction with adequately tuned mechanical shafts and linkages. Recent work specifically targeting unmanned underwater vehicle applications further validates the relevance of compact harvesting systems. Zhang et al. (2024) developed a multi-directional wave energy harvester designed for UUV integration, demonstrating that distributed motion capture significantly enhances energy availability in underwater missions [11].

2.4 Simulation and performance prediction

Model-based design and simulation enable thorough virtual testing prior to fabrication. Several studies employed software such as MATLAB Simulink, ANSYS Workbench, and CFD to model device performance under varying conditions. Xia et al. (2024) designed an energy management model embedded within their multi-roller structure TENG, which optimized the output profile based on system response [12].

These simulation tactics guided our strategy: structural analysis in ANSYS was employed to contrast stress, deformation, and torque in three wing designs, while the entire mechanical-electrical conversion model was constructed in Simulink to predict voltage and current under wave-like excitation. Ouro-Koura et al. (2024) also support this simulation-first strategy by demonstrating how predictive modelling techniques can be used to design and optimize ocean thermal energy harvesting systems for powering unmanned underwater vehicles prior to physical deployment [13].

2.5 Flexibility to real-world conditions

For a wave energy system to be feasible, it needs to operate under actual ocean conditions. Sathyanarayana and Seelam (2024) evaluated the wave energy potential along the Indian coast and suggested Tamil Nadu as a suitable location for near-shore harvesting [14]. Additionally, Zhao et al. (2024) present a detailed hydrodynamic analysis of a floating platform coupled with an array of oscillating bodies, demonstrating the feasibility and stability of such systems under realistic ocean conditions. This directly validates the geographic and environmental applicability of our project, particularly for deployment in coastal and offshore regions with varying wave characteristics [3].

The literature studied validated that small-scale, structurally robust, and hydro dynamically reactive wing-based devices are progressively practical for local wave energy harvesting. Advances in biomimetic design, structural analysis, and multi-mode energy conversion set the stage for novel systems that are not only efficient but also environmentally adaptable, such as Tamil Nadu's moderate coastal waters. Through the combination of mechanical simulation with energy modeling, our study leverages this work to provide a streamlined and simulation-validated route to scalable marine energy solutions. Hybridization of wave energy technologies has also been explored to improve efficiency and adaptability. Chen et al. (2024) demonstrated that combining oscillating water column and point absorber principles can significantly enhance conversion performance compared to standalone systems [15].

3 Review of literature

3.1 Problem definition

Unmanned Underwater Vehicles rely on battery power, limiting mission duration and requiring frequent recharging. This research work seeks to develop a compact wave energy harvesting mechanism to convert ocean surface motion into electrical energy, providing continuous power and reducing external intervention.

3.2 Objectives

- To develop multiple wing designs having the capability of converting mechanical energy from surface wave motion into usable energy.
- To conduct a structural analysis to study and compare the response of stresses and deformations caused by wave and hydrostatic loads.
- To create a mechanism that takes mechanical energy from the oscillating motion of wings to rotational energy, towards electrical power.
- To simulate the entire energy harvesting system on Simulink and estimate voltage and current outputs.

4 Methodology

The research work followed a structured design and simulation approach to develop a sustainable energy harvesting mechanism tailored for an Unmanned Underwater Vehicle (UUV). The core aim was to extract usable energy from underwater wave-induced motion using a mechanical system that replicates oscillatory behavior observed in submerged environments

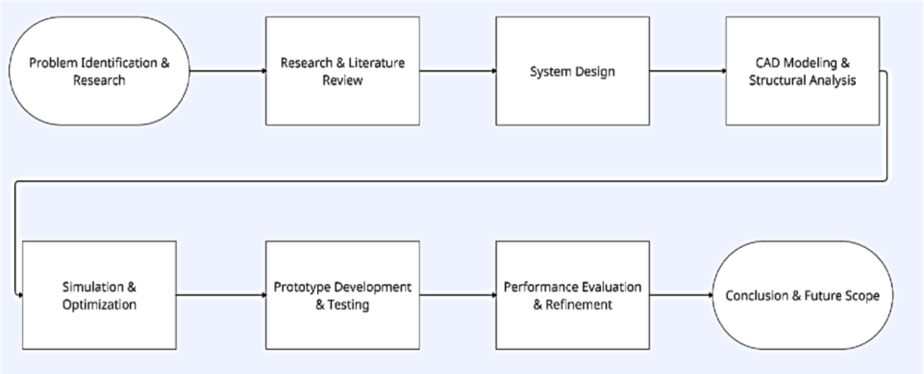


Fig. 1. Methodology

Materials Used

Polylactic Acid (PLA) was selected as the primary material for 3D printing various structural components of the prototype. Its use enabled rapid and cost-effective fabrication of the components during the prototyping phase. However, PLA possesses low tensile strength, poor fatigue resistance, and limited durability in marine environments. Since the prototype was just a proof of concept, carbon fiber was selected for realistic structural analysis and future UUV deployment due to its extremely high strength-to-weight ratio, excellent corrosion resistance, and fatigue performance under cyclic wave loading. This transition ensures both structural safety and long-term underwater operability.

Design and Reference Dimensions

The physical layout and mechanical structure of the prototype were modeled using SolidWorks, with the dimensions of the Dive-LD UUV serving as a reference. This ensured that the wing design was consistent with the form factor and hydrodynamic characteristics of a realistic underwater vehicle. Special focus was given to the wing geometry and placement to maximize interaction with wave forces.

Mechanism Mockup

After several trial-and-error methods for trying to convert the oscillating motion of the wave into a rotary motion inside the UUV, the following mechanism design gave us the best chance of getting the desired results.

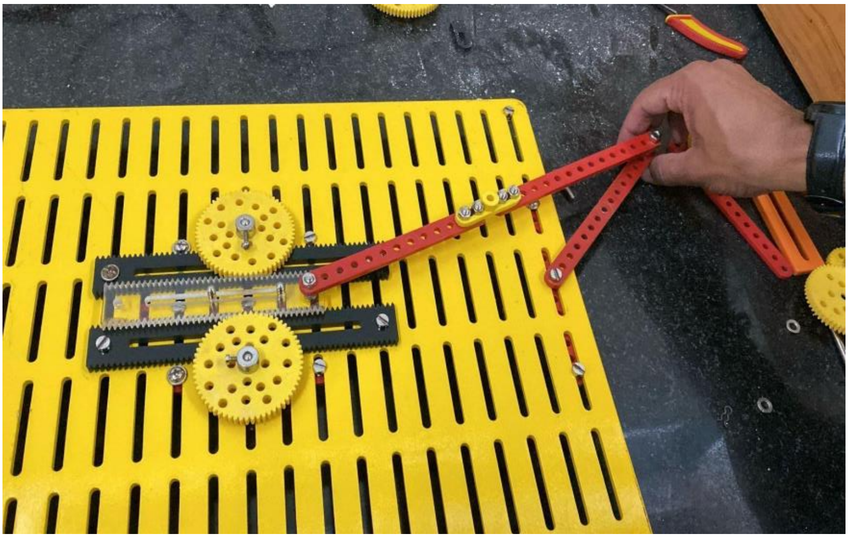


Fig. 2. Physical mockup

In order to start on the mechanism that would transform wave energy into rotational motion—and eventually into electricity—a substantial amount of research was done on wing designs employed in Unmanned Underwater Vehicles (UUVs). From this research, multiple designs were created and compared to decide which of them would be best suited for our system's purposes.

Wing Design Iteration 1

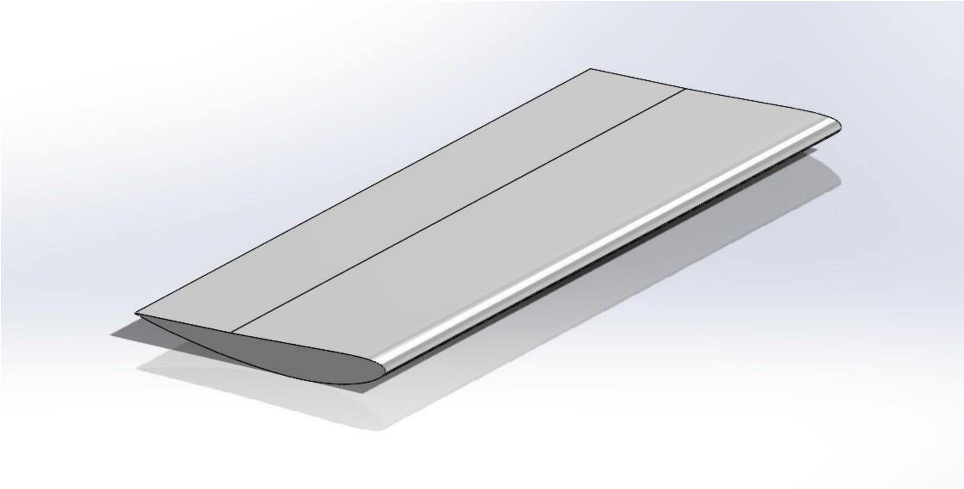


Fig. 3. Iteration 1

Wing Design Iteration 2

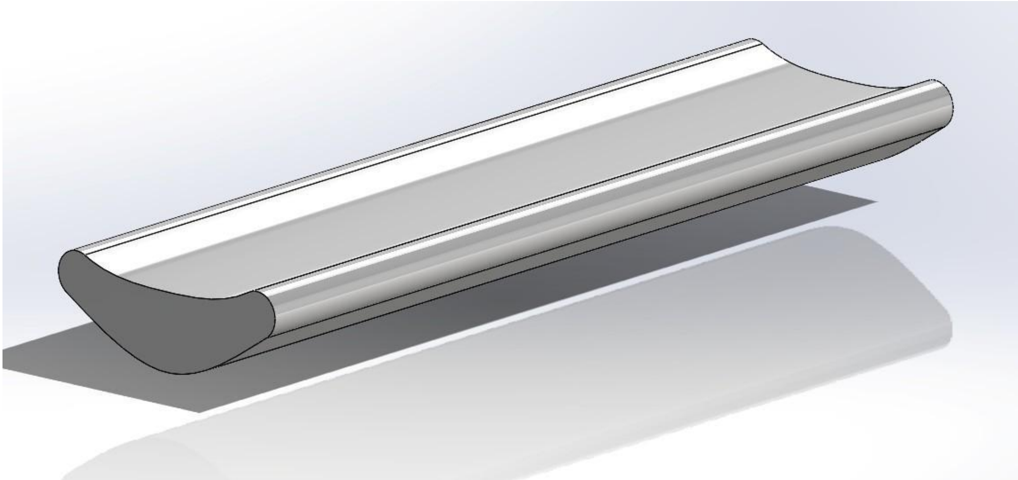


Fig. 4. Iteration 2

Wing Design Iteration 3

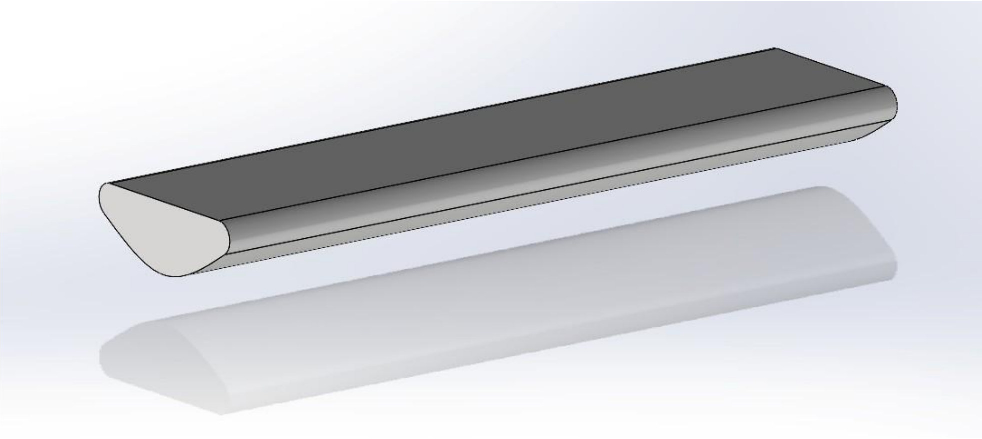


Fig. 5. Iteration 3

Analysis Tools

ANSYS was primarily utilized for structural analysis. Load-bearing components such as the connecting rod and the wing base were evaluated for deformation and stress distribution. This analysis ensured that the PLA-printed components could withstand cyclic wave-induced loads without failure. Although ANSYS Aqua was referenced for hydrodynamic input values, its usage was minimal and not central to the simulation process.

To identify the most appropriate wing design for the research work, a structural analysis was conducted on each configuration using ANSYS Workbench. The results were compared based on stress, strain, and deformation. The best-performing design was chosen for further hydrodynamic analysis.

The estimation of external forces was grounded in fluid mechanics and wave theory. The following equations were used during the design phase:

- Hydrostatic Pressure: $P = \rho gh$ - Wave Pressure: $P = (1/2)\ \rho gH$
- Wave Force Acting on the Connecting Rod: $F = P \times A$
- Moment on the Connecting Rod: $M = wL^2/2$

Where:

- ρ is the density of water,
- g is the acceleration due to gravity,
- h is the depth,
- H is the wave height,
- A is the area subjected to pressure,
- w is the distributed load,
- L is the length of the connecting rod.

The mesh size was kept at 5 mm for both structural and hydrodynamic analysis. This was to get a more detailed and accurate result.

The boundary conditions for the structural analysis were decided after careful calculation.

These were applied to the wing designs, and the analysis was run on each of them.

- *Hydrostatic Pressure*

$$P=\rho gh=1000\times9.81\times0.05 = 490\text{Pa}$$

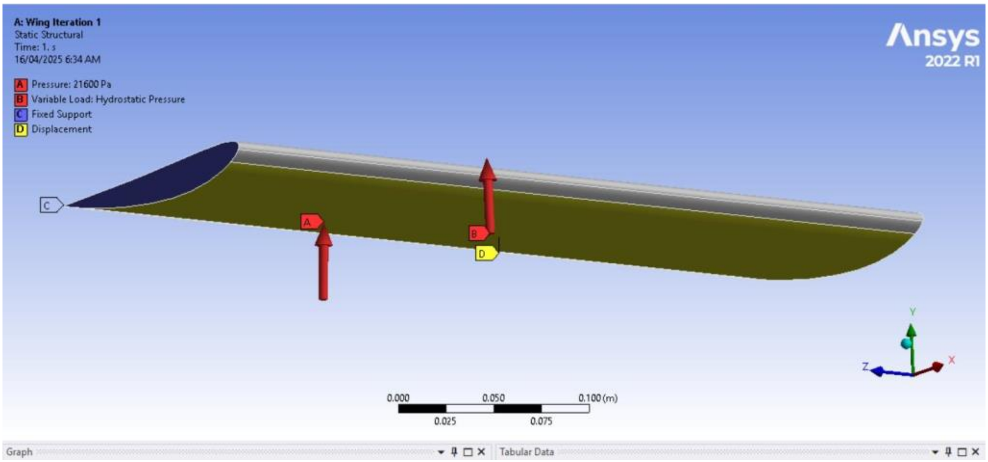
- *Wave Dynamic Pressure*

Peak wave height ~4.3 m during monsoon (ref: Tamil Nadu coastline research).

$$P = \tfrac{1}{2}\ \rho gH=0.5\times1025\times9.81\times4.3 = 21{,}600\text{Pa}$$

- Fixed point to imitate the wing being held onto the UUV

Wing Design Iteration 1

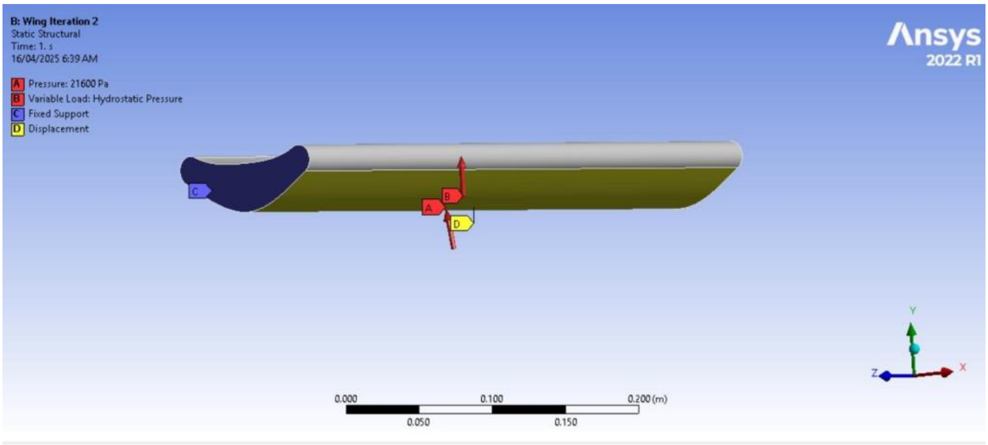


A: Wing Iteration 1
Static Structural
Time: 1. s
16/04/2025 6:34 AM

A Pressure: 21600 Pa
B Variable Load: Hydrostatic Pressure
C Fixed Support
D Displacement

Fig. 6. Boundary conditions for Iteration

Wing Design Iteration 2

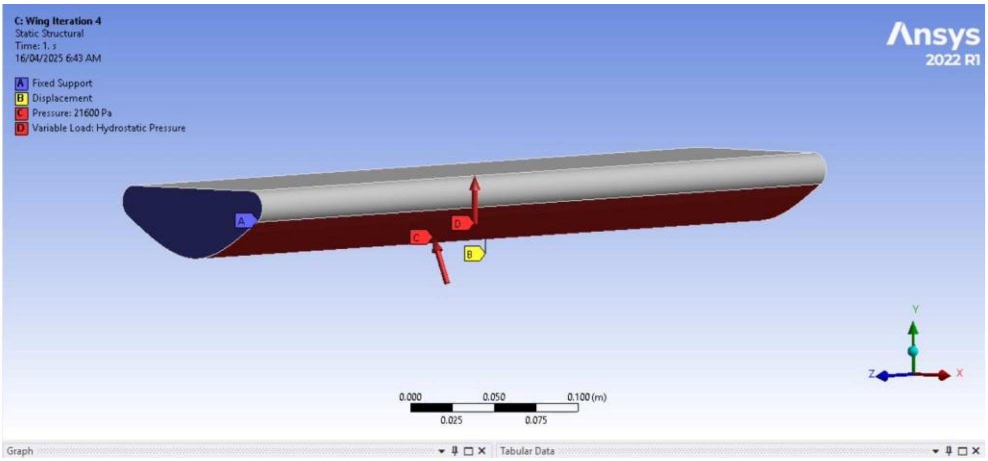


B: Wing Iteration 2
Static Structural
Time: 1. s
16/04/2025 6:39 AM

A Pressure: 21600 Pa
B Variable Load: Hydrostatic Pressure
C Fixed Support
D Displacement

Fig. 7. Boundary conditions for Iteration 2

Wing Design Iteration 3



C: Wing Iteration 4
Static Structural
Time: 1. s
16/04/2025 6:43 AM
A Fixed Support
B Displacement
C Pressure: 21600 Pa
D Variable Load: Hydrostatic Pressure

Fig. 8. Boundary conditions for Iteration 3

Iteration 3 showed the lowest stress concentrations in the structural analysis (Refer Table 1) and was therefore selected for prototyping, subsequent analysis, and simulation. The next objective was to conduct a hydrodynamic analysis on the selected iteration.

The hydrodynamic analysis was done in Ansys AQWA Solver. The boundary conditions were set up after referring to the Indian National Centre for Ocean Information Services (INCOIS), which is a government website used to track ocean and current movements.

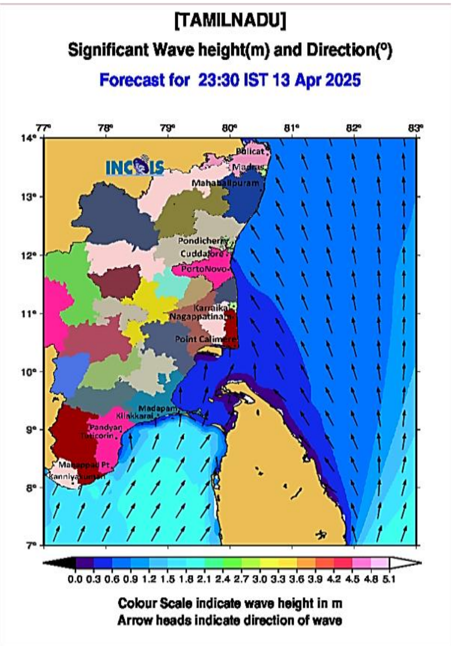


Fig. 9. Data from the Indian National Centre for Ocean Information Services.

The boundary conditions for the hydrodynamic analysis were taken as follows,

- *Wave amplitude*
  This value was taken to be 1m
- *Wave frequency*
  This value ranged from 0.04 Hz to about 0.5 Hz

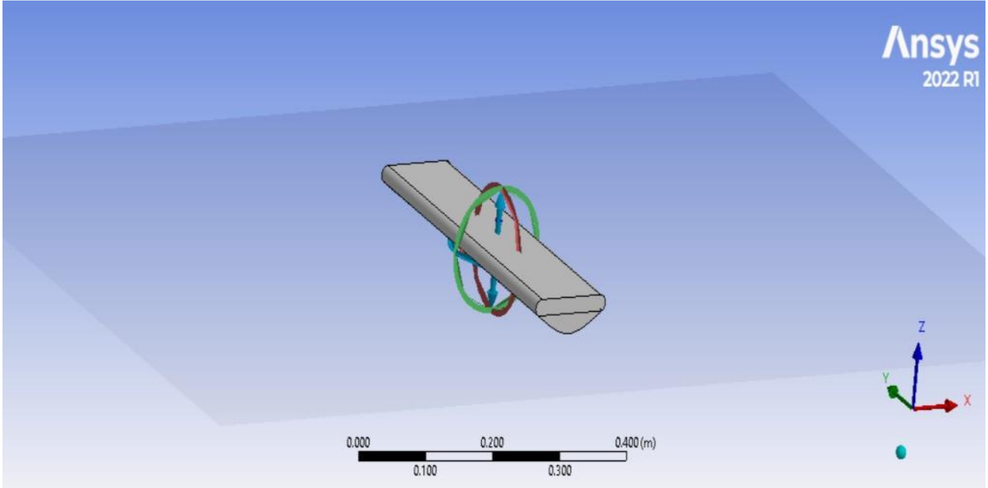


Fig. 10. The boundary conditions for hydrodynamic analysis

Final Design in SolidWorks

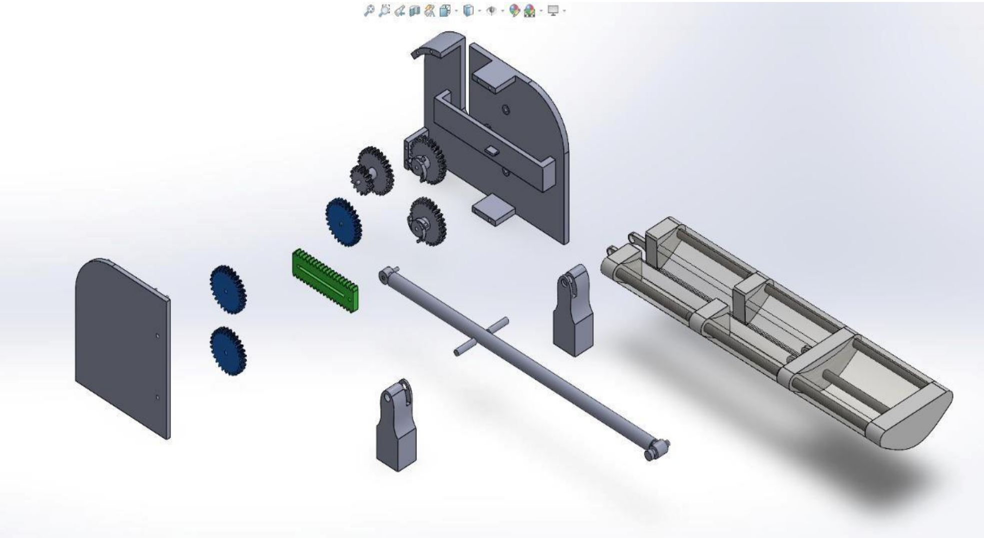


Fig. 11. Exploded view in SolidWorks

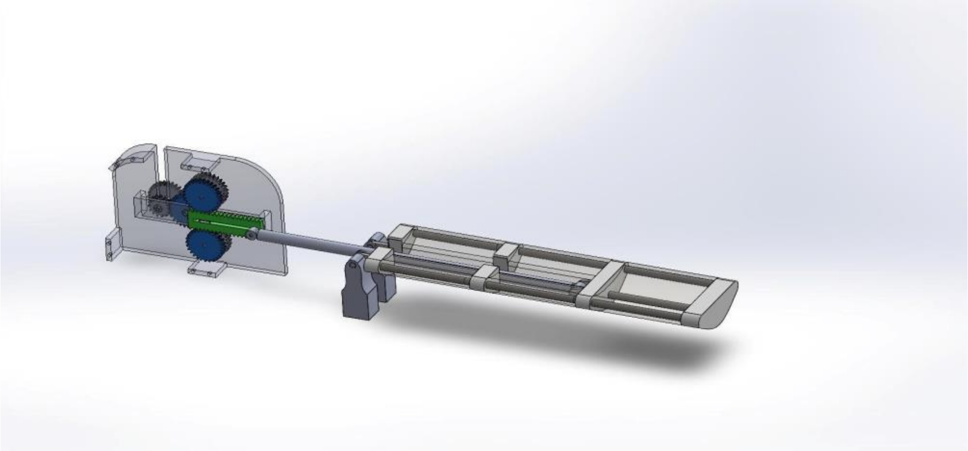


Fig. 12. Final assembly in SolidWorks

The connecting rod in the proposed mechanism was expected to be the part onto which the most amount of stress would occur due to waves. It was a necessity to analyze the connecting rod to check if it could withstand the harshest of weather and physical conditions.

Boundary Conditions were given to the rod made of (Carbon Fiber 290 GPa) using mathematical formulas previously used for the structural analysis done on the wing.

- *Wave Dynamic Forces*
  $F=P\times A=21{,}600\times(0.47\times0.15)=21{,}600\times0.0705 \approx 1{,}500N$
- *Moment caused by waves*
  $M = wL^2/2 \approx 350$ Nm
- *Hydrostatic force*
  $F= 20N$

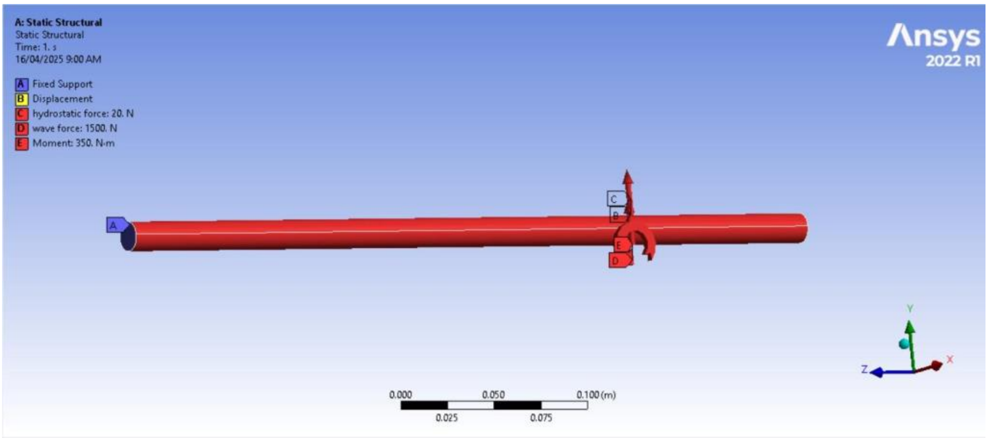


Fig. 13. Boundary conditions for connecting rod

Simulation Tool

To predict the mechanical behavior of the system, MATLAB Simulink was used for dynamic modeling. The energy harvesting mechanism was treated as a classical mass-spring-damper system. The governing differential equation used to simulate system response under periodic wave excitation is:

$$m\ddot{x} + c\dot{x} + kx = f(t) \qquad (1)$$

Where:

- m is the mass of the oscillating component,
- c is the damping coefficient,
- k is the spring constant,
- x is the displacement,
- f(t) is the external wave force.

For implementation in Simulink, this was re-formulated as:

$$\dot{x} = (1/m) \times (f(t) - c\dot{x} - kx) \qquad (2)$$

This allowed time-domain simulation of oscillatory motion, essential for evaluating the mechanism’s ability to capture energy from wave forces.

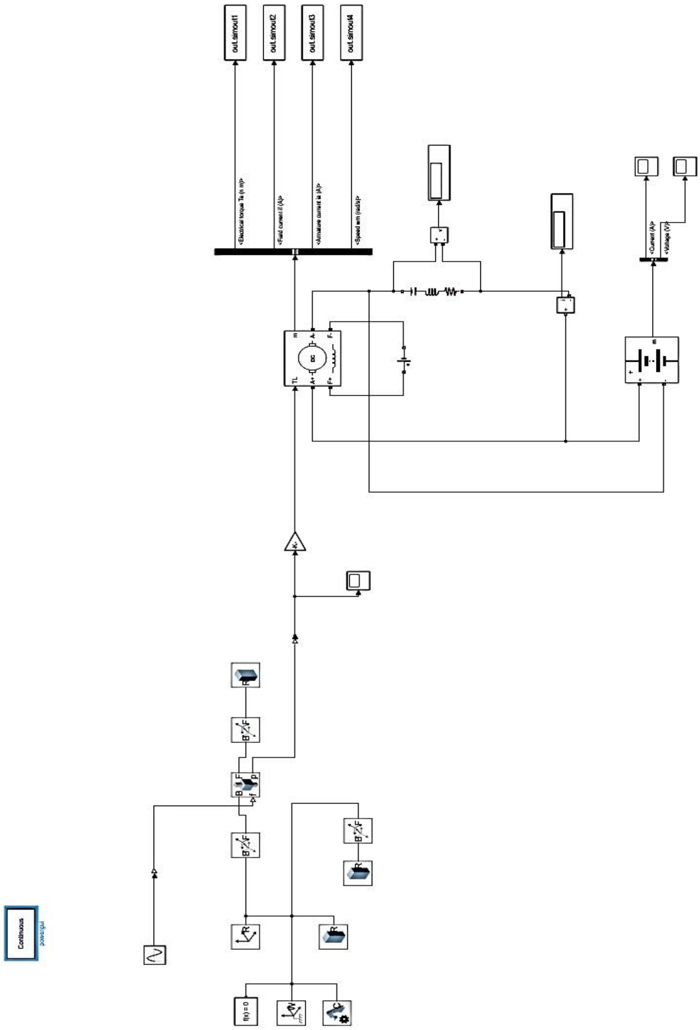


Fig. 14. Circuit diagram in Simulink

The circuit diagram below was simulated using Simulink to estimate the current and voltage developed by the mechanism due to the wave-induced water body motion.

Development of Prototype

To convert the conceptual design into a working mechanism, all the elements of the system were manufactured via 3D printing. The parts were printed from polylactic acid (PLA), a biodegradable thermoplastic that is easy to print, dimensionally stable, and has adequate mechanical strength for use in prototyping processes. The prototype features primary mechanical components like gears, shafts, support plates, linkages, and the wing base—all accurately printed to fit correctly and assemble together. Foam padding was employed to mimic buoyant wing structures and permit testing in water-like conditions. The assembly included checking the dimensional fit, range of motion, and making sure mechanical linkages reacted as desired to simulated wave inputs. The physical model generated was an important step in the verification of the mechanical design.

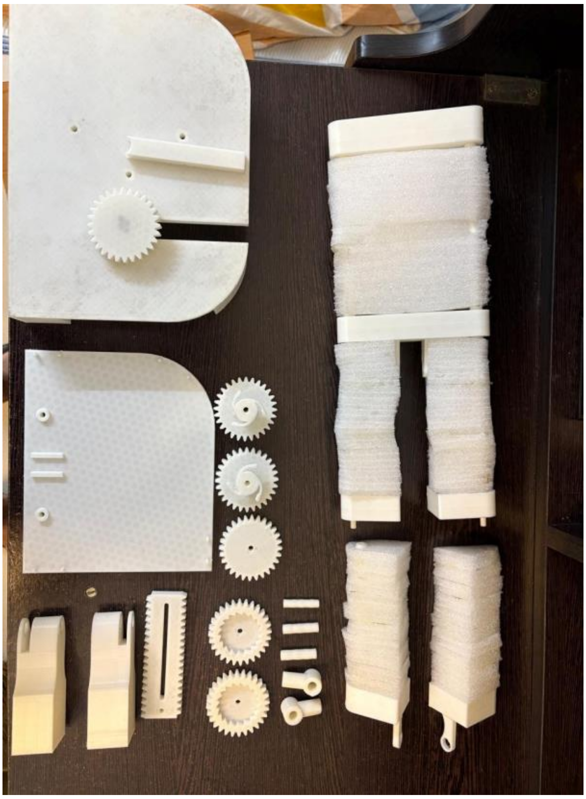


Fig. 15. Prototype development

5 Results and discussion

The findings for the structural analysis were tabulated and compared with each other. From this, the best design was selected for the hydrodynamic analysis.

Results from Structural Analysis of the Wings

Wing Design Iteration 1

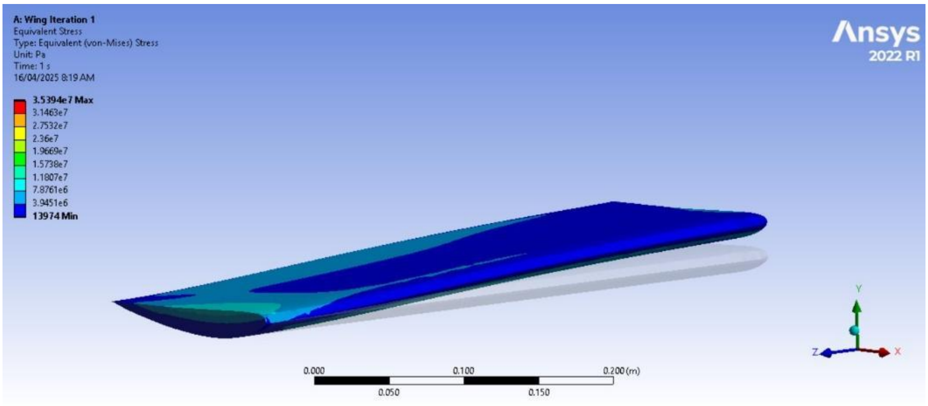


Fig. 16. Result of Iteration 1

Wing Design Iteration 2

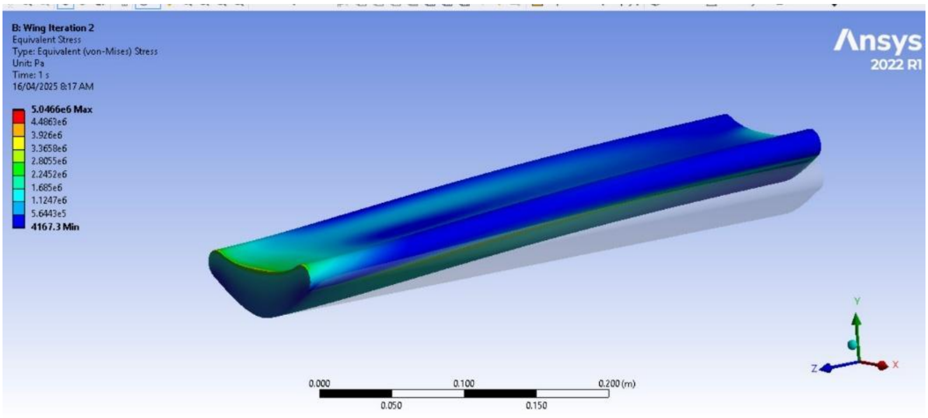


Fig. 17. Result of Iteration 2

Wing Design Iteration 3

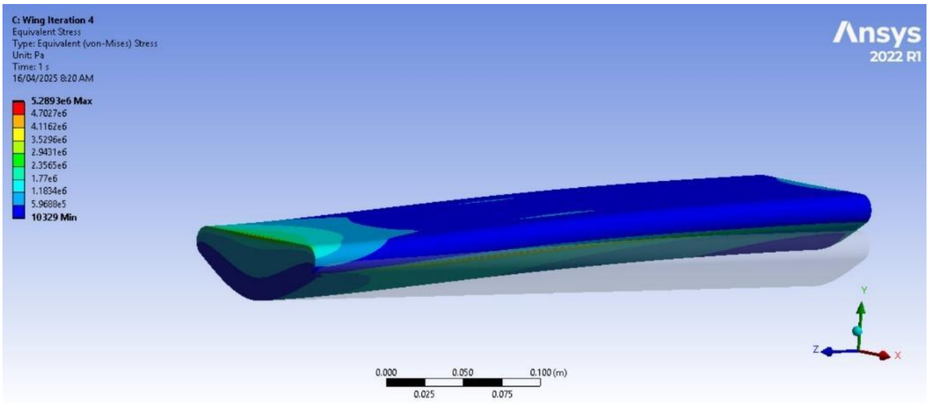


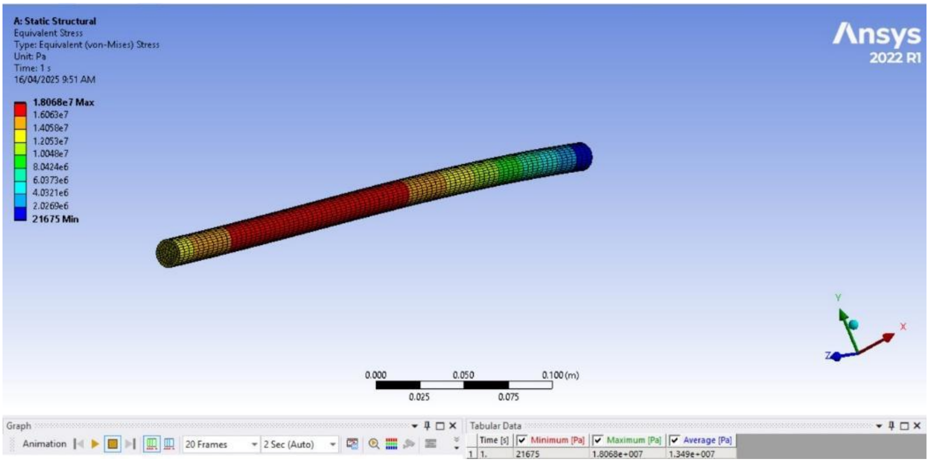
Fig. 18. Result of Iteration 3

Table 1. Structural analysis results of wings

Design	Total Deformation (m)	Directional Deformation (m)	Equivalent Strain	Equivalent Stress (Pa)	Max Principle Strain	Max Principle Stress (Pa)	Strain energy (J)
Design 1	5.89e-5	1.00e-6	0.00122	3.539e7	0.00057	3.56e7	0.00027
Design 2	5.88e-5	3.60e-7	0.000336	5.246e6	0.00018	3.39e6	7.79e-6
Design 3	5.80e-5	1.90e-7	0.000334	5.046e6	0.00017	3.19e6	1.42e-6

From the table, it is evident that the most optimal design is the third iteration. This design had the least stress and deformation that was caused due to the wave-generated pressures. This design was used for the hydrodynamic analysis, and the next section shows the results from that.

Results from Structural Analysis of the connecting rod



A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1 s
16/04/2025 9:51 AM

20 Frames
2 Sec (Auto)

	Time [s]	☑ Minimum [Pa]	☑ Maximum [Pa]	☑ Average [Pa]
1	1.	21675	1.8068e+007	1.349e+007

Fig. 19 Results of connecting rod

Table 2. Structural analysis results of connecting rod

Component	Equivalent Stress (Pa)	Equivalent Strain	Total Deformation (m)
Connecting Rod	1.80e+7	1.08e-3	4.09e-4

Since the Yield Tensile Strength and Compressive Tensile Strength of Carbon Fiber is 5e+9 Pa, the connecting rod will be able to withstand the forces that act upon it easily. Even during high tides and harsh weather conditions, the connecting rod will be able to handle the stresses and deformations caused by the waves.

Results from Hydrodynamic analysis of the Wing

The hydrodynamic analysis was done to check if the wing would have pressure concentrations while it interacts with waves. Pressure concentration on the surface would mean the design is not ideal for aquatic or marine usage. The concentrations would eventually weaken the wing and cut short its lifetime

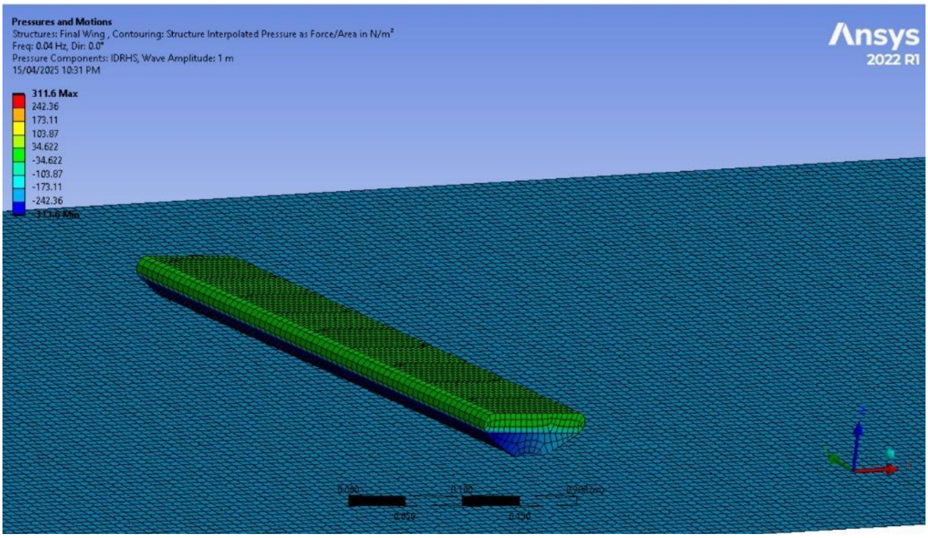


Fig. 20. Result of hydrodynamic analysis

Table 3. Hydrodynamic analysis results

Component	Max Pressure (Pa)	Avg Pressure (Pa)
Wing Design	1.80e+7	1.08e-3

The maximum hydrodynamic pressure acting on the wing was found to be 311.6 Pa. This value is extremely small when compared to the tensile strength of carbon fiber (≈ 5×10^9 Pa), indicating a very high factor of safety. From the contour, it is visible that the surface inside and outside the water has no particular stress concentrations. This indicates that the flow remained smooth with a balanced pressure distribution, confirming the design's reliability under wave conditions. Furthermore, the stress-free pressure distribution confirms that the structural integrity observed in ANSYS directly correlates with the hydrodynamic stability obtained from AQWA analysis.

Results from Simulink simulation

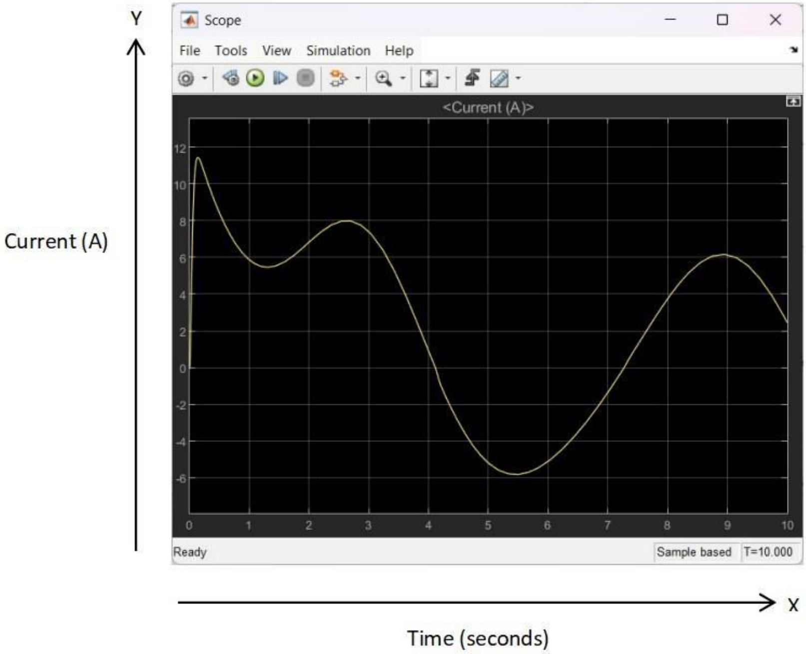


Fig. 21. Current graph

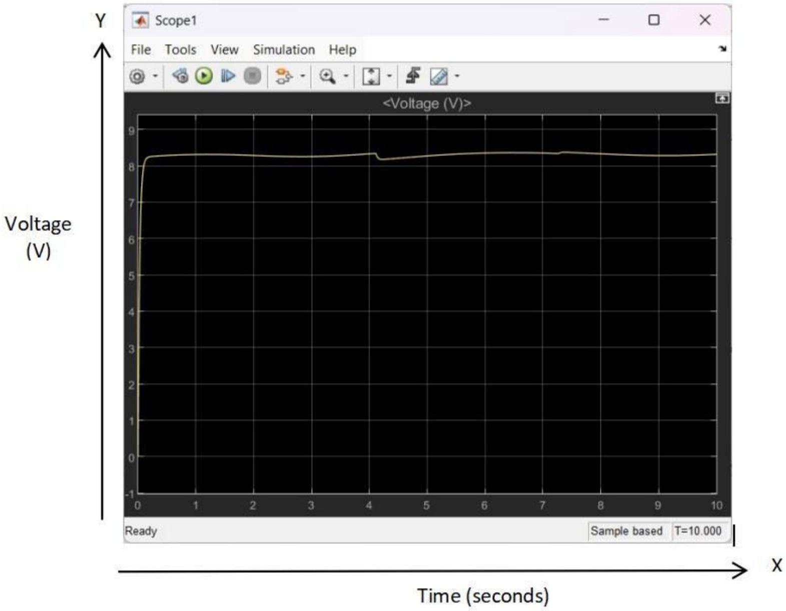


Fig. 22. Voltage graph

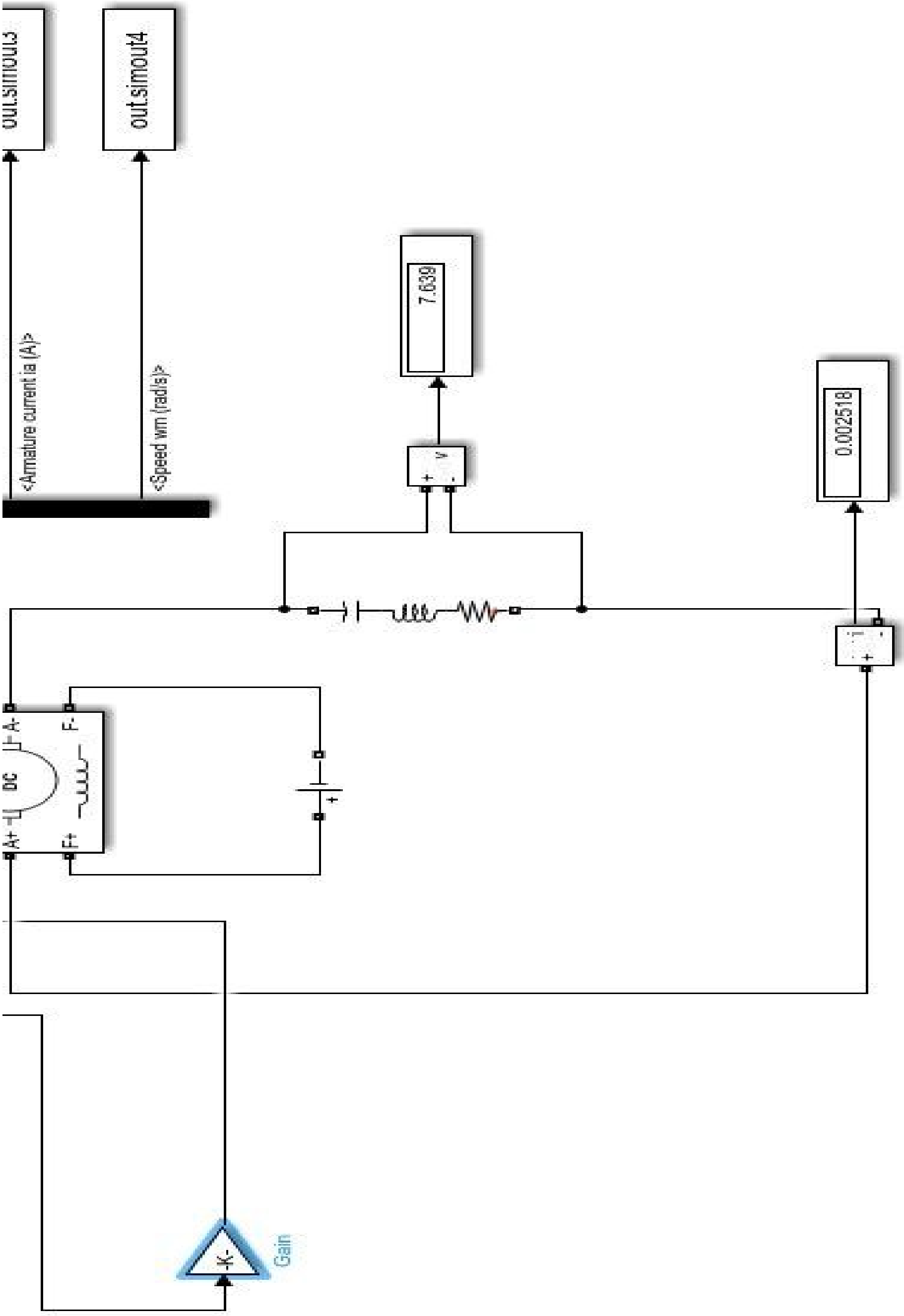


Fig. 23. Input Signal

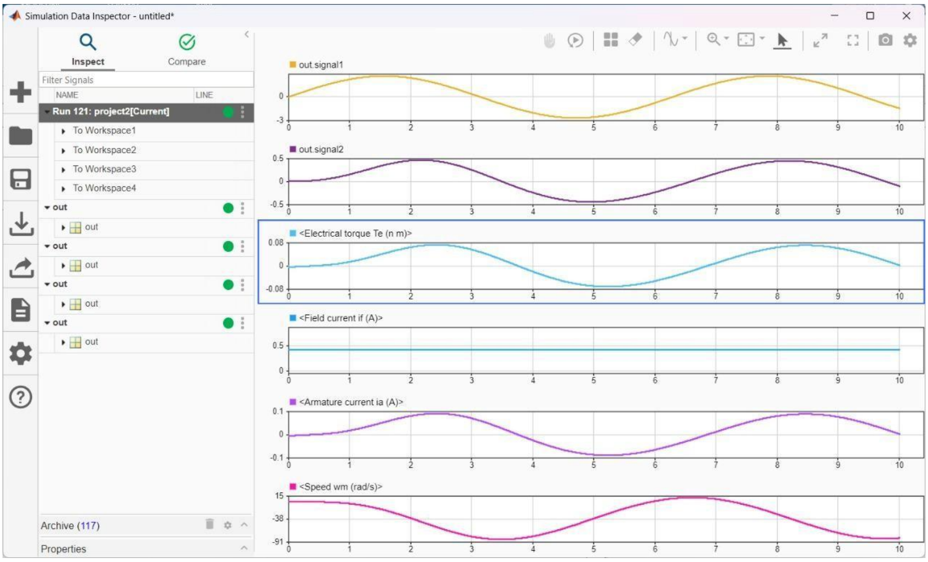


Fig. 24. Generator Output

The simulation of the envisioned mechanism for a UUV proves the feasibility of ocean wave-induced flapping motion to generate electrical power and charge a battery. The main observations from the graphs are mentioned in the next section.

The sinusoidal input waveforms validate realistic wave motion being successfully translated by the flapping wing mechanism to the DC generator. The Simulink model incorporated a permanent magnet DC generator with an assumed electrical efficiency of 85% and a rack and pinion mechanism with 90% mechanical efficiency, accounting for frictional and contact losses in the energy conversion calculations.

Battery Voltage is constant at 8V after an initial increase, which shows proper reception of energy and voltage regulation. Battery current exhibits dynamic charging behavior such as peak charging and natural oscillations in sync with wave energy input.

The detectable electrical output from the voltmeter and ammeter in the Simulink circuit was found to be 7.63V and 0.0025A, respectively.

6 Conclusion

Three varying wing configurations were created utilizing SolidWorks in the hope of utilizing wave energy by surface interaction. Each of these was modelled with precision, and keen attention was paid to structural geometry and mechanical practicability.

Structural analysis of the three designs was performed on ANSYS Workbench, where stress and deformation were compared. The most effective design was then assessed further using hydrodynamic analysis in order to gain insight into how it performs in real-world wave conditions.

The chosen design was simulated as a stand-alone energy harvesting system in MATLAB Simulink, in which wave motion was converted to mechanical rotation and then to electric output. The simulation was used to estimate the voltage and current expected during operating conditions.

While assembling the 3D-printed components, practical challenges such as shaft misalignment, gear backlash, tolerance errors, and increased friction at contact interfaces were encountered. Notably, the initial gear thickness caused excessive friction, requiring reprinting with reduced thickness to minimize friction among the interfaces. These issues slightly affected mechanical smoothness but provided valuable insight into improving manufacturing precision in future iterations. The research work nonetheless illustrates the viability of the design.

Future improvements include scaling up the wing dimensions, integrating energy storage management systems, and experimentally validating the output in real ocean conditions will further enhance system reliability. The inclusion of multi-directional wing arrays can significantly increase power generation efficiency.

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