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Design and Analysis of Self-Energising Unmanned Underwater Vehicle (UUV)

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Abstract

This research focuses on the development of a self-energizing underwater vehicle that utilizes wave energy to power its circuit. The objective of the research work is to demonstrate the feasibility of harnessing renewable energy sources in an underwater environment and showcase the potential for sustainable power generation. To ensure the structural integrity of the vehicle under water, rigorous simulation analysis has been conducted using ANSYS software. The hull design has undergone thorough scrutiny to determine its ability to withstand water pressure at depths of up to 5 meters. The simulation results confirm that the submarine's hull design is robust and capable of withstanding the expected operating conditions. This study holds great significance in the field of marine engineering as it explores alternative energy sources for underwater applications. By harnessing wave energy, this work contributes to the development of sustainable technologies that can potentially revolutionize underwater operations. The use of renewable energy sources minimizes environmental impact and reduces reliance on traditional power sources. Throughout this research, challenges were encountered, including optimizing the turbine system efficiency, ensuring reliable power transfer, and maintaining the structural integrity of the submarine. These challenges were addressed through careful design considerations and iterative improvements. The knowledge gained from this study can be applied to various underwater applications such as marine exploration, environmental monitoring, and data collection. Future research and development should focus on enhancing the turbine design, integrating advanced power management systems, and conducting field tests to validate the system's performance in real-world-scenarios.

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1. Introduction

An Unmanned Underwater Vehicle (UUV) is an unmanned, untethered vehicle designed for various underwater tasks that require minimal human supervision. Recent advancements in UUV technology have expanded their roles in critical missions such as underwater communication, intelligence retrieval, surveillance, naval operations, military defence, and oceanography.

To understand the vehicle, several principles come into play, differentiating it from a traditional ship. The first principle is Archimedes' Principle, which states that when an object is partially or completely submerged in a fluid, it experiences an upward buoyant force equal to the weight of the fluid it displaces. If the weight of the submerged object matches the buoyant force, it will float in the fluid.

Another principle relevant to UUVs is Bernoulli's Equation, which states that in a flowing liquid where there is a continuous connection between particles, the total head (energy) of each particle remains constant. This principle is important for understanding fluid dynamics and the flow of water around the UUV.

Newton's Third Law of Motion is also crucial for UUVs. It states that every action has an equal and opposite reaction. In the context of UUVs, this law helps explain how they move. Propellers play a significant role in generating thrust, and as they push water in one direction, an equal and opposite force propels the UUV forward. UUVs are equipped with various sensors such as side scan sonar, inertial navigation systems, magnetometers and various sensors and actuators for efficient operation as explained in [7].

To power a UUV, utilizing wave energy as a self-energizing source is proposed, which was inspired from [10]. Wave energy can be converted into electrical energy using a generator. Some estimates suggest that wave energy could power a turbine for up to 18-22 hours a day in ideal locations. This is particularly valuable as a growing proportion of electricity generation comes from intermittent renewable sources. The wave energy conversion process involves a turbine, like a wind turbine, with blades rotating at a speed determined by the strength of the tides. The turbine is connected to a gearbox, which turns a generator, producing electricity. Studies have indicated that wave energy converters can efficiently charge UUVs. For energy storage, standard Lithium-ion batteries are suitable for UUVs. These batteries have been extensively used in marine environments and are readily available.

A UUV consists of various units integrated into a hull design. The control unit manages the UUV's mobility by controlling the propellers and facilitating internal communication between sensors and actuators. The communication unit includes an RF transmitter and receiver for signalling. The navigation unit determines the UUV's location coordinates. The electronic unit comprises of sensors, actuators (such as temperature and pressure sensors), and components like DC motors and H-bridges. Lastly, the power unit consists of generators, a battery storage unit, and a battery supply unit. This comprehensive design enables the UUV to self-energize and sustain its operations in the underwater environment.

Hydro Power Feasibility

Typically, turbines are installed in wave streams for wave energy generators. A swift-moving body of water produced by tides is called a wave stream. A turbine is a device that harnesses the power of fluid flow. This may be either water or air. Wave energy is more potent than wind energy because water is much denser than air. In contrast to wind, tides are steady and predictable. If wave generators are employed, a consistent, dependable stream of electricity is produced. Since the devices are huge and disturb the tide that they are seeking to capture, placing turbines in wave streams is challenging. Depending on the size of the turbine and the location of the wave stream, the environmental impact could be severe. In order to prevent marine life from becoming entangled in the system, wave generator turbine blades also rotate slowly. It is estimated that the turbine can produce (12xn) volts by connecting 'n' turbines in series. The estimated generation of a turbine would be the same if 'n' turbines were connected in parallel. Once the energy was converted and generated, a Li-ion battery charging module is used, to store the required charge power to supply it to the whole system when it is required. This way, reserved power can be used in any uncertain circumstances.

2. Related Works

Yang et al., [1] has comprehensively covered all the currently known methods for designing and analysing Autonomous Underwater Vehicles (AUVs). By encompassing these various techniques, the study demonstrated a comprehensive understanding of the field's existing methodologies and approaches. To ensure successful autonomous navigation over extended distances, it is crucial for systems to possess stability that enables them to endure significant attitude changes caused by external factors like waves. The ability to withstand these disturbances is paramount for maintaining the desired trajectory along the entire path.

The study [2] organized its investigation into two categories: body and/or caudal fin propulsion, and median and/or paired fin propulsion. Within these categories, the researchers have presented modern approaches concerning the structural designs, actuators, and sensors used. Additionally, the study reviewed the locomotion characteristics of various fish species and examined robot designs that are inspired by them. The study has also outlined the features of smart soft actuators and sensors.

The primary objective of [3] is designing the body of the Hull Cleaning Robot (HCR) to minimize drag to the greatest extent possible. The work focused on the physical structure and chassis of HCRs, providing insights into the design. Souto et al., [4] discussed a robotic system that consists of two identical modules that can attach independently to a surface, allowing the device to navigate over or around edges. To model the hydrodynamics of the fish, Dong et al., [5] divided the structure into distinct components, namely the body, left pectoral fin, right pectoral fin, and tail. The forces were computed through Computational Fluid Dynamics simulations. Kim et al., [6] aimed to merge the advantages of compact and lightweight AUVs with the manipulation capabilities typically associated with ROVs.

Petillot, et al [7] incorporated path control in both the horizontal and vertical planes of an AUV, and the use of six degrees of freedom was explored. The P-AUV protocol was developed in [8] to support ad hoc networks of AUVs with position-aware routing and medium access capabilities. Since the protocol operates solely based on local decisions, the mobility of sensors does not negatively impact performance. In the design of the new AUV controller, Van, et al., [9] suggested that discrete part's capsule remains unchanged. Furthermore, a significant portion of the experiment's parameters were simulated rather than observed in real-world scenarios. Moreover, the real-time versions of UML/SysML lack the necessary constructs for modelling internal continuous behaviours associated with each state on the state machine diagram.

Zhao et al., [10] focused on a wave-powered AUV equipped with onboard power harvesting capabilities. Throughout the AUV's operation, an Arduino, which is a low-power Microcontroller Unit board, remains powered continuously and controls the operational states of all other devices. Research [11] is another animal inspired model. Computational efficiency is observed, with the Spalart-Almaras, k-epsilon, and k-omega eddy viscosity-based models requiring less computational time compared to RSM, LES, and DNS.

Communication for underwater vehicle was discussed in [12]. Here the working frequency is set at 868 MHz. Data transfer between nodes is achieved using the RFM9X LoRa module, implementing the LoRaWAN protocol. However, the theoretical link budget model does not include power degradation resulting from miscellaneous losses. As a result, the range achieved is relatively limited. Underwood et al., [13] focused on achieving fuel savings of approximately 3 to 4 percent by adjusting the trim. Here, the application of strip theory and Green function is explored to estimate the forces and motions experienced by the ship.

Rescue robot was implemented in [14], where the AUV is comprised of a standard tail and a modular open-user configurable payload. However, the efficiency of the AUV is compromised using a magnetic coupling for the propellers. To address this, efforts are made to reduce the size and power consumption of AUV sensors, which in turn enhances the overall efficiency of the AUV system. Dielectric Elastomer Actuator based device was implemented in [15]. The device described primarily consists of three components: a remote control, an ROV (Remotely Operated Vehicle), and an air bag system. The remote control was equipped with a telemetry receiver and an RF transmitter. The device was compact in size, offering portability and convenience. Furthermore, it boasts a wide range of access, with a capability of up to 4 kilometres.

Harun et al., [16] claimed that submarine's construction utilizes aluminium material to reduce weight and withstand high-pressure conditions. By eliminating the need for human operators inside the vehicle, the UUV minimizes the risk to human life, particularly in warfare situations. Furthermore, the work highlighted the UUV's capability to inspect submerged pipelines used for crude oil transfer and communication cables.

The UUV discussed in [17] combined the fundamental characteristics of both vehicle types and was controlled by manipulating the thrust forces generated by its six thrusters. This control is achieved through the implementation of a closed-loop control system specifically developed for the UUV. The UUV can produce a maximum horizontal thrust force of up to 160 Newtons. However, to ensure the motors are not pushed to their limits and to prevent issues such as integrator windup in the controller, certain precautions are taken. A new Autonomous Underwater Vehicle (AUV) equipped with Interferometric Real and Synthetic Aperture Sonar (IRSAS) was implemented in [18]. With IRSAS, a detailed bathymetry map can be created for surveys of hydrothermal deposits. The cruising time exceeds 12 hours, providing an extended operational capability.

Forward/astern movement and rotation in the system were achieved by the presence of two propellers mounted side-by-side in [19]. Additionally, two vectored propellers enabled the vehicle to perform up/down and sideways movements. The maximum speed attainable by the system is approximately three knots. The system was designed to travel forward on the surface for a predetermined duration and execute smooth turns while maintaining surface navigation.

3. Proposed Work

This section discusses the essential hardware and software components utilised to complete the research, emphasizing their crucial role in achieving the goals. The self-energizing submarine project aims to design a compact and efficient underwater vehicle capable of utilizing wave energy for its propulsion and energy needs. In this report, the step-by-step design process involved in creating the submarine hull and ensuring its structural integrity using SolidWorks and ANSYS software have been discussed.

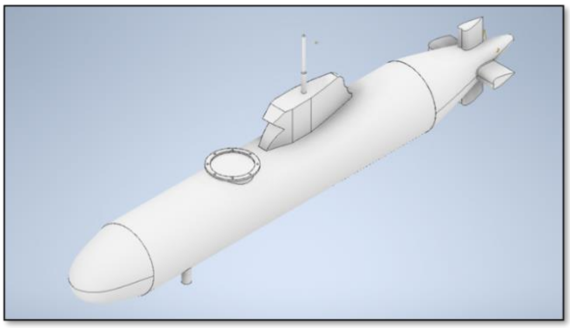

Figure 1. Isometric View of The Design

The primary objective is to demonstrate the feasibility of using PLA material for the hull, and its ability to withstand the hydrostatic pressure at a depth of 5 meters. The project commenced with the use of SolidWorks, a leading 3D modelling software, to design the submarine hull. The software's powerful features were utilized to create a detailed 3D model of the hull as shown in **Figure 1**, incorporating the necessary components within the design as shown in **Figure 2**. To ensure precise dimensions and the seamless integration of components, STEP files of the required components were imported and placed inside the hull during the design phase. This step allows to verify if all required components could be accommodated comfortably within the hull structure.

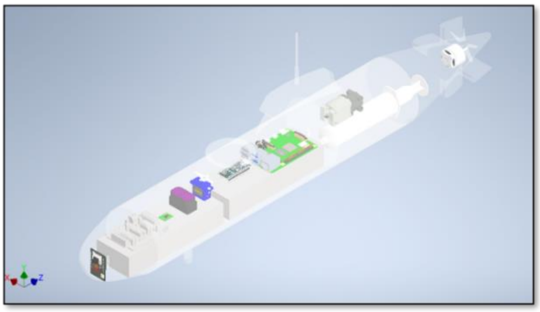

Figure 2. Transparent View of The Design

ANSYS FEA with Theory of Maximum Principal Stress

Once the SolidWorks design is complete, the next critical phase is to assess the structural integrity of the hull. For this purpose, the design was exported from SolidWorks and imported into ANSYS software. ANSYS is a powerful tool for conducting Finite Element Analysis (FEA), enabling engineers to simulate and analyse complex structures to understand their mechanical behaviour under various conditions. The principle of maximum principal stress is a fundamental concept in structural mechanics and material analysis. According to this principle, failure in a material occurs when the maximum value of normal stress acting on a point within the material reaches a critical limit. This Stress Strain plot is depicted in **Figure 3.** This principle assumes that the material will fail if the maximum principal stress exceeds its ultimate strength. By evaluating the stress state at various points within a structure or component, engineers can determine potential failure locations and assess the structural integrity. The principle of maximum principal stress provides valuable insights into the design and analysis of structures, enabling engineers to make informed decisions regarding material selection, load distribution, and overall safety. It serves as a critical tool in ensuring the reliability and performance of various engineering applications, ranging from bridges and buildings to aerospace components and mechanical systems.

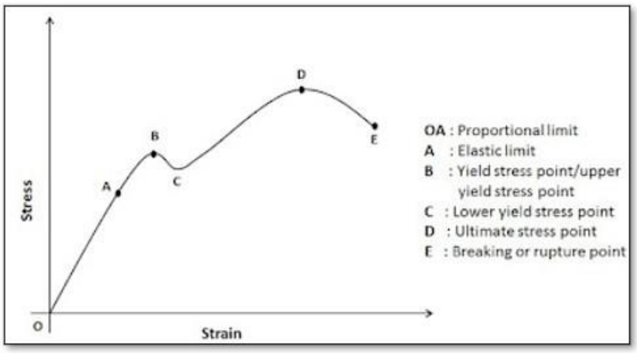

Figure 3. Stress-Strain Plot

For the self-energizing submarine project, the material selected for the hull was PLA (Polylactic Acid). The material properties considered for the analysis were:

Material Density: 1.24 g/m³

Young's Modulus: 3420 MPa

Poisson's Ratio: 0.3

Tensile Yield Strength: 35.6 MPa

Assumptions for FEA:

The following are the reasons behind the assumptions made for FEA:

Consideration of Only the Hull

The decision to focus solely on the hull for stress analysis was driven by the understanding that the hull experiences the most significant pressure difference. As the hull is hollow and filled with air, it is the primary structure responsible for withstanding the hydrostatic pressure and maintaining the integrity of the submarine. By isolating the hull in the analysis, the structural behaviour and stress distribution could be prioritized in this crucial component.

Homogeneous and Isotropic Material

In FEA simulations, assuming the material to be homogeneous and isotropic is a common practice, especially when analysing solid structures. Homogeneous refers to the material having consistent properties throughout its volume, while isotropic implies that the material exhibits the same mechanical behaviour in all directions. By assuming these properties, the complexity of the analysis is reduced, as the material can be modelled with simplified material properties and behaviours. While this simplification may not capture all material nuances, it provides a reasonable approximation for many engineering applications.

Overall, these assumptions were made to strike a balance between accuracy and feasibility in the analysis process. By focusing on the hull and assuming homogeneous and isotropic material properties, the analysis was able to be streamlined, computational complexity was reduced, and meaningful results for the structural integrity assessment of the submarine hull was derived.

Mesh Analysis

In the context of FEA, mesh analysis plays a crucial role in accurately representing the geometry of the structure being analysed. The purpose of meshing is to divide the complex geometry of the hull into smaller, simpler elements called finite elements. These elements form a mesh, which is a discretized representation of the structure. Mesh analysis is vital because it allows for the calculation of stress and deformation at discrete points within the structure.

The process of meshing involves dividing the hull's surface and volume into numerous smaller elements, typically triangles or quadrilaterals in two-dimensional analysis and tetrahedrons or hexahedrons in three-dimensional analysis. Mesh analysis conducted in ANSYS is depicted in **Figure 4**. The number and size of the elements in the mesh have a significant impact on the accuracy of the analysis. A fine mesh with smaller elements captures more detail but requires more computational resources, while a coarse mesh with larger elements may sacrifice accuracy.

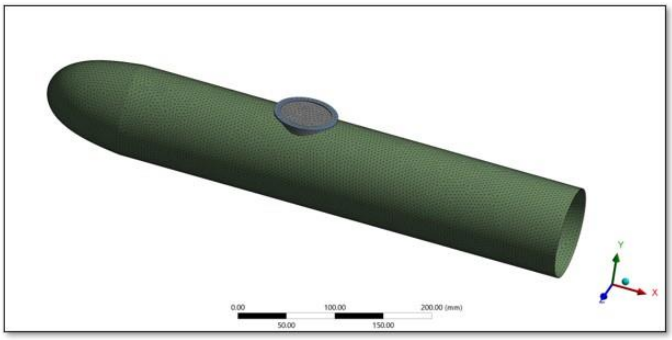

Figure 4. Mesh Analysis

In the case of the self-energizing submarine project, mesh analysis was performed using ANSYS software. The software allows for the creation of a mesh by dividing the hull's surface and volume into a defined number of nodes and elements. In this work, a total of 154,863 nodes and 102,132 elements were generated to ensure an appropriate level of detail and accuracy in capturing the hull's geometry and stress distribution.

The external casing of the system was designed using CAD and ANSYS, taking various factors into consideration. The goal was to ensure optimal placement and protection of the internal components. Simultaneously, the internal circuitry was carefully constructed, paying attention to detail and precision.

The hardware requirements for this research include an Arduino Uno microcontroller board, a 5V DC motor, an LM7805 voltage regulator, an XL6009 booster module, a 3.7V 1200mAh lithium-ion battery, a 2-channel relay, a TP4056 Li-ion charging module, and a 12V micro hydro turbine generator. These components are essential for building a system that can generate and regulate power from a hydro turbine. The Arduino Uno acts as the control unit, managing the motor, relay, and charging module. The voltage regulator and booster module ensure stable power supply and voltage conversion. The Li-ion battery and charging module enable efficient energy storage and recharging. On the software side, the Arduino IDE is required to program the Arduino Uno microcontroller, allowing for precise control and automation of the system. Additionally, ANSYS software is utilized for simulation and analysis purposes, while Solid works Design serves as the software design tool for creating and visualizing the mechanical components of the system.

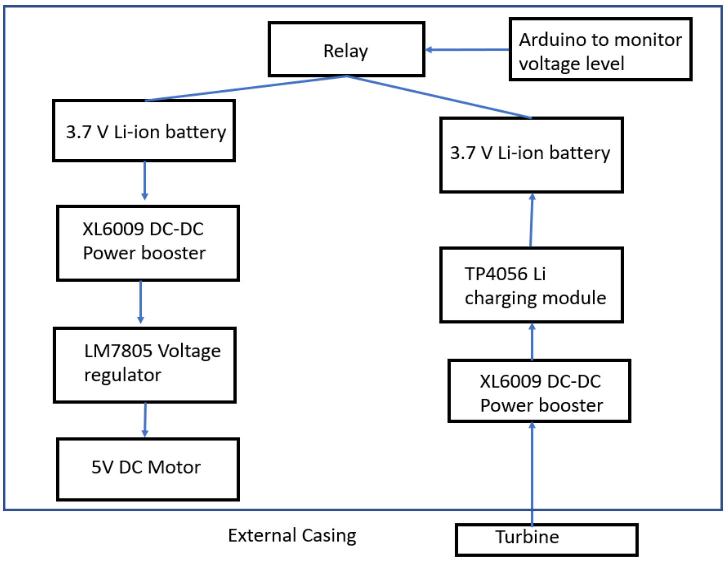

Figure 5. Block Diagram of The Proposed Work

The Self-Energizing Underwater Vehicle System is divided into four distinct components for its implementation as shown in **Figure 5**: the discharging circuit, charging circuit, unifying the two circuits, and the external casing. The discharging circuit is responsible for the propulsion of the system, utilising a 5V motor. To power the motor, a 3.7V, 1200mAh Li-ion battery is employed. The battery's output voltage is boosted using an XL6009 Booster module, which operates within an input range of 3 volts to 32 volts. The XL6009 module provides an adjustable output voltage range from 5 volts to 35 volts, ensuring that the motor receives appropriate voltage for efficient operation. The internal circuit connections is depicted in **Figure 6.**

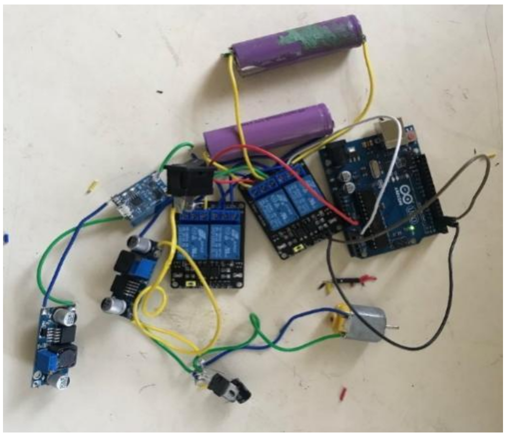

Figure 6. Internal Circuitry

To stabilize the voltage provided by the XL6009 module, it is connected to an LM7805 voltage regulator. The LM7805 regulator has a fixed output voltage of 5 volts, ensuring a stable and regulated power supply for the motor. Capacitors are connected to the input and output terminals of the LM7805 regulator to filter out any voltage ripples or noise, providing a smoother and more reliable voltage supply to the motor.

The charging circuit plays a crucial role in the system. To harness the output effectively, an XL6009 booster module is connected in series with the turbine's output. With this setup, the voltage is increased to the ideal amount for effective charging. The boosted output from the XL6009 module is then connected to the input of the TP4056 Li-ion battery charging module. It provides a regulated charging current to safely charge the 3.7V 1200mAh Li-ion battery. Additionally, the TP4056 module incorporates overcharging protection, monitoring the battery voltage during the charging process. The charging process is stopped once the battery reaches the predetermined threshold, preventing overcharging and ensuring the battery's longevity and safety.

To facilitate the integration and coordination of the discharging and charging circuits, an Arduino uno microcontroller and a 2-channel relay system are employed.

The first relay serves the purpose of switching between the charging battery and the discharging battery based on the voltage level in the discharging circuit. The Normally Open (NO) terminal of the first relay is connected to the terminals of charging battery, the Normally Closed (NC) terminal is connected to the terminals of discharging battery, and the discharging load terminal is connected to the Common (COM) connection point. This configuration allows for seamless switching between the power sources.

Continuous voltage monitoring in the discharging circuit is achieved by connecting the positive terminal of the discharging battery to an analog pin on the Arduino. The Arduino can continuously check the analogue voltage input to monitor the voltage level. The relayPin is switched to HIGH to create a trigger whenever the voltage falls below the predetermined threshold of 2V, indicating the need to switch power sources.

When the trigger is activated, the relay is automatically switched, causing the charged battery to power the discharging circuit. This ensures uninterrupted operation of the system. The positive terminal of the charging battery is also connected to an analog pin on the Arduino uno to monitor its voltage level.

In the second relay, the COM terminal is connected to the charging circuit. The NO terminal is connected to the discharging battery, and the NC terminal is connected to the charging battery. This configuration allows for swapping the batteries between the charging and discharging circuits. The same trigger signal from the Arduino is utilized to activate the second relay and initiate the battery swap. This mechanism ensures that the batteries are utilized efficiently, optimizing the power distribution within the system.

4. Results and Discussion

Hydro-Static Pressure Calculation:

In the design process of the self-energizing submarine, one important aspect to consider is the depth at which the submarine will operate. The depth has a direct impact on the hydro-static pressure experienced by the hull. To assess the structural integrity of the hull design, the hydro-static pressure at a depth of 5 meters is calculated.

The hydro-static pressure is determined by the depth of the water and is calculated using the equation,

$$P=\rho gh$$

Where, ρ is density of water i.e, ρ= 1 $Kg/mm^3 = \frac{1}{1000} Kg/mm^3$

g is acceleration due to gravity i.e., g= 9.81 m/s^2

h is depth under water i.e., h= 5 m= 5000 mm]

The density of water is commonly considered to be 1kg dm^{-3} The acceleration due to gravity is approximately 9.81 m/s^2.

Substituting these values into the hydro-static pressure equation, the calculation becomes:

$$P=\frac{1}{(100)^3}\times 9.81\times 5000=\mathbf{49.05\times 10^{-3}MPa}$$

The above calculated value represents the hydro-static pressure exerted on the submarine hull at a depth of 5 meters.

ANSYS Stress Analysis

By incorporating this pressure value into the ANSYS software analysis, the stress distribution and structural behaviour of the hull were able to be assessed under the specific hydrostatic pressure conditions. The "Equivalent Stress Distribution plot" generated by ANSYS provide insights into the pressure experienced at different regions of the hull.

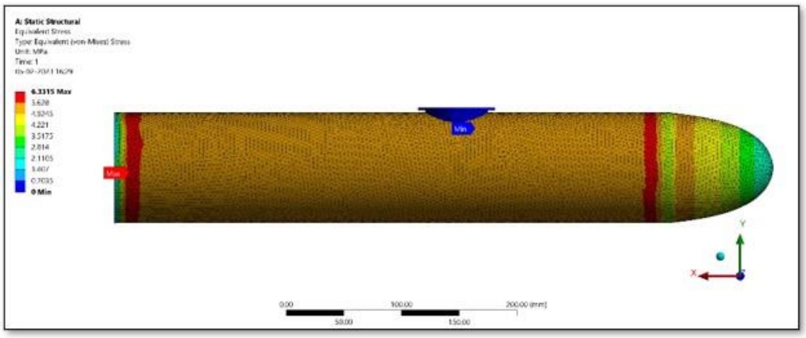

Figure 7. Equivalent Stress Distribution Plot

In accordance with **Figure 7,** the maximum stress value obtained from the analysis, in this case, was found to be 6.33 MPa (mega pascal). It is important to compare this maximum principal stress with the material's yield strength to ensure the structural safety of the hull. In this research, the PLA material was selected, which has a yield strength of 35.6 MPa.

Since the maximum principal stress of 6.33 MPa is well below the yield strength of PLA, which is 35.6 MPa, it indicates that the hull design can withstand the hydrostatic pressure at a depth of 5 meters. This result assures that the submarine's structural integrity remains intact, providing the necessary confidence in the chosen design and material.

Factor of Safety

The factor of safety is a critical parameter used in engineering to assess the margin of safety between the applied stress and the material's capacity to withstand it. In the context of the self-energizing submarine project, the factor of safety was calculated to evaluate the reliability and structural integrity of the hull design.

To determine the factor of safety, the yield stress of the PLA material was compared to the maximum equivalent stress obtained from the FEA analysis. The yield stress represents the point at which permanent deformation or failure of the material is likely to occur. In this research, the yield stress of PLA was determined to be 35.6 MPa.

By dividing the yield stress by the maximum equivalent stress, the factor of safety was calculated. In this case, the factor of safety is given by:

Factor of Safety = Yield stress of the material / Obtained maximum equivalent stress

FOS = 35.6 MPa / 6.33 MPa FOS ≈ **5.62**

The factor of safety of 5.62 indicates that the hull design has a substantial margin of safety. It signifies that the maximum stress experienced by the hull is only a fraction of the material's yield strength. A higher factor of safety implies a more robust and reliable design, as it indicates a greater capacity to withstand unexpected loads or variations in operating conditions. According to the design and analysis conducted using ANSYS, the estimated weight of the external casing model for the Whole Self-Energizing Underwater Vehicle System is 250 grams. Based on the analysis results, Polylactic Acid is determined to be the optimal material choice for the casing. However, for the prototype implementation, Polyethylene Terephthalate (PET) has been opted due to its availability and feasibility.

Figure 8. Transparent View of The Prototype with Internal Circuit

During the assembly process, careful consideration was given to the placement of the internal circuitry within the casing. The prototype is depicted in **Figure 8** and the side view is depicted in **Figure 9.** The components were positioned to ensure proper functionality and efficient use of space. To provide additional protection against water ingress, the model was sealed using waterproof tape, which helps to create a watertight barrier between the internal components and the external environment.

Figure 9. Side View of the Prototype

Special attention was paid to sealing the holes and edges to improve the waterproofing of the casing. A glue gun was used to seal any holes or openings in the hull, preventing water from entering the circuitry. This procedure is critical for maintaining the system's integrity and longevity, as well as preventing any potential harm from water exposure. The voltage in circuit was monitored using Arduino serial monitor as shown in **Figure 10**.

Through practical testing, it was determined that the turbine used in the system generates a maximum voltage of 12V and a current of 0.1A. However, under normal operating conditions, the turbine does not reach its maximum potential.

```
const int relay1Pin = 2;  // Pin connected to the control terminal of Relay 1 (R1)
const int relay2Pin = 3;  // Pin connected to the control terminal of Relay 2 (R2)
const int battery2Pin = A0;  // Analog pin connected to measure the voltage of Battery 2 (B2)

const float minimumVoltage = 2.0;  // Minimum voltage threshold for triggering the relays

void setup() {
  pinMode(relay1Pin, OUTPUT);
  pinMode(relay2Pin, OUTPUT);
  digitalWrite(relay1Pin, LOW);
  digitalWrite(relay2Pin, LOW);
  Serial.begin(9600);
}

void loop() {
  float batteryVoltage = readBatteryVoltage();
  Serial.print("Battery Voltage: ");
```

```
Battery Voltage: 3.72V
Battery Voltage: 3.74V
Battery Voltage: 3.73V
Battery Voltage: 3.74V
```

Figure 10. Arduino Battery Monitoring

5. Conclusion

In conclusion, the development of the self-energizing underwater vehicle and the potential for utilizing wave energy as a renewable power source for underwater applications have been demonstrated. Through the integration of a turbine system and careful design considerations, the prototype successfully converts wave energy into electrical energy, enabling the submarine to power its circuitry and charge a secondary battery. The ANSYS simulation analysis performed on the submarine’s hull confirmed its structural stability and ability to withstand water pressure at depths of up to 5 meters, ensuring the safety and functionality of the submarine during operation. In future, more efficient and compact systems would be created, improving the power output and reliability of self-energizing submarines. Exploring advanced battery technologies or alternative energy storage solutions, such as supercapacitors, to enhance the overall energy storage capacity and performance of the submarine would be focussed. The future work would also integrate advanced autonomous navigation systems and intelligent control algorithms to enhance the submarine’s ability to operate independently and efficiently, optimizing energy usage and power generation and conduct field trials and real-world testing of the self-energizing submarine prototype.

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