Marine Energy Collegiate Competition 2022

Written Report

Texas A&M University at Galveston

NaviBuoys

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Submitted by: Aggies by the Sea

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1. Executive Summary

Recently, the maritime industry has experienced a significant increase in marine activities such as shipping, offshore aquaculture, and oceanic mineral exploration [1]. An essential requirement to facilitate this growth is the need to build buoys for safe navigation and data communications. Texas A&M University at Galveston (TAMUG) MECC team came up with their first iteration of building NaviBuoy this last year. The developed prototype works as a proof of concept.

The developed NaviBuoy consists of a simple cylindrical shape for a flotation device to utilize the wave motion. To keep it stabilized on one axis (allow only the vertical axis), it has a spar that is fixed to the seafloor, as shown in Fig. 1. A linear generator is used for converting the wave action into electricity. A linear generator consists of a coil and changing magnetic field. To condense all the systems into one space, the power take-off (PTO) system (including the coil) is inside the buoy with magnets inside the spar. As the energy generated is dependent on the wave motion, which is intermittent and discontinuous, a state-of-the-art energy storage system whenever there is no significant wave height.

The team attracted many maritime companies during one of the seminars. The companies provided inspirational ideas for next year's group and different applications the companies want for their missions. The team left the note for modular designs for NaviBuoys for next year's team to work on.

Because this was the first iteration of NaviBuoy, the team heavily focused on the PTO system to make sure the team has sufficient electrical power to charge the battery and power up electrical systems.

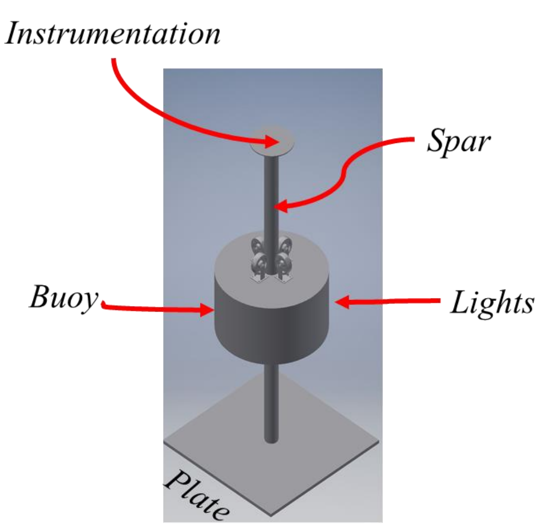

Fig. 1 - NaviBuoy made in Inventor

Fig. 2 - 3-D Printed Model of NaviBuoy

2. Business Plan

2.1 Concept Overview

This is the team's first prototype of NaviBuoy. It is a simple design to follow the wave motion and is fixed to the seafloor. It is powered by a direct-drive linear generator (DDLG) with the coils inside the buoy and the neodymium magnets in the spar. The reason the team went with a DDLG is that the team wants the maximum energy transfer from the waves to the buoy [2]. The electricity produced by the DDLG will be rectified by the full-bridge rectifier. Then, it will go through the maximum power point tracking (MPPT) system for regulating the charging current of the lithium-iron-phosphate battery (LFP). The developed NaviBuoy is used for powering the navigational lights that are specified by the United States Coast Guard (USCG) regulations and their Aids to Navigation (ATON).

With its optimal design and reliable operation (with an embedded LFP battery), NaviBuoy will provide a sustainable solution for powering navigational lights, without relying on solar and/or wind power or without the use of heavy batteries or connection from the grid. With the projected exponential increase in shipping companies and other maritime businesses since the start of 2021 [1], this solution has good potential to become a sustainable solution. This buoy would greatly reduce the number of groundings by ships and barges through the ship channel. Having validated the proof of concept, the next design attempts to increase the power rating of the system to accommodate weather tracking systems.

With the prototype development and deployment by the team, this project has proved to be another strong step in the ongoing quest to make the TAMUG campus self-reliant and sustainable. The developed prototype will prove to be an excellent start for the next-year team members, and it will help in encouraging other undergraduate students to participate in these events thereby helping them to develop critical thinking and problem-solving skills. The challenges faced during the projects and the developed solutions will be demonstrated to the visiting high-school students during the laboratory visits. This activity will encourage the students to participate in green-energy efforts especially related to the blue economy.

The major environmental aspect is the elimination of solar or wind or grid-connected structures and replacing them with a marine-friendly and wave-powered navigation system. With further design iterations, it will be possible to increase both the power rating and operational efficiency of the system. The other environmental aspect is that the LFP used does not contain nickel or cobalt, both of which are supply-constrained and high in cost [3]. As of 2021, LFP is projected to surpass lithium nickel manganese cobalt oxide (NMC) batteries and grow in the market [4].

2.2 Relevant Stakeholders

NaviBuoy's business model targets the maritime shipping industry. The first iteration of NaviBuoy focuses on navigational safety ships/boats nearby territorial waters. Further iterations will expand to government organizations such as the USCG, and National Oceanic and Atmospheric Administration (NOAA) by integrating meteorological data and wireless communications. During the team's industry seminar, multiple companies took interest in NaviBuoy and provided other ideas to meet their demand.

2.2.1 Prime Ocean

During the seminar, the team talked with one of the representatives from Prime Ocean. They are an offshore drilling company from the Gulf of Mexico. The team caught the attention of Prime Ocean that the team can potentially replace their emergency diesel generator or employ a fleet of buoys to power their oil rig. The company also suggested that even if there is no wave height for the DDLG, the team can implement a hybrid energy source such as solar power. That way, the company does not have to spend money on procuring the fuel and maintaining its diesel engine. In addition, Prime Ocean also wants to reduce the carbon emissions being released into the atmosphere from its generators by using clean energy. Another idea Prime Ocean wants to do is put the DDLG in its four support columns.

Oil rigs, typically consume between 20-30 m^3 of diesel per day [5]. Because Prime Ocean works in the Gulf of Mexico area, their oil rigs experience about one-to-two-meter wave heights. NaviBuoy's current design in those conditions will produce around 500 watts. By implementing DDLG to the support columns, the rig will produce about 2 kilowatts of power. The team concluded that NaviBuoy needs to find other ways to increase power output from the DDLG or design a fleet of NaviBuoy and connect it to the oil rig.

2.2.2 Weeks Marine

The team contacted a representative for Weeks Marine. Weeks Marine is a maritime construction company that spans from North America to South America. Their main specialty is marine construction, dredging, and other marine services [6]. Their main power and propulsion are diesel-electric based. They took interest in our project and the concept of point-absorber buoys such that they want to reduce the load on the diesel engine to only propulsion systems and power their dredging system by using wave energy. By using NaviBuoy, not only will they produce power from the waves, but they will also provide additional navigational safety for other mariners out in the ocean, especially at night time. With the team's current design of NaviBuoy, this will meet the demand of Weeks Marine.

2.3 Market Opportunity

In 2012, the market for ocean sensors and observation was estimated to be $16 billion and projected to increase over time [7]. As emerging technology continues to grow within the ocean observation and navigation sector, the prices will continue to increase due to the increased demand for power. To meet the power demand from navigational safety and to compete with other renewable energy sources, NaviBuoy will provide both sea safety and marine energy harnessing.

When the team was going through the sub-system selection for the buoy, the team picked out the most cost-effective and innovative technology that the world has to offer. The Department of Energy (DOE) compared the prices of LFP with NMC batteries that are being used for electrical storage. LFP batteries were first reported to have a levelized cost of electricity (LCoE) of 12.5 watt-hours/$ [8]. It turns out that the LCoE was 6% lower than NMC. LFP also lasts 67% longer than NMC batteries. Even though the initial cost of LFP is higher than the majority of the popular batteries, it still has a lower LCoE, making it cost-effective for power storage and NaviBuoy [9].

2.4 Development and Operations

Although the immediate team's goals are to provide navigational lighting for the Galveston ship channel, a much broader scope can be applied to the said buoy. The power that this buoy can provide can be utilized to power many applications that can have other purposes such as providing power to drill ships or even offshore weather stations. Further development would be required, specifically in the spar to achieve these results; however, the buoy itself can withstand an offshore environment currently. The team has gained a valuable relationship with a local island fabrication shop (IMC; Industrial Material Corp.), that would be capable of producing one buoy every two weeks. Given this, the team would be able to provide a total of twenty-six buoys per year, which would allow for an offshore buoy farm to be implemented. The team would also require more funding for this to take place and additional human resources to handle logistics, as well as feasibility.

The current MECC team has been trying to recruit members for the upcoming year to further the research and development of this project. Thus far, the undergraduate students have expressed interest in joining this effort due to the overall motivation in renewable energy sources, as well as the potential in the buoy currently built. The inaugural team has proven that this concept can provide sufficient power for purposes of navigational lighting, and future work can be conducted to not only enhance the overall electrical system; but also expand upon its rudimentary ideas to provide carbon-free and renewable power.

2.5 Financial and Benefits Analysis

After analyzing the team's financial expenses for the project including material purchases as well as pursuing professional guidance, the team ultimately calculated the device to cost a total of $5000. This number is small considering the cost of current buoys in production, and the benefits of this device far out way the overall cost. Given more funds, time, and resources for future competitions, future teams would have the possibility of bringing this cost down and increasing the power rating of the system. Materials purchased could be found at a cheaper cost if purchased in bulk as well as the utilization of an assembly line attitude where the team creates multiple buoys with a process results in a much lower manufacturing cost.

3. Detailed Technical Design

3.1 Design Objectives:

The design objectives of this project are listed below:

- To design and build a renewable energy converter from the energy provided by the ocean
- To improve the efficiency of this device by implementing a multi-magnet system that will prove useful in low-light conditions where other forms of renewable energy are not readily accessible
- The team also has a desire to harness this energy and then use it in the form of navigational lights for the Galveston ship channel.

The above design objectives can be specified into target value to further clearly provide the specification of different components as given in Table 1 below.

Table 1 Design Objectives

	Design Objective	***Units***	***Target Value / Range***
1	Electrical Power	Watts	<= 400 W
2	Safe, Reliable, Renewable	Unitless	Zero Carbon Emission
3	Navigation Lighting	Volts	12 V

3.2 Design Components:

The components required for successfully completing the above-mentioned objectives can be segregated into three categories. They are:

Power Production:

- Design of current-carrying coils
- Magnets – material, their orientation, and their location on the Buoy body
- Spar – for allowing only vertical motion of the Buoy.
- Body – to ensure water-tight assembly for battery safety.

Storing power:

- Battery storage will be used for filtering out the intermittency and discontinuity of mechanical input from wave motion. For this purpose, different battery alternatives will be evaluated.

Load:

- A potentiometer will be connected as a load to test the system. Decreasing the resistance will increase the current output up to the rated value.

3.3 Proposed System/Concept:

To meet the design objectives, the team has done extensive brainstorming to list every possible solution. For better understanding, the team has functionally decomposed the desired structure, as shown in Fig. 1.

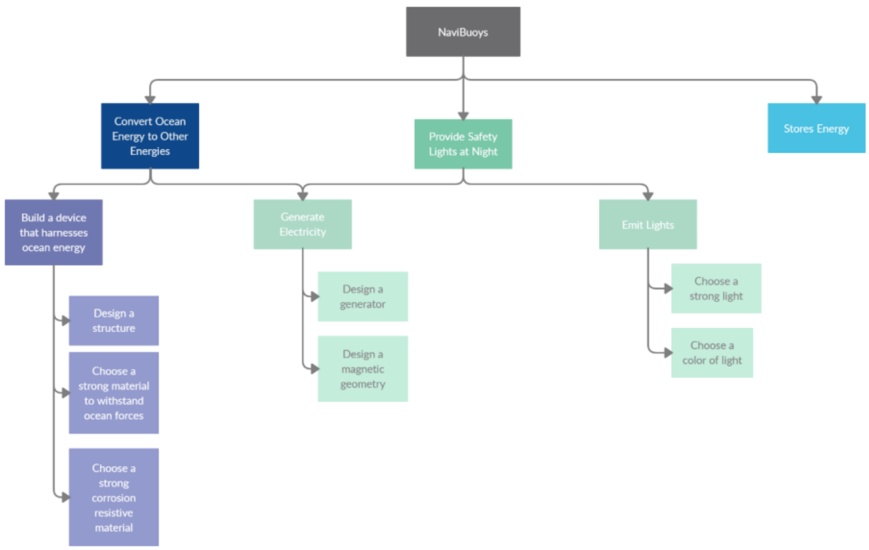

Fig. 1. Electric Wave Generator functional decomposition

To meet this functionality requirement, different concepts are discussed (summarized in Table 2).

Table 2 Different concepts capable of meeting the requirements

Sub-Functions	Concepts				
	1	2	3	4	5
Build a device that harnesses ocean energy	Oscillating Water Columns	Overtopping Device	Point Absorbers	Terminators	Attenuators
Generate Electricity	Linear Generator	Hydraulics	Thermoelectric Material	Piezoelectric Material	Photoelectric
Emit Lights	LED	Incandescent	Compact Fluorescent	Halogen	
Stores Energy	Battery	Flywheel	Accumulators		

These listed options are then rated based on their weights, material requirements, cost, etc. The final outcomes selected are now used for making the final design. In this design, the wave motion will be utilized to push a buoy (a point absorber) up and down a spar. The spar is used to stabilize the buoy and restrict the motion only on the vertical axis. To ensure this, the spar is fixed to the seafloor. For generating power from the wave motion, a linear generator will be used. This generator consists of a coil assembly and a changing magnetic field. The current-carrying coils will be placed inside the buoy, whereas the static magnets will be placed in the spar. As the buoy moves up and down, the magnetic field experienced by the coils changes, thereby inducing a current in the coils. This variable frequency and intermittent power will be rectified using electronic circuitry to charge a battery bank. This battery bank helps in filtering out the variability in wave motion-based power generation. The output of the battery bank is used for powering navigational lights that will be on top of the buoy. These lights will help get ships and boats where they need to go safely.

3.4 Design Description:

In the design analysis of the point absorber buoy, many components were analyzed to ensure a working buoy. Components such as electrical including battery, and buoy material and operation were all taken into consideration when calculating the various loads needed and being applied. The components along with the analysis required are listed in Table 3.

Table 3 Engineering Analysis Requirements

Item #	**System Component or part description**	**Description of analysis needed for the design, sizing, specifying, or selecting component**
1	Buoy	Will the buoy be buoyant with the given material? Will the buoy withstand the wave forces?
2	Linear Generator	How much voltage will the generator produce? How much power will the generator produce?
3	AC/DC Converter	How much will the diodes have to withstand the reverse voltage?
4	Lithium Iron Phosphate Battery	How long will the linear generator take to charge the battery? How long will the battery last at a given load?

For the feasibility of the design, the following boundary conditions are defined:

Strength of Mag Flux: 0.7 T

Wavelength of Wave: 5 m

Frequency: 0.3 Hz

Wave Amplitude: 2 m

Speed of Horizontal Wave: 0.7 m/s

Coil Turns: 30

Density of Seawater at 20°C

3.4.1 Dimensions of the Floating Buoy:

System Component Description: Dimensions of the Floating Buoy

Component Idealization (Description): Buoy will be buoyant to follow the wave action and it will not be fixed onto the spar.

Mathematical Analysis of System Component:

Space being cleared out

Length_1 = 1ft

Length_2 = 1ft

Depth = 2 ft

Surface Area = 8 ft^2

Volume = 2 ft^3

$$SA = 4 * lh = 1\,ft * 2ft * 4 = 8\,ft^2$$

$$V = lwh = 1\,ft * 1\,ft * 2\,ft = 2\,ft^3$$

Floating Buoy

Radius = 1.5 ft

Height = 2 ft

Surface Area = 32.99 ft^2

Volume = 14.14 ft^3

$$SA = 2\pi r^2 + 2\pi rh = 2\pi(1.5ft)^2 + 2\pi(1.5ft)(2ft) \approx 32.99\,ft^2$$

$$V = \pi r^2 h = \pi(1.5ft^2)(2ft) \approx 14.14\,ft^3$$

Overall Buoy

Material Thickness: 0.125 in = 0.0104 ft

$$SA_{Overall} = SA_{Buoy} - SA_{Space} \approx 22.99\ ft^2$$

$$Volume_{Shell} = SA_{Overall} * Thickness = 0.239\ ft^3$$

Density of 6061 Aluminum = 168.555 lbs/ft^3

Weight = 40.36 lbs = 18.3 kg

$$Weight = \rho V \approx 40.36\ lb \approx 18.3\ kg$$

Analysis Results Interpretation:

Weight of the buoy is approximately 40.36 lbs or 18.3 kg at the given dimensions.

3.4.2 Generator Sizing:

System Component Description: Generator sizing

Component Idealization (Description): Assuming ideal conditions such as perfect energy transfer and no losses. The generator will be greater than 51% of the total energy system.

Mathematical Analysis of System Component:

Faraday's Law/Induced Electromotive Force

$$\varepsilon = -N\frac{d\Phi_B(x,t)}{dt} = -N\Phi_{B,0}(kx' - \omega)\cos(kx - \omega t)$$

where, N = Number of Turns

Voltage Amplitude

$$Voltage\ Amplitude = \max(\varepsilon) \approx 21.11\ V$$

Therefore, RMS Voltage is

$$V_{rms} = \frac{V_{amp}}{\sqrt{2}} \approx 14.93\ V$$

Generator's Inductance

$$L_{Generator} = \frac{N^2\mu_0 A}{l} = \frac{30^2\mu_0(\pi * 0.3048m^2)}{0.6096\ m} \approx 1.776\ mH$$

Generator's Resistance

$$R_{Generator} = \frac{\rho l}{A} = \frac{(1.75 * 10^{-4})(30 * \pi * 0.6096m)}{\left(\frac{\pi(0.32004 * 10^{-3}m)}{4}\right)} = 40\Omega$$

Analysis Results Interpretation:

At the given speed of the waves, the induced rms voltage will produce approximately 15V.

3.4.3 AC to DC Conversion with Zener Regulation:

System Component Description: AC to DC conversion with Zener regulation

Component Idealization (Description): Voltage drop across the diode is 0.7 V. Zener diode breakdown voltage is at 21 V. Current will be heading towards MPPT and Battery Management System

Mathematical Analysis of System Component:

Full Bridge Rectifier

$$V_{out} = V_{rms} - 1.4V = 13.53V$$

Peak Inverse Voltage = 19.83 V

Analysis Results Interpretation:

The diode needs to withstand at least 20V in reverse bias conditions.

3.4.4 Lithium Iron Phosphate Battery:

System Component Description: The Lithium Iron Phosphate Battery system is designed to supply electrical power to navigational lights on the buoy.

Component Idealization (Description):

Lithium Iron Phosphate Battery System model will contain MPPT Charger to charge, Battery Management System for overcharging protection, and Navigational Lights as the load.

MPPT will be used to regulate output voltage and output current.

Battery Management System prevents overcharging.

Arduino will control when the light turns on/off when solar panels reach a certain voltage value. Power source will be from the Li-ion batteries.

LED will produce about 800 lumens at 10 watts. They will be connected in series and will be in a shape of a circle to be visual at 360°.

Batteries will be configured in series (to increase voltage).

Mathematical Analysis of System Component:

MPPT will sense the capacity of the batteries to control the flow of current.

Solar Panel Specification:

Max Power at STC = 100W

Open-Circuit Voltage = 21.6 V

Short-Circuit Current = 6.24 A

Arduino Control:

Turn on/off the switch at 5V

LED:

Power Rating: 10 W

Voltage Rating: 2V

Minimum current to light up: 20 mA

$$P = \frac{V^2}{R}$$

Lithium Ion Batteries:

Nominal Voltage: 3.6V

Max Voltage: 4.2V

Nominal Capacity: 3200mAh

Not Protected

Series Configuration:

$$V_{DC,Total} = 7 * 3.6V = 25.2V$$

Total Resistance of LEDs:

$$R_{LED} = \frac{2V}{20mA} = 100\ \Omega$$

$$R_{Total} = \left(\frac{6}{100\Omega}\right)^{-1} \approx 16.\bar{6}\Omega$$

Current Limiting Resistor Sizing:

$$I_{LED} = \frac{2V}{16.6\Omega} \approx 116mA$$

Kirchhoff's Voltage Law:

$$25.2V = 116mA\ (R_{limiter} + 16.6\Omega)$$

$$R_{limiter} \approx 193.4\Omega$$

Standard Size of Resistor: 200Ω

Charging Time

Case 1: Only Wave Energy

Generator RMS Current: 80 mA

$$t = \frac{Ah}{I_{gen}} = \frac{3200mAh}{80mA} \approx 40\ hours$$

Case 2: Solar and Wave Energy

$$t = \frac{Ah}{I_{gen} + I_{solar}} = \frac{3200\ mAh}{0.08\ A + 4.63\ A} \approx 0.68\ hours$$

Discharge Time

$$t = \frac{Ah}{I_{LED}} = \frac{3200mAh}{116mA} \approx 27.59\ hours$$

3.5 Detailed Drawing:

The two main components are the buoy itself and the spar which the buoy will move in a vertical motion given various wave heights. In Figure 2, overall buoy design is shown. Fig. 3 shows the overall design.

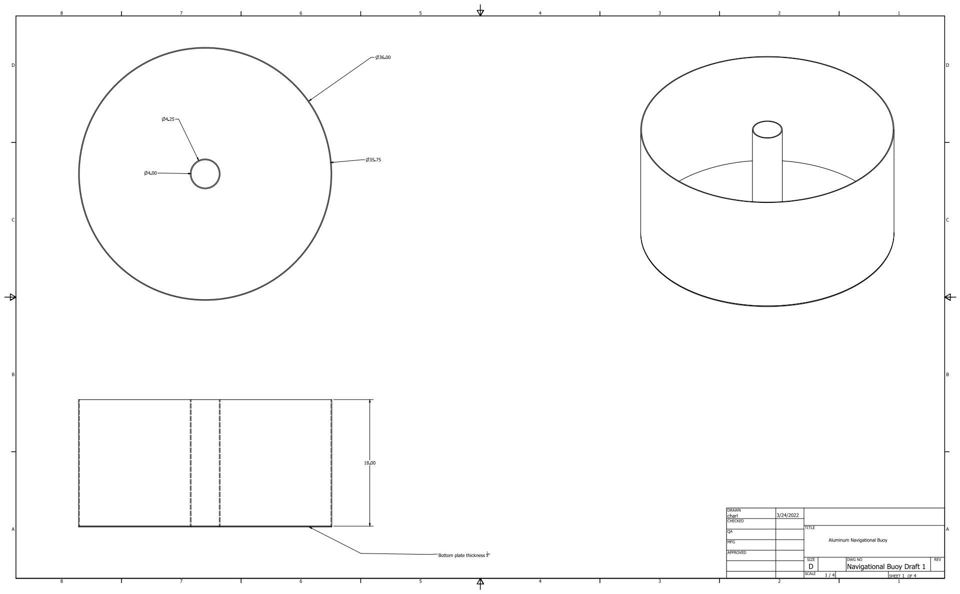

Fig. 2. Overall Buoy design

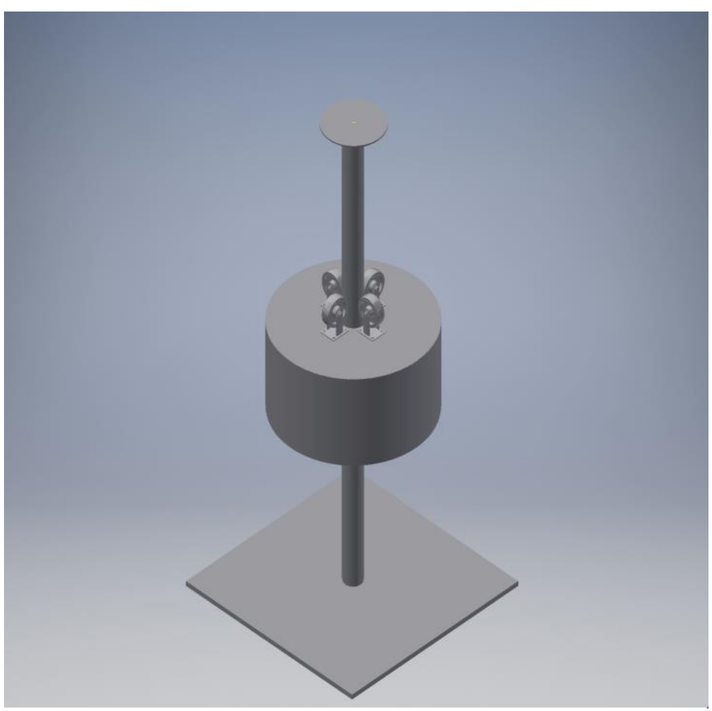

Fig. 3: Final design

3.6 Mathematical Modeling and Simulation Results:

EveryCircuit was used to simulate the electrical design of the given circuit, based on the derived specifications. Fig. 4 shows the model circuit of NaviBuoy. The 1Hz ac source along with R = 1.3kΩ and L = 2H indicates the linear generator, followed by the diode-bridge rectifier. The 12V-dc voltage source represents the battery and the LED loads are connected to the output with a switch and a resistive load.

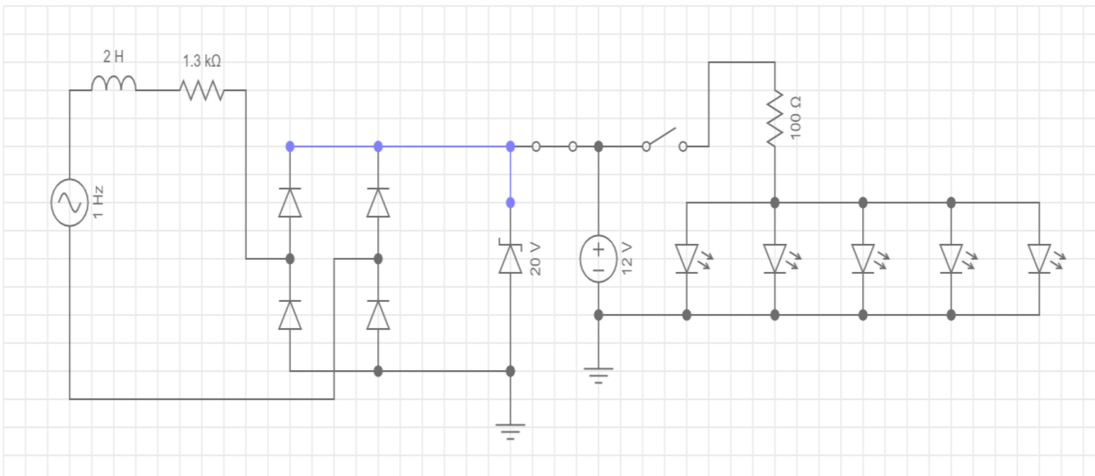

Fig. 4: Model Circuit of NaviBuoy made in EveryCircuit

3.7 Simulation Results:

The detailed simulation results of the design are presented in Fig. 5 to Fig. 8. For verification of the linear generator and ac-dc diode-based rectifier, the phase voltage and currents are shown in Fig. 5 and Fig. 6 respectively. The different forces in the buoy are shown in Fig. 7. The resulting friction force and PTO force are shown in Fig. 8. It should be noted that friction forces represent a smaller portion of the PTO forces.

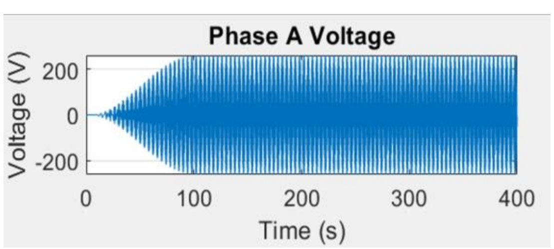

Figure 5: Simulated NaviBuoy's Voltage

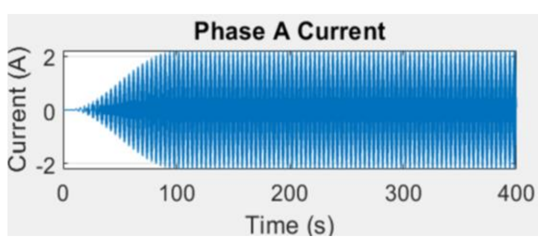

Figure 6: Simulated NaviBuoy's Current

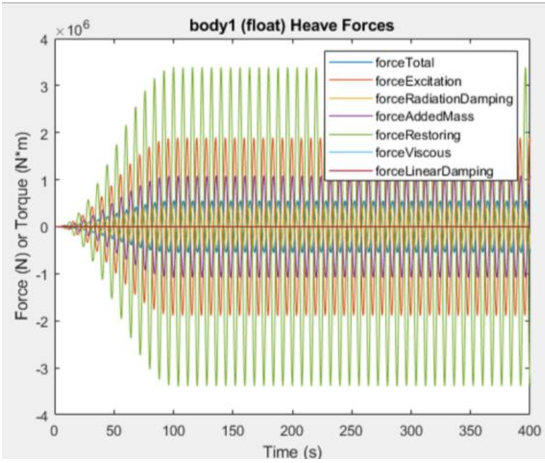

Figure 7: Simulated NaviBuoy's Heave Forces

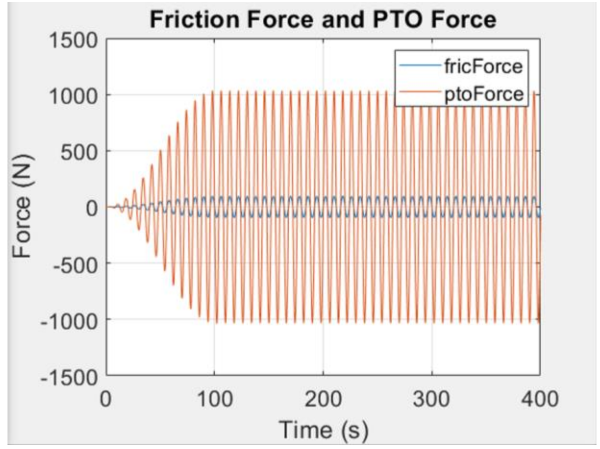

Figure 8: Simulated NaviBuoy's PTO and Friction Force

3.8 Hardware Demonstration:

The developed Buoy is tested (detailed in Build and Test Report). The real-time voltage generation from the NaviBuoy is shown in Fig. 9. At slow speeds, the team was able to turn on the LED; however, at high speeds, the team was able to burn the LED.

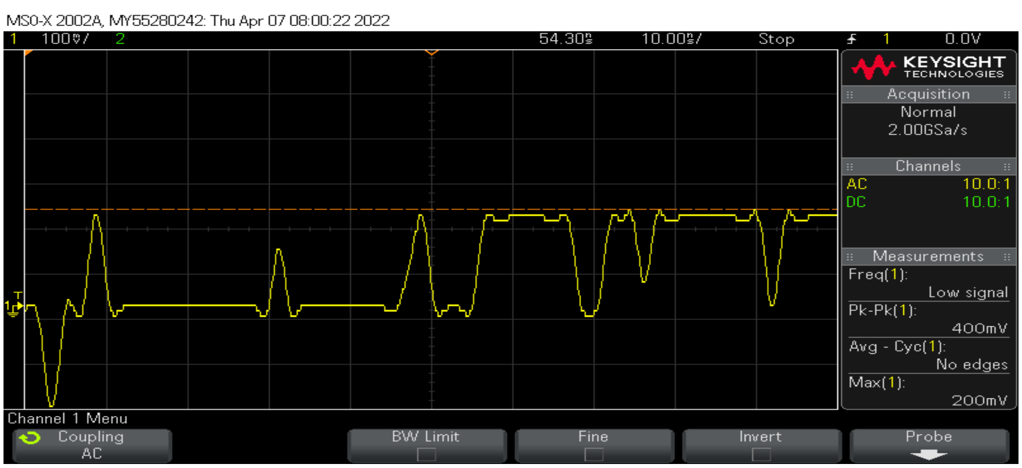

Figure 9: Real-Time Oscilloscope Reading of Model NaviBuoy

4. Conclusion

Wave energy is emerging as an attractive renewable energy source for powering off-shore loads such as oil rigs, navigation lights, and weather tracking systems. To explore this renewable energy option further, the MECC team at TAMUG has designed, built, and tested the NaviBuoy. The NaviBuoy extracts power from the wave motion through a simple linear generator to power navigational lights placed on the top of the buoy. A Linear generator consists of moving coils (as per the wave motion) in the presence of a static magnetic field. For improved power reliability, a battery system is also embedded in the buoy. To restrict the movement of the coils to only the vertical axis, the buoy is fixed to the seafloor through a spar.

For optimal design of the NaviBuoy, a detailed functional decomposition is explored initially. This process helped in brainstorming and coming up with different choices available for achieving the individual functional requirements. These options are evaluated to select the optimal ones in terms of weight, cost, and time feasibility. The next stage was to design the different components of the system based on the given specifications and operational constraints. Once the design is finalized numerically, a detailed mechanical design is done in Inventor. This helped in the generation of the different mechanical drawings required for 3D printing and other assembly purposes. Further, the electrical system is simulated using EveryCircuit and Simulink to validate the obtained design and feasibility to support the operation as per mandated by the challenge. The simulation results validate the performance of the electrical system, and also the capability to withstand different forces, typically observed during the real-time operation. Finally, the built prototype is tested and the results obtained show the ability of buoy to power navigation lights, even at low wave speeds. With further design effort and optimization, it will be possible to power additional loads with the buoy system.

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