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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF WAVE ENERGY HARVESTING THROUGH BUOY EFFECT

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ABSTRACT

Wave energy is a reliable source for power production from the perspective of certainty. The study focuses on determining an appropriate buoy structure of specific material to develop a mechanism to harvest wave energy from a catchment area cost-effectively. In addition, it includes designing different shaped buoys structures as well as simulating these individually using SolidWorks and ANSYS software and comparing these structures to determine the most efficient one. Afterward, the buoy structure or float is used to design an entire mechanism to harvest wave energy. The simulation analysis shows that the tulip-shaped buoy is the most efficient structure from the perspective of strength and durability as it can withstand maximum stress compared to spherical and cylindrical buoys. Moreover, this study represents the significant effects of wave heights on the power production of this wave energy harvesting mechanism. The experimental study demonstrated that it generated a minimum of 5 mV and a maximum of 95 mV from the lowest and highest wave heights respectively. This mechanism can be used in remote places with the availability of different catchment areas.

Keywords: *Harvest, Wave energy, buoy, Wave heights, Design, Simulation*

NOMENCLATURE

Symbol	Abbreviation
F_b	Buoyancy force
F_g	Gravitational force
F_s	Slamming force

1. INTRODUCTION

Nowadays, highly developed countries are showing increasing demand for energy production and a statistical report states that the energy demand will be 100% higher in 2040 than in 2016 [1]. Besides, the fossil fuel depletion, ecological requirements, and safety policies of the environment claim for dependency on renewable energy sources [2]. Renewable energy is collected from variable renewable energy resources in the energy system which is naturally replenished in a human timescale such as sunlight, wind, rain, tides, waves, and geothermal heat [3]. It requires no fuel cost and can be harvested most of the time in a year [4]-[5]. Wave energy drawn from waves can serve better as it is always formed in ponds, rivers, and seas regardless of time and weather among all renewable sources [4], [6]−[9]. As the wind blows across the water surface, it transfers the energy of winds to waves only when the speed of waves above the water surface is slower than the wind [10]. Friction and pressure differences between the upwind and water surface force the development of shear stress into water that causes the growth of waves [11]. The wave energy production has a spacious range of output with varying wave height, wave speed, water density or wavelength to produce energy [12]. In contrast, it can produce a significant amount of energy with low wave speed, low wavelength, and low wave height due to its characteristics of flow [13]. However, among other energy production sources, the hydroelectric process requires a large initial investment and sometimes threatens the environment. In addition, the expense and inconsistent availability of solar and wind power make it disadvantageous and cannot contribute significantly to total energy production [10].

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Solar energy is weather dependent as well as requires a high initial cost and area for power generation which results in a drop in power production [14]. According to the U.S. Energy Information Administration, Utility Scale Electricity Generation by energy source, 2019 (Source: Energy Information Administration) 17.5% of total energy was produced from renewable energy sources among which 37.71% was produced from hydropower as shown in Fig. 1. However, this data comprises marketed production solely. In the case of non-marketed energy production, some steps have been taken without the involvement of the government to fulfill the necessity of personal requirements [15]. Many research works have been conducted to produce wave energy and convert it to electricity along with some literature suggestions [16]−[23].

Safian et al. [16] used piezoelectric material to harvest vibrational energy caused by the buoyancy force of ocean waves. Besides, the energy production increased along with the thickness of piezoelectric material resulting in a greater production with PZT-5H than PZT-5A in the same condition. However, the result was anticipated to produce 2.5 kWh monthly using 100 mechanisms. These data made the process inapplicable whereas, Leijon et al. [4] studied a wave power utilization mechanism using a linear generator placed on a seabed directly connected to a floating buoy of point absorbing category. The generator piston was rotated directly by the buoy movement and spring was used to build up and counteract the movement. However, the design and fabrication require expert maintenance as well as it loses its efficiency during heavy storms. In contrast, Viet et al. [17] showed a mass-spring system harvester to transfer wave motions into mechanical vibration and a piezoelectric device for amplifying and collecting the produced electrical energy. The RMS of generated electric power increased from 20W to 103W as the wave amplitudes changed from 1 m to 2 m and it increased from 3.3 W to 4.65 W with the rise of wave height from 0.02 m to 0.05 m. In the case of mass, the RMS increased from 0.4 W to 25.5 W due to an increase of mass from 5 kg to 100 kg for the steel lever. However, the relation was inversely proportional in the case of the wave period. It decreased from 6 W to 4 W with an increase in wave period from 4 seconds to 7 seconds [18]. He et al. [19] represented Pelamis wave energy converter in their research outside of the Xiamen Bay Sea area. Response of the three sections and the swing angle range were affected by the wave period and wave height. Retzler et al. [20] introduced an experimental investigation of damping and excitation of a slow drift of Pelamis to harvest wave energy. Lindroth et al.[21] studied wave energy measurements conducting short-term, medium-term, and long-term experiments using removable harbors, removable sidewalls, and a capacitive probe array of five points. Mueller et al.[22] reported on harvesting ocean wave energy with a piezoelectric coupled buoy using electrical generators. Murray [24] reported a novel two-stage piezoelectric wave energy harvester. The authors introduced a prototypical design consisting of a float, pump, and arm and computer simulation to harvest wave energy at the port of Pecem in San Goncalo do Amarante, Ceara State in Brazil as Brazil's coasts have a higher potential for energy production up to 87 GW [25]. Though it has been an insatiable desire to use wave energy for consumption, the issue of costing and maintenance has become a challenge without proper funding. The main concern of this paper is to establish a cost-effective mechanism to harvest energy from waves using the buoyancy force of water in remote areas with the availability of water bodies. The most efficient float structure is designed and simulated before fabricating the experimental setup. This procedure does not require any advanced technology or huge initial investment and it offers the flexibility of materials and dimensions.

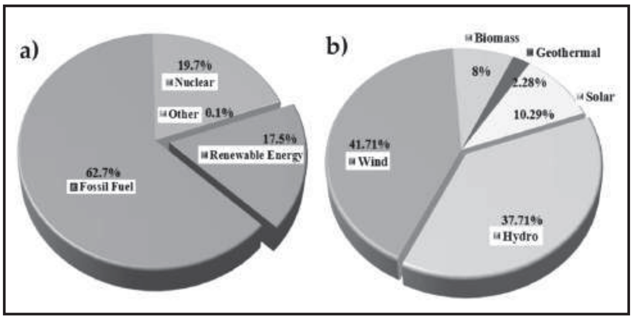


Fig. 1 (a) Pie Chart of Energy Consumption, 2019 and (b) Pie Chart of Renewable Energy Consumption, 2019.

2. MATERIAL AND METHODOLOGY

2.1. Materials

Polyvinyl chloride rigid material possesses resistance to corrosion, chemical rotting, abrasion, and weathering [26]. It is also available, cost-effective, and light in weight. Hence, this material was selected for designing and simulation of the float in this research due to its properties (density, tensile strength, impact strength, Young's Modulus, melting point, water absorption, specific heat, heat transfer co-efficient, etc.).

2.2. Methodology

Three different buoy geometries are designed in SolidWorks such as spherical, cylindrical, and tulip (combination of cylindrical and conical shape) [27]-[28] as shown in Fig. 2. The volume is kept at 0.1131 m^3 and the thickness of every wall is 0.04 m in all structures for accurate and easier comparisons with a hollow inside.

These structures are simulated using the finite element method (FEM) ensuring identical boundary conditions in ANSYS (student version-16.0). In addition, equivalent stress (Von-Misses) analysis and directional deformation analysis were conducted on these structures. The simulation results are shown in Figs. 3-5 for the three structures respectively. It is worthy to mention that equivalent stress analysis was performed to find out the most suitable geometry for the buoy structure as the structure that experiences minimum stress is considered to be more efficient than other structures for the same applied load. The forces acting on the buoy structure are gravitational force and buoyancy force where both of these forces act opposite to each other.

In boundary conditions, 0.05 MPa to 0.30 MPa load is applied to represent the buoyancy force in six steps towards the positive vertical direction on each structure. The applied pressure is kept within this range to ensure the maximum stress within the elastic limit for each buoy. It is observed that the maximum stress of spherical buoy structure is 4.689 x 10^6 N/m^2 which is less than the ultimate strength of Polyvinyl chloride (PVC) rigid material as shown in Fig. 3.

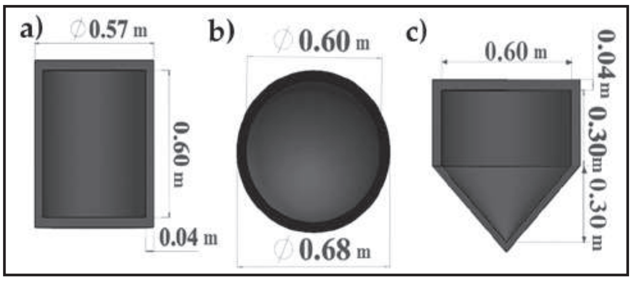


Fig. 2 (a) Cylindrical Buoy; (b) Spherical Buoy; and (c) Tulip Buoy.

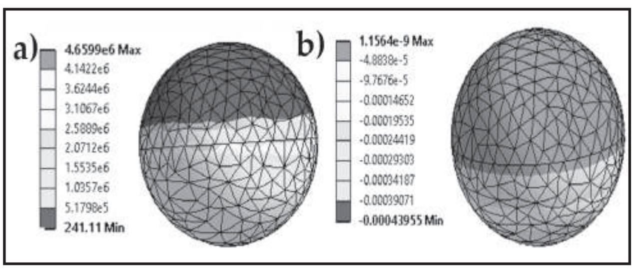


Fig. 3 (a) Equivalent Stress (Von- Misses) Analysis of Sphere Buoy and (b) Directional Deformation Analysis of Sphere Buoy.

However, maximum stress of 1.266 x 10^7 N/m^2 is observed for Cylindrical-shaped buoy and 3.816 x 10^6 N/m^2 for a tulip-shaped buoy as shown in Fig. 4 and Fig. 5, respectively.

In addition, deformation analysis was performed to observe the maximum displacement of each buoy structure. The buoy structure representing maximum deformation for the identical load applied to each structure is considered to experience maximum displacement towards the positive vertical direction. Furthermore, this maximum vertical motion will be utilized for power production according to this proposed mechanism. Hence, the structure with maximum displacement represents the appropriate geometry for the buoy structure to harvest wave energy. It is observed that maximum directional deformation for spherical buoy is 1.1564 10–9 m towards the positive vertical direction, whereas 1.1805 10–3m for cylindrical buoy structure and 3.2586 10–7m for tulip-shaped structure. The simulation result suggests that the cylindrical buoy will be more efficient in providing maximum vertical motion. In contrast, the stress analysis result refutes as the cylindrical structure is ascertained to experience maximum stress than the other two structures. Hence, excluding the cylindrical shape, the second maximum displacement is observed to be in a tulip-shaped buoy structure. The stress analysis and directional deformation analysis are plotted for each buoy structure as shown in Fig. 6.

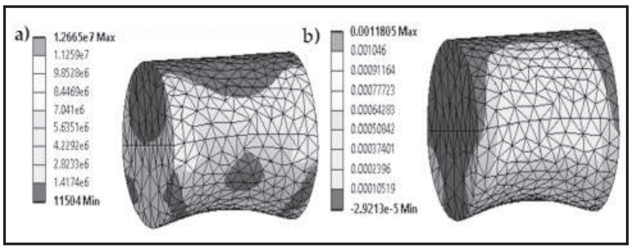


Fig. 4 (a) Equivalent Stress (Von- Misses) Analysis of Cylindrical Buoy and (b) Directional Deformation Analysis of Cylindrical Buoy.

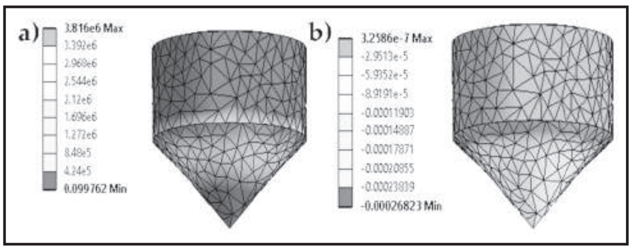


Fig. 5 (a) Equivalent Stress (Von- Misses) Analysis of Tulip Buoy and (b) Directional Deformation Analysis of Tulip Buoy.

The horizontal axis represents the time and the vertical axis normalizes the equivalent stress in MPa and vertical directional deformation in m. It is concluded that the tulip-shaped structure is assuring minimum stress with a maximum directional deformation. Hence, the tulip-shaped structure was chosen for designing and fabrication of the proposed mechanism to harvest wave energy efficiently and cost-effectively with the help of the buoy effect. The structure is needed to be very light in weight as the buoyancy force was used to make this simple procedure work. The buoyancy force (F_b) has to be equal to or greater than the gravity force (F_g) to make the buoy float [28]-[29]. The gravitational force generally also includes the slamming force (F_s) [28] which is neglected in both theoretical and experimental calculations in this research work.

The structure consists of floats, pulleys, belts, links, an alternator, and a voltmeter. Tulip-shaped floats placed on the water function as point absorber buoys. The energy of waves provides movement to the floating structures to create a translation motion in the vertical direction as the wave flows. This translation motion is transferred to the links connected to the floats and the other ends of the links are connected to a pulley mechanism consisting of two pulleys and two belts. The translation motion is converted into a rotary motion connected to an alternator through a shaft. Hence, the shaft rotates with the pulleys as well as the alternator starts generating power. The amount of current flow is calculated by ohm's law from the measured voltage and resistance. Moreover, the wave heights are observed every time by using a measuring scale when voltage and resistance values were taken. It is noted that the amount of energy production differs with every different wave height.

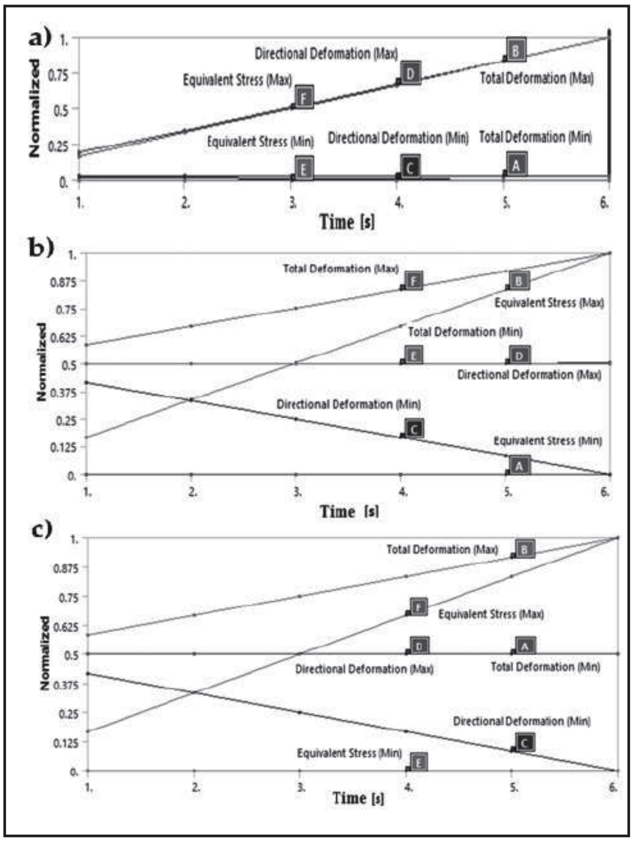


Fig. 6 Graphical Analysis of (a) Spherical Buoy Structure; (b) Cylindrical Buoy Structure; and (c) Tulip Buoy Structure.

3. EXPERIMENTAL SET-UP

In this mechanism, the structure of float is determined consciously as it absorbs the buoy effect and provides a force to the pulley through links. Tulip-shaped floats are used due to their geometrical configuration. Besides, the center of gravity of the float is always at the bottom center of the body irrespective of its level of emersion in the water. The physical experimental setup is shown in Fig. 7. The weight of the mechanism needs to be as minimum as possible to facilitate the easy rotation of the pulleys for proper functioning. The pulley is mounted on the shaft as well as ensures smooth rotation.

Both the pulley and links can slide over the shaft to get a proper position whereas the small pulley is mounted on another shaft fixed at its position. There is no relative motion between the floats and

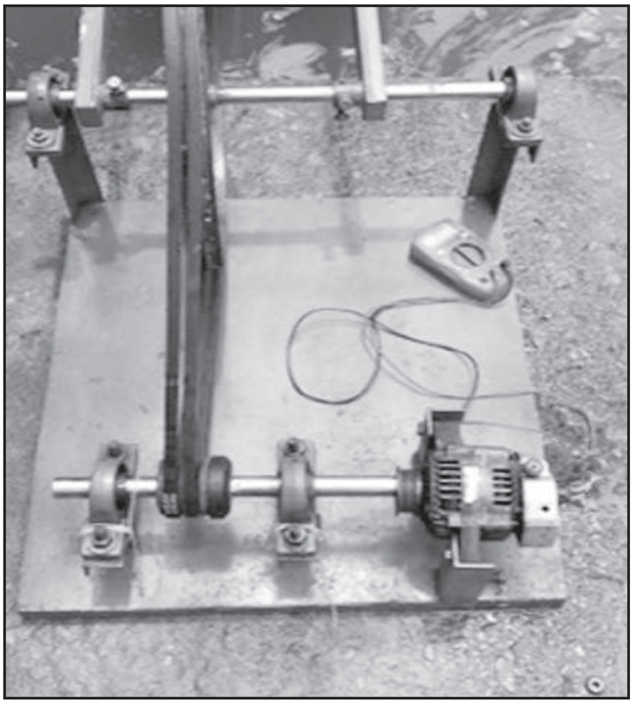


Fig. 7 Experimental set-up.

the links or it may reduce the efficiency of the experiment. The floats are airtight sealed to prevent any leakage. There is an 8:1 ratio between the diameters of small and big pulleys implying that the small pulley gets four full rotations while the big pulley completes a half rotation. V-belts are the most efficient in the case of small-distance transmission [29]. However, it will be difficult to cut grooves at the peripheral boundary of the pulleys due to their geometrical structures and strength. As a result, flat belts have been used in this construction. Two flat belts run side by side instead of a single wide belt to provide a very conveying system [30]. One end of this shaft is fixed on the baseplate by bearing and another end is fixed with the rotor of the alternator.

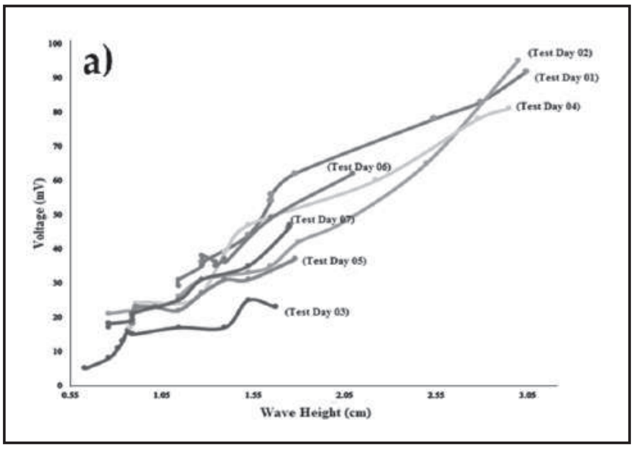
4. EXPERIMENTAL RESULTS AND DISCUSSIONS

Experimental investigations were carried out every fifteen minutes for five hours a day to take readings of voltages, internal resistances, wave heights, and temperature for seven days. The voltage was in the 2000 mV range, and wave heights were measured in inches using a measuring scale. The average internal resistance of the alternator was observed to be 666 Ω. The current flow and power were calculated from the voltage and internal resistance by using Ohm's law.

Fig. 8(a) and 8(b) represents the change of voltage and power with wave heights respectively. The graph lines represent the relationship of wave heights with voltages and powers for consecutive seven-day data values of voltage, wave height, and power.

It is noticed that voltage and power production represents nearly identical result through the plotting.

The first, second, and fourth days show comparatively larger output results due to the large wave heights. The power production increased linearly with the wave height whereas it remained steady on the third and fifth days. It can be shown from Fig. 8(a) and Fig. 8(b) that a maximum voltage of 95 mV and a maximum power of 13.55 $x10^{-6}$ W has been produced on the second day with a wave height of 3.0 cm. In contrast, the minimum wave height of 0.625 cm provides the minimum voltage of 05 mV and minimum power of 0.04 $x10^{-6}$ W. The graphical plotting of the data represents the dependency of power production and voltage on wave heights. It is worthy to mention that water and the ambient temperature do not have any significant effects on the power production as the temperature variation is within a very short range



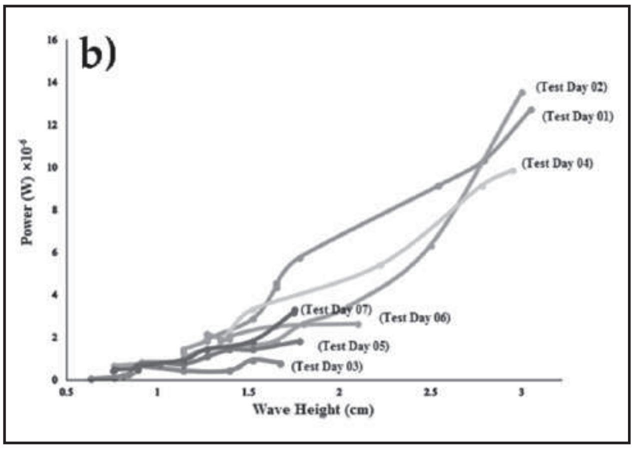


Fig. 8 Graphical representation of measured a) voltage and b) power for different wave heights.

from 29˚C to 32˚C. In contrast, a higher temperature range may vary the output. The wave energy production system does not have any adverse effect on the environment or fuel cost. However, power production has not been up to the mark in commercial aspects due to various barriers such as the deficiency of awareness and information, limitation of technologies, and capital cost, resulting in the deprivation of utilizing wave energy. Despite these restrictions, the number of new concepts and technologies for harvesting wave energy is increasing. Various prototypes have been built with identical motives such as the Oscillating Water Column device in Japan (The Mighty Whale) [30], Japan (Sakata) [31], Scotland [32] Kerala state, India [33]; Heavy Body Buoys in Denmark [34], Sweden [35], Holland [36] and Norwegian buoy [37] along with different Oscillating Body Systems and Moorings. The majority of these approaches are for larger production, theoretical explanations, huge initial investments, and expert maintenance whereas the main aim of this research work is to harvest wave energy with minimum investment, simple maintenance, and low cost. This technology could be used in the production of electricity for individual use and also for commercial aspects.

5. CONCLUSION

The study represents the design of an oscillating body system combined with a belt pulley mechanism for energy conversion. The result shows that energy can be harvested from waves using this mechanism efficiently using buoyancy force solely. Different buoy structures are compared through the simulation by ANSYS to find out the most suitable geometry. Hence, the complete CAD model of the machine set-up is designed in SolidWorks with proper dimensions followed by the fabrication according to the designed. The materials of each part are chosen considering the aspects of weight, strength, durability, and availability. The data from the experiment clearly shows a positive result in energy production. The minimum voltage of 5 mV and power of 0.04×10^{-6} W is found due to the minimum wave height whereas the maximum voltage of 95 mV and power of 13.55×10^{-6} W is found for a maximum wave height of 3.0 cm. Though the output result is not very satisfactory, for remote areas, this mechanism can be used to fulfill the basic needs of daily lives. The places, where mankind struggles to get national grid power or other electrical services from different organizations, can use these mechanisms with the availability of water bodies. It will not require any expert maintenance and this can be a simple solution for those remote places to produce electricity for meeting necessary demands.

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