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Development of an Ocean Wave Energy Harvester using an Array of Flexible Piezoelectric Sensors

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ABSTRACT

The ocean offers vast opportunities for unprecedented energy harvesting where most studies had concentrated on large scale energy harvesting from the ocean waves. However, there were minimal studies on low-scale energy harvesting. This study focuses on ambient, low-scale energy harvesting which theoretically can be used to power low energy consumption electrical appliances. The inherent characteristic of piezoelectric materials which can convert mechanical energy to electrical energy has created an alternative to generate energy from renewable sources including ocean waves. Initially, this study started with preliminary work which consisted of the development and testing of a lab scale piezoelectric energy harvester (PEH-1) which was tested along the beach area of Kuala Nerus, east coast of Malaysia. Results from PEH-1 had shown that the high tide produced more power level compared to low tide experiments. The findings from the first phase of this study served as a foundation study towards the development of an upscaled version of the PEH-1 in relation of mechanical and electronics, which was termed as PEH-2. Testing for PEH-2 was conducted in the coastal area of Pulau Bidong Laut, Kuala Nerus. Results from the second part of the study had shown that approximately almost 80% of the power harvested correlated linearly with wind speed, however after reaching 0.7W the peak dips down which was probably due to the instability of PEH-2 to be used in harsh open seas environment. This study had shown the feasibility of utilizing piezoelectric material to harvest low-scale power, however, several in-house modifications needed to be made for it to be fully functionable.

1. Introduction

Technological development during the past few decades has resulted in modern renewable energy supply becoming extremely competitive in a number of situations. Currently, renewable energy contributes about 21.5% of the total global energy used in 2020 and the trend in 2021 is set to expand by more than 8% to reach 8 300 TWh, the fastest year-on-year growth since the 1970s with solar PV and wind are set to contribute two-thirds of renewables growth [1]. The largely

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untapped renewable energy resources from the ocean remains an inexplicable interest to the researchers and conglomerates worldwide despite the unpredictable nature of the ocean itself. Generation of large-scale ocean wave energy with minimal operational cost to this date still remain as the main objective for energy providers worldwide [2-5].

The energy of the oceans is stored partly as kinetic energy from motion of the waves. Tidal energy, ocean thermal energy and wave energy make up the types of ocean energy resources. Tidal energy generates power during the surge of ocean waters during high tide and low tide, in which the worlds' first tidal power plant was opened in 1966 at Brittany, France [6], making this technology as one of the well-established technologies in the renewable energy by the ocean wave field. Ocean thermal energy which was first initiated in the 1970s, utilizes the differences in water temperature between ocean surface water and deep ocean water to drive a turbine or generator which later on translated into energy harnessing at an exorbitant scale [7].

The combination of forces due to the gravity, sea surface tension and wind intensity are the main factors of the origin of sea waves [8]. Wave energy remains at an experimental stage, with only a few prototype systems actually working as the technicalities in 'controlling' and utilizing the ocean wave energy remains relatively not well-known to the public [3]. Two percent of the world's coastal waters have wave power densities that are great enough for extracting wave energy that equates to 480 GW of power output for 4200TW h/yr of electricity generation [8]. The global theoretical energy from waves corresponds to 8x106 TW h/yr, which is about 100 times the total hydroelectric generation of the whole planet [9]. To produce this energy using fossil fuels, it would result in an emission of 2 million tonnes of CO_2 [10]. This means that wave energy could contribute heavily towards reducing pollutant gases level in the atmosphere.

Most of the studies taking advantage of the three aspects of the ocean energy detailed above, concentrated on large scale energy harvesting where not many have ventured out into small-scale, ambient energy harvesting from the ocean waves. Ambient energy harvesting, or energy scavenging, is a process that captures small amounts of energy from wind, sunlight, vibration and radio frequency that would otherwise be lost as heat, light, sound, vibration or movement [11]. Energy harvesting has the potential to replace batteries for small, low power electronic devices.

This project proposes to take advantage of the continuous surge of energy from the ocean waves and the inherent ability of piezoelectric materials where the crystalline structure of piezoelectric materials may transform mechanical strain energy into electrical energy. The power generation from mechanical vibration using vibration surrounding the power harvesting device which is used as an energy source and converts it into useful electrical energy in order to power other devices. The idea of capturing the energy surrounding an electronic system and converting it into usable electrical energy that could extend the lifetime of the power supply or provide an endless supply of energy has captivated many researches and brought much attention to power harvesting [12].

Piezoelectric materials exhibit notable energy generation density compared to the other different small-scale energy harvesters, that is about three times higher than the others [13]. Piezoelectric materials for harvesting ocean energy have recently been reviewed where it was shown that most piezoelectric energy harvesters based on ocean wave motion can be employed to power buoys and measurement devices, which correspond well with the low frequency ocean wave motion [14,15]. PZT or Lead Zirconate Titanate, is a polled ferroelectric ceramic, widely used in piezoelectric energy harvesting, however due to some of its drawbacks, including brittle structure and fatigue growth risks in high-frequency loadings, limited it widespread usage in energy harvesting [16]. PVDF, also known as polyvinylidene fluoride, was developed to improve the efficiency of piezoelectric energy harvesters to overcome the demerits of PZT [17]. PVDF exhibits a higher tensile strength value, which is about 2.6 times higher than PZT's strength value [18] signifying its durability to be utilized in harsher environment such as the open seas water.

This study was segregated into two phases where the initial part of the study includes the development and testing of small-scale piezoelectric energy harvester (PEH-1) circuit followed by the second phase of this study which consists of embedding the upgraded version of the PEH-2 circuit into a floating device integrated with paddle to ensure that proper energy harvesting can be conducted in the open seas. In the first part of the study the PEH-1 was tested near the shorelines of Tok Jembal beach, Terengganu while the efficacy of PEH-2 to harness energy was tested in the open seas which are on the coastline of Bidong Island, Terengganu.

2. Methodology

The preliminary part of the experiment includes the construction of PEH-1 circuit as shown in Figure 1. This circuit was set up by using Proteus 8 Professional. The piezoelectric material used was made from PVDF material which are Pro-Wave's FS-2513P piezoelectric lead-pin type film with voltage sensitivity of 70 mV/ms^{-2}. It should be noted that the FS-2513P piezoelectric film was extremely sensitive and a slight stress or vibration would produce small units of electricity. Due to its superior piezoelectric strain constant (g value), which are 10-20 times larger than piezoelectric ceramic, making it an ideal candidate for mechanoelectrical sensor. The piezoelectric sensor films were placed at the side of the breadboard facing the sea-water as the films will come into direct contact with the sea-water. Whereas, the electrical circuits were soldered on the other side of the breadboard as a precautionary measure to reduce the risk of saltwater getting into contact with the electronic component of the PEH-1 circuit.

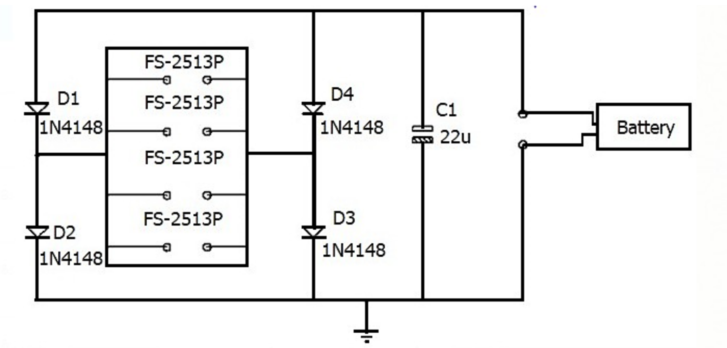

Fig. 1. Schematic drawing of piezoelectric energy harvester-1(PEH-1) circuit

Testing of PEH-1 was carried out at Tok Jembal beach. This experiment was conducted for 25 minutes for each session during high tide and low tide. Four piezoelectric sensors had been arranged in parallel configuration to harness a larger amount of electrical energy compared to series configuration. The energy harvested was stored in a rechargeable battery (Energizer CHVC5USB 2x AA 1300mah Rechargeable Batteries). The wind speed also had been recorded by an anemometer (MULTICOMP, MP780120) to study the effect of wind towards ocean waves and later on energy harvested by PEH-1.

Wind speed, wave height and the time duration of the test, all three of these controllable and uncontrollable experimental parameters of PEH-1 affected the amount of power harvested. The weather also played an indisputable fact towards determining the overall result. Good weather conditions prior to 1-2 days must be considered before the experiments take place since rain or strong ocean waves may hamper the testing process of the prototype. The electronic circuit was enclosed in a waterproof plastic container and the piezoelectric sensor was strategically placed on the periphery of the container so it can harvest energy from the small ripples of ocean waves at the beach.

Preliminary results gained from the testing of PEH-1 has prompted the development of PEH- 2 in which basically 4 units of PEH-1 circuits were connected in series connection to ensure higher power harvested. Prior to that, series and parallel configurations of the 4 units of PEH-1 has been tested and it was demonstrated that series configuration produced more power in which the schematic drawing of the circuit for PEH-2 was shown in Figure 2.

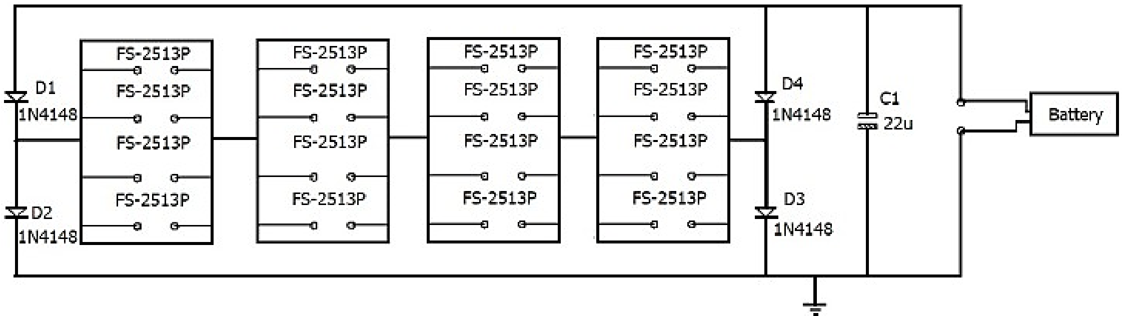

Fig. 2. Schematic drawing of piezoelectric energy harvester-2 (PEH-2) circuit in which 4 units of PEH-1 circuit was connected in series

The circuits were integrated in a floating device built in-house as shown in Figure 3. The floating device was developed from durable PVC pipes, designed and mechanically constructed to withstand the harsh environment in the open sea to mimic the movement of a buoy as demonstrated in Figure 3a. The large paddle located near the bottom of this device will sway according to the frequency of ocean waves. The movement of ocean waves will cause the small paddle of this floating device to come into contact with piezoelectric sensors which in turn will generate energy as shown in Figure 3b. Harvested energy was stored in a rechargeable battery placed inside a water-proof PVC enclosure which also houses the piezoelectric energy harvester (PEH-2) circuit. An acoustic wave and current profiler (AWAC-600 kHz, Nortex Norway) was used to measure significant wave height which is correlated to wind speed. The measurement was taken at the pelagic coast near Bidong Island, where a wave meter and PEH-2 was used concurrently. The measurements were taken approximately 10 km off the shore, where the winds and waves are relatively strong.

(a) (b)

Fig. 3. (a) PEH-2 integrated with a floating device and (b) small paddle initiating energy harvesting from the piezoelectric sensor film

The capability of PEH-2 to harvest energy was tested along the coast of Bidong Island, Terengganu, Malaysia where measurement was taken at a 10 minutes interval involving 32 points which are signified by the numbers in Figure 4. Bidong Island is one of the islands in the state of Terengganu and is surrounded by the South China Sea in the eastern part of Peninsular Malaysia. This uninhabited island that covers an area of 260 hectares and is located eight nautical miles from Merang beach, Terengganu mainly served as a research station for nearby universities.

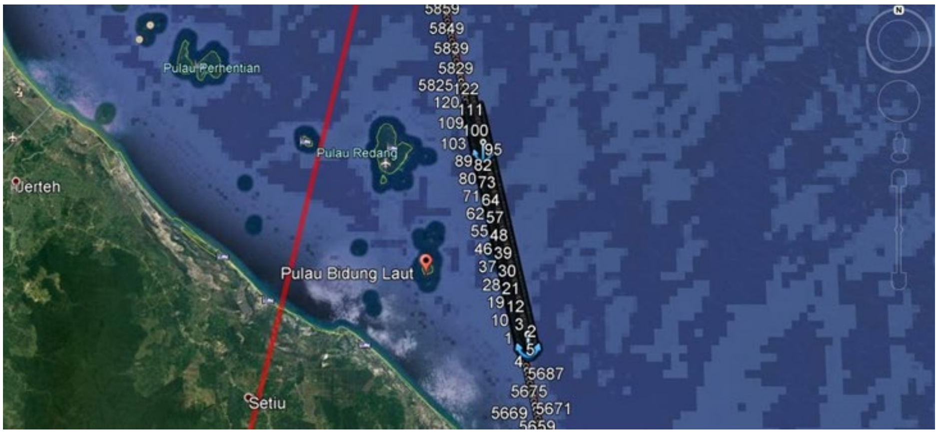

Fig. 4. The location of the testing point of PEH-2, which were conducted along the coast of Bidong Island

3. Results

Results for this study comprises of results from PEH-1 which was tested along the shoreline of a beach in Kuala Nerus and results from PEH-2 (upscaled version of PEH-1), was conducted along the coastline of Bidong Island, an island that is located in the district of Kuala Nerus. The testing of PEH-1 was conducted at Tok Jembal Beach,Kuala Nerus for 7 days during high tide and low tide. Table 1 showed the correlation between the speed of wind and harvested power by PEH-1 where the measurements were in triplicate and then averaged. The relative standard deviation or coefficient of variance is 5.31%.

Table 1
Readings taken at Tok Jembal beach during high tide and low tide

Time	Wind speed during high tide (ms^{-1})	Power generated (W)	Wind speed during low tide (ms^{-1})	Power generated (W)
Day 1	2.38	2.315	1.24	1.175
Day 2	2.84	2.085	1.40	1.045
Day 3	3.40	2.560	1.98	1.250
Day 4	3.30	2.010	1.30	1.585
Day 5	2.57	1.800	2.11	1.365
Day 6	3.19	2.540	1.67	1.030
Day 7	3.12	2.555	1.95	1.030

From Table 1, it was shown that the speed of wind had direct correlation with power harvested by PEH-1 where higher wind speed will create stronger ocean waves which in turn will produce more force exerted on piezoelectric films. The principal tidal forces are generated by the moon and sun. As the earth spins on its own axis, ocean water is kept at equal levels around the planet by the Earth's gravity pulling inward and centrifugal force pushing outward [19]. At most places, the tidal change occurs twice daily. The tide rises until it reaches a maximum height, called high tide and then falls to a minimum level called low tide. Table 1 had shown that wind speed during high tide on average showed higher velocity compared to during the low tide period. The effect of wind on sea level and therefore on tidal heights and times is not constant and depends largely on the topography of the area in question. In our study, a considerable fraction of Tok Jembal beach encompasses rock forts, thus, these selected areas are more susceptible to strong wind gusts. Spiking petrol prices has ignited the energy crises in the 1970s, which revoked interest in renewable energies from various research parties including a probability density function (PDF) analysis of wind speed in numerous wind energy applications [20]. $H_{1/3}$ which is the significant wave height, is the average of the highest one-third of all waves transversing during a period. It is one of the most frequent themes in reported wave statistics, and hence is widely known in studies of sea surface physics and physical oceanography [21]. $H_{1/3}$ is a scaling depth that predicts the region over which bubbles are ejected and ocean turbulence is generated when waves break [22]. This study employs the Andreas algorithm [23] which taking into account the typical equilibrium-sea approximation to predict the significant wave height (in meters) which are directly correlated to wind speed as stated in Eq. (1):

$$H_{1/3} = 0.030U^2 \quad (1)$$

where U is the wind speed (in ms^{-1}). Testing of PEH-2 which utilized 4 PEH-1 circuit in series

further reinforced the theory that higher value of wind speed correlates with larger amount of power generation by the piezoelectric sensors of PEH-2 as shown in Figure 5 below where it was demonstrated that wind speed played a significant role in determining the amount of power harnessed. The power harvested value were averaged over 3 points of measurement, a slight slope towards the end of measurement showed that the prototype is not durable enough to withstand the harsh sea condition which translated into the decline of power harvested level despite the higher wind speed measured.

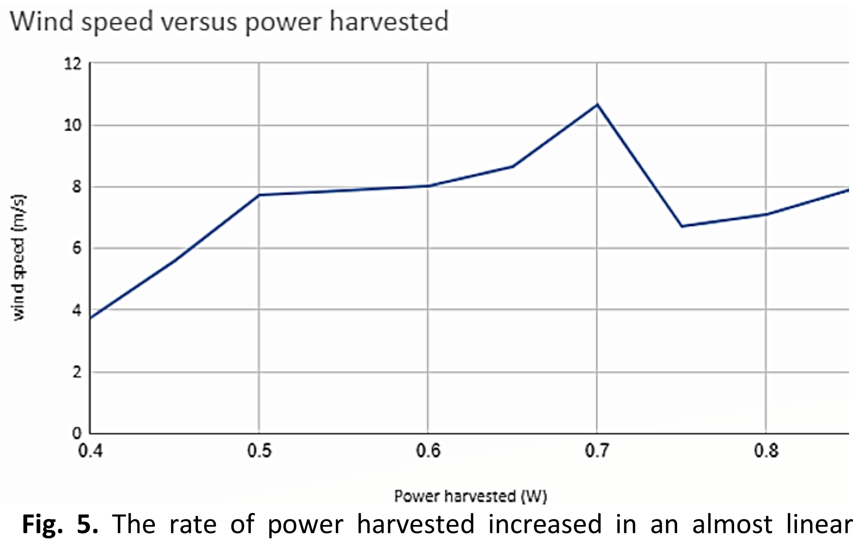

Fig. 5. The rate of power harvested increased in an almost linear manner with higher wind speed

Wind energy has a considerably larger energy density than solar energy, adding to the irrefutable fact that wind energy is also available for 24 hours all year round. Ocean-wave energy, which was a direct output of wind energy, is more persistent and spatially concentrated than the wind energy [24,25]. Theoretically, the amount of ocean-wave energy is concisely described in Eq. (2) below where per unit area of sea surface a stored energy amounting to an average of:

$$E = \rho g H^2 m0/16 \quad (2)$$

which is associated with the ocean wave, where $\rho=1030\ kg/m^3$ is the mass density of seawater, and $g=9.81\ m/s^2$ is the acceleration of gravity, whereas H_{m0} is the significant wave height for the actual sea state [26]. The largely under-harnessed resources of sea wave-power level in most tropical countries water is below 20 kW/m [27] which heralded significant prospects in the ocean wave renewable energy field.

Wave buoys including drifters, metoceanic, aquaculture or navigational buoys played an instrumental part in marine activities including trade, resource economics and research [27-29]. The electronics component embedded in the buoy is essential to obtain and accumulate data (sea water climate, water quality), to assist vessels in navigation towards safety in time of distress as well as for security reasons. Typically, buoys are stationed at a remote location for long stretches of time. Hence, it is not feasible to supply power to the electronics components embedded in the buoy using conventional approaches, thus alternative methods of supplying continuous, undisturbed power to these buoys should be explored.

Large scale ocean wave energy harvesting is a thoroughly researched study worldwide in the quest of discovering the next generation of renewable energy in lieu of the decreasing conventional energy reservoir [30-32]. However, ambient, small-scale energy harvested from the movement of objects due to ocean currents remains largely unexplored [33-35]. A recent study had reported the feasibility of spar-buoy scaled model integrated with a piezoelectric energy harvesting system that has been able to harvest energy sufficient to maintain the basic operational system of the prototype [36]. In this study, we are proposing the advent of utilizing piezoelectric unique characteristics in harvesting energy from buoys to supply energy for the sensors and lighting equipment integrated into the buoy. Results from this study had shown the mechanical design of the prototype is not rugged enough to weather large ocean waves. In the future, to ensure the workability of the prototype several modifications are needed including enclosing a shock and water-resistant closure to the piezoelectric energy harvester system and to embed the mechanically-modified piezoelectric energy harvester system to an actual buoy.

4. Conclusions

It can be concluded that this study might serve as foundation for the development of new generation low-cost ambient energy harvesters which might not only be feasible to be integrated into buoy but also to small fishing boats. Commercial fishing boats may travel in the sea up to 30 days on which they are largely dependent on power generators to supply electricity. Whereas, in the case of smaller, private boats which are usually out in the sea from dawn till dusk daily, many did not have the luxury of owning a power generator to be installed in their boats since it is quite an expensive commodity for them. This prototype might be beneficial to those fishermen especially in times of distress where the power generator is not functioning, this prototype might be able to supply continuous power of electricity. This prototype will also provide a more cost-friendly alternative for many fishermen to own a low-scale energy generator at a relatively lower price than the conventional power generator.

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