ICMIEE20-165

An Ocean Wave Energy Harnessing Model Using Piezo-Electric Device

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ABSTRACT

Worldwide the renewable energy demand has risen sharply over the past decades due to its environmental benefits compared to conventional fossil fuel power generation. The ocean is a vast source of renewable energy i.e. tidal energy, wave energy, wind, and ocean thermal energy. In this research, a model for extracting ocean wave energy using a piezo-electric device is considered. Piezoelectric materials when pressed, the atomic structure inside the materials change which cause a formation of dipole moment. This formation produces change in voltage differences across the piezoelectric materials. These piezo materials hold many potentials for renewable energy generation by reducing the consumption of oil and gas energy because of having the capability to generate electricity from renewable sources. The objective of this research is to explore relationships between the ocean wave and piezo material; for example, the relationship between significant wave height and amount of energy generated by the piezoelectric device. A model has been developed to study the relationships and prospects. Some interesting results have been produced which indicate the future potential of using this procedure in Bangladesh and around the world as well. Further developments are also recommended as a guide for future research.

Key Words
Renewable Energy, Ocean Wave Energy, Piezoelectricity, Mathematical Model

1. Introduction

One of the major causes of global warming is Carbon dioxide emissions from the uses of fossil fuels. Approximately forty percent of world CO_2 emissions are emitted from electricity generation plants through the combustion of fossil fuels to generate the required heat needed to power steam turbines; this burning of fossil fuels causes problems in various aspects such as air pollution, the rise of sea-level, greenhouse effect, finally desertification. It is predicted by the Intergovernmental Panel on Climate Change (IPCC) that, in 2050, the global sea level will rise to approximately 0.2 m compared to the sea level in 2010 [1] as well as the island will gradually vanish, and reduction of the land area will happen. Considering these circumstances, the generation of renewable energy has become an important factor to protect the environment. There exists a variety of processes for renewable energy generation such as solar, wind, ocean wave, tide, and ocean thermal energy. The ocean covers almost two-thirds of the earth's surface, on which we live. It is a greater source of renewable energy. Various ocean energy converter has been developed to harness energy. Several places are producing electricity from tides.

In La Rance, France, the biggest tidal barrage power plant is located which has been operating since 1966, generates 240 MW of electricity. Wave energy played an important role to generate electricity. Several wave energy conversion devices have been developed. An oscillating water column is an energy harnessing system that harnesses electrical energy from ocean waves by rotating the turbine via pushing the air into the generator using ocean waves [2]. The power buoy is a submerged buoy, inside it, a piston follows wave movement to output energy from an internal generator. In Europe, researchers developed a floating device that floats a generator on the ocean surface and waves drive that generator. Traditional wave devices have low power generation potency and unable to come up with stable electricity. To overcome these issues, this study proposed piezoelectric materials to convert wave energy to electrical energy.

Piezoelectric materials have the ability to generate internal electric charge from applied mechanical stress. These materials are applied in various industries such as the automobile industry, the medical industry, the offshore industry, and the information communication industry. Piezoelectric material's output energy depends on external force and it is expected to collect high energy from the ocean where the maximum amount of force is expected to be collected. This paper investigates the relationship between the voltage generated by piezoelectric material and various other parameters such as wave height, wave period, wavelength, and different waters.

2 Literature Review

This section discusses literature review on the developments in wave energy harnessing and the fundamentals of piezoelectric materials.

2.1 Developments in Wave Energy Harnessing

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Over the years a significant research works have been carried out all over the globe. For example, Taylor et al. [3] developed a small underwater river power generator that used an "eel-shaped" model and piezoelectric material for energy harnessing. In another study, Akaydin [4] used Cantilever Flow Induced Vibration method where, Polyvinylidene Fluoride, shortly known as PVDF or piezoelectric polymer, cantilever beam was used. The incoming wave will hit the cantilever and the electrical energy can be harvested. Researcher Murray [5] developed the oscillating system and created a two-stage method to generate power from waves Based on the heaving and pitching motion. In this system, the wave is responsible for moving the mechanical model and this model will hit the piezoelectric material to generate power.

Bodies Mounted to the Ocean Bottom- this method uses the piezoelectric polymers (such as PVDF) installed in a shallow sea bed by Zurkinden [6]. If the model is closer to the sea surface, water particles have more velocity at both the direction: Horizontal and Vertical. So, the cantilever beam will bend more than usual which results in more power generation than the conventional model. Floating energy harvesters have great potentials in renewable energy harnessing. To harness energy from the motions of water particles, Burn [7] designed a floating harvester. Burn's design comprises a semi-submerged plate that is in a position to maneuver up and down in response to surface water waves. A piezoelectric member is mechanically coupled to this semi-submerged plate that is responsible for straining and de-straining the piezoelectric member alternately in direct response to its up and down movement.

Toma et al. [8] proposed a system that is able to scavenge energy from water motions. Piezoelectric materials and therefore the characteristic periodic movements of bodies are used in this system. Within the cylinder, piezoelectric disks were impacted by an apparatus like the pendulum as the cylinder is able to oscillate during water flow. This energy harvester is anchored to the sea bed by flexible cords. A prototype of this harvester was fabricated and tested through an experiment. The harnessed average power output of the prototype is 2.2 ± 0.3 μW with a length, diameter, and weight of 78 mm, 24 mm, and 0.71 kg, respectively. Based on the piezoelectric effect, a pitching energy harvester has been developed by Viet et al [9]. The harvester is built by a mass-spring system with a lever based piezoelectric device. The spring is connected to that device in a series configuration which makes the harvester become flexible. The applied force from ocean waves on the piezoelectric device is low which ends up in lower power outputs. For this reason, a force magnifying device with a lever is introduced and installed in the harvester system which magnifies the impact force generated from ocean waves to higher power output. After conducting the simulation, the authors observed that the power output increases with ocean wave amplitude, the mass of the spring system, sizes, Young's modulus of the lever, and a decrease in the ocean wave period.

Based on the above literature review, it has been noticed that most of the energy harvesters are expensive and complicated by nature and therefore practical application is challenging. With the view in mind, this study attempts to model a simple energy harvesting system that can establish the relationship between ocean waves and electricity generated by piezoelectric material.

The fundamental theory of piezoelectric material and the general equation of voltage output for piezo material has been explained in the next section.

2.2 Piezoelectric Fundamentals

The principle of the piezoelectricity is to covert the mechanical stress energy into electrical energy [10]. Once an external force is applied to piezoelectric material, its internal atomic structure changes which causes the formation of a dipole moment, the energy will be conveyed by the electric charge carriers which leads to the generation of an electrical current in the crystalline. Where dipole moment is a measurement of the separation of positive and negative electric charges within a system. This phenomenon depends mainly on the fundamental structure of the crystalline. On the other hand, if external electrical voltage is applied as an input to piezo material's crystalline terminal, a mechanical deformation in the crystal shape will happen.

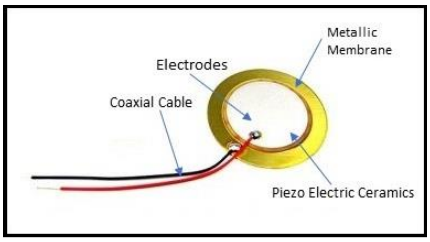

Fig.1 Piezoelectric element.

For a unidimensional piezoelectric material like figure 1, it is managed by a constitutive equation, that is by combining the electric field E, the electrical induction D, mechanical strain S, and the stress T. The linear electrical behavior of the material,

$$D = \varepsilon E \quad (1)$$

Hooks Law for linear elastic material,

$$S = sT \quad (2)$$

Now, the coupled equations, of which the strain-charge form is,

$$S = sT + dE \quad (3)$$

$$D = dT + \varepsilon E \quad (4)$$

Where,

$\varepsilon =$ The permittivity at constant Stress

$s =$ The compliance at constant electric field

$d =$ The piezoelectric charge co-efficient

When applying an external force (stressing the piezoelectric materials) it leads to an electric charge accumulation $Q_3 = D_3 A_3$ on the electrodes of area A_3, electric charge density D_3.

Then, the voltage is $V_3 = \frac{Q_3}{C_3}$ and the electric charge density is $D_3 = d_{33} T_3$. Where, $T_3 = \frac{d_{33} F_3}{A_3}$ and $C_3 = \frac{\varepsilon^T{}_{33}\, A_3}{t}$. Here, t is the piezoelectric material thickness.

So, the voltage output when applied a certain force F_3 can be calculated from [10],

$$V_3 = \frac{F_{33}}{A_{33}} \left(\frac{d_{33} \times t}{\varepsilon^T{}_{33}} \right) \quad (5)$$

Here,

F_{33} = Applied force in N

A = Piezo ceramic area in m^2

d_{33} = Piezoelectric charge co-efficient in $\frac{pC}{N}$ unit in the direction 3 (parallel to direction in which ceramic element is polarized) per unit stress applied in direction 3) or induced strain in direction 3 per unit electric field applied in direction 3

t = Piezo ceramic thickness in meter

ε^T = Permittivity at constant stress

The relative permittivity ε_r , is the ratio between the absolute permittivity of the piezoelectric material ε, and the vacuum permittivity, ε_0. Considering piezoelectric coupling factor K_p, the generated voltage:

$$V_3 = \frac{F_{33}}{A_{33}} \left(\frac{K_p \times d_{33} \times t}{\varepsilon_r \varepsilon_0} \right. \quad (6)$$

Where, $\varepsilon_0 = 8.854 \times 10^{-12}\ Farads/meter$.

3. Piezoelectric Materials

Piezoelectric materials (PM) can be classified as crystalline, ceramic and polymeric piezoelectric materials. Lead Zirconate Titanate (PZT), Lead Titanate, Barium Titanate is most commonly produced piezo electric material. Some materials have relatively wide band gap such as Gallium nitride and Zinc oxide which can generate an instantaneous polarization inside their lattice on application of a force. PVDF are organic polymer piezoelectric material.

Table 1 Various type of Piezo-materials coefficients [11].

Material Type	Charge Co-efficient (d_{33}) pC/N	Free Relative Permittivity (ε_r)	Coupling Factor (K_p)	Mechanical Quality Factory (Q_m)
Type 100 Hard PZT	250	1100	0.55	300
Type 200 Soft PZT	400	1600	0.55	100
Type 300 Very Hard PZT	200	800	0.55	800
Type 400 Barium Titanite	100	700	0.23	400
Type 500 Hard PZT Low ε^T	150	300	0.40	800
Type 600 Very Soft PZT	500	2500	0.55	100
Type 700 Lead Titanite	40	150	0.10	500
Type 800 Lead Metaniobate	70	200	0.10	20
PVDF Polymer Type	16.5	12	0.14	-

Figure 2 shows an analysis of force vs. generated voltage of different type of piezo materials. It can be seen from the figure that with the increase in applied force generated voltage increases linearly for all kinds of piezo materials. A comparative analysis reveals the type 500 generates more voltage than type 700 at a higher applied force. Output voltage was calculated using the eqn. (1) considering the diameter of piezoelectric material is 100 mm and the thickness 2 mm.

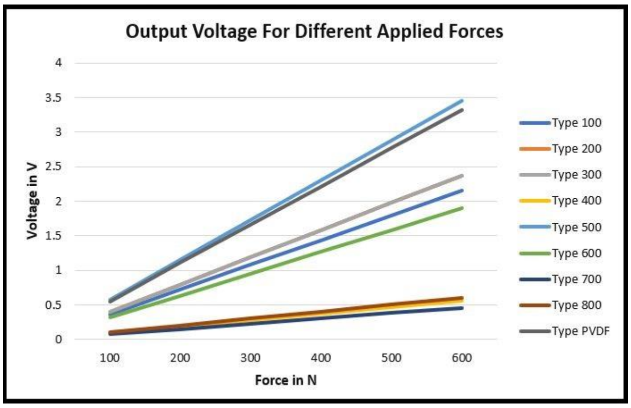

Fig.2 Output voltage for different applied forces.

4. Mathematical Model of Ocean Wave and Energy Equation

A piezoelectric ceramic disc of diameter D is subjected to an attack of waves which are H meter high, L meter long and T seconds in period, total force F at θ position at a location z meter below SWL, the water depth is d meter. Drag co-efficient C_D and inertia co-efficient C_m and fluid density ρ in figure 3.

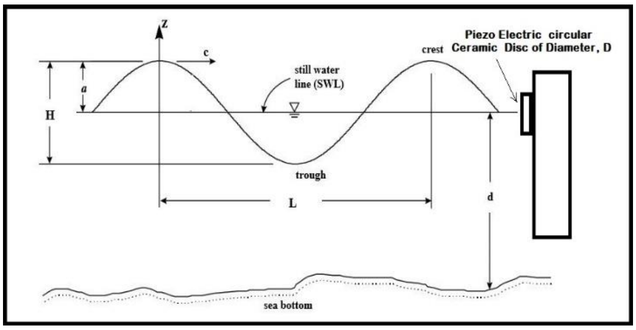

Fig.3 Schematic diagram of a wave.

By using Morison Equation, total wave force on D diameter piezoelectric disc can be calculated,

The Morison's equation [12],

$$F = \frac{1}{2} C_D \rho D u|u| + C_m \rho \frac{\pi D^2}{4} \dot{u} \quad (7)$$

Where,

F = Total force in line with the wave direction in N/m
C_D = Co-efficient of drag
C_m = Co-efficient of inertia
ρ = Mass density of fluid in kg/m^3
D = Diameter of the circular piezoelectric material in meter.
u = Flow velocity in m/s
$\dot{u}$ = Acceleration of fluid in m/s^2

Flow velocity, u and fluid acceleration $\dot{u}$, can be calculated as,

u

$\dot{u}$

Here,

H = Wave height in meter
T = Wave period in Second
d = Water depth in meter
k = Wave number
z = Location of piezoelectric disc in meter

Now equation (7) can be written as,

$$F = \left(\frac{1}{2} C_D \rho D \left(\frac{\pi H \cosh k(d+z)}{T \sinh kd} \cos\theta\right)^2 + C_m \rho \frac{\pi D^2}{4} \frac{2\pi^2 H \cosh k(d+z)}{T^2 \sinh kd} \sin\theta \right) \quad (8)$$

Combining the equations (6) and (8),

$$V_3 = \left(\frac{1}{2} C_D \rho D \left(\frac{\pi H \cosh k(d+z)}{T \sinh kd} \cos\theta\right)^2 + C_m \rho \frac{\pi D^2}{4} \frac{2\pi^2 H \cosh k(d+z)}{T^2 \sinh kd} \sin\theta \right)\left(\frac{K_p \times d_{33} \times t}{A_{33} \times \varepsilon_r \varepsilon_0}\right)$$

$$= \left(\frac{1}{2} C_D \rho D \left(\frac{\pi H \cosh k(d+z)}{T \sinh kd} \cos\theta\right)^2 + C_m \rho \frac{\pi D^2}{4} \frac{2\pi^2 H \cosh k(d+z)}{T^2 \sinh kd} \sin\theta \right)\left(\frac{K_p \times d_{33} \times t}{\frac{\pi}{4} D^2 \times \varepsilon_r \varepsilon_0}\right) \quad (9)$$

This equation is a comprehensive relationship between voltage generated by piezoelectric material and ocean wave profile. This equation will result in a significant number of graphical representations that could enable researchers analyze the relationships as stated earlier.

5. Theoretical Model

In this section, the theoretical model for harnessing wave energy is described in detail. Based on the theorical background as discussed above a set of input parameters were chosen to construct the theoretical model. These parameters are shown in table 2.

Table 2 Parameter and their respective values for construction of theoretical model.

Parameter	Value	Unit
d_{33}	150	pC/N
ε_r	300	
ε_0	8.854	pF/m
K_p	0.4	
D	0.1	meter
t	0.002	meter

C_D	1	
C_m	2	
ρ	870-1030	Kg/m^3
H	0.5-5	meter
T	10-60	second
d	60	meter
z	10-50	meter
θ	45˚	degree
L	50-100	meter

5. Results and Discussions

It can be seen from the figure 4 that, with the increase in wave height, the generated voltage increases. However, an interesting phenomenon is observed that with the increase in water depth the generated voltage reduces significantly. This is perhaps due to the fact that the water particles velocity is much lower towards the sea bottom. In other words, at a higher wave height, the generated voltage seems to increase exponentially as the position of piezoelectric material approaches towards the surface.

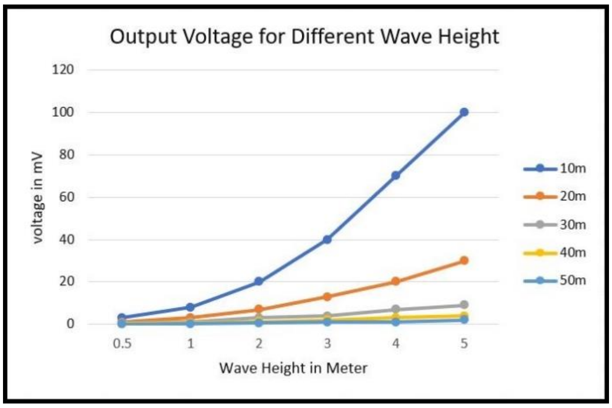

Fig.4 Output voltage for different wave height.

Figure 5 shows the relationship among wavelength, position for piezoelectric device under water and the voltage generated. This figure illustrates that with the increase in wavelength, the output voltage from piezoelectric device increases. For example, at the position of the device 10 m below the Still Water Line (SWL), for 50 m wavelength the voltage output is 40 mV and it is increased to 130 mV for 100 m wavelength. It is again observed that with the increase in water depth the generated voltage reduces significantly e.g., voltage reduced 130 mV to 4 mV for 100 m wavelength under 50 m below the SWL. Finally, at a higher wavelength, the generated voltage seems to increase exponentially as the position of piezoelectric material approaches towards the surface.

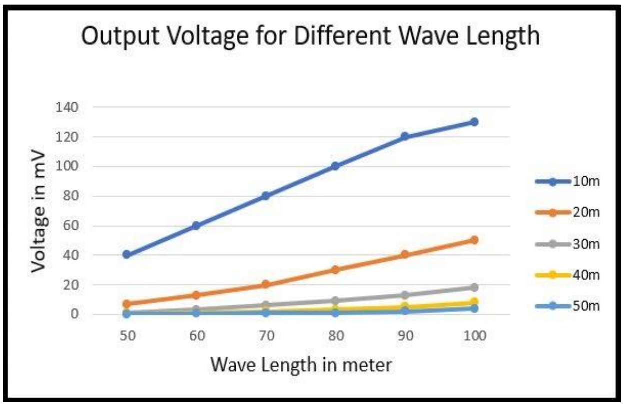

Fig.5 Output voltage for different wavelength.

For the different wave periods, different voltages are generated and the figure 6 shows this relationship for various positions of piezoelectric device underwater.
From the figure, it is observed that with the increase in wave period, the output voltage from piezoelectric device decreases this time. For example, at the position of the device 10m below the Still Water Line (SWL), for 10 s wave period the voltage output is 100 mV and it is decreased to 0.1 mV for 60 s wave period; that is 6 times increase in wave period causes 100 times reduction in output voltage. With the increase in water depth the generated voltage reduces significantly e.g., voltage reduced 100 mV to 0.1 mV for 60 s wave period for 50 m below the SWL.

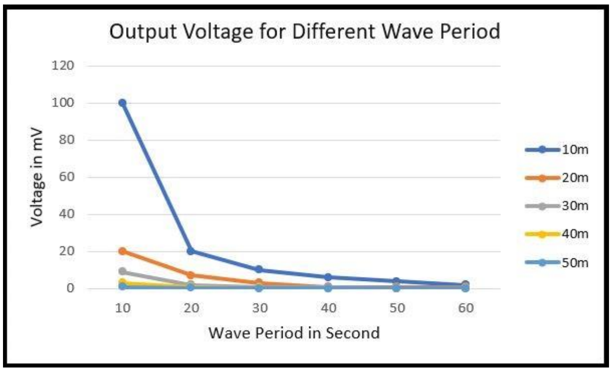

Fig.6 Output voltage for different wave period.

Figure 7 illustrates the relationship among voltage output and type of fluid (Fresh Water, Sea Water, Crude Oil). This is because the salinity of sea water changes from region to region and also ship accidents causing oil spills change the density of water. The density of freshwater is 1000 kg/m3, sea water is 1030 kg/m3 and 870 kg/m3 for crude oil. At 10 m below the SWL the voltage is 100 mv for both fresh and sea water and 80 mV for crude oil. However, with the increase in water depth the generated voltage reduces significantly from 100 mv to 1 mV.

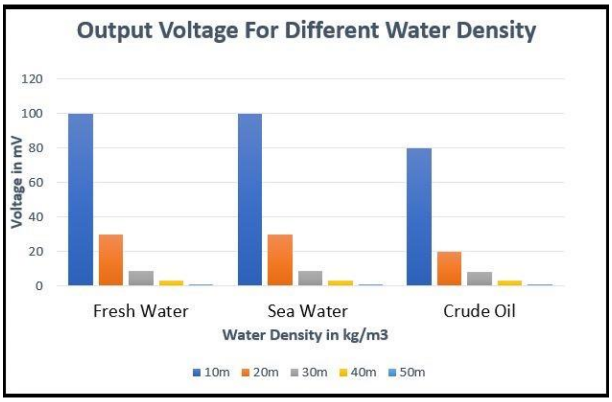

Fig.7 Output voltage for different waters.

6. Conclusion and Recommendation

In this paper, a mathematical model of wave energy harnessing by piezoelectric device has been developed. Further, the effect of applied force on different type piezoelectric material, effect of wave height, wavelength, wave period and water density on a piezoelectric disc has been studied from this model. The study shows that voltage generation is higher towards the water surface compared the sea bottom. With this fact in mind, considering the practicality of harnessing ocean wave energy, floating ocean structures seems to have better potential compared to fixed ocean structures. The study reveals that there is a promising prospect on harnessing wave energy using this technique.

Based on the investigation carried out in this research the following recommendations can be complied:

1. In this theoretical study several parameters (wave height, wave period, wavelength, water types) were assumed to have ideal case data. For future study it is recommended that this ideal data is updated and taken as practical as possible.
2. Extensive study using full scale models and advanced numerical models are highly recommended.
3. Further development on improved piezoelectric devices is recommended.
4. For future studies, research on floating structure-based energy harnessing systems is recommended.

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