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Piezoelectric Energy Harvesting from Direct Buoyancy Force

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ABSTRACT

In today's world, there is a strong tendency toward using renewable energy due to a significant decrease in fossil fuels resources. Recently, many researchers are doing research on piezoelectric energy harvesting. Considering this point that piezoelectric needs an oscillatory load for producing electricity, any type of ambient vibration can prepare this opportunity to use piezoelectric for energy harvesting. In this paper, a mechanism has been designed which converts the ocean waves into an oscillatory load by a cubic buoyant. In fact, buoyancy force has been used in order to induce a cylindrical piezoelectric. In this mechanism, the cubic buoyant has been fixed by a rod which is connected to the piezoelectric surface in order to prevent the buoyant from horizontal movement. When an ocean wave passes through the mechanism, the submerged buoyant creates an oscillatory load according to Archimedes buoyancy force principle. A finite element simulation has been done to derive the strain versus time, and the output power has been calculated by mathematical modeling. The simulation has been done for two types of piezoelectric which are induced by the frequency of 1 and 2 Hz. The effect of piezoelectric dimension are discussed, and the output electricity up to 10 µW for the frequency of 2 Hz is generated by using a cylindrical piezoelectric with diameter and height of 3 cm and 10 cm, respectively.
Keywords: Energy harvesting, Piezoelectric, Buoyancy force

1. INTRODUCTION

In recent years, due to the increasing reduction of fossil fuel resources, the trend towards renewable energy has increased dramatically. In addition to reducing these resources, pollution from fossil fuels and the lack of uniform distribution of these resources around the world and environmental changes have led to more investment in the use of renewable energy. Renewable energies include wind energy, geothermal energy, solar energy, and so forth.

One of the newest methods in the field of renewable energies is using piezoelectric effect or, in other words, piezoelectricity. The direct piezoelectric effect was discovered by Curie brothers in 1880. When a piezoelectric material is induced by a mechanical stress, it generates a temporary electricity which is called direct piezoelectric effect. In addition, when an external voltage is applied to these materials, they experience deformation that is called converse piezoelectric effect.

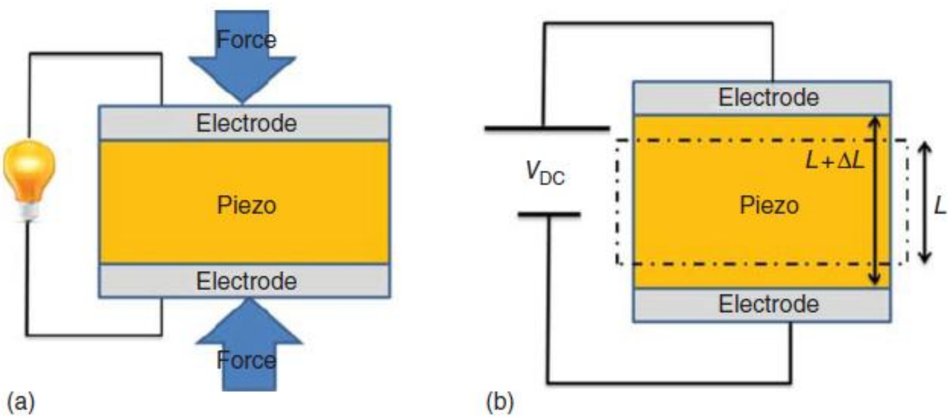
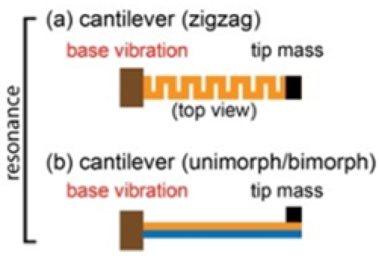


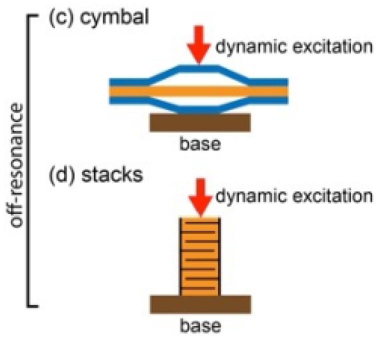
Fig. 1. Direct piezoelectric effect (a) and converse piezoelectric effect (b) [1]

There are many ambient vibration sources, such as ocean waves [2], walking on the ground [3], train railways [4], and wind energy [5], which can be used for piezoelectric energy harvesting. As an example, A. Moure et al. [6] used piezoelectric cymbals for vibration energy harvesting in asphalt in order to use moving vehicles for inducing piezoelectric cymbals and producing electricity. As a result of the experiment, they could obtain 16 µw electricity for the pass of one heavy vehicle wheel. In addition, they estimated that 65 MWh electricity can be obtained annually if they use 30,000 piezoelectric cymbals. In the energy harvesting field, there are several attempts to use ocean waves as a vibration source. Many researchers have designed several mechanisms to induce piezoelectric materials by drag force or buoyancy force. For example, X.D. Xie et al. [7] designed a cantilever attached by piezoelectric patches and a proof mass which uses longitudinal wave motion in order to put these piezoelectric patches under strain for collecting electrical energy. This mechanism generated electrical power up to 55 W. To illustrate more, N.V. Viet et al. [8] designed a floating box which includes a spring-mass system to convert wave motion to vibration. Two levers transfer this vibration to piezoelectric bars for producing electricity. The electrical power up to 103 W could be harvested from this research. There is a common point among previous studies that the buoyancy force has not been used directly to induce a piezoelectric bar. As a matter of fact, it has been used to vibrate a mechanism or, a cantilever beam with piezoelectric patches. For instance, Zheng Lin et al. [9] designed a mechanism which includes a buoyant and several cantilever beams. The buoyant includes several teeth and moves vertically alongside a vertical shaft. These teeth excite the cantilever beam from their initial position while the buoyant is moving upward by a sea wave.

Generally, methods of piezoelectric energy harvesting can be divided into resonance and off-resonance method. In the resonance method, using cantilever is the most common way in energy harvesting because they vibrate with high frequency, which is one of the most effective parameters in the output electricity. In addition, in this method, the fabrication of piezoelectric cantilever is simple and inexpensive. In the off-resonance method, piezoelectric cymbals or stacks are the most common configuration. In this method, the vibration frequency is much lower than the resonance method due to the higher stiffness and natural frequency of cymbals and stacks. Even though in the off-resonance method, it is so hard to find an ambient vibration source with a high frequency, but they are not sensitive to high mechanical load and stress which makes them an appropriate choice in a situation that the applied force is so high.



(a)



(b)

Fig. 2. Resonance (a) off-resonance (b) configuration in piezoelectric energy harvesting [10].

The main purpose of this paper is using the off-resonance method in piezoelectric energy harvesting by buoyancy force.

2. PRINCIPLE AND MODELING OF THE MECHANISM

2.1 Archimedes' Principle of Buoyancy

If an object is floating on a fluid surface, there is a vertical force which prevents the object from sinking, and this vertical force is termed "Buoyancy Force". For a submerged object, the buoyancy force of the fluid is equal to the weight of the displaced water. It is clear that the object volume is equal to the volume of the displaced water [11].

$$F_{Buoyancy} = \rho_{fluid} V_{object} g \tag{1}$$

Where ρ_{fluid} is the density of the fluid, V_{object} is the volume of the submerged object, and g is the earth's gravity. It is clear that the amount of applied force and its frequency depend on the wave amplitude and period respectively.

2.2 Mechanism Structure

In this research, a cubic buoyant with dimensions of (50, 50, 20) cm is connected to a rod with diameter and height of 25 mm and 330 mm respectively. The rod passes through a hollow cylinder with dimensions of outer diameter, inner diameter, and height of 50 mm, 25 mm, and 100 mm respectively. The hollow cylinder is welded to a horizontal arm which its height can be easily adjusted according to the gap between buoyant and sea surface. When a sea wave passes through the buoyant, the rod desire to move vertically due to the buoyancy force of the sea surface but, the rod touches the cylindrical piezoelectric with radius and height of 15 mm and 10.2 mm respectively, and this contact prevents the buoyant from any vertical movement. At this moment, the cubic buoyant submerges inevitably. If the sea wave covers the buoyant completely, the maximum amount of load induces the piezoelectric surface. Assuming density of 1000 kg/m^3 for the sea water, the maximum amount of buoyancy force can be calculated by Eq. (1) as:

$$F_{Buoyancy} = \rho_{fluid} V_{object}\, g = 1000 \times (0.5 \times 0.5 \times 0.2) \times 9.8 = 490 N \qquad (2)$$

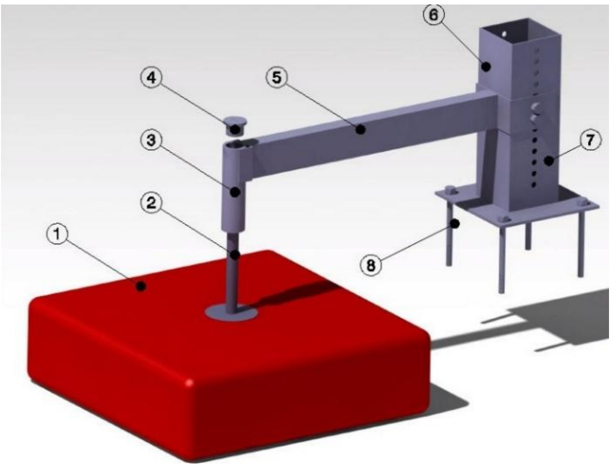


Fig. 3. An isometric view of the mechanism which includes a cubic buoyant (1), vertical rod (2), hollow cylinder (3), a screw for keeping the piezoelectric inside the cylinder (4), horizontal arm (5), a column for adjusting the horizontal arm height (7), and 4 screws for holding the mechanism

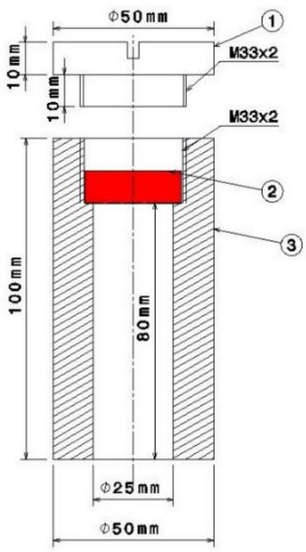


Fig. 4. The hollow cylinder details, including the screw for keeping the piezoelectric inside the cylinder (1), cylindrical piezoelectric (2), and the hollow cylinder body

3. Piezoelectric Materials

Lead zirconate titanate (PZT) is the most common type of piezoelectric materials that is widely used in energy harvesting [12]. In this research, PZT-5H (APC 855) and PZT-5A (APC 850) are considered for the simulation and mathematical calculations.

3.1 Piezoelectric materials properties

For simulation of piezoelectric material in Abaqus (CAE), a finite element software, several material properties need to be assumed for the designed model, such as elastic matrix, density, dielectric matrix, and so on. The material properties for PZT-5H (APC 855) and PZT-5A (APC 850) are summarized in Table 1.

Table 1. Material properties of two types of piezoelectric [13]

Material properties	symbol	PZT-5A	PZT-5H
Density (kg/m^3)	ρ	7700	7780
Elastic matrix (GPa)	c_{11}^E	147	114
	c_{12}^E	105	75.7
	c_{13}^E	93.7	72.4
	c_{33}^E	113	111
	c_{44}^E	36.6	26.3
	c_{66}^E	21.2	19.2
Piezoelectric voltage constant (v m/N)	g_{13}	-0.0106	-0.0073
	g_{33}	0.0267	0.0156
Elastic Modulus (GPa)	Y_{11}^E	59	54.8
	Y_{33}^E	43.1	55.6
Dielectric matrix ($\times 10^{-8}$ F/m)	ε_{11}^S	1.00005	1.78062
	ε_{33}^S	0.80889	1.7523
Piezoelectric charge constant ($\times 10^{-10}$ C/N)	d_{31}	-1.7	-2.59
	d_{33}	4.25	6.4
	d_{15}	5.06	6.16

3.2 Piezoelectric materials formulation

A cylindrical piezoelectric with radius and height of 30 mm and 10.2 mm has been shown in Fig. 5. The coordinate system of piezoelectric material is shown by 1, 2, and 3 which are similar to x, y, and z. The direction of 3 is perpendicular to the cylinder base. The suffixes of piezoelectric material properties represent the coordinate system. For instance, the first suffix of charge constant d_{31} represent the direction of mechanical load, and the second suffix shows the direction of polarization. To illustrate more, d_{33} means that our mechanical load is applied alongside direction of 3, and electricity has been generated in the same direction.

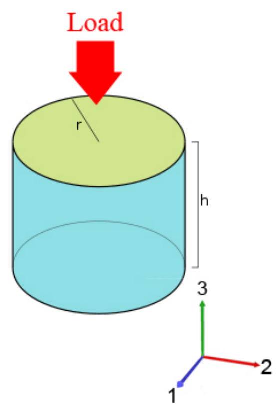


Fig. 5. A cylindrical piezoelectric and its coordinate system

For the cylindrical piezoelectric shown in Fig. 6 and a mechanical load in direction of 3, the electric charge Q (Coulombs) will be generated by multiplication of force (F) and charge constant as below:

$$Q = Fd_{33} \tag{3}$$

The charge density D (C/m^2) can be calculated as below:

$$D = \frac{Q}{A} = \sigma d_{33} \tag{4}$$

where A is the area of cylinder base (m^2), and σ is normal stress (Pa) in direction of 3. The relation of charge density and electric field E (V/m) is expressed as:

$$D = \varepsilon_r \varepsilon_0 E \tag{5}$$

where ε_r and ε_0 are relative dielectric constant and dielectric constant of the air (8.85×10^{-12} F/m), respectively. Combining Eq. (4) and Eq. (5) gives:

$$\varepsilon_r \varepsilon_0 E = \sigma d_{33} \tag{6}$$

Another material property of piezoelectric materials is piezoelectric voltage constant g_{33} (Volts m/N) which can be calculated as below:

$$g_{33} = \frac{d_{33}}{\varepsilon_r \varepsilon_0} \tag{7}$$

Equating Eq. (6) and (7) simplifies the electric field E (V/m) as below:

$$E = \sigma g_{33} \tag{8}$$

The output voltage (V) for a mechanical load F (N) is expressed as:

$$V = h\frac{F}{A} g_{33} \tag{9}$$

where h (m) refers to the piezoelectric height, and A (m^2) represents the area of cylindrical piezoelectric base which is equal to πr^2.

The electric power P over a time period t is expressed as:

$$P = \frac{VQ}{t} \tag{10}$$

which is simplified by equating Eq. (3), Eq. (9), and Eq. (10) as below:

$$Pt = Fd_{33} h \frac{F}{\pi r^2} g_{33} = \pi r^2 d_{33} g_{33} \left(\frac{F}{\pi r^2}\right)^2 \tag{11}$$

According to the Hooke's law $\sigma = \frac{F}{\pi r^2} = Y\epsilon_{33}$, the integration over time gives the output energy as:

$$W_{33} = \tfrac{1}{2}\int_0^t \pi r^2 h d_{33} g_{33} \left(\frac{F}{\pi r^2}\right)^2 dt = \tfrac{1}{2}\pi r^2 h d_{33} g_{33} Y^2 \int_0^t \epsilon_{33}^2 dt \tag{12}$$

Where Y is the young module and ϵ_{33} is the normal strain when the cylindrical piezoelectric is induced by mechanical stress. According to the second power of strain, the generated electricity changes with applied stress nonlinearly [14]. In addition, Eq. (12) reveals that except for dimensions of piezoelectric materials, piezoelectric charge constant d_{33} and piezoelectric voltage constant g_{33} affect the output electricity or generally, output energy. In fact, it is preferable to choose a type of piezoelectric with a higher $d_{33}.g_{33}$, but any increase in piezoelectric charge constant d_{33} leads to a significant increase in the dielectric permittivity ε and consequently, a large decrease in piezoelectric voltage constant g_{33} [10]. For instance, in Table 1, the charge constant d_{33} of PZT-5A (APC 850) is equal to 4.25×10^{-10} C/N, and its voltage constant is equal to 0.0267 V m/N, however, the charge constant d_{33} of PZT-5H (APC 855) is more than PZT-5A (APC 850), and its voltage constant is lower.

4. Finite Element Simulation and Discussions

For the simulation of this research, PZT-5H (APC 855) and PZT-5A (APC 850) are assumed, and as it mentioned before, a cylindrical piezoelectric with radius and thickness of 15 mm and 10.2 mm, respectively, is modeled in Abaqus (CAE). The piezoelectric is examined when it is induced by an oscillatory load. It is assumed that the cubic buoyant submerges completely while a sea wave passes through the mechanism. In this situation, the buoyancy force is an upward load, however, the weight of vertical rod in Fig. 3 is a downward load, and it must be reduced from the maximum buoyancy force in Eq. (2) for more accurate simulation. The vertical rod is made of steel with density, diameter, and height of 7800 kg/m^3, 25 mm, and 330 mm, respectively. The maximum force is calculated as below:

$$F_{\max} = F_{buoyancy} - \rho_{steel} V_{rod}\, g = 490 - 7800 \times \frac{\pi \times 0.025^2 \times 0.33}{4} \times 9.8 = 477.6N \qquad (13)$$

According to this point that in piezoelectric energy harvesting, an oscillatory load must induce the piezoelectric, two oscillatory loads with the frequency of 1 Hz and 2 Hz are assumed. The amplitude of these loads is equal to the maximum force in Eq. (13).

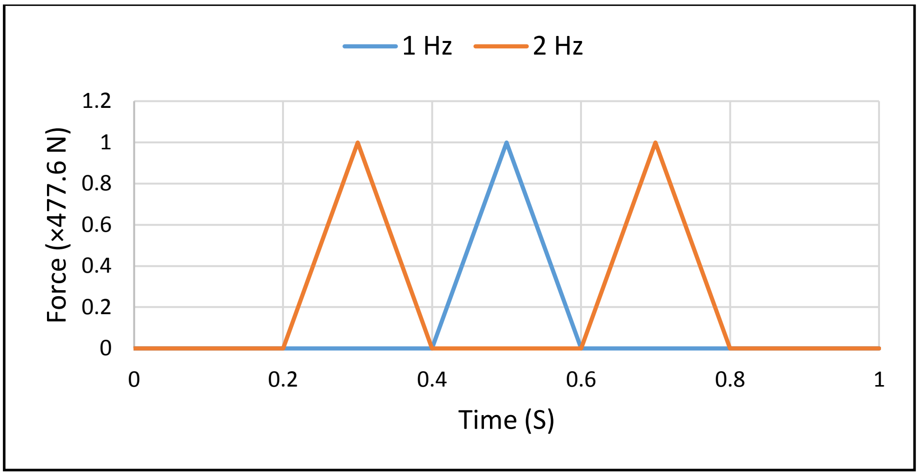
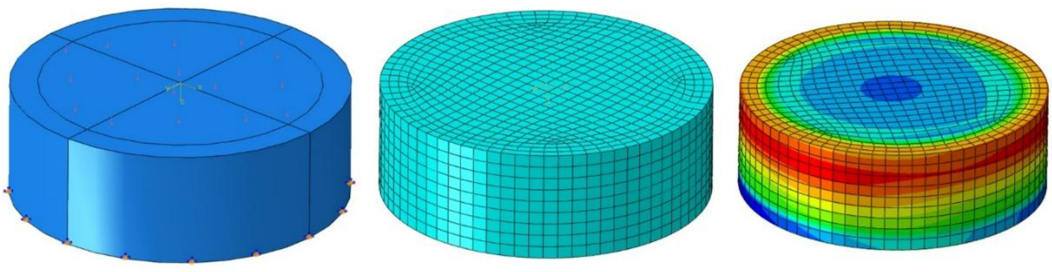


Fig. 6. Force vs time graph of two loads with different frequencies

In the simulation, material properties are assigned to the 3D model, and boundary conditions and the oscillatory load are defined. In addition, appropriate mesh size is assigned to the model.



(a) (b) (c)

Fig. 7. Boundary condition (a) meshing (b) contour configuration (c) of the 3D model in Abaqus (CAE)

According to Eq. (12), the strain versus time graph must be derived as the output of the simulation. For each type of the mentioned piezoelectric materials, the simulation must be done in order to calculate maximum strain in the direction of 3. Moreover, each step frame of the simulation must be examined in order to add its details to a chart, and considering the squared strain in Eq. (12), these points must be squared. Subsequently, the graph of the squared strain versus time must be examined. The integration over time must be calculated to estimate the output energy. It is clear that increasing frequency leads to a significant increase in integration of the graph due to much more area between the graph and the horizontal axis. Consequently, the output energy increases for higher frequencies.

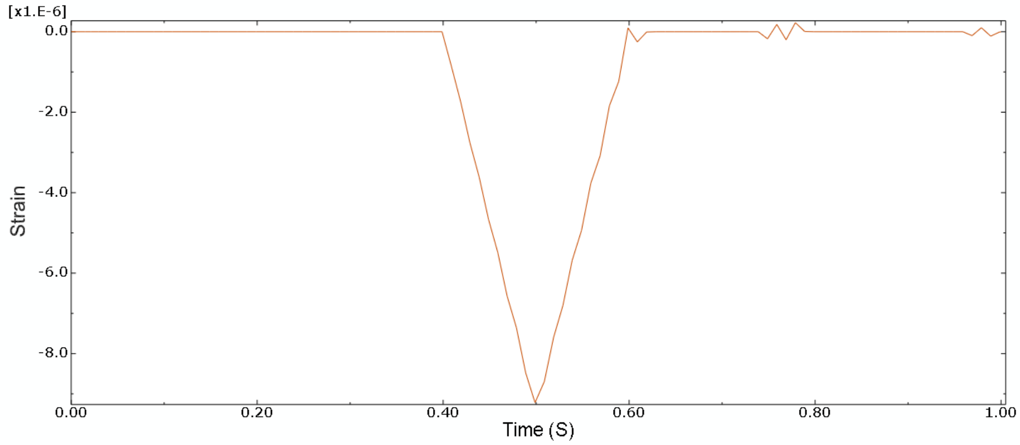


Fig. 8. Strain versus time graph of PZT-5A when is induced by maximum force in Eq. (13) and frequency of 1 Hz

In this finite element simulation, for each time increment, the strain has been calculated, and according to Eq. (12) they must be squared point by point.

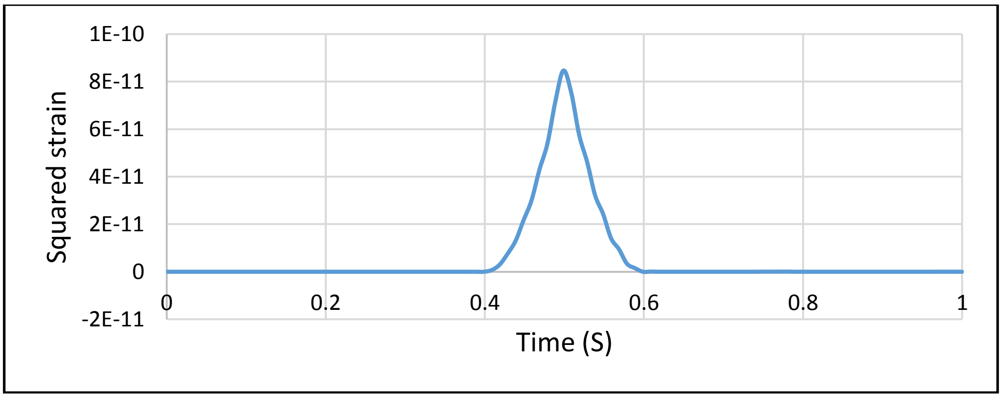


Fig. 9. Squared strain versus time of Fig. 8

The integration over time in Fig. 9 is equal to 8.46×10^{-12}. By substituting material properties from Table 1 and dimensions of the piezoelectric into Eq. (12), the output energy will be 6.428×10^{-7} J. By dividing the output energy by time period, the output power is calculated. According to this point that the time period is equal to 1 S, the output energy and power are identical. The same simulation and calculation have been done for the frequency of 2 Hz.

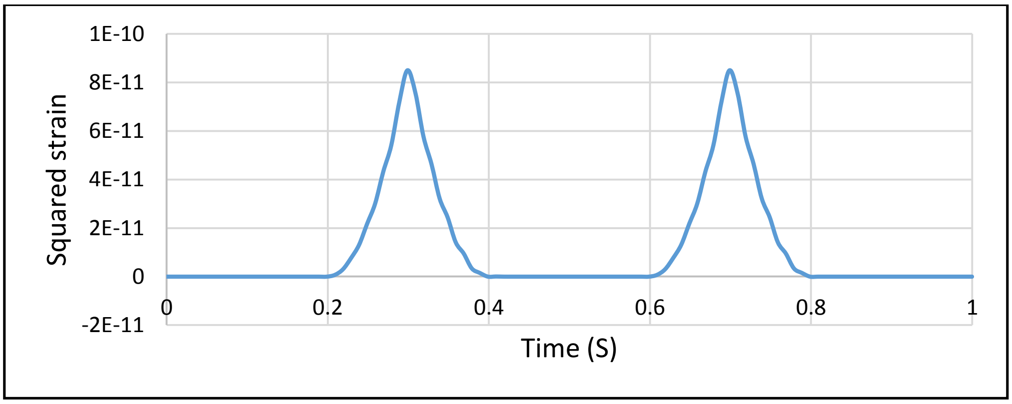
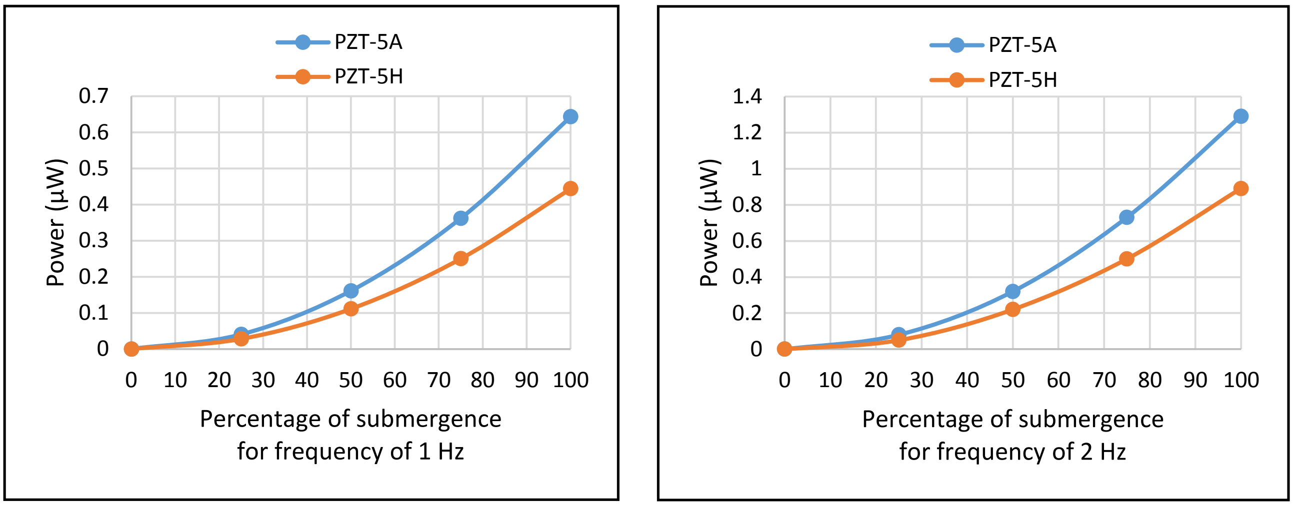


Fig. 10. Squared strain versus time of PZT-5A when is induced by maximum mechanical load and frequency of 2 Hz



(a) (b)

Fig. 11. Output power versus percentage of submergence with frequency of (a) 1 Hz and (b) 2 Hz

Even though the mechanism is designed for a cylindrical piezoelectric with radius and thickness of 15 mm and 10.2 mm, respectively, it is possible to use thicker piezoelectric materials by a simple change in the mechanism structure. For this reason, different heights of PZT-5A (APC 850) have been analyzed, and considering this point that any increase in the dimensions results in an effect on the strain, the finite element simulation must be done for any kind of change in the piezoelectric dimensions in order to derive new strain versus time graphs.

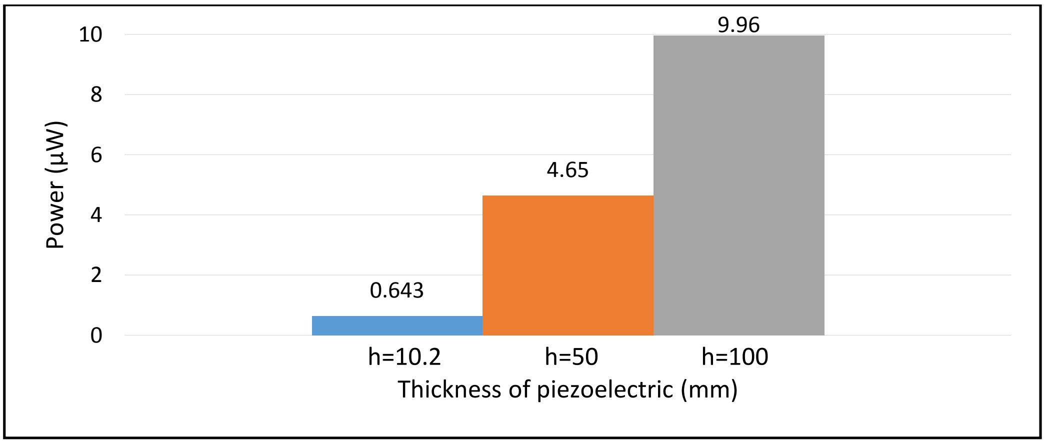


Fig. 12. Output power versus different thicknesses of the cylindrical piezoelectric (PZT-5A)

The impact of piezoelectric thickness is totally obvious in Fig. 12. As a matter of fact, the output energy has increased nonlinearly for the thicker cylindrical piezoelectric. Even though it is assumed that in the off-resonance method, the output electricity is higher due to utilizing larger piezoelectric materials which tolerate much more stiffness, but the output power of this paper is not considerable enough to be applicable. To illustrate more, it is anticipated that using 100 mechanisms can generate electricity up to 2.5 KWh monthly, which seems to be inapplicable. The weak point of ocean waves is their low frequency, which is the most important parameter. Nonetheless, the strength of this mechanism is that the maximum buoyancy force can be utilized in order to induce the piezoelectric, and according to the direct impact of buoyant size on the buoyancy force, the mechanical load can be increased easily by using larger buoyant. There are some other aspects which restrict the buoyant dimensions, and also will differ the mathematical results from the experimental results. In fact, increasing the buoyant dimensions leads to much more surface area between buoyant and passing waves, and subsequently, a horizontal drag force will stick the vertical rod to the surface of the hollow cylinder. Definitely, this contact creates a friction force which reduces the effect of buoyancy force. Moreover, increasing the buoyant dimensions and drag force might damage the mechanism by loosening the supporting screws and bending the vertical rod. In the simulation, two harmonic frequencies are assumed, however, there is not any anticipation that ocean waves will induce the piezoelectric with harmonic frequency. Moreover, after passing the sea waves through the mechanism, there is some minor vibration which induces the piezoelectric surface, and they are not considered in mathematical calculations due to their unpredictable behavior. The speed of sea waves varies in different climate conditions, and consequently, the period of time that the piezoelectric is experiencing strain is different, which affects the integration of strain graph over time and the output electricity.

5. CONCLUSION

In this research, a mechanism has been designed to convert ocean waves to an oscillatory force in order to harvest energy from a cylindrical piezoelectric. It includes different parts such as cubic buoyant, supporting screws, a cylindrical piezoelectric, and a vertical rod. If the buoyant submerge into water inevitably, the buoyancy force is equal to the weight of the displaced water, according to Archimedes' buoyancy principle. This mechanism prevents the buoyant from vertical displacement in order to force the buoyant to be submerged while a sea wave passes through the mechanism. Considering the sea wave height and speed, an oscillatory load will be created. Its amount entirely depends on the buoyant submergence and sea wave height, and its frequency is directly related to the velocity of sea waves. A mathematical formulation has been derived for the mechanism, but the strain versus time graph must be derived by finite element software. This process has been simulated in Abaqus (CAE) for frequencies of 1 and 2 Hz. By integration of squared strain over time, and substitution in the related equation, the output energy has been calculated. The material properties and standard dimension of the cylindrical piezoelectric have been chosen from American Piezo Company. In addition, the effect of submergence, or in other words, amount of mechanical load has been analyzed for both frequencies. The final results show that the generated electricity increases from the frequency of 1 Hz to 2 Hz. Moreover, PZT-5A output electricity is greater in comparison with PZT-5H in the same condition. For this reason, the simulation for different thicknesses has been done, and it shows that the output electricity increases for thicker piezoelectric, nonlinearly. The maximum generated electricity is equal to 9.96 μW, and it is related to PZT-5A with radius and height of 3 cm and 10 cm, respectively, when the sea waves pass with frequency of 2 Hz. Even though it is anticipated that the output electricity is higher in the off-resonance method, but the low frequency of sea waves clarifies the importance of frequency in piezoelectric energy harvesting.

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