Wave Energy Harvesting System Using Piezocomposite Materials

Zakaria Malki, Chouaib Ennawaoui, Abdelowahed Hajjaji, Mohamed Eljouad, Yahia Boughaleb

Marine energies are a strategic channel for renewable energies to diversify and complement the global energy mix. From this perspective, several researches have seen the light in order to allow the maximum exploitation possible of the energy estimated at 80,000 TWh/year, presenting multiple vacant possibilities concerning energy not yet exploited on a large scale. The purpose of this paper is the use of ocean vibratory energy coupling with a smart composite material in order to harvest the maximum power. This study will be devoted to the design, modeling, and simulation of a floating harvester energy system that combines the mechanical strength and flexibility of polymer with the high piezo and pyroelectric activities of ceramic. The harvester system is composed of a mass-spring system used to transfer wave movements to mechanical vibrations, and two piezoelectric lever devices will be used to amplify and convert the harvested mechanical vibration into electrical power. With this flexible device, the maximum power harvested is 56.45 µW/mm^2, using PU/PZT composite with the optimal resistance of 108 MΩ. Considering these results, this system can be used in very different ways in marine applications.

KEY WORDS
~ Wave energy
~ Energy harvesting
~ Piezoelectric material
~ Renewable energies
~ Mass-spring system
~ Flexible device

Ecole Nationale Des Sciences Appliquées El Jadida, Laboratoire des Sciences de l'Ingénieur Pour l'Energie, El Jadida, Maroc
e-mail: Zakariamalki07@gmail.com

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1. INTRODUCTION

Continued growth in global energy consumption, high sensitivity to shifts in demand and socio-political conflicts over the price of oil and, above all, the need to reduce CO2 emissions, reflected in Kyoto city, Copenhagen, and Durban, which are behind the world's energy strategies (Soerensen and Weinstein, 2008; Gudelj and Krčum, 2013), encourage us to take an economic, technical, and social interest in the study of new technologies for the use of renewable energies. The oceans are directly or indirectly at the root of many forms of renewable energy as their large surface area, volume, and thermal capacity make them the largest collector and accumulator of solar energy on our planet (Mutsuda et al, 2019).

The energy of the Sun (and the Moon) is accumulated by seawater in different forms, which produce different effects both on the sea and on the land (Taylor et al., 2001). By focusing on the use of these forms of energy in or on the sea, the following types of marine renewable energies (MREs) emerge (Sorensen and Weinstein, 2008):

- 8,000 - 80,000 TWh/year for wave energy
- 8,800 TWh/year for tidal current energy
- 2,000 TWh/year for osmotic energy
- 810,000 TWh/year for ocean thermal energy

Among all renewable resources, we will focus more particularly on wave energy. The swell carries a considerable energy. It results from the effect of wind on marine surfaces.

The average power of the resource is quantified in kW per linear meter (Mustapa et al., 2017).

The wave energy does not require any fuel and is easy to maintain and exploit as it does not produce any waste. This energy is competitive compared to another source of energy; when it is installed with a minimum power of 6.8GW, in the field of competitiveness it is located between 0.5 and 0.6 M €/MW (Mustapa et al., 2017; Gudelj and Krčum, 2013).

2. VIBRATION ENERGY HARVESTING

Over the last ten years, numerous research projects have emerged on the study of micro-generators generating electricity from ambient vibrations. This interest in the recovery of ambient energy is closely linked to the desire to be able to measure, monitor, process data from a sometimes hostile environment, and to be able to communicate them completely independently (Zurkinden et al., 2007). When a large number of sensors are dispersed in an environment, it is necessary for them to be provided with a power supply with the longest possible service life to limit maintenance, which is also impossible under certain conditions (Tabbai et al., 2018).

Many energy sources can provide sufficient power levels to power communicating autonomous systems (Alaoui-Belghiti et al., 2019): mechanical energy resulting from vibrations, loads or constraints, solar photovoltaic energy from the Sun or artificial lights, energy electromagnetic energy, thermal energy, or even chemical energy resulting from bio-logical processes are examples of natural energies or that inherent to an industrial process, which is currently considered to be packaged in useful production (Ennawaoui et al., 2016). The comparison of these different sources is delicate because it depends on many factors and the application considered. Nevertheless, classical comparative studies have been able to compare the power densities of several conventional sources. It appears that the exploitation of the energy of the ambient vibrations makes it possible to obtain potentially a high density of energy after the solar energy (Yang et al., 2020). This source also has the advantage of being simpler to implement (fewer constraints than a photovoltaic system) and being available in many fields of application, especially in industrial environments, or transport, where the use of autonomous sensor networks can be envisaged. Due to this availability, the vibrations are also very diverse, presenting for typical applications (Ennawaoui et al., 2019).

Energy recuperated from vibrations typically consists of 4 units:

- A mechanical device to optimize mechanical vibrations,
- A device whose objective is to convert mechanical energy into electrical energy,
- An electrical extraction circuit that will convert the recovered electrical energy into exploitable electrical energy,
- Finally, a device for managing and storing energy.

Improving the power density of the generators and their bandwidth requires the optimization of each conversion unit. In this article, we will focus on the first two units: namely, the mechanical system to optimize mechanical vibrations, and the device that allows the conversion of mechanical energy into electrical energy. As communicated in this section, the sources of vibratory energies are diversified in nature, but we will be particularly interested in the recovery of mechanical energy resulting from wave movements.

3. PIEZOELECTRIC HARVESTER SYSTEM

Several WEC (wave energy converter) systems have been developed in order to extract the maximum of the existing power (Viet et al., 2016; Viet et al., 2017; Viet et al., 2018) most of these systems can be classified by type as follows (Xie and Wang, 2017):

- Piezoelectric coupled cantilever energy harvester
- Piezoelectric bar energy harvester
- Ring generator excited by the magnetic force

These three types have major disadvantages that prevent the goal of maximum power extraction (Xie et Wang, 2017) the disadvantages depend on system components, piezoelectric material, and waves. These disadvantages are:

- Low efficiency because the wave energy does not have a uniform strain distribution on the piezoelectric surface.
- Low wave frequency [0.1 - 0.5 Hz] which induces a long period of piezoelectric loading.
- The rotary excitation style of the ring generator cannot match the linear motion of the uplift buoy on the wave.

We have chosen to develop an energy-harvesting application within the waves; an energy harvester that generates electricity during wave oscillation with a little extra force in order to power a wearable sensor with low consumption using a different material (the composite PZT/PU 50% and PVDF). The response of the energy harvesting system using those materials and composites has been studied in order to determine the optimal material to be chosen for this application. The system described in this paper is designed for the realization of a wave energy harvesting system with higher efficiency and with the possibility of performing maintenance and replacement operations more easily.

The FEH (Floating Energy Harvester) consists of two piezoelectric lever devices connected by a mass-spring system. The mass in the system is attached with small wheels that serve to reduce friction. The mass-spring system is used to transfer wave movements into mechanical vibrations, which are subsequently transferred and amplified by the two piezoelectric levers into electrical energy. The Floating Energy Harvester was designed using CAD software CATIA V5 2016 (Fig. 1).

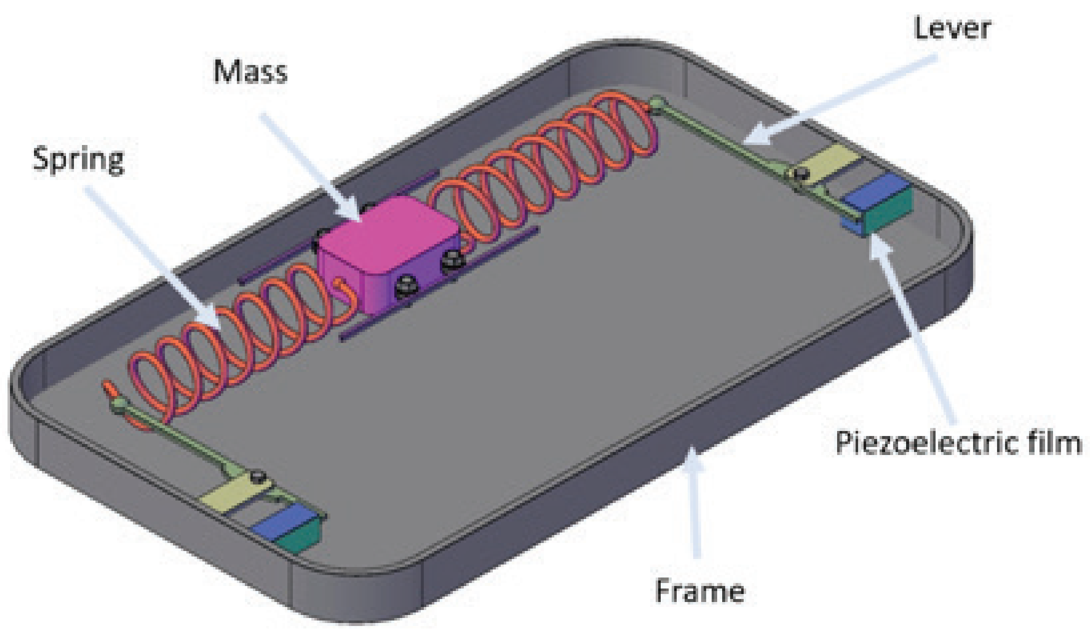

Figure 1.
Sketch of the wave energy harvester.

Regarding the disadvantages mentioned before, our system is concerned only with the low frequency of the waves for this purpose. To remedy this situation, we will use two masses that will, in turn, excite piezoelectric films in opposition of phase. In this way, we can increase the excitation frequency of the films to double the wave frequency.

4. THEORETICAL MODELING

There are many types of piezoelectric materials. In this paper, the work is mainly focused on piezoelectric flexible materials such as bulk polymers and piezocomposites. These materials convert mechanical energy while being deformed or subjected to stress (pressure, vibration, or force) in electricity. They are able to generate an electric charge when a mechanical load is applied to them. This property of piezoelectric materials is considered by researchers to develop various piezoelectric harvesters to power electrical devices. On the other hand, the modeling of the system consists in identifying the behavior of the latter as a function of the different parameters affecting the ability of this system to harvest and transform the wave energy into electrical energy (Anton and Sodano, 2007). In addition, the analytical model is presented, allowing to verify how the effect of different parameters can be shown, including the dependency of the excitation frequency, applied force, and it is described how these characteristics affect the system performance, and what the maximum limit is for the extractable power density.

4.1. Mechanical System Modeling

In order to deduce the force applied on the piezoelectric material, we will work on the two ends of the levers; on the side of the material, we will consider its mechanical characteristics (Young's modulus) in order to have the formula of the force. On the other side, the balance of forces will let us know the force applied at this end.

$$Y = \frac{\sigma}{\varepsilon} \qquad (1)$$

σ and ε are the applied stress and the relative elongation;
or

$$\sigma = \frac{F}{S} \qquad (2)$$

(with S = a.b)
and

$$\varepsilon = \frac{\Delta l}{l} \quad (3)$$

Then

$$Y = \frac{F.l}{S.\Delta l} \quad (4)$$

So

$$F = \frac{Y.a.b.\Delta l}{l} \quad (5)$$

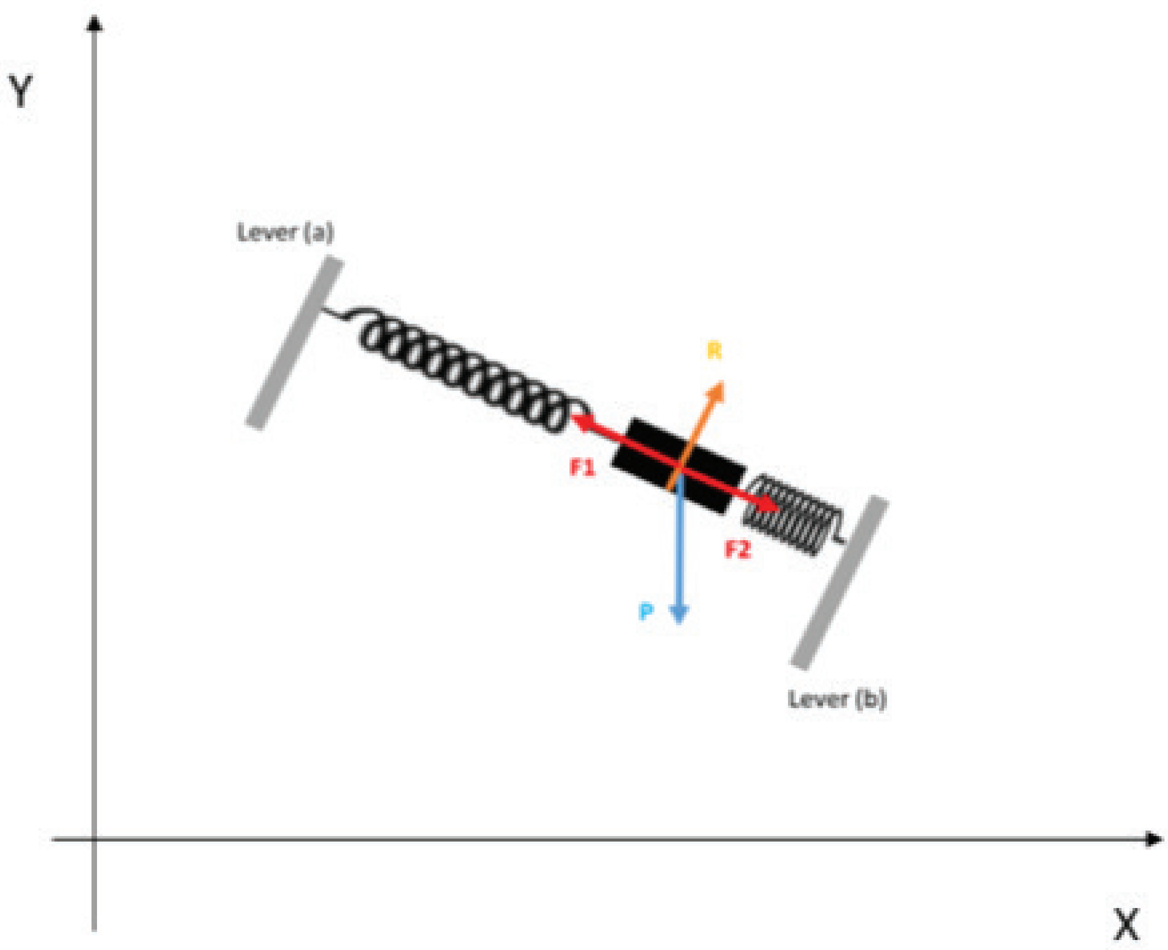

Figure 2.
A profile sketch of the interior design of FEH.

P, R, F1, and F2 are respectively the weight, the reaction of the support, right spring, and left spring.

$$\sum \vec{F} = m \frac{d^2x}{dt^2} \tag{6}$$

with k1= k2= k, (0-x1) = (0-x2) = Δl'
By projecting on x axis:

$$mg \cos(\alpha) - 2k\,\Delta l' = 0 \tag{7}$$

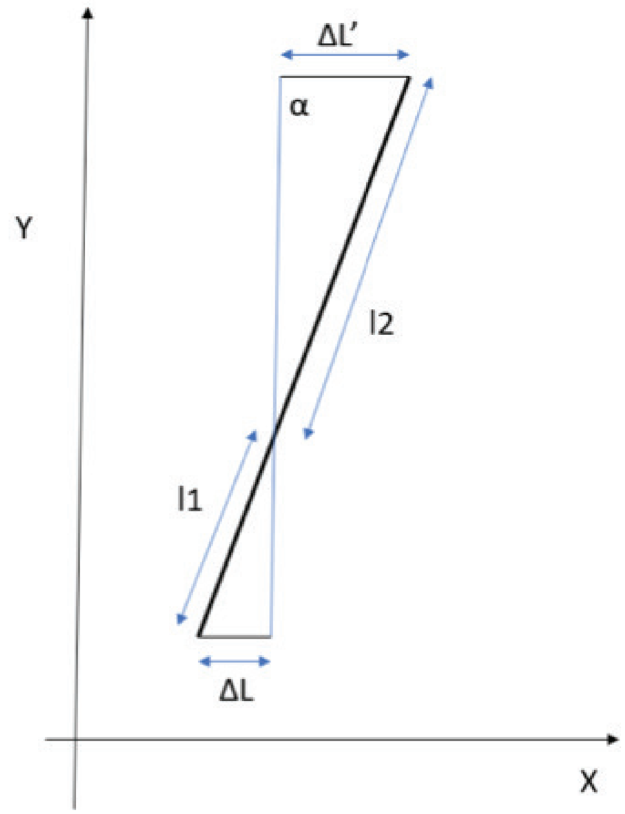

Figure 3.
Forces' balance applied during system excitation.

$$\Delta l = l_1 \sin\left(\frac{\pi}{2} - \alpha\right) = l_1 \cos(\alpha)$$

$$\Delta l = l_2 \sin\left(\frac{\pi}{2} - \alpha\right) = l_2 \cos(\alpha) \tag{8}$$

Then

$$\Delta l = \frac{m.g.\, l_1 \cos(\alpha)}{2.l_2.k} \tag{9}$$

Finally,

$$F = \frac{Y.a.b.m.g. \cos(\alpha)}{2.l.n.k} \tag{10}$$

with n=l2/l1 (9)

4.2. Piezoelectric Materials Modelization

Based on the potential thermodynamics and energy exchange principles, the piezoelectric phenomenon can be formulated with the following equations (Anton and Sodano, 2007):

$$S = s^E . T + d_t . E \tag{11}$$

$$D = d_t . T + \varepsilon^T . E \tag{12}$$

The first equation defines the mechanical response of the material, while the second equation defines the electrical response. Where S is the strain; T is the stress; E is the electric field; D is the electrical displacement; dt is the piezoelectric electromechanical coupling coefficient; s^E is the conformity, which relates the stress and strain to a constant electric field; ε^T is the dielectric permittivity, which indicates the charge stored in the capacitive element of the piezoelectric material under constant stress; and the indices represent the direction of each property.

In the literature, we have two popular and common transduction modes or vibration modes called longitudinal and transverse modes. The d33 coefficient is called the longitudinal coefficient, which describes the longitudinal mode when the stress is applied in the same direction as the electric displacement generated. The d31 coefficient is called the transverse coefficient, which describes the transverse mode when the applied stress is in a direction perpendicular to the direction of the electric displacement generated. In this paper, the principal mode is transverse mode; the applied force is perpendicular with the polarization direction (Todaro et al., 2017).

It is possible to express the T Stress as a Strain function S, given by:

$$T = \frac{S - d_t . E}{s^E} \tag{13}$$

Hence, the expression of the electric displacement D

$$D = dt \, . \frac{S - d_t . E}{s^E} + \varepsilon^T . E \tag{14}$$

The current supplied in the polymer in the case of a transverse mechanical stress is expressed in the form:

$$I = A . \frac{\partial D}{\partial t} = A . \left(\varepsilon^T - \frac{d_t^2}{s^E}\right) \frac{\partial E}{\partial t} + A . \frac{d_t^2}{s^E} \frac{\partial S}{\partial t} \tag{15}$$

The voltage across at purely resistive load is as follows:

$$E = E_R = - \frac{RI}{e} \tag{16}$$

The expression of the current will be:

$$I = -A\left[\left(\varepsilon^T - \frac{d_t^2}{s^E}\right) \frac{R}{e} \cdot \frac{\partial I}{\partial t} + \frac{d_t}{s^E} \cdot \frac{\partial S}{\partial t}\right] \tag{17}$$

In the frequency domain, the expression of the current becomes:

$$I = - j . w . A\left[\left(\varepsilon^T - \frac{d_t^2}{s^E}\right) \cdot \frac{R}{e} \cdot I + \frac{d_t}{s^E} \cdot S_M\right] \tag{18}$$

$$I = \frac{j.w.A. \frac{d_t}{s^E} .S_M}{\left[1 + j.w. \frac{R}{e} .A. \left(\varepsilon^T - \frac{d_t^2}{s^E}\right)\right]^2} \tag{19}$$

In the transverse mode, the expression of the electrical power is obtained from the equation:

$$P = \frac{R\,(w.d_{31} . F)^2}{1 + \left[w. \frac{R}{e} .A. \left(\varepsilon^T - \frac{d_{31}^2}{s^E}\right)\right]^2} \tag{20}$$

with: $S_M = s^E . \frac{F}{A}$

By substituting the expression of Eq. (8) in Eq. (18), the power harvested using piezoelectric materials can be expressed by:

$$P = \frac{R\,(w.d_{31} . F)^2}{1 + \left[w. \frac{R}{e} .A. \left(\varepsilon^T - \frac{d_{31}^2}{s^E}\right)\right]^2} \tag{20}$$

$$P = \left(\frac{1}{4} \cdot R \cdot \omega^2 \cos(\infty)^2\right) \left(\frac{\left(\frac{yab}{l} d_{31}\right)^2}{1 + \left(\frac{\omega RA}{e} \left(\varepsilon T_{33} - \frac{d_{31}^2}{s_{11}^E}\right)\right)^2}\right) \left(\frac{mg}{nk}\right)^2 \tag{21}$$

Y, l1, l2, m, K, d33, ω, A and ε 33T are respectively Young's modulus (N / m^2), length of the upper part of the bar (m), length of the lower part of the bar (m), mass (kg), springs' stiffness (N /m), piezoelectric coefficient (C/N), pulsation (rad/s), active surface (m^2), and permittivity (F/m); with a, b, and e: the dimensions of the film (m). According to Eq. (19), the electrical power harvested by piezoelectric material is dependent on numerous factors such as frequency and strain. The modification of these factors could increase the power value.

5. SIMULATIONS & RESULTS

These simulations, using MATLAB R2019b, are of paramount importance in the dimension of the equipment of our system at the level of the mechanical components, and at the level of the choice of the materials used for mechanical energy harvesting, not to mention taking into consideration the characteristics of the waves.

The power harvested shown is a function of load resistance R calculated at different frequencies for the piezoelectric materials in transverse modes. The harvested power density was calculated from the relation $P=R.I^2$ and the fundamental relations of the piezoelectric effect, which has been demonstrated in the theoretical background.

5.1. Piezoelectric Materials

After the theoretical model of the piezoelectric effect in transverse vibration mode, this part is dedicated to determine the values of the power density in two studied cases. The objective is to discuss the simulation results of the power harvested using piezoelectric polymer and piezo composite. We considered two parallelepiped structures: PVDF (Ennawaoui et al., 2018) and a PU/PZT 50% (Rjafallah et al., 2018) with a length L=2.5 mm, width l=2.5 mm, and thickness e=70um. Table 1 and Table 2 show the characteristics of the films that can be used in the model.

Table 1.
Electromechanical properties of PU/PZT 50%.

Properties	Symbol	Value	Unit
Piezoelectric coefficients	d33	170	pC/N
	d31	2	pC/N
Young's modulus	Y	1,006	N/m^2
Permittivity	ε33	10	pF/m
Poisson ratio	υ	0.46	IS
Dynamic range	P	1,006	N/m^2

Table 2.
Electromechanical properties of Polyvinylidenefluoride (PVDF).

Properties	Symbol	Value	Unit
Piezoelectric coefficients	d33	33	pC/N
	d31	23	pC/N
Young's modulus	Y	2.1009	N/m^2
Permittivity	ε33	106	pF/m
Poisson ratio	υ	0.3	IS
Dynamic range	P	5.1009	N/m^2

We chose to start with this simulation of power that varies depending on the load because it will lead us to both targets: the load that we can feed through this system, as well as the nature of the material to use to maximize the harvested power based on a comparison of two piezoelectric materials with different characteristics.

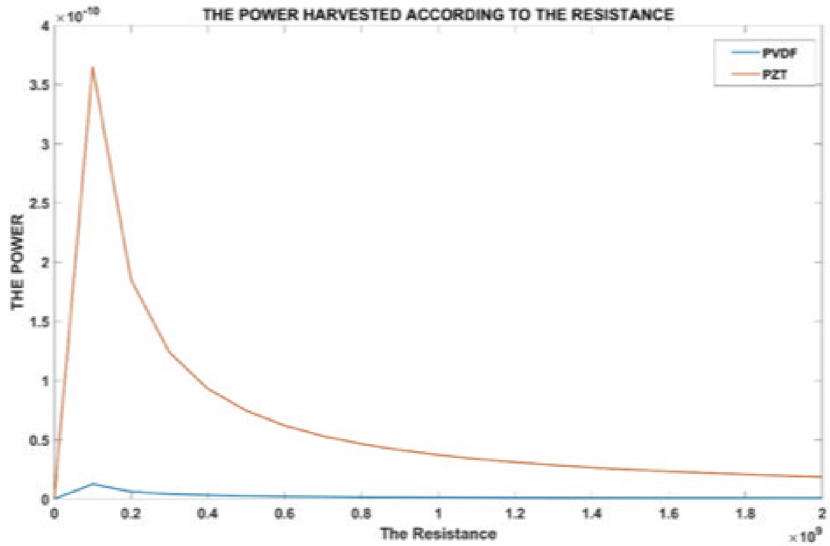

Figure 4.
Power harvested as a function of load resistance in cases of PU/PZT and PVDF.

From Figure 4, we can notice that the optimal load s of the order of 108 KΩ, and that the recovered power is of the order of 350 μW for a film of 6.2 mm2, whereof, as can be seen from these determined values, the density of power of the PU/PZT 56.45 μW / mm^2, while for the PVDF this power remains within the limit of 4.03 μW / mm^2. As already mentioned, it is clear that the PU/PZT 50% has a higher harvested power than that of PVDF, which is due to the characteristics in terms of energy conversion. Given the optimal load found and the magnitude of the converted energy, the latter can be used for several uses, which are discussed later in this paper.

5.2. Effect of Frequency on Power Harvested

Among the parameters that also infect this power is the frequency of the waves, this parameter represents for our system the impact of mechanical stress of the piezoelectric films. We considered that the frequency of solicitation is equal to the frequency of the waves.

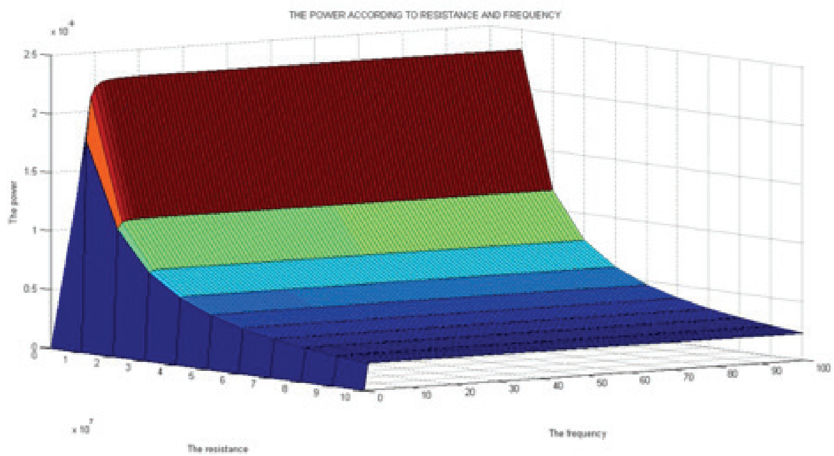

Figure 5.
Power harvested by a piezoelectric material as a function of load resistance and frequency.

Figure 5 illustrates this impact of the stress on the films by the frequency of the waves; we notice that the more important the frequency, the more important the recovered power is until the saturation point of 4Hz is reached.

If we take into account the history of the waves in some coastal cities of Morocco (Table 1), we find that the wave frequency remains in the range of [0.04; 0.09] Hz, which can also allow to recover a significant energy.

5.3. Influence of Wave Parameters on Harvested Power

Since our energy source is the movement of the waves, the power recovered by piezoelectric material, therefore, depends on the intrinsic parameters of the latter, and since we have already processed the parameter of frequency, we will start in a second step the other parameters to know the height and length.

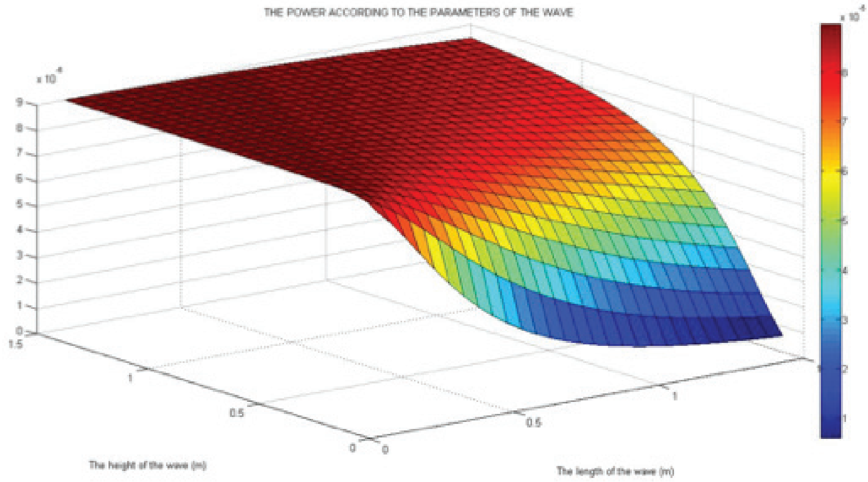

Figure 6.
The power harvested in function of wave parameters.

Figure 6 displays the results of the power harvested by varying height and length with a fixed value of mechanical frequency of 0.3 Hz, force applied F = 50 N while retaining the three thicknesses. We note that this power evolves proportionally with the height of the waves while it has a contradictory relationship with the parameter of the length. This behavior, along with the length, confirms the results found as a function of the frequency because, in addition, the length is important, more than the frequency is low so the recovered power is less important.

5.4. Influence of System Parameters on Harvested Power

This power also depends on the quantities of the components of the energy recovery system: namely, the stiffness of the springs and the mass.

Figure 7 shows that the power increases by increasing the mass, while it is the inversely proportional to the stiffness. This behavior can be explained by the fact that the larger the mass, the greater the force applied on the lever. On the other hand, if the order of stiffness is important, more difficulties occur in transporting this force towards the lever. Since we worked during our dimensioning with the springs in the mode of transport of effort, the stiffness must not exceed the 0.1 N/m for a mass of 5 kg, as shown by the simulation.

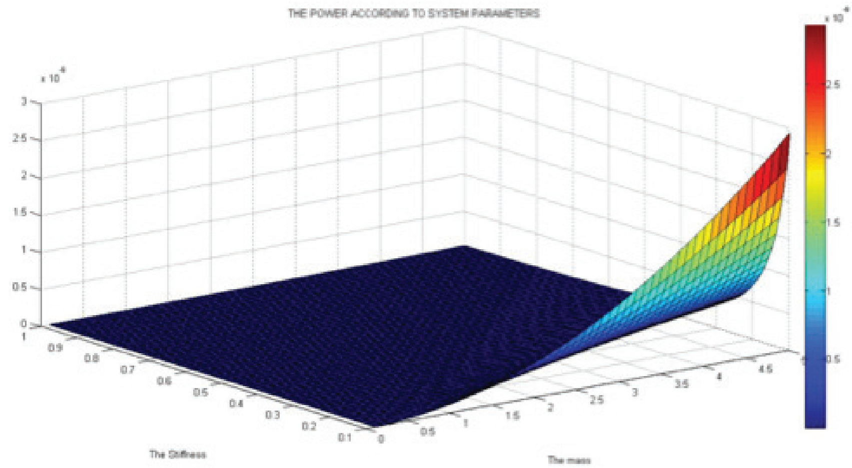

Figure 7.
Power harvested by a piezoelectric material as a function of system parameters.

6. COMPARISON OF MEMS ENERGY RECOVERS

The table below summarizes a selection of Microelectromechanical Systems (MEMS) energy recovers based on piezoelectric thin films. Since thin films compared to bulk materials have electromechanical coupling coefficients, the comparison of the performance of the apparatus must be done with reference to the density of the power and not to the power itself (Todaro et al., 2017; Gudelj and Krčum, 2013).

The parameters used to compare these devices are power generated, beam area, device volume, resonant frequency, power density and normalized power density under optimal load.

Table 3.
Comparison of MEMS energy harvester's performances (Ramadan et al., 2014; El Fatnani et al, 2018; Lifi et al., 2019; Zhang et al., 2019; Ennawaoui et al., 2019; Muralt et al., 2009; Shen et al., 2008; Van Minh et al., 2013; Marzencki et al., 2008; Elfrink et al., 2009; Alamin Dow et al., 2014; Andosca et al., 2012).

Authors	Material	Mode	Power (µW)	Optimal load (KΩ)	Beam area (mm2)	Volume (mm3)	Frequency	Power density (µW/mm3)
Muralt et al., 2009	Sol-gel PZT	33	1.4	Not reported	0.96	0.264	870	5.3
Shen et al., 2009	Sol-gel PZT	31	0.32	16	3.36	0.77	184	0.41
Lee et al., 2009	Aerosol PZT	31 33	2,76 1.29	150 510	4.5	0.43 0.61	256 214	6.42 2.11
Isarakorn et al., 2011	Epitaxial PZT	31	13	5.6	2.5	0.15	2,300	87
Le Van Minh, 2013	KNN	31	0.731	90	0.81	0.306	1,509	2,39
Sung Sik Won, 2016	KNN	31	3.62	9.6	5	2	132	1.81
Wang, 2015	ZnO	31	0.98 1.25	380 600	11.5	11.5	1,300 1,313.4	0.085 0.109
Marzencki et al., 2008	AIN	31	0.8	450	0.96	0.5	1,495	1.6
Elfrink et al., 2009	AIN	31	22.4 (unpackaged)	Not reported	31.45	17.18	528	1.3
Andosca et al., 2012	AIN	31	32	82.6	65.32	14.16	58	2.26
Authors' work, 2020	PU/PZT	31	352	108	6:2	1,875	15	187,733

A comparison between the parameters is needed for the final result. Table 3 gives an overview of the balance between Literature and Floating Energy Harvester. This system is focused on efficiency, economics, and implementation. The comparison shows the potential of mass spring system for use in power harvesting applications and provides a means of choosing the piezoelectric device to be used estimating the amount of time required for it to recharge a specific capacity battery.

This Table also demonstrates the role of the use of a composite material such as PU / PZT with a high piezoelectric coefficient in order to be able to harvest the power of the order of 300 uW, something which can extend the circle of applications to be promoted for this system.

7. CONCLUSION

The purpose of this paper is to design and study a wave energy recovery system with piezoelectric composites, we found that this system has a recovered power magnitude, which allows it to be classified among the systems designed for the recovery of the same energy source (wave energy). These results are mainly due to the choice of material and the performance of this system.

The simulations have proved that the use of PU/ PZT piezocomposite in this system for harvesting and the transformation of vibrational energy of the waves can produce up to a power of 56.45 $\mu W/mm^2$, which encourages its use for feeding of several systems in marine applications. From the point of view of technological and fundamental understanding, the electromechanical properties and energy harvesting capacities of piezocomposites are of great importance in order to improve mechanical and electrical performances of electronic devices.

Since this system is limited by the frequency of the waves, which is also the solicitation frequency of the composites, this value is considered low compared to what the system can harvest with frequencies above 15 Hz; therefore, we had to mention that these results could be improved, e.g., by the use of a piezoelectric-magnetic hybrid system, i.e., those by exploiting both the recovery with the use of piezoelectric materials and with a magnetic system (coil-magnet). Future work will focus on this objective to improve the skills of this system in the harvesting and transformation of wave mechanical energy.

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