

Sea motion electrical energy generator for low-power applications

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Abstract- The main problematic about electronic systems deployed in the sea for long periods of time, is to find a feasible way to supply them with the necessary amount of power and no direct supervision. In this paper a new idea is proposed and studied to supply deep sea low-consumption devices using low-cost disk piezoelectric elements. These piezoelectric components, together with a horizontal balance-like physical pendulum, create an electrical power generator that harvests the mechanical energy brought by the sea movements, preferably from the heave and pitch motion that sea waves induce in a moored-floating body as might be a buoy. The main purpose of this system is to unrelate the rate of impacts to the piezoelectric material from its natural oscillation frequency, making it viable to harvest energy from a slow motion environment such as the sea. Equations relating the energy extraction are presented and different experimentations are worked out to characterize the piezo elements. Finally a prototype with a proposed electronic harvesting system is built and tested in a real medium, showing the results before concluding the article.

Keywords— Energy harvesting, piezoelectric, sea waves motional energy, marine sensors networks, impacts.

1. INTRODUCTION

The increase of sea electronic instrumentation, system and sensor deployments to study the maritime medium has led to an era where powering these devices is a key point in order to avoid wiring or maintenance costs. In order to design a self-contained power source and create a wireless-autonomous electronic system, energy harvesting is a feature that is becoming popular from the last decades and it is being applied to low-consumption devices that obtain their own energy from the environment they are designed to work in. Sea water

motion provides big amounts of kinetic and potential energy that can be converted into electrical power. This conversion can be accomplished, between others, using piezoelectric elements, which deliver electrical charge from an applied deformation in their molecular structure. Nowadays, some studies use the piezoelectricity to harvest energy from vibrations [1-6] and a few of them use mechanical impacts to obtain energy [8-11]. The main problematic in all referred cases, is that the configuration used in all of these studies is highly dependent on the resonant frequency of the piezoelectric element; thus presenting a real hurdle to use these methods in slow motion environments, where the obtained energy could be of one or less microwatt [3]. Because of the low frequency of the sea motion, usual bending piezo elements are not really convenient and low-cost disk piezoelectric units (Figure 1) are used instead in this work, together with a new impacting method.



Figure 1. Disk piezoelectric element

These piezoelectric devices produce electrical energy when a mass impacts them, providing high power levels for low-frequency mechanical harvesting environments. This is possible due to the resonance achieved in each impact if the element has the possibility to move freely at its center, where the impact occurs.

Moreover, the main objective of this implementation is to power low-consumption devices deployed in the sea bottom (as acoustic tags or marine sensors). Some studies [3], [6] use the deep water flows obtaining poor results, but the system proposed here draws upon a floating body, such as a buoy, to deliver all the energy into the

impacting structure that can be placed in the bottom or in the sea surface.

The paper is organized as follows. Section 2 describes the proposed system. Section 3 studies the impacting equations and theoretical values of the piezoelectric disk devices. Section 4 shows the results from a prototypal design and some characterization of the piezoelectric elements. Section 5 concludes the work and presents future research.

2. SYSTEM IMPLEMENTATION

The physical design of the mechanical to electrical energy converter is the key point of this system, and many ideas were listed to create a free-ball movement which impacts the disk piezoelectric.

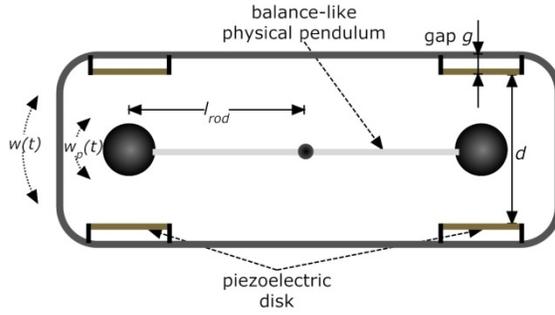


Figure 2. Proposed energy converter system

The final proposed energy converter system (Figure 2), consists of a box that encloses two diagonally-situated or four identical piezoelectric disks which are impacted at their center by two spherical masses that balance a physical pendulum. The components featured throughout all the experimentation processes are PZT material built disks, with a resonance frequency of a few kHz and a diaphragm diameter of 1.5cm and 3.5cm (Murata 7BB-35-3L0). The two identical spherical masses of mass M_s are attached to the end of a long thin rod of length l_{rod} and mass m_{rod} . d is the distance between the piezoelectric disks and $\omega(t)$ and $\omega_p(t)$ are the swing oscillation movements of the chassis and the pendulum respectively. Each piezoelectric disk has its center displacement limited by a stop (gap g) between the disk and the internal case wall, which lets the disks resonate with every excitement impact, thus generating electrical energy.

To obtain the maximum efficiency from the kinetic and potential energy provided by the waves, pitch and heave motions are studied separately to excite the containing box, and different mooring configurations of the energy converter container are shown using a buoy (Figure 3 and Figure 4).

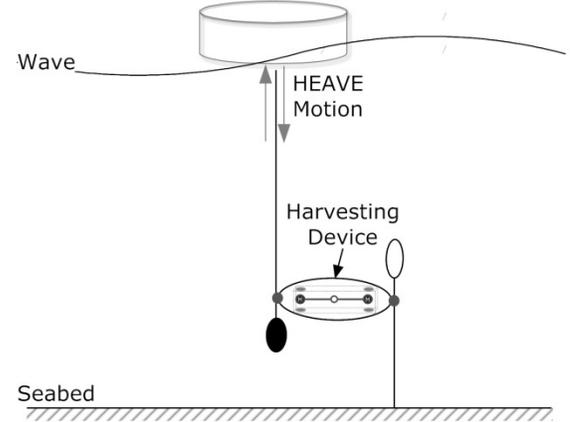


Figure 3. Mooring configurations for sea heave motion energy conversion

The configuration presented in Figure 3, takes advantage of the up and down heave motion of a floating body or buoy by attaching the energy conversion system on one of its sides to the mooring line. The pulling force created by the sea motion, destabilizes the pendulum-based system creating continuous impacts in the piezoelectric elements. A heavy mass attached near the bottom extreme of the mooring line, together with a small floatable body, creates a pull-down force at the other side of the cage. The total work done on the buoy by its motion can be approximated by Zhang et al. [7] equations:

$$W = F \cdot z \quad (1)$$

$$F = \frac{1}{4} \cdot \rho \cdot g \cdot \pi \cdot z^2 \cdot l_b \quad (2)$$

Where W is the work performed in Joules, F is the force applied to the buoy by the incident wave and l_b is the buoy length.

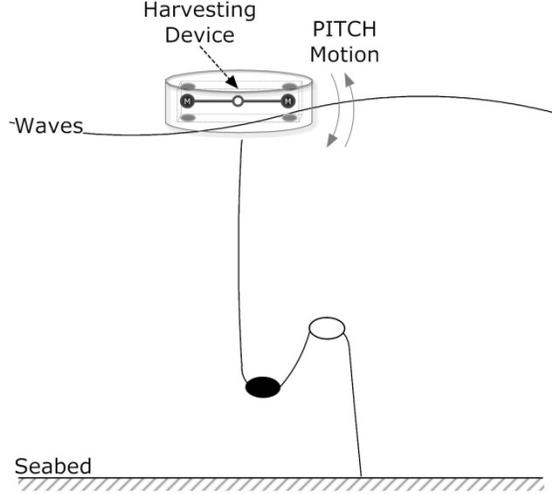


Figure 4. Mooring configurations for sea pitch motion energy conversion

The configuration shown in Figure 4 is based in the oscillating pitch motion that the sea waves induce in the buoy. In this case, the pendulum-based system is disposed inside the buoy, experiencing a complete reversal movement in the wave direction sides. This is true because the gravitational axis of the buoy remains normal to the water surface, creating an angular displacement of the harvesting system of the same amount. This oscillating movement makes the masses of the pendulum impact all piezoelectric elements in a complete wave period. In this case, the buoy can be approximated as an ideal pendulum with the mass center located at the very bottom of the chassis. The total work done on the buoy for half a wave cycle would be:

$$W = m_b \cdot g \cdot h \quad (3)$$

$$h = H(1 - \cos \theta) \quad (4)$$

Where W is the work performed in Joules, m_b is the total buoy mass in kilograms, g is the gravitational acceleration, h is the change in elevation of the mass center, H is the height of the buoy, and θ is the angular pitching displacement.

3. IMPACT PENDULUM-BASED ENERGY GENERATOR DESCRIPTION

As it was described before, the obtaining of energy in the proposed system comes from the deformation suffered by the piezoelectric disks due to the impacts of the two masses from the

destabilized pendulum. This mechanical to electrical energy conversion is fully dependent on the piezoelectric characteristics. To study the performance of the system, these characteristics are studied in the case of ideal impacts.

In the first instance, the consecutive relations between the electrical and mechanical coupling in piezoelectric elements given by IEEE Std. [12] are as follows:

$$S_{ij} = s_{ijkl}^E T_{kl} + d_{kij} E_k \quad (5)$$

$$D_i = e_{ikl} S_{kl} + \varepsilon_{ik}^T E_k \quad (6)$$

Where S_{ij} is the total strain along a certain axis, s_{ijkl}^E is the piezoelectric material elastic coefficient, T_{kl} is the stress applied in a certain direction, d_{kij} and d_{ikl} are strain piezoelectric coefficients, E_k is the electrical field, D_i is the electrical displacement, e_{ikl} is the piezoelectric coefficient and ε_{ik}^T is the electrical permittivity of the disk. The subscripts $(i,j,k$ and $l)$ express the direction of the vector in a three orthogonal X,Y,Z set of axes, where Z is the direction of the electric polarization. It is common to express together the sets of ij as p and kl as q , with values from 1 to 6.

In the case of study, an equation describing the strain along the X axis is derived from (5), taking into account the stress suffered in both X and Y axis, and denoted as T_1 and T_2 . For an orthogonal ideal impact with a round-shaped body, these stresses are equal, thus, (7) is obtained integrating along the impacting area.

$$\frac{F}{A_I} = \frac{S_1}{s_{11} + s_{12}} + e_{31} \frac{V}{t} \quad (7)$$

Where F is the applied force, A_I is the impacting area where the stress is derived from and e_{31} is by definition the relation between the strain coefficient and the sum of the elastic coefficients.

By the other hand, the resulting electrical field is created along the Z axis, thus integrating (6) along the piezoelectric material yields to (8).

$$\frac{Q}{A} = e_{31} S_1 - \varepsilon_{33}^S \frac{V}{t} \quad (8)$$

Where Q denotes the charge, A is the total area of the disk diaphragm and V is the induced voltage along the thickness t of the piezoelectric film.

If the gaps underneath the center of the piezoelectric disks permit them to resonate like a membrane on each impact, the charge Q can be ideally represented as a sinusoidal, and its relation with the voltage and load is function of the resonance frequency, but not meaning that the external excitation has to match this frequency.

Modeling each piezoelectric element as a charge source with a series resistor, a parallel capacitor and loaded with an external resistance and defining the young modulus Y_{11+22} as the inverse of the sum of the strain coefficients s_{11} and s_{22} , the final equation that relates voltage and applied force (9) is obtained.

$$\frac{V}{F} = \frac{j \cdot \omega \cdot R_T \cdot A \cdot e_{31} \cdot t}{j \cdot \omega \cdot R_T \cdot A \cdot (e_{31}^2 + Y_{11+22} \cdot \varepsilon_{33}^S) + Y_{11+22} \cdot t} \cdot \frac{1}{A_I} \quad (9)$$

For the experimentation, a lead-zirconate-titanate element (PZT-4) is used, and the material coefficient values are as follows:

$$\varepsilon_{33}^S = 5.62 \cdot 10^{-9} \frac{C}{m \cdot V} \quad (10)$$

$$e_{31} = -5.2 \frac{C}{m^2} \quad (11)$$

$$s_{11} = 12.3 \cdot 10^{-12} \frac{m^2}{N} \quad (12)$$

$$s_{12} = -4.05 \cdot 10^{-12} \frac{m^2}{N} \quad (13)$$

The electrical and design characteristics of the Murata 7BB-35-3L0 low-cost piezoelectric used in the final experimentations are:

$$R_S(\text{at resonance}) = 200\Omega \quad (14)$$

$$C_L = 30\text{nF} \quad (15)$$

$$\omega_{\text{resonance}} = 18850 \frac{\text{rad}}{\text{s}} \quad (16)$$

$$t = 0.23\text{mm} \quad (17)$$

$$\varnothing_{\text{Diaphragm}} = 25\text{mm} \quad (18)$$

Because the impacting elements are round-shaped balls, the impacting area would be a circumference and its diameter is measured with an ink mark in the piezoelectric surface caused by the impact.

$$\varnothing_{\text{Impact}} = 1.2\text{mm} \quad (19)$$

One of the basic tests worked out consists on a direct measure of the element output when an impact occurs. A load of $100\text{M}\Omega$, added to the parallel capacitor and series resistor, represents the load of the scope using a 1:100 probe. Taking this last value

and (10) – (18) into (9), and calculating the modulus, gives a final relation of:

$$\frac{V}{F} = 0.627 \frac{V}{N} \quad (20)$$

The voltage-force relation is interesting to know and easy to compare with experimental results, although the real remarkable feature in an energy generator is the amount of power it can deliver or the quantity of energy. In this case, the instantaneous power per newton is obtained squaring (20) and dividing the result by the equivalent load impedance ($R_{eq} = 1968\Omega$). A result of 0.2mW/N is obtained. Furthermore, because the impacts are not continuous over the time, the time dependence is avoided by integrating the power over a period between impacts and obtaining the electrical energy in Joules produced by the system, or another way is to obtain the real power as (21)

$$P = 0.2 \cdot \frac{t_{\text{imp}}}{T} \frac{\text{mW}}{\text{N}} \quad (21)$$

Where t_{imp} expresses the time along which the deformation of the piezoelectric element takes place and T is the period between impacts. So, as it may be obvious, the obtained power has a direct dependency on the quantity of impacts per unit of time and the energy of those impacts, which leads to a longer or shorter response of the material.

4. PIEZOELECTRIC CHARACTERIZATION AND EVALUATION OF THE SYSTEM

Different experiments have been worked out to test the feasibility of the system and to characterize the piezoelectric elements. A first testing prototype is built (Figure 5) over a shaking table to experiment the behavior of the disk piezo elements to ball impacts with different frequencies and forces. In Figure 5 the output voltage of an impact is shown together with the impacting experiment in the shaking table.

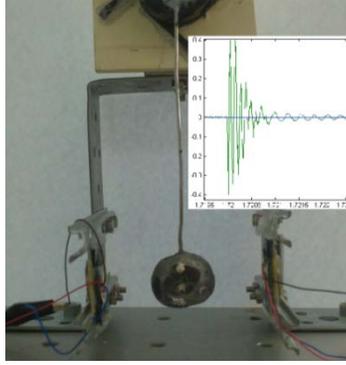


Figure 5. Disk piezo testing pendulum and output voltage

As Figure 5 shows, the voltage output is sinusoidal, and is coincident with the resonant frequency of the piezoelectric element, demonstrating the assumption of resonant response to impacts. May it be informed that the disk elements were attached around its edges, leaving a free space in the center area.

In order to characterize the piezoelectric elements, another test-bench is built to control the mechanical energy provided by a free-falling ball which impacts a disk piezo element. This energy is calculated using the initial height, ball mass and final measured deformation, as well as subtracting the loss of energy due to the rebounds presented in the impact. This can be done with the conservation criteria equations and the observed time between impacts when rebounds are present. Table 1 shows some results obtained from testing the impacts of different round bodies to the piezoelectric elements in a free-fall, using a 100MΩ probe.

Table 1. Free-fall characterization with 100MΩ

Height [cm]	Weight [gr]	Voltage [Vpeak]	Rebound [ms]	Deform [um]
6	3.2	63.8	53.36	17.5
6	4.63	77	72.63	23.8
6	12.539	128	93.35	60
8	3.2	55.6	60.72	21.7
8	4.63	84	84.92	27.6
8	12.539	155	115.75	49.7
10	3.2	70	75.6	26.9
10	4.63	106	95.47	38.6
10	12.539	169	119.5	84.8

Table 1 is used to find the relationship between the output voltage and the applied force,

calculated with the weight, height and deformation, where finally a mean value of $V/F=754.4mV/N$ is obtained, which does not differ much from the theoretical value (20).

Another interesting feature of the piezoelectric disks used in the energy generator, is the energy conversion efficiency. This mechanical to electrical energy conversion efficiency is analyzed acquiring the electrical output energy provided by each impact using the DSP capabilities of an oscilloscope. The mechanical energy is calculated with the free-fall energy conservation equations, and subtracting the amount of energy not transferred in the first impact by knowing the time between the rebounds. Table 2 shows the results of this experiment where a load of 100Ω is connected to the piezoelectric element. Moreover, because the duration of the impact varies from one experiment to another, a 1ms generation reference has been taken into account to compare all the tests within the same time window. The efficiency in the first 1ms of energy transfer is shown also in the table.

Table 2. Efficiency of the mechanical to electrical energy conversion of the PZT-4 disk piezoelectric

Height [cm]	Weight [gr]	Efficiency (%)	Efficiency 1ms (%)
6	3.2	1.134	0.791
6	4.63	0.877	0.674
6	12.539	0.566	0.31
8	3.2	1.59	0.75
8	4.63	0.835	0.748
8	12.539	0.446	0.312
10	3.2	0.804	0.718
10	4.63	0.855	0.809
10	12.539	0.496	0.335

As the results in Table 2 show, the conversion efficiency of the PZT-4 material elements is pretty low, even more if the impact is made by a heavy body. A conversion efficiency between 0.7% and 0.8% seems to be a repetitive value.

To finally test the system described in this article, a functional prototype is built (Figure 6). Two lead balls are glued at both extremes of a thin rod center-fixed in a brushless motor rotator. The stator is fixed in a cage with two PZT-4 piezoelectric disks, which receive impacts from the lead balls every time the cage is destabilized.



Figure. 6 Sea motion electrical energy generator prototype

Figure 6 shows the ensembled system, which also includes some electronics to harvest the generated electrical energy. The electronic system, attached to the top of the case, includes an energy harvesting evaluation kit (IPS-EVAL-EH-01), featuring the high efficiency regulator chip MAX17710 which also manages the input and output charge of an ultrathin THINERGY® MEC battery. This solid-state battery is charged by the energy that both piezoelectric elements provide. The solar energy cell is part of the harvesting board, but is not used for this specific experiment. Additionally, a data-logger and a control board are designed using a PIC microcontroller. This board enables the 3.3V output of the harvester chip, loaded with a 1KΩ resistor, every three minutes. While the output is enabled, the PIC senses it using a low-power Operational Amplifier in a buffer configuration to avoid the charge effect of the ADC. When the output decreases, reaching a threshold of 2.7V, it is disabled until the next three minutes have elapsed. The PIC also counts how many microseconds the output has been enabled, and stores it in its internal flash memory so the data can be recovered after the experiment.

The cage is attached to a buoy in one of its extremes, leaving the other move freely with the oceanic motion. Although this configuration was supposed to locate the cage near the bottom surface, the experimentation was performed with the cage in the top surface. The whole system was deployed at around 200 meters from the Mediterranean Barcelona shore, obtaining 24 hours of data. It should be noted that the sea level that day was between 0 and 1, with medium wave heights of 23cm and wind speeds varying from 0.5 to 3m/s, that is to say there was almost no sea movement.

The results provided by the PIC are shown in Figure 6. This chart reveals how much time the electrical energy generator has provided 10.89mW (Y axis) and when it was activated in the 24 hour period (X axis). It can be observed how, besides the first increase of energy at the beginning, the generation of energy was decreasing.

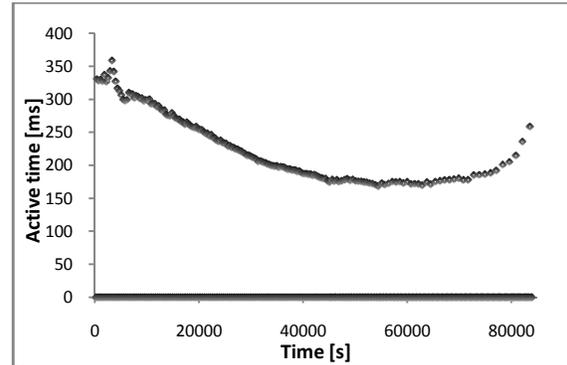


Figure 6. Final results from the prototype experiment

The total amount of electrical energy harvested during the experiment was 435.16mJ. As it was acquainted, the sea was completely calm and even with those conditions the chip was enabled during hundreds of milliseconds every three to twelve minutes, consuming almost 11mW. These results give positivity to continue with further experimentation.

5. CONCLUSIONS

A new idea about harvesting energy from the ocean is proposed and evaluated, featuring the uncommonly used disk piezoelectric elements to obtain electrical energy from the sea motion using an impact-based system. A theoretical analysis is presented, estimating how much power could the PZT-4 piezoelectric material deliver. Different tests are worked out to evaluate the impacts and piezoelectric elements, characterizing these last ones and comparing the obtained results with the theoretical analysis. An exhaustive free-fall body impact testing with different weights and heights, has proven that the efficiency decreases if the impact is too powerful.

Finally a prototype is built and tested in the sea, and even though it did not generate a big amount of electrical energy, it gives an idea of how much power can be obtained or which kind of systems can

be fed with the proposed system. The obtained results give hope to think that this system can be implemented and applied to power small nets of underwater or water-surface wireless sensors, which was the main aim of this investigation. This nets would acquire data and communicate with the nearest node every certain time, remaining in a sleep mode the rest of the period.

By the other hand, higher levels of sea motion can produce great amount of energy if the system is designed with the correct materials. Because it can work well in non-sunny conditions, complementing a solar panel based system would be another application, providing energy during the night or in cloudy days, where the sea motion is also increased. Moreover, as the main idea is to harvest energy from motional environments with excitation frequencies not tuned with the natural frequency, the system can be implemented in mediums other than the sea, where the energy from a kinetic movement can be harvested, such as remote controls or other moving electronic devices.

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