

Experimental validation and modeling of plucked piezoelectric for underwater energy harvesting system

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Abstract – Underwater wireless sensing systems are envisioned for stand-alone applications and as an addition to cabled observatory systems such as the OBSEA marine observatory. Therefore, this work presents a solution on how to generate power for marine wireless sensors using underwater motion energy. In this part it is described a prototype based on a Bristol cylinder which can generate electrical voltage using piezoelectric bimorphs. Collecting water motion energy using piezoelectric energy harvesting is particularly difficult due to the mismatch between the low frequency of water kinetics and the high-frequency requirements of piezoelectric transducers. Therefore, to achieve frequency up-conversion we propose the use of the plucking technique applied to piezoelectric energy harvester. Experimental results show that the proposed energy harvester achieves a maximum power density of $350\mu\text{W}/\text{cm}^3$.

I. INTRODUCTION

Today, both the underwater communication technologies and the sensor technology are mature enough to motivate the idea of underwater sensor networks. Underwater wireless sensing systems are envisioned for stand-alone applications and as an addition to cabled systems. For example, cabled ocean observatories are being built on submarine cables to deploy an extensive Fiber-optic network of sensors (cameras, wave sensors and seismometers) covering miles of ocean floor [1, 2]. These cables can support communication access points, very much as cellular base stations are connected to the telephone network, allowing users to move and communicate from places where cables cannot reach. In Figure 1 is illustrated the OBSEA underwater observatory (www.obsea.es) having fiber-optic and power cable for communication with the shore station and acoustic modem for communication with underwater wireless instruments.

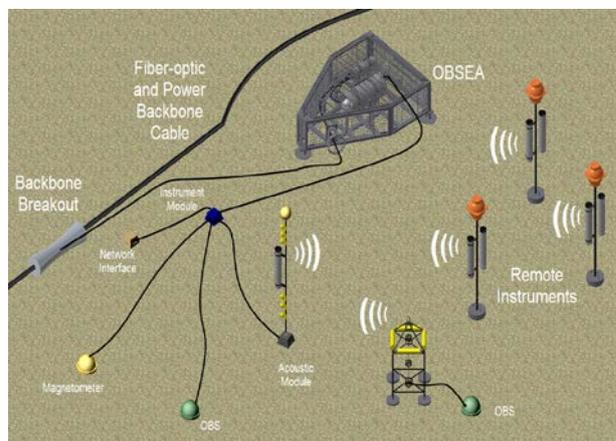


Figure 1 Diagram of underwater observatory. Shows hybrid communication system, measurement equipment with wireless and wired access in underwater environment

However, to turn this idea into reality, one must face the problem of providing powering solutions for long term deployments. The energy requirements of low-power electronics have steadily decreased with advancements in efficient circuitry such that energy harvesting systems can be considered feasible solutions in providing power to self-powered systems. Conventional autonomous low-power marine instruments, such as recorders capable of measuring a wide range of environmental parameters, from surface and subsurface temperatures, salinity, wave energy, and current flow, rely on batteries to provide power to the device. The use of batteries, however, presents several drawbacks including the cost of battery replacement as well as limitations imposed by the need of convenient access to the device for battery replacement purposes. Marine instruments, for example, are often used in remote locations, therefore, access to the device can be difficult or impossible. By scavenging ambient energy

surrounding an electronic device, energy harvesting solutions have the ability to provide permanent power sources that do not require periodic replacement. Such systems can operate in an autonomous, self-powered manner, reducing the costs associated with battery replacement, and can easily be placed in remote locations.

Among the ocean areas where harvestable energy is available, the most interesting ones are the areas with tidal and ocean currents and the shallow water areas with significantly wave-induced oscillatory currents at the sea bottom. Particular, wave-induced oscillatory currents at the sea bottom are interesting for harvesting device because of the body dynamics placed in these areas [3, 4]. The path of water displacement in gravity waves is roughly circular motion. In deep water, the path becoming smaller with depth before finally disappearing as the depth increases beyond the zone of wave disturbance and wave motion does not reach the seabed. In shallow water, the water particles have an elliptical orbit and wave motion is felt at the seabed as shown in Figure 2.

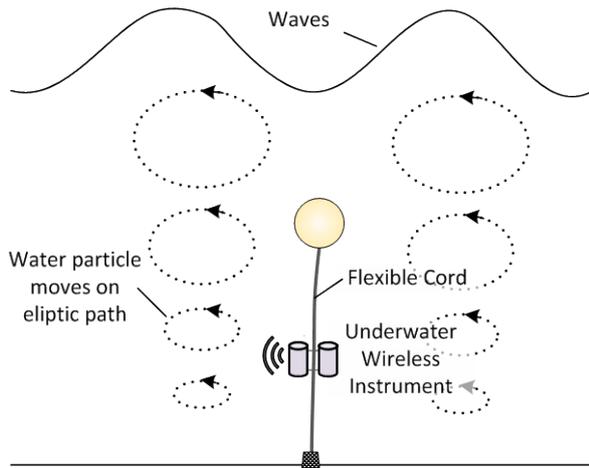


Figure 2 Underwater wireless instruments dynamics in water circular motion induced by waves.

Existing research on underwater piezoelectrics energy harvesters focuses primarily on lab-scale studies, while modeling and other forms of quantification are often overlooked. In this area, piezoelectric materials have been used widely to generate electrical energy from ambient vibration produced by ocean wave energy [5-9]. However, because of the very low frequency oscillations of an ocean platform such as a buoy, using these methods based on vibration electrical energy generators pose great challenges.

Although some underwater energy harvesting devices have been developed with piezoelectrics [10, 11], these

devices do not consider all the parameters in order to optimize the mismatch between the low frequency of water kinetics and the high-frequency requirements of piezoelectric transducers. Therefore, automatic test setup and computational model for wideband vibration-based piezoelectrics energy harvesting are necessary to evaluate the various parameters of underwater energy harvesters and direct the design strategies to improve the energy harvesting performance [12].

In this paper, we develop a new harvesting system for underwater energy harvesting. New system configuration and piezoelectric bimorph materials are employed to improve the efficiency of energy conversion. A computational model is proposed to describe the relationship between the harvester motion and output voltages under various operating conditions. The proposed model is utilized to estimate several key parameters of the underwater energy harvester that are critical to further optimizing its design.

II. CONCEPT OF THE RESONANT, PLUCKED – DRIVEN VIBRATION ENERGY HARVESTER

In contrast with the conventional bimorph, resonant, vibrational energy harvester, the plucked-driven piezoelectric harvester shown in Figure 3 comprises two beams. One is a piezoelectric generating beam with a high resonant frequency; the second is a short driving beam, plectra. When the plectra impacts the generating beam, vibration is excited first at the system's coupled vibration frequency and then at the generating beam's higher resonant frequency, producing electrical power.

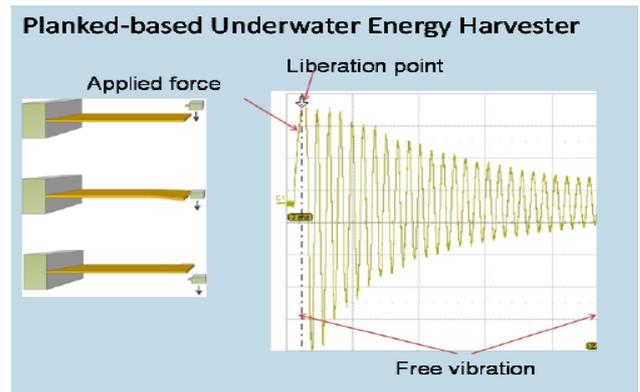


Figure 3 Plucked-driven vibration energy harvester

This plucked-driven approach offers several advantages, the first being increased efficiency because of the optimization of the mismatch between the low frequency of water kinetics, which is the impact-driven of the coupled vibration energy harvester, and the high-frequency requirements of piezoelectric transducers.

The underwater harvesting device designed to use this planked-driven approach is based on an internal pendulum, with plectra's attached to the internal radius and piezoelectric beams fixed to the pendulum axle, as illustrated in the Figure 4.

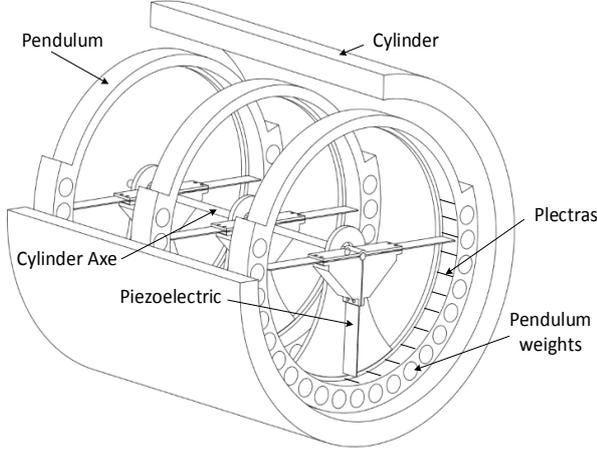


Figure 4 Schematic representation of the proposed underwater energy harvesting systems having three pendulums with three piezoelectric elements for each pendulum

Impacts between the plectra's and the piezoelectric beams are similar to an inelastic collision. Therefore the plectra impacts the piezoelectric beam and they undergo coupled vibration for part of a cycle until they separate [12]. The kinetic energy of the plectra may be considered to be converted to potential energy, primarily of the piezoelectric beam and to a lesser extent of the plectra, without additional loss [13].

During the impact phase, the plectra (spring constant k_d) impacts the piezoelectric beam (spring constant k_p) and transfers energy to it. The beams vibrate together with a combined spring constant (a coupled stiffness) of $k_d + k_p$. During free vibration phase, the plectra and the piezoelectric beam separate. The piezoelectric beam vibrates with exponentially attenuating amplitude at its own resonant frequency ω_p , while the plectra moves with the pendulum motion at the ambient frequency ω_a until it impacts the piezoelectric beam during the next cycle.

Based on the displacement of the piezoelectric beam, D_p , one can calculate the maximum open circuit voltage generated as:

$$V = -d_{31} t_p \sigma_s / \epsilon = (-d_{31} t_p / \epsilon) (3k_p D_p L_{p3} / b_p t_p^2)$$

Where d_{31} is the piezoelectric coefficient, t_p is the thickness of the piezoelectric beam, σ_s is the stress on the surface of the piezoelectric beam and ϵ is the dielectric

constant of the piezoelectric layer. The parameters L_{p3} and b_p are the length and width of the piezoelectric beam, respectively.

III. EXPERIMENTS AND DISCUSSION

1. Test setup

The underwater harvesting device was demonstrating using a 25.2 cm external diameter, 20.2 cm internal diameter, 2.5 cm thick epoxy resin pendulum with a mass of 330 g, not uniformly distributed. On the internal diameter of the pendulum there were fastened vinyl plectra's of 5.7 mm long, 20 mm wide, 0.3 mm thick. Three piezoelectric beams, model V21BL (Mide Technology Corporation) of 9.05 cm long, 1.44 cm wide and 0.78 mm thick were attached to the pendulum axle with a offset angle of 90 degrees. As shown in Figure 5, the energy harvester was mounted on a cylinder bind to a shake table for testing. A high sensitivity magnetic velocity sensors (SM-6 with 28.8 V/m/s from Input-Output Inc. Stafford, TX, USA. and GS-11 with 85 V/m/s from OYO GeoSpace Technologies, Houston, Texas, USA) attached to shake table measured the acceleration generated by this and a commercial gyroscope (MPU-6050, InvenSense's MotionFusion) fastened to the harvester device measured the rotation generated by shake table.

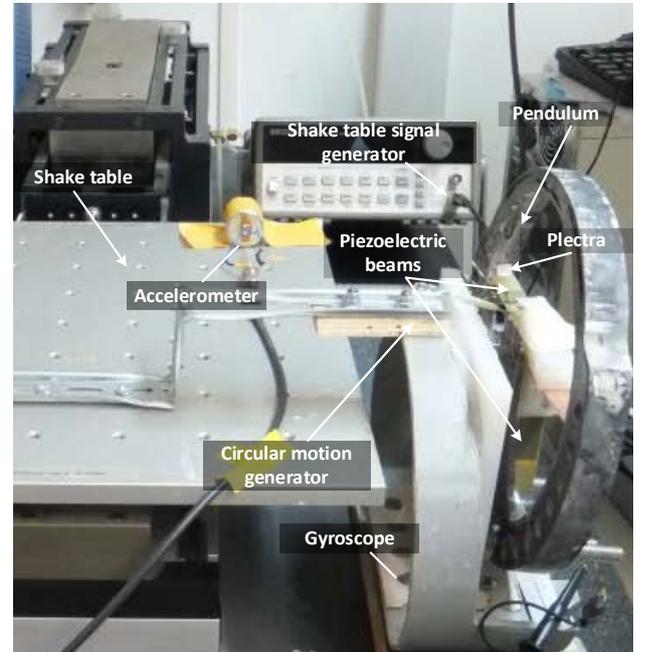


Figure 5 Illustration of the prototype energy harvesting device mounted on a cylinder attached to the shake table, showing the pendulum with the plectra's, the piezoelectric beam, the accelerometer and the gyroscope

Sinusoidal drive signals were applied over a range of frequencies between 0.1 Hz to 0.33 Hz, and the output voltage was measured with a matched load resistance of 120 k Ω .

2. Experimental results

Figure 6 plots the instantaneous output voltage of the two plunked vibration piezoelectric beams for a driving rotation of the harvesting device of 25 rad/s at 0.33 Hz and with only one plectra facing the piezoelectric beam. The maximum peak-to-peak voltage is 30 V. The generating beam's voltage is exponentially attenuated, as expected. Also for the free vibration, the vibration frequency of the piezoelectric beam is approximately equal to the resonant frequency ω_p .

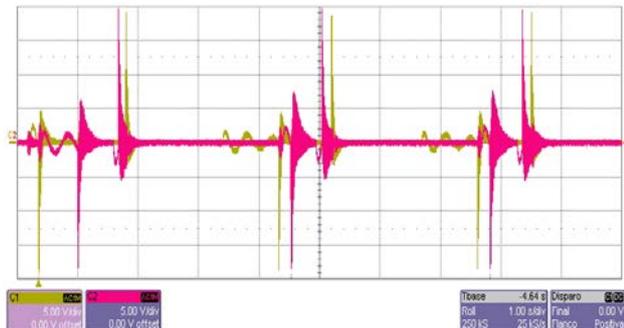


Figure 6 Output voltage of two piezoelectrics plotted versus time for a rotation of the harvesting device of 25 rad/s at 0.33 Hz and with only one plectra facing the piezoelectric beam.

Figure 7 plots the instantaneous output voltage of a single plunked vibration piezoelectric beam for a driving rotation of the harvesting device of 25 rad/s at 0.33 Hz and with several plectra's facing the piezoelectric beam and with 5mm gap. The maximum peak-to-peak voltage is 30 V. The impact phase between the piezoelectric beam and the plectra's appears several times per cycle depending on the maximum rotation angle of the harvesting device and after each impact occurs the free vibration phase.

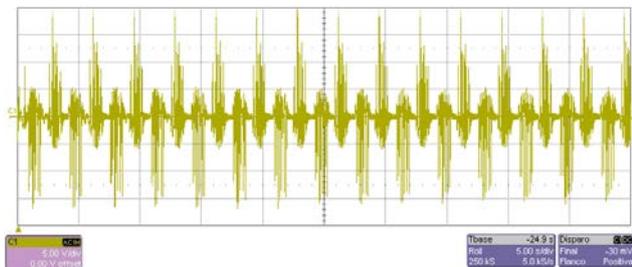


Figure 7 Output voltage of a single piezoelectric plotted versus time for a rotation of the harvesting device of 25 rad/s at 0.33 Hz and with several plectra with 5 mm gap

facing the piezoelectric beam.

IV. CONCLUSION

A new idea about harvesting energy from the ocean underwater motion is presented and evaluated. The harvesting device based on piezoelectric beams uses a plunked-driven vibration approach produced by the rotation motion of a pendulum system to obtain energy from the underwater elliptical motion. Different tests are worked out to evaluate the impacts between plectra beams and piezoelectric beams, characterizing these and comparing the obtained results with the theoretical analysis. Finally a prototype is built and tested in a shaker table test setup, obtaining good and hoping results to think that this system can be implemented and applied to power small nets of underwater wireless sensors.

Testing the operation of the pendulum harvesting device in various situations we find it appropriate to power the low power underwater wireless sensors. We also show that the distribution of plectra's on the internal diameter of the cylinder is closely related to the rotation of the cylinder induced by the waves. For low rotations, less than 0.23 rad is better to work only with the central piezoelectric, and for rotations higher than 0.23 rad to work with all three piezoelectric.

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