POWERING LOCOMOTION OF UNDERWATER MICROROBOTS WITH PIEZOELECTRIC ENERGY HARVESTING

Nikki Hart
ECE 4320, Cornell University, Ithaca, NY, USA

ABSTRACT

In this paper, the use of a piezoelectric bimorph energy harvester is explored for application in the field of underwater microrobots. Specifically, existing research in piezoelectric energy harvesters for ocean applications is built upon for use in flood conditions and scaled down for use in powering microrobots. Based on an estimate of the power density of an underwater microrobot, it was found that such a device could produce a sufficiently high power density to power an underwater microrobot when driven by a force at 1.3 Hz. This paper demonstrates the viability of the use of piezoelectric generators to power microrobots remotely and for sustained periods of time.

INTRODUCTION

Motivation

One of the major challenges of designing microrobots is finding suitable power sources for microrobots operating remotely or for long durations of time [1]. Locomotion of such small robots presents another challenge, especially for underwater robots, which face high forces relative to their mass and can lack stability or the ability to traverse large distances [2]. Existing research on underwater microrobots focuses on the latter, often using tethers or magnetic fields to power or drive robots; as a result, remote applications of these robots have not been widely explored.

Meanwhile, high-power-density and low-maintenance power sources are being investigated in ocean engineering and underwater applications. Energy harvesting, the process of converting energy from a physical environment into usable electrical energy, can be used in conjunction with or as a replacement for other power sources [3] because of its lack of need for maintenance, replacement, or replenishment. Examples of strategies for harvesting energy in underwater environments include piezoelectric MEMS generators and nanogenerators [3] as well as other piezoelectric generators and power extraction systems [4].

This project synthesizes and expands on research from multiple areas of MEMS devices, aiming to utilize energy harvested from floods to propel locomotion of microrobots in water. Multiple applications of piezoelectric generators were explored; it was determined that the application that maximized power generated and minimized power expended on resisting impedance to the microrobot's locomotion would be areas flooded with standing water through which vehicles, people, or other bodies passed. In this application, power can be generated and stored when there is fluid flow, and power can be used for locomotion when there is no fluid flow to oppose it.

Such microrobots could be invaluable for flood monitoring and search-and-rescue missions when larger bodies pose a danger in rapidly-flowing water or face difficulties navigating in small spaces in natural disasters.

Operating Conditions

Piezoelectric generators have largely been applied to ocean engineering applications because of the natural waves from which energy can be harvested. These waves tend to be both low frequency—often under 1 Hz—and low acceleration—less than 1 G [5]. However, much larger frequencies can be generated by from certain device designs or flow conditions; for example, vortex-induced vibrations (VIV) generated from vortices shed around bluff bodies are often used in energy harvesting applications, and self-induced vibrations can be used for energy harvesting when the speed of the fluid flow exceeds a critical speed value [4].

The field of microrobotics and the application of floods pose additional challenges; in addition to the large forces small bodies might experience, flood conditions vary greatly, and the forces and frequencies present are not well-documented. As a result, ranges of values as well as assumptions are applied to the analyses in this paper. Finally, because this paper explores device design for the generator and not the robot, as well as because the chosen application is in standing water, existing research on VIV and SEV are not applicable here.

Device Description

This paper explores the design of a piezoelectric bimorph generator. This form of generator was chosen for its ability to harvest power from a variety of flow conditions as well as its propensity to generate AC power. This power can be used in its initial state or converted to DC using a common piezoelectric generator rectifier circuit as shown in Figure 1 below.

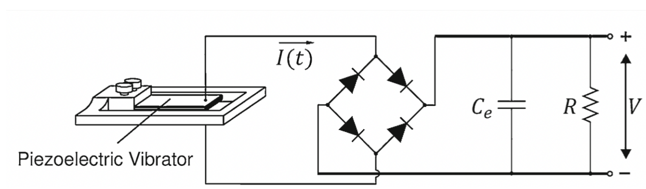

Figure 1: Piezoelectric energy harvesting circuit [6].

This piezoelectric bimorph device uses PZT, one of the most commonly-used piezoelectric materials. Because it has a high coupling coefficient, it has the potential to generate more power than other piezoelectric materials; in addition, it has a high elastic modulus and relatively high tensile strength, making it suitable for electro-mechanical applications [4].

METRICS AND MATERIAL PROPERTIES

For these analyses, a benchmark power density value of 10000 W/m^3 was used to evaluate the success of the device design. This value was estimated using the power density of a 17mm×6mm×14mm jumping microrobot consuming 6.4mW of power [7]. From this power density of 4481.8 W/m^3, it was assumed that an underwater microrobot would consume about half the power, and the objective of this device design was determined to be a piezoelectric generator that could take up approximately one-fifth of the volume of the robot, therefore having a power density five times that of the robot as a whole. The calculated necessary power density was approximated as 10000 W/m^3 for simplicity.

Material properties of PZT also served an important part of the analyses. These values are summarized in Table 1 below.

Table 1: Piezoelectric and material properties for PZT [8].

Symbol		Value	Units
Composition		Lead Zirconate Titanate	
Central shim		Stainless steel	
Relative Dielectric Constant	K_3	1700	
	K_1	1700	
Curie Temperature		~360	C°
Coupling Coefficient	k_{33}	0.69	
	k_{31}	0.35	
Piezoelectric Strain Coefficient	d_{33}	360e-12	m/V
	d_{31}	180e-12	
	d_{15}	550e-12	
Piezoelectric Voltage Coefficient	g_{33}	25e-3	V m/N
	g_{31}	11e-3	
Density		7600	Kg/m3
Elastic Modulus	Y^E_{33}	4.9e+10	N/m2
	Y^E_{11}	6.3e+10	

In addition to these values, a bending strength of 114.8 MPa [9] was used to evaluate the factor of safety of the beam in bending in subsequent sections.

DERIVATIONS AND PRELIMINARY ANALYSIS

To estimate the power density of such a device, the voltage produced by a beam bending under a static load *F* was approximated as the following [10]:

$$V = \frac{3lg_{31}}{2wt}F \tag{1}$$

This value was assumed to be the amplitude of the AC output voltage of a piezoelectric bimorph beam under a force of amplitude *F* and frequency *f*. Because operating a piezoelectric beam at resonance will produce significantly higher displacements and thus higher output voltages, the resonance frequency of the beam was calculated under the assumptions that the total thickness of the piezoelectric material is approximately equal to the thickness of the entire beam and that the mass of the beam is concentrated at the end of the beam:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{1}{\varrho lwt}\frac{Ewt^3}{4l^3}} = \frac{1}{4\pi}\frac{t}{l^2}\sqrt{\frac{E}{\varrho}} \tag{2}$$

To calculate the maximum power output, it is assumed that the beam is operating at its resonance frequency regardless of its dimensions; then, the piezoelectric beam is modeled as a capacitor and its energy output is multiplied by the frequency to find power:

$$P = \frac{1}{2}\frac{\varepsilon_0\varepsilon_r wl}{t}V^2 f \tag{3}$$

Combining these equations, the power density, or power per unit volume, can be calculated:

$$PD = \frac{9}{32\pi}\frac{\varepsilon_0\varepsilon_r {g_{31}}^2}{w^2t^3}\sqrt{\frac{E}{\varrho}}F^2 \tag{4}$$

While this derivation assumes the device's density is independent of the device dimensions and materials and that the device thickness is that of the piezoelectric, which may not always hold true, this estimate shows an inverse cubed relationship between thickness and power density, as well as an inverse square relationship with the width. Thus, power density can be maximized most effectively by minimizing thickness and width; however, practical considerations such as the feasibility of manufacturing a device with very low-thickness depositions as well as the need to minimize the device's resonant frequency for applications in flood conditions must be considered. Because vibration conditions in water tend to be low-frequency, for such a device to be used in existing flood conditions without external driving forces, the resonance frequency must be low. Finally, all device dimensions are constrained by the bending strength of the material, for which the factor of safety is calculated below:

$$FoS = \frac{\sigma_{bending}}{\sigma_{applied}} = \frac{\sigma_{bending}}{6F}\frac{wt^2}{l} \tag{5}$$

Equations 2, 4, and 5 were examined and entered into a MATLAB script where device dimensions could be changed manually and metrics, such as a factor of safety of at least 1.5 and the aforementioned benchmark power density of 10000 W/m^3, could be verified. Based on the equation for frequency, the objective was to maximize the length of the device and minimize the thickness; based on the power density equation, the objective was to minimize both thickness and width; and based on the factor of safety equation, or constraining equation, the objective was to maximize both thickness and width. In order to minimize frequency as much as possible, ideally to a value of no more than 1 kHz, a proof mass of mass m_{proof} was added to the script, modifying the above equations as follows:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{1}{\varrho lwt + m_{proof}}\frac{Ewt^3}{4l^3}} \tag{6}$$

$$FoS = \frac{\sigma_{bending}}{\sigma_{applied}} = \frac{\sigma_{bending}}{F + gm_{proof}}\frac{wt^2}{6l} \tag{7}$$

The material properties of PZT shown earlier in Table 1 were used for these calculations, as well as a force value of approximately 29 µN. Due to limited documentation of the magnitudes of forces underwater, especially in standing-water flood conditions, it was assumed that the largest force value the analysis could depend on would be approximately equal to the water pressure force at the bottom of a typical flood depth of 3 meters. The 29 µN value was calculated from Equation 8 below:

$$F = \varrho_{water} ghA \tag{8}$$

From this analysis, the device dimensions and results shown in Table 2 below were generated.

Table 2: Device dimensions and resulting metrics generated from derivations and analysis in MATLAB.

Description	**Variable Name**	**Value**
Width	w	20 μm
Length	l	50 μm
Thickness	t	2.5 μm
Proof Mass	m_{proof}	260 μg
Factor of Safety	FoS	1.5
Resonance Frequency	f	1.959 kHz
Power Density	PD	551.3 kW/m^3

FABRICATION

As a preliminary evaluation of these device dimensions, an ideal cantilever beam with these dimensions and without the proof mass was simulated in COMSOL. The device was designed to maximize PZT thickness relative to the total thickness of the beam;

to that end, electrode thickness was minimized using atomic layer deposition (ALD) to deposit aluminum electrodes of 50 nm thickness. The remaining thickness was allotted to the PZT and SiO2 insulating layers, with two 1 μm layers of PZT and a single central 0.3 μm layer of SiO2. Because of the promising results of these simulations, discussed in the next section, a process flow using these dimensions and no proof mass was envisioned, and a not-to-scale representation of the layers in the bimorph is included in Figure 2.

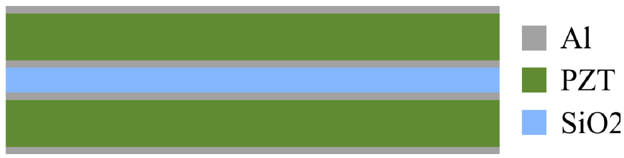

Figure 2: Layers of piezoelectric bimorph generator.

SIMULATIONS

Due to the uncertainty in forces experienced by such devices in the given conditions, all static and piezoelectric simulations were run with a parametric sweep over the distributed force applied at the top of the beam. Values ranged from 1 μN to the pressure-based value of 29 μN, using a step value of 3.5 μN.

First, a static stress simulation was run, and the largest force value of 29 μN produced the plot shown in Figure 3 below. The maximum stress in all simulations, shown on the legend below, was 38.4 MPa, producing a factor of safety of 2.99 in bending.

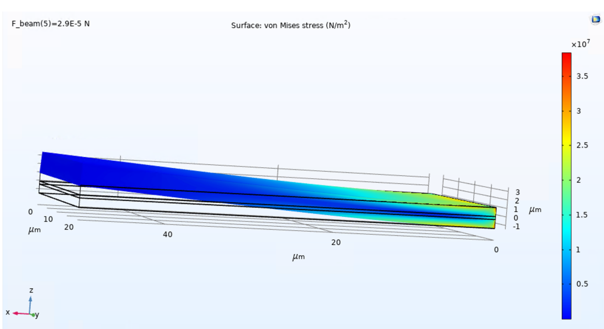

Figure 3: Static stress simulation results on piezoelectric bimorph beam using a distributed load of 29 μN on the top face.

The maximum electric potential produced was then plotted against the force applied for each simulation. This produced a linear relation between force and electric potential with a range of voltage values from 0.058 V to 2.53 V.

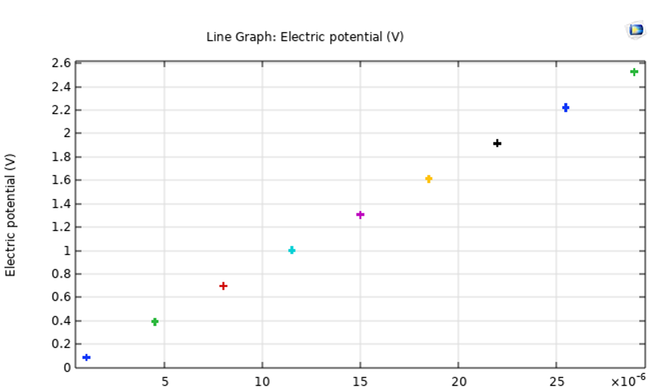

Figure 4: Voltage vs. applied force for piezoelectric bimorph beam.

These values were used in Equation 3 to calculate the minimum frequency required to produce the benchmark power density value of 10 kW/m^3. For the minimum distributed load applied, 1 μN, it was found that the beam would have to be driven at a minimum frequency of 2.5 kHz; for the maximum distributed load applied, 29 μN, the minimum frequency would be 1.3 Hz.

Finally, an eigenfrequency simulation was run to find a better approximation for the resonance frequencies of the beam. The eigenfrequencies are summarized in Table 3. The most relevant value, the resonance frequency associated with a transverse force and displacement, is 0.62 MHz; the displacement is shown in Figure 5.

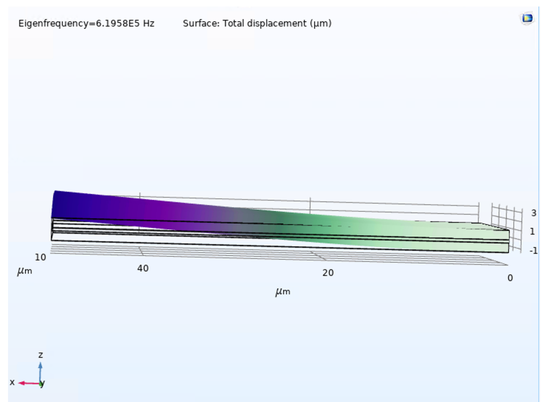

Figure 5: Displacement of beam in response to first eigenfrequency.

Table 3: Resonance values found in COMSOL eigenfrequency simulation.

Eigenfrequency	Value (MHz)
1	0.62
2	2.95
3	3.82
4	4.28
5	9.36

CONCLUSIONS

The results of these analyses are promising for the use of piezoelectric generators to be used in conjunction with or as a replacement for current methods of powering underwater microrobots. It was shown that for forces on the order of magnitude of ten micro-Newtons, a voltage of 2.53 V and a sufficient power density to power an underwater microrobot can be produced. Additionally, it was found that this power density can be achieved with a frequency as low as 1.3 Hz, very near the frequency of waves found in the ocean.

Due to challenges with accurately modeling flood conditions, the forces used to simulate this power generation were based heavily in assumptions and estimations. An important aspect of the future work of this project is finding an existing model or creating a new model for fluid flow in the operating conditions described in the Introduction.

Furthermore, while the order of magnitude of the benchmark power density is likely correct, the lack of focus on the power challenges of underwater microrobots thus far poses another barrier to supporting the conclusions of this paper. As underwater locomotion for microrobots develops, it is important to consider how the application of such robots will be realized and how these robots may operate while remotely powered.

Finally, while the resonance frequency of the piezoelectric bimorph was only briefly investigated, the high resonance frequency suggests no natural flood conditions will cause the beam to resonate, causing the displacement and voltage output to be lower. Reducing the resonance frequency of MEMS devices below the MHz range is a challenge in the broader field of MEMS; developments in this area could also be applied to the results of this project to maximize power output.

ACKNOWLEDGEMENTS

I would like to thank Dr. Ved Gund for his help in navigating the many challenges of exploring an unfamiliar subject area. His feedback and dedication, as well as the feedback of all who attended the poster presentation, were invaluable in the development of this project, helping me produce interesting and meaningful results.

REFERENCES

[1] F. Dragomir and O. E. Dragomir, “Microrobotics: Present, challenges, perspectives,” *2014 IEEE International Conference on Robotics and Biomimetics (ROBIO 2014),* 2014, pp. 1904-1909, doi: 10.1109/ROBIO.2014.7090614

[2] Chen, Y., Wang, H., Helbling, E. F., Jafferis, N. T., Zufferey, R., Ong, A., Ma, K., Gravish, N., Chirarattananon, P., Kovac, M., & Wood, R. J. (2017). A biologically inspired, flapping-wing, hybrid aerial-aquatic microrobot. *Science robotics*, *2*(11), eaao5619. https://doi.org/10.1126/scirobotics.aao5619

[3] Action Nechibvute, Albert Chawanda, Pearson Luhanga, "Piezoelectric Energy Harvesting Devices: An Alternative Energy Source for Wireless Sensors", *Smart Materials Research*, vol. 2012, Article ID 853481, 13 pages, 2012.https://doi.org/10.1155/2012/853481

[4] Jbaily, A., Yeung, R.W. Piezoelectric devices for ocean energy: a brief survey. *J. Ocean Eng. Mar. Energy* 1, 101–118 (2015). https://doi.org/10.1007/s40722-014-0008-9

[5] Kováčová, V., Bouton, O., Gérard, M., Defaÿ, E., & Polesel, J. (2021). Polymer based piezoelectric energy harvesting from ocean waves. ISAF ISIF PFM conference.

[6] Priya S, Inman DJ (2009) Energy harvesting technologies. Springer, New York

[7] Bhushan, Palak & Tomlin, Claire. (2019). An Insect-scale Untethered Laser-powered Jumping Microrobot.

[8] T. S. Low and W. Guo, "Modeling of a three-layer piezoelectric bimorph beam with hysteresis," in Journal of Microelectromechanical Systems, vol. 4, no. 4, pp. 230-237, Dec. 1995, doi: 10.1109/84.475550.

[9] Anton, Steven & Inman, Daniel. (2012). Bending Strength of Piezoelectric Ceramics and Single Crystals for Multifunctional Load-Bearing Applications. IEEE transactions on ultrasonics, ferroelectrics, and frequency control. 59. 1085-92. 10.1109/TUFFC.2012.2299.

[10] Piezo element products group. Fuji Ceramics Corporation. (n.d.). http://www.fujicera.co.jp/en/product/bimorph/.

CONTACT

Nikki Hart, tel: +1-936-697-2630; njh84@cornell.edu