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## On developing an optimal design procedure for a bimorph piezoelectric cantilever energy harvester under a predefined volume



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### ABSTRACT

A typical vibration harvester is tuned to operate at resonance in order to maximize the power output. There are many design parameter sets for tuning the harvester to a specific frequency, even for simple geometries. This work studies the impact of the geometrical parameters on the harvested power while keeping the resonance frequency constant in order to find the combination of the parameters that optimizes the power under a predefined volume. A bimorph piezoelectric cantilever is considered for the study. It consists of two piezoelectric layers and a middle non-piezoelectric layer and holds a tip mass. A theoretical model was derived to obtain the system parameters and the power as functions of the design parameters. Formulas for the optimal load resistance that provide maximum power capability at resonance and anti-resonance frequency were derived.

The influence of the width on the power is studied, considering a constant mass ratio (between the tip mass and the mass of the beam). This keeps the resonance frequency constant while changing the width. The influence of the ratio between the thickness of the middle layer and that of the piezoelectric layer is also studied. It is assumed that the total thickness of the cantilever is constant and the middle layer has the same mechanical properties (elasticity and density) as the piezoelectric layer. This keeps the resonance frequency constant while changing the ratio between the thicknesses. Finally, the influence of increasing the free length as well as of increasing the mass ratio on the power is investigated. This is done by first, increasing each of them individually and secondly, by increasing each of them simultaneously while increasing the total thickness under the condition of maintaining a constant resonance frequency. Based on the analysis of these influences, recommendations as to how to maximize the geometrical parameters within the available volume and mass are presented.

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## 1. Introduction

Energy harvesting from vibration has received a great interest over the last decades as an available power supply for portable devices and wireless sensors. The piezoelectric transducers have received the most considerable attention among other vibration-to-electricity transducers. They are applicable to low-scale and MEMS devices, in addition to their simple structures and high power density [1]. The cantilever has been the major proposed geometrical design, due to its simplicity, ease

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of use and applicability to small-scale devices. Many researchers have introduced models to estimate the power of the cantilever harvester [2–4]. In order to maximize the power, a typical harvester was tuned to operate at resonance [5–8]. However, there are many design parameters that influence the resonance frequency of the vibration harvester.

Al-Ashtari et al. [9] showed that the system parameters and characteristic frequencies were sensitive to even small manufacturing tolerances. Kim et al. [10] demonstrated that a small change in the proof mass geometry affected the resonance frequency and the strain distribution along the device length. Wang and Meng [11] investigated the tip displacement, the current response and the output voltage at different resistances and reported that the larger tip displacement didn't necessarily result in the higher voltage response, but the larger load resistance did always lead to the higher voltage. Kim et al. [12] proved that higher piezoelectric coupling did not necessarily yield increased power since the optimal load resistance was affected. Williams and Yates [13] reported that the power was proportional to the cubic of resonant frequency. Kamel et al. [14] studied the relationship between the power and the resonance frequency depending on the excitation and the device conditions. If the resulting mass acceleration was constant, then, the power was inversely proportional to the resonance frequency since increasing the frequency meant decreasing the displacement. But, if the resulting mass displacement was constant, then the power was proportional to the cubic of the resonance frequency. Patel et al. [15] altered the importance of varying multiple parameters simultaneously to keep the natural frequency constant.

Quintero et al. [16] presented a geometrical study of a thinned bulk-PZT-based energy harvester on a flexible polymeric substrate. They displayed that the optimal ratio between the length of the PZT layer and the non-piezoelectric substrate was 1. They recommended the full coverage of the piezoelectric layer on the substrate. Hofmann and Twiefel [17] carried out a parametric study to find an optimized design of a bending bimorph piezoelectric actuator. It was shown that the width should be maximized as much as possible, taking the available space into account. Takei et al. [18] introduced the design of piezoelectric MEMS cantilevers formed on a silicon-on-insulator wafer for energy harvesting from harmonic vibration. From the simulation results they reported that, in order to maximize the power, the ideal length ratio of the proof mass to the cantilever beam was 1.5. In addition, preferences for the thickness of the top layer and the piezoelectric layer were provided. Aboulfotoh and Twiefel [19] demonstrated the importance of considering the volume when designing the vibration harvester. Wang and Cross [20] studied the influence of the ratio between the thickness of the elastic layer and the piezoelectric layer of bimorph and unimorph piezoelectric bending actuators. The influence of the ratio on the normalized tip deflection was varying according to the material of the elastic layer. Parametric studies have been also introduced to optimize the power output of piezoelectric energy harvesters in [21–22].

From the previous review, the results of the parametric studies can't be generalized because the studies were dependent of the characteristics of the proposed piezoelectric energy harvesters. Studying the influence of a unique design parameter on the power output of the piezoelectric energy harvesters does not lead to the main target of optimizing the power since the optimal load resistance and the eigenfrequencies are affected. In this paper, the influences of the geometrical parameters on the maximum power as well as the optimal load resistance are studied. The investigations will include varying the geometrical parameters simultaneously in order to keep the resonance frequency constant. Based on the analysis of how geometrical parameters affect the power, recommendations to optimize the maximum power will be presented.

## 2. Bimorph piezoelectric cantilevers

The energy harvester considered for the study is in the form of the cantilever shown in Fig. 1. It consists of two symmetrical piezoelectric layers in parallel connection and a middle non-piezoelectric layer. The cantilever has a free length of  $l$ , a total thickness of  $h$  and a width of  $b$ . Each piezoelectric layer has a total length of  $l_c$ , a thickness of  $h_p$ , a density of  $\rho_p$  and a modulus of elasticity of  $E_p$ . The middle layer has a thickness of  $h_s$ , a density of  $\rho_s$  and a modulus of elasticity of  $E_s$ . The two piezoelectric layers and the middle layer are assumed to be perfectly glued together and no slipping occurs between them. The ratio between the thickness of the middle layer and that of the piezoelectric layer is  $h_{sp}$  where  $h_{sp} = h_s/h_p$ . The cantilever holds a tip mass of  $m_t$ . The mass ratio between the tip mass and the mass of the beam is  $\beta$  where  $\beta = m_t/(\rho_s l_s b_s h_s + 2\rho_p l_p b_p h_p)$ . The fixation of the cantilever is assumed to be rigid. An input excitation of a displacement  $u(t)$  is provided at the fixation. The transversal displacement at the tip at any time  $t$  is  $x(l, t)$ .

The modeling procedure is based on the discretization of the continuous Euler-Bernoulli beam utilizing the Rayleigh-Ritz method into a single-degree-of-freedom (SDOF) system. The second eigenfrequency is much higher than the first one for the considered cantilever. Thus, the first mode shape is sufficient to describe the deflection. Fig. 2 shows the representation of

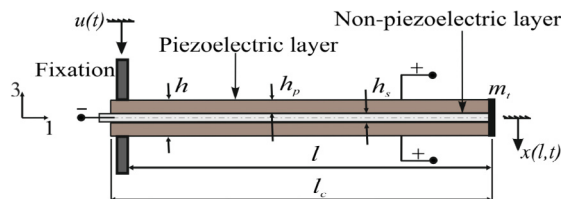


Fig. 1. A sketch of a bimorph piezoelectric cantilever.

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