OPTIMIZING A PIEZOELECTRIC ENERGY HARVESTING SYSTEM

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Abstract. The piezoelectric effect, through which some materials can convert mechanical stress to electrical energy and vice versa, sees a wide array of applications due to its ease of implementation and effectiveness at smaller scales. Piezoelectric materials have emerged in applications such as structural health monitoring and piezo-based smart structures. One such application is energy harvesting; piezoelectric materials can be used to provide power for micro scale devices, in part due to their high efficiency. However, the significantly lower power output of these transducers limits their applicability. This study focuses on comparing different configurations of a piezoelectric energy harvesting system for a motor. By modelling several configurations, this study aims to identify the configuration with the highest sustainable power output. Keywords: Energy Harvesting, Piezoelectric materials, Power generation, Vibrations

1. INTRODUCTION
Energy harvesting is the process of harnessing energy from ambient sources and storing the energy for future use. This is an old concept and has been achieved using windmills and water turbines. Energy harvesting did not gain enough attention because of the high-power requirements and the low energy conversion efficiencies of the harvesters; however, it has now gained significant attention. This is mainly due to the global movement towards green energy from ambient sources. There are three major mechanisms for energy harvesting, electromagnetic, piezoelectric and electrostatic harvesting [1]. Of these piezoelectric mechanisms show minimum material requirements with better energy conversion efficiencies.

Piezoelectric materials are a type of material that develop an electric field when they are stressed or deformed because of vibrations. This is known as the direct piezoelectric effect. Conversely, when an electric voltage is applied across the material, it deforms and vibrates [2]. The direct piezoelectric effect is of prime importance to the process of energy harvesting using piezoelectric materials. It is this mechanism that allows a piezoelectric material to absorb mechanical energy from a vibrating structure in contact and generate electrical energy from it. This is a class of energy harvesting called vibration – based energy harvesting. The harvester consists of a cantilever beam made up of layers of the piezoelectric material and one non – piezo material (shim) that provides strength and stiffness. This is connected to the vibrating host structure and an alternating voltage is induced in the electrodes surrounding the piezo layers due to the dynamic strain from the host structure. A large range of piezoelectric materials can be used to create the harvester.
1.1 Modelling Techniques

Erturk et. al. [3] presented a modelling method of the harvester beam based on the analytical modal analysis method, which is an accurate distributed parameter model. Initially, early models used a lumped parameter single degree of freedom structure, however it was later shown that these models provided very imprecise results for distributed parametric systems [4]. A more precise model for the distributed parameter system has been made using the Rayleigh Ritz formulation and then the Hamiltonian Principle to get the mass and stiffness matrices in the transformed space [5]. A great improvement was made in the analytical modelling of the harvester by Erturk et. al. [6] by applying analytical modal analysis to the Euler – Bernoulli model of a unimorph with uniform section without a tip mass as shown in figure 1. The piezoelectric relations were added to precisely account for the coupling. The same technique is also applied to a bimorph. These methods are, however, approximate and validated over only a small frequency range. These parameter models are also based on a simple resistive impedance.

![Figure 1. a) A unimorph and b) bimorph piezoelectric harvester [7].](image)

1.2 Geometric Configurations

Various configurations of the energy harvester have been tested to find out the maximum energy harvesting capability. Different parameters are tested such as the tuning the resonant frequency of the piezoelectric harvester or changing the number of piezoelectric material layers in the harvester. Maximum power is generated when the resonant frequency of the harvester matches that of the input vibrations. There is considerable loss in power generated when the two frequencies vary [8]. The energy transformative ability of the piezoelectric material also depends on the coupling mode that the harvester uses. Two practical modes exist, which are the –31 mode and the –33 mode [9]. These are shown in fig. 2. The –31 mode is less efficient in coupling than the –33 mode, however the former is more efficient for energy harvesting in low intensity vibrations since it provides more strain in the harvester [10]. The –33 mode generates greater power output for high intensity vibrations condition.
The shape of the harvester can also affect the power generation. The rectangular cantilever shape is most widely used by researchers of piezoelectric energy harvesters. However, using a trapezoidal shaped cantilever beam gives a continuous distribution of the strain throughout the structure unlike the rectangular shape which would contain a non-uniform strain distribution. The former configuration generated more power than the latter for the same volume of PZT material used [12].

2. METHODOLOGY

Piezoelectric elements generally consist of one or more layers of a piezoelectric material bonded to a shim. For the purposes of our study, we will consider a piezoelectric bimorph which consists of a stainless-steel shim, with PZT bonded to both sides of the shim. We aim to compare two separate configurations of the piezoelectric energy harvesting system.

The first configuration will consist of a single piezoelectric bimorph bonded to the top of the motor surface such that a sideways deflection of the motor (a deflection in the x-axis) will correspond to the 33 mode of the bimorph. The second configuration will consist of two bimorphs mounted on opposite sides of the motor, such that a vertical deflection of the motor (a deflection in the y-axis) will correspond to the 33 mode of the bimorph.

The bimorphs are the same thickness and width, but the length chosen is the optimal length for each configuration (70mm for a single bimorph and 60 mm for two bimorphs). These lengths were determined by directly optimising for maximum deformation at the base of the bimorph.

A preliminary modal analysis of the motor is conducted to obtain the mode shapes associated with the motor and its constraints. The motor is modelled as a steel stator and copper rotor spinning at 1500 rpm.

![Figure 2](image)

Figure 2. -31 and -33 piezoelectric coupling modes.

![Figures 3 (a) (b)](image)

Figures 3 (a) (b). Different mode shapes of the motor.
Modal analyses of the two separate energy harvester configurations were then conducted to obtain the modes of vibration for each configuration, which can then be used to obtain the deformation frequency response to a specified vibration.

Figures 4 (a) (b). Comparison of mode shapes for a) single bimorph and b) double bimorph configurations.

We obtain the deformation frequency response of the base of the bimorph for a specified input vibration. For the same input vibration, the maximum base deformation of the bimorphs was 21.0 mm for the single bimorph configuration and 13mm for each bimorph in the two-bimorph configuration.

Figures 5 (a) (b). single bimorph maximum base deformation.
The values of base deformation can be input into the transfer function to obtain the voltage generated by each configuration.

3. RESULTS

Given the same input vibration, the two-bimorph configuration marginally outperforms the single bimorph configuration, producing peak voltages of 41.5 V and 32.2V respectively. However, the model doesn’t account for the damping effect of the piezoelectric elements and it can be assumed that the difference in voltage generated between the two configurations will be very small, making the first configuration more effective.

4. CONCLUSION AND FUTURE SCOPE

It can be concluded from the simulation study that there is no considerable voltage difference between that generated from the single bimorph configuration and the double bimorph configuration when accounting for damping due to electrical impedance. Therefore, accounting for vibration and the amount of material used, the single bimorph configuration is preferred. The simulation can be further improved by considering the backward mechanical coupling. The study can be subsequently validated through experimentation. Considering the cost of lead zirconate titanate (PZT), a low-cost solution can be developed.

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