A PIEZOELECTRIC HARVESTER WITH AN INTEGRATED FREQUENCY-TUNING MECHANISM

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Abstract: We report the development of a piezoelectric energy harvester, whose resonance frequency can be tuned electrically by applying mechanical preloads through piezoelectric actuators. The harvester is similar to a design presented in [1], where a cantilever beam is equipped with two lateral arms which deliver an axial preload to the tip of the beam in order to change its resonance frequency. In this work, the main beam and arms are cut out of one dual-layer piezoceramic plate. The polarization and the electrodes are designed in such a manner, that the main beam generates electrical power in a vibrating environment, while the arms can be used as piezoelectric actuators in order to tune the resonance frequency of the whole structure. This compact and simple design promises a low priced fabrication at large scale.

Keywords: Piezoelctric converter, tunable resonance frequency, energy harvesting

INTRODUCTION

For the efficient application of a vibrational energy converter, it is important, that its resonance frequency matches the frequency of the ambient vibration [2]. Hence, during the design process of an energy scavenger, the frequency and the acceleration amplitude of the exploited vibrations must be known in order to find the appropriate dimensions for the spring constant, the seismic mass and the conversion mechanism deployed in the harvester. Nevertheless, this optimization is limited to environments with a constant vibrational frequency and does not work whenever the ambient frequency does vary. This is the case on engines and gears in which rotating parts with variable rotational speed are included, like e.g. a car engine. A promising way to harvest electrical power in this kind of environment is the usage of generators with a tunable resonance frequency. Frequency tunable energy converters have therefore drawn more and more attention during the last years. There are basically two ways to reach a notable frequency shift. The first way is to change the effective mass of the system, which is done in [3] by modifying the mass distribution on a cantilever beam. The second, more common way to change the resonance frequency of a generator consists in varying the spring constant of its resonator. This can be done by changing the spring stiffness, e.g. by modifying the second moment of area of a cantilever beam [4]. The spring constant can also be varied by adding additional restoring forces e.g. via magnets [5, 6] or by affecting the resonator's spring constant with mechanical forces like e.g. axial preloads on a beam [7]. In this work axial preloads are applied to a cantilever beam, and the presented results can be considered as a continuation of the work presented in [1].

DESIGN

The resonance frequency of a cantilever beam can be varied by applying axial preloads [8, 9]. The axial force leads to an additional moment when the beam is bent which reduces the restoring force in case of a compressive load and augments it when a tensile load is applied. The axial load can be applied through two lateral arms connected to the tip of the main beam [1]. The force needs to be created by some way and the obvious way to do so is by using piezoelectric actuators. To obtain high forces and a large actuator displacement at a reasonable voltage, the piezoelectric actuator should be as long as possible. Therefore it makes sense to use the full length of the arms and to substitute the arms by a long piezoelectric actuator. The fact, that the piezoelectric effect is also used to convert the kinetic energy of vibrations into electrical power suggests using the same material for both generator and actuators. The electrodes of a dual layer piezoelectric plate can be configured in two ways, allowing to use the bimorph both as a bending actuator (Figure 1) or as a direct actuator (Figure 2). A bimorph piezoelectric structure can be perforated in order to obtain three parallel cantilever beams. The beams are laterally connected to each other at their bases and their free ends. The surface electrodes are then designed in a way that a voltage can be applied to the arms, while the main beam acts as a generator (Figure 3).

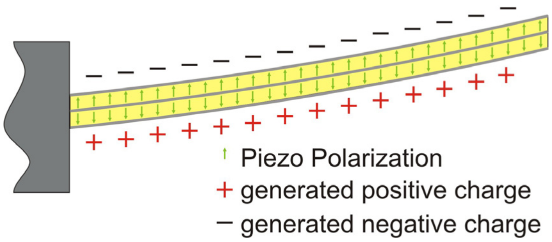

Fig. 1: Piezogenerator (main beam).

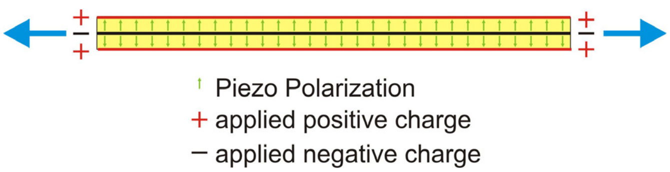

Fig. 2: Piezoactuator (arms).

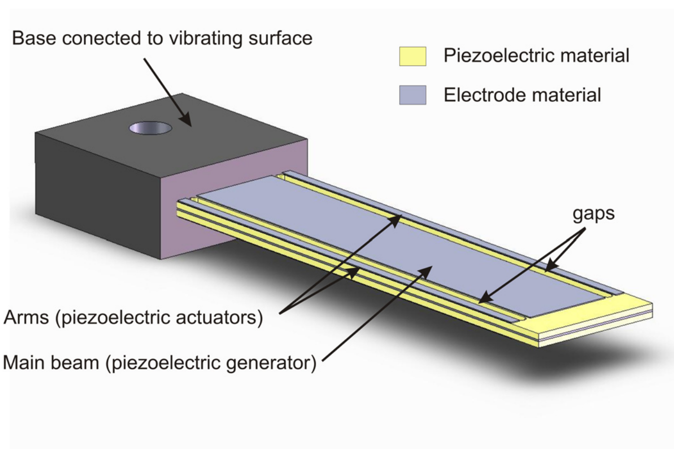

Fig. 3: Generator with arms made out of one dual layer piezoelectric plate.

SIMULATION

Numerical simulations were performed in order to obtain a structure with a high resonance frequency shift at a minimum actuator voltage. By carrying out modal analyses of prestressed structures with ANSYS, the resonance frequency was obtained with different voltages applied to the piezoelectric actuators situated in the lateral arms. It was thereby found out, that the gap between the arms and the main beam should be as small as possible. This is due to the fact that a more compact connection between arms and main beam performs a smaller deformation of this connection under load, and thus less force is annihilated by the junction. The simulations further showed, that at a given material thickness, the cantilever beam and the arms should be as long as possible. The length of the beam should therefore be chosen as long as feasible. Furthermore, the resonance frequency shift at a given voltage gets smaller if the beams are thicker. This has two reasons. The first reason is that the electric field is reduced at a bigger electrode interspace and therefore the piezoelectric displacement is reduced. The second reason is the increased stiffness, which implies, that the additional restoring force carries less weight compared to the beams natural restoring force. The thickness of the piezoelectric bimorph should thus be chosen as small as possible. In a next step, the width of the arms was optimized. As a result, the overall width of the arms and the width of the main beam have the same order of magnitude. Due to this symmetry, a compressive load on the main beam corresponds to an equal tensile load on the arms and vice versa. The resonance will therefore shift to lower frequencies for both positive and negative voltages applied to the actuators. To break this symmetry, in [1] the stiffness of the arms was enhanced in order to be able to augment the resonance frequency. As we want to keep the production process as simple as possible, this solution is not practicable with the new design. Instead of that, the relative lengths of the arms and the main beam was varied, with the result that a higher tuning effect is obtained when the arms are longer than the main beam. This effect can also be used without changing the overall length of the harvester by simply shortening the main beam in relation to the length of the arms. Figure 4 shows the percental resonance frequency shifts of harvesters with a constant arm length of 28 mm. By shortening the main beam in relation to the length of the arms, a nearly linear dependence between resonance frequency and actuator voltage is obtained even at low actuator voltages. Beside the possibility of bidirectional frequency tuning, the main advantage of longer arms is the large frequency gradient even at low actuator voltages.

EXPERIMENTAL SETUP

The dual layer piezoceramic plates were obtained by agglutinating the ground electrodes of two thin piezoceramic (PZT) single layer plates. An overlap within the base makes sure that the ground electrodes can still be contacted. With a pulsed ND:YAG-Laser, the perforations separating the arms from the main beam are cut into the plate, and with the same laser the different surface electrodes are separated from each other. The obtained structure is wired and clamped onto a shaker performing sinusoidal oscillations (see figure 5). The actuator electrodes situated on the surfaces of both arms are then connected to a voltage supply, while the surface

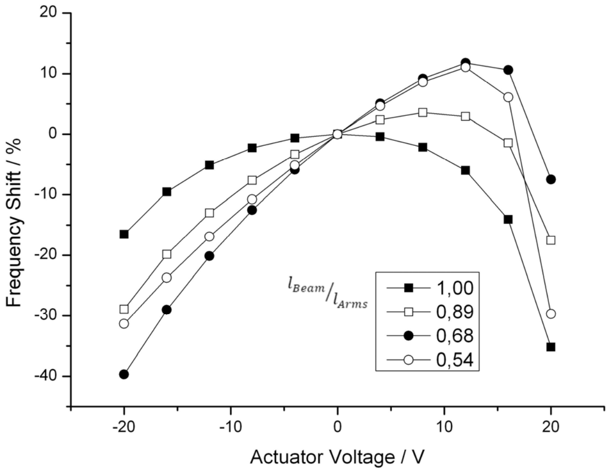

Fig. 4: Simulation Results: With a main beam shorter than the lateral arms, the frequency tuning effect can be enhanced and a larger frequency tuning gradient at low voltages is achieved. For a better comparability, percentaged frequency shifts are displayed.

electrodes of the main beam are connected to a Meilhaus data acquisition card in order to obtain resonance curves with a LabVIEW Program. Two different harvesters were analyzed. The first device was made of two 100 µm thick plates with an arm and beam length of 24.5 mm, while the second harvester was made of two 55 µm thick plates and with a beam length of 19 mm and an arm length of 28 mm. To realize the different cantilever beam lengths, a polymer base with two blocks was used (see figure 5). In both cases, the main beam was 3 mm wide and the arms 0.9 mm wide with a gap of 100 µm between arm and main beam.

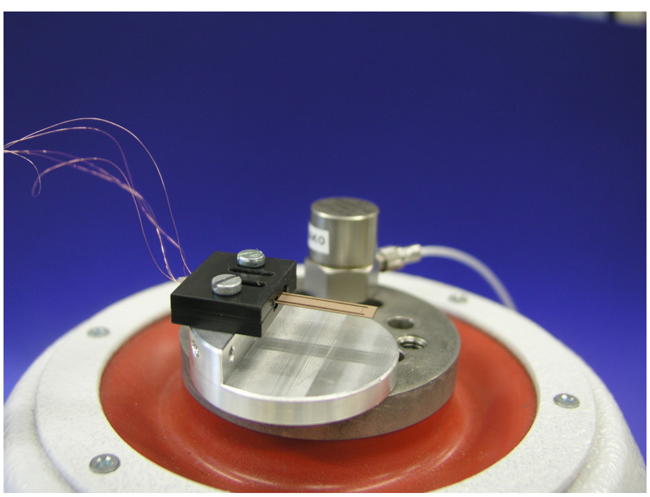

Fig. 5: Experimental Setup. The harvester is clamped to a shaker performing sinusoidal oscillations. In the background, an accelerometer can be seen.

RESULTS

Device 1 made of two 100 µm thick piezoceramic plates and with short arms showed the expected behavior (figures 6 and 7). The resonance frequency was reduced both with positive and negative voltages applied to the actuators. With an applied voltage of 70 V, the frequency could be shifted from 130 Hz to 115 Hz. At an acceleration amplitude of 0.35g, the power output for this generator ranged between 3 and 6 µW. The second harvester (device 2) made of two 55 µm piezoceramic plates showed a higher frequency shift at lower voltages due to the longer arms and the thinner piezoelectric ceramic plates (see figures 8, 9 and 10). With voltages between -20 V and 20 V a frequency range between 133 Hz and 170 Hz could be covered. It has to be mentioned, that the structure with the longer arms showed highly asymmetrical resonance curves (figure 8). While the edge to low frequencies is steep and resembles the resonance curves of a damped harmonic oscillator, the edge towards lower frequencies is complanated. Furthermore, an important hysteresis was observed which will have to be considered during the resonance frequency adjustment.

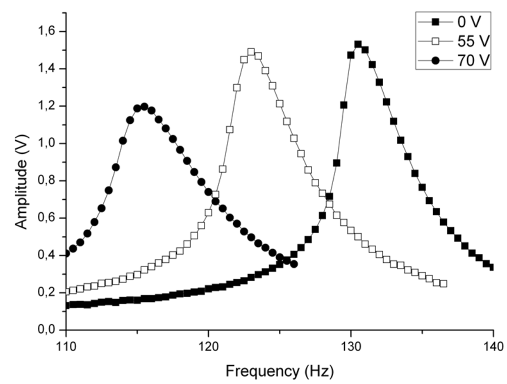

Fig. 6: Resonance curves of device 1 for a positive actuation voltage.

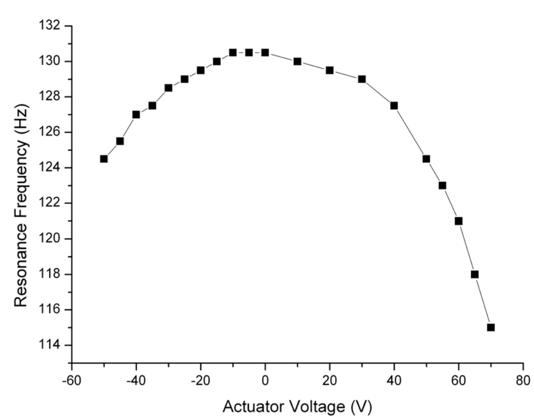

Fig. 7: Frequency shift of device 1 for positive and negative actuation voltages.

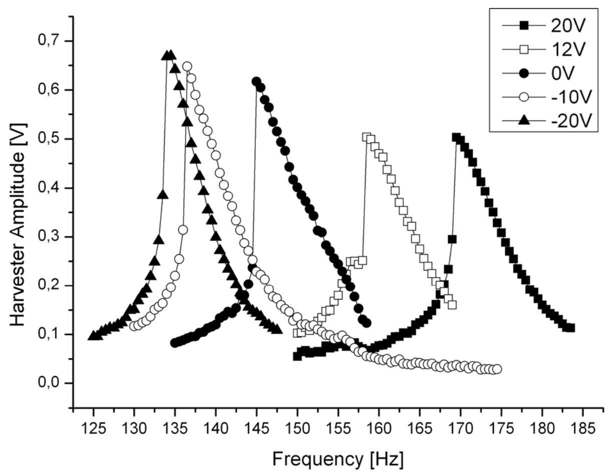

Fig. 8: Resonance curves for device 2 at different positive and negative actuator voltages.

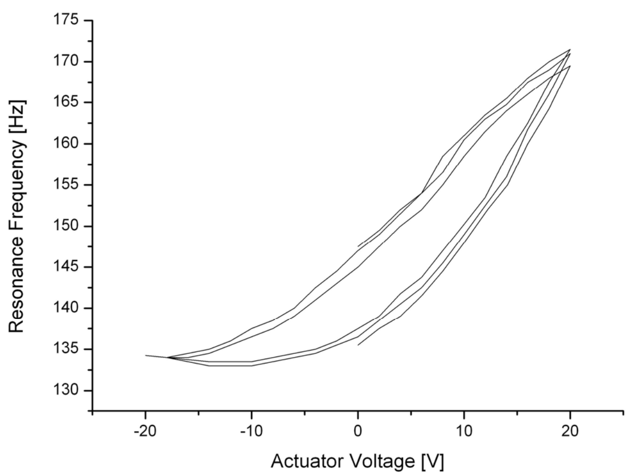

Fig. 9: Hysteresis Curve of device 2 at a voltage range from -20 to 20V.

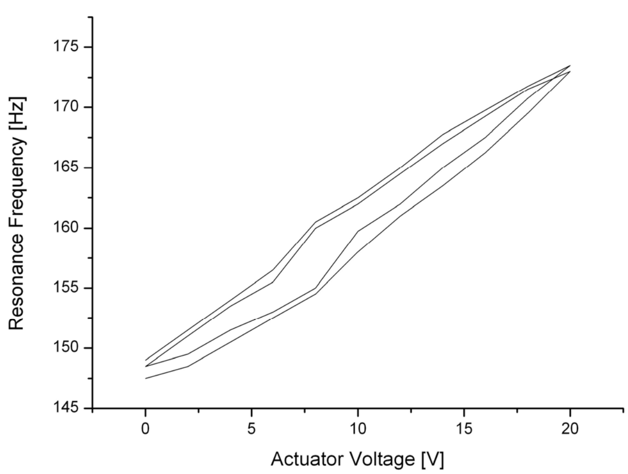

Fig. 10: Hysteresis Curve of device 2 at a voltage range from 0 to 20 V.

DISCUSSION AND OUTLOOK

We have presented a frequency tunable structure for energy harvesting with an integrated resonance frequency tuning mechanism. A successful experimental implementation of the structure was realized and the frequency tuning range could be enhanced by choosing the lateral arms to be longer than the main beam. It is planned to use a microcontroller to monitor the ambient vibrational frequency and to adjust the harvester's resonance frequency. To ensure the power supply of this controller, the low power output obtained so far needs to be enhanced, e.g. by adding a tip mass to the free end of the beam.

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