A COMPACT PIEZOELECTRIC ENERGY HARVESTER WITH A LARGE RESONANCE FREQUENCY TUNING RANGE

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Abstract: We present the first piezoelectric energy harvester with a self-sufficient frequency tuning mechanism. The system consists of a frequency tunable piezoelectric generator combined with a control unit made of a low power microcontroller with some peripheral electronics. The deployed generator is an enhanced version of the device presented in [1], manufactured from a triple layer piezoceramic plate. Its relatively large output power (up to 90 µW @ 0.6 g) combined with its efficient low-power tuning mechanism, allowed us to build a device which is not only self-sufficient, but which also delivers up to 90% of the harvested energy for the operation of the supplied embedded system. The amount of energy required for the largest tuning step is in the range of 200 µJ, which signifies that the recovery will take place within a few seconds. The presented system is able to self-tune its resonance frequency between 188 Hz and 150 Hz (with 2 V to 50 V actuator voltages respectively).

Keywords: piezoelectric converter, frequency tuning, energy harvesting

INTRODUCTION

The general weak point of nearly all energy harvesting devices is given by the fact that each environment offers unique forms of energy, which makes it difficult to develop off-the-shelf solutions. Moreover, these unique conditions may also vary in time, which narrows the application-spectrum of energy scavengers further down. In the field of vibrational energy harvesting, the most concerning temporal variation is a non-constant vibrational frequency. To be efficient, the resonance frequency of a vibrational energy harvester needs to match exactly the frequency of the ambient vibration. For this reason, a precise analysis of the environmental conditions has to be carried out before designing or choosing the adequate vibrational harvester, and these conditions are not allowed to vary over time.

To overcome this restriction, two different approaches have been considered in the past years: Broadband generators and frequency tunable generators. A broadband energy harvester can e.g. consist of several resonators with different eigenfrequencies [2]. This guarantees, that a mismatch of one resonator will be covered by another resonator. The advantage of this concept is its simplicity and robustness. On the other hand, the large number of generators increases the total weight of the device, without increasing its output power – at a given frequency most of the resonators will be off-resonant, and will therefore suffer from a poor coupling. For this reason, frequency tunable generators are attracting more and more attention [3]. They allow to benefit from the total seismic mass at all frequencies, which augments the obtained output power per gram and thus their power density. Nevertheless a couple of challenges have to be met in order to build such a frequency tunable generator: The average power demand of the tuning mechanism must be much lower than the generated power, the output power should be as high as possible over the whole tuning range and finally a control unit is required in order to detect, whether a tuning step is necessary or not. Several frequency tuning mechanisms for vibrational energy harvesting have been developed by different groups during the past years [3], but to our knowledge, in only one case an electromagnetic harvester was equipped with a self-sufficient frequency tuning mechanism [4].

This generator takes 2.11 h to generate enough power for one large tuning step (64 to 78 Hz). With a comparable tuning range and a recovery time of only a few seconds, this first landmark was significantly improved by the device presented in this work.

GENERATOR CONCEPT

A viable way to shift the resonance frequency of a cantilever beam persists in adding axial preloads to it [5]. The preload generates an additional torque, which will change its sign depending on the direction of the beam deflection. This torque will therefore directly contribute to the restoring force and hence modify the spring constant and the corresponding resonance frequency. In previous publications [1,6] we have shown, that a practicable way to apply these preloads consists in adding lateral arms to the cantilever beam, which are meant to pull or to push the tip of the cantilever beam in order to generate the axial preload.

To generate a maximal additional torque, it is important, that the deflection curves of the cantilever beam and the arms differ. When clamped to the same socket as the cantilever beam, even in the best case, the deflection lines will be very similar (Fig. 1a). The maximal obtainable torque will be proportional to the angle $\alpha$. One way to obtain different deflection lines consists in choosing different clamping points for the cantilever beam and the lateral arms [1]. By repositioning the clamped end of the arm behind the socket of the cantilever beam, the deflection lines will automatically differ (Fig. 1b).
A further enhancement of the applied torque can be reached if two opposed cantilever beams are used, with the arm connecting their respective tips. As depicted in Fig. 1c, the greatest possible value for the angle $\alpha$ can be significantly augmented, as long as the two cantilever beams swing in a synchronous way. This design was chosen for the following work.

![Fig. 1: Mode shapes of a swinging cantilever beam with different ways to apply axial preloads through an independent arm.](image)

The task of the arms is not limited to the delivery of the preload. As the required force needs to be generated somehow, and piezoceramic material is deployed for the generator anyway, it is obvious to use the same material as an actuator. Due to the fact, that the obtained displacement will grow with the length of the piezoelectric actuator, we decided to use the whole length of the arms as a piezoelectric actuator. Furthermore, with this design, the complete weight of the arm will contribute to the seismic mass which will increase the efficiency of the generator.

One important aspect which has to be considered is the possible eigenmodes and eigenfrequencies of this system. We want this device to have only one dominant resonance frequency when the cantilevers swing in their first natural mode. To obtain a stable oscillation of the system, a design was chosen which contains only one arm and two pairs of opposed cantilever beams (Fig. 2). With one arm connecting the tips of all four cantilever beams, we will obtain a resonator consisting of four springs and one common seismic mass. The spring constants of the four cantilever beams will add to one main spring constant, which will determine the main resonance frequency of the system. Furthermore, the use of one single actuator offers the option to mount an additional weight (e.g. the control unit, the battery, the embedded system or all of them) to the center of the actuator, in order to further enlarge the seismic mass.

![Fig. 2: Schematic of the working principle (not to scale).](image)

**FABRICATION**

The whole piezoelectric structure is made of one triple layered piezoceramic plate. The layers have an alternating polarization and each of them is 100 µm thick. As shown in Fig. 3, the same plate can be used as a linear piezoactuator (Fig. 3a) or as a piezogenerator in a bending mode (Fig. 3b), depending on the configuration of the electrodes. In the actuator mode all three layers are equally used. In the generator mode, only the external layers contribute piezoelectrically, while the middle layer serves to increase the distance between the active layers and the neutral axis. After preparing the electrode structure of the single layers, they are agglutinated. Then the beams are structured. For the separation of the electrodes, as well as for the structuring of the whole device, a pulsed Nd:YAG-Laser was used. The structured piezoceramic plate is then put on a polymer.

![Fig. 3: Electrode configuration of the actuator (a) and the generator (b).](image)
Fig. 4: Frequency tunable generator

socket (see Fig. 4) and the electrodes are connected to the corresponding contact pins. The socket can then be mounted to the vibrating surface.

CONTROL UNIT

To adjust the resonance frequency in an autonomous way, an ultra low power control-unit was developed. A microcontroller (Atmel XMEGA) determines the ambient vibrational frequency by analyzing the voltage delivered by the generator before rectification. By means of a look-up table, the adequate actuation voltage is determined and delivered to the piezoelectrical actuator by a step up converter steered from the microcontroller. Both the controller and the step up converter are powered by a storage capacitor, which is fed by the rectifier connected to the harvester described above. The operating voltage of the system is 2 V. The step up converter is able to deliver voltages up to 50 V. The piezoelectric actuator has a capacitance of 150 nF which means that the converter will only be switched on for a very brief period of time (~10 µs). The exact amount of time will of course depend on the actuator voltage to be set or to be maintained. At higher voltages, the losses will increase, which means that a larger effort has to be made in order to conserve the appropriate actuator voltage. During the dc-dc-conversion, the actuator voltage is monitored by the controller in order to switch off the converter as soon as the desired value is reached. The voltage detection contains a potential divider, which needs to be disconnected from the actuator when no adjustment is done, in order to avoid leakage currents. When active, the control unit has a relatively high power demand, which is why it is only activated in predefined intervals. In the work presented here, those intervals were chosen to be 20 s. A shorter interval is possible, but the average power consumption of the control unit would increase by doing so. The microcontroller is switched to a power-saving sleeping mode when not active (~2 µW). While active, a clock-rate of 32 kHz is chosen for the frequency detection. During the time-critical operation of the step-up converter, the clock rate is scaled up to 2 MHz.

EXPERIMENTAL RESULTS

The experimental characterization of the presented device was carried out on a shaker, performing sinusoidal oscillations. At first, the tuning mechanism was connected to an external voltage supply in order to determine the resonance frequency in dependence of the actuator voltage. Fig. 6 shows the results of a long term measurement, where the actuator voltage was swept between -30 V and +45 V. The frequency curve shows a high gradient over the whole range. A slight inevitable hysteresis effect, which is typical for piezoceramic actuators can be observed. The output power, determined at the optimal load resistance ranges between 60 µW and 90 µW at an acceleration amplitude of 0.5 g and exhibits a minor dependence on the actuator voltage.

The frequency curve obtained with this measurement was used to determine a look-up table for the control unit. Due to the hysteresis effect, the underlying function is a multivalued function, which means, that for a perfect adjustment of the actuator voltage, its history should be known and considered. But as the hysteresis effect is not very pronounced, and its consideration would come along with an extensive calculation, we did not take the hysteresis into account in our tuning algorithm. Instead, the measured multivalued function was transformed into a single-
valued function by taking the average of both function values in order to fill our look-up table with one unique voltage value for every frequency interval.

Another important point is the preservation of charge and hence the conservation of force on the deployed actuator. To obtain a fairly passive tuning mechanism, the device must maintain an adjusted resonance frequency for a certain time, even when disconnected from the voltage source. Therefore, the fabrication process with the pulsed laser was optimized in order to reduce the leakage current of the piezoactuator to less than 0.1 nA at 10 V. Fig. 7 shows the drop of output power of the device at different frequencies after being separated from the voltage source which was previously set to the optimal actuator voltage. The power drop is due to the fact, that the voltage leakage will put the device out of tune. The lower the frequency, the higher is the required actuator voltage, which is why the power drop is more accentuated for 150 Hz than for 180 Hz. Nevertheless, even for high actuator voltages, it takes several minutes, until the power drop gets relevant.

The control unit was equipped with the look-up table and connected to the frequency tunable harvester. As can be seen in Fig. 8, the narrow resonance curve of the harvester without control unit could be significantly broadened and a plateau was obtained, reaching from 150 Hz to 188 Hz. Towards lower frequencies, a small decline of the plateau is observed, which can be explained by the fact that these off-resonant frequencies correspond to higher actuator voltages which require more power to be maintained. The level of this plateau is slightly lower than the power maximum of the non-controlled device. This power gap corresponds to the energy required to power the control unit. At this point, we would like to underline, that this apparently “lost” power is partly used to run the microcontroller which is capable to also accomplish tasks of an embedded system, powered by the frequency tunable harvester.

**CONCLUSION AND OUTLOOK**

We present a piezoelectric energy harvesting system, which is able to self tune its resonance frequency over a wide frequency range with very low energy costs. Under an acceleration amplitude of 0.6 g, the harvester generates much more energy than required by the tuning mechanism. It is planned to further enhance the tuning range by applying also negative voltages to the actuator. The efficiency and the tuning range could also be augmented by reducing the thickness of the piezoelectric layers.

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**REFERENCES**


