AN ENERGY-AUTONOMOUS SELF-TUNABLE PIEZOELECTRIC VIBRATION ENERGY HARVESTING SYSTEM

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ABSTRACT

A vibration energy harvesting system is presented, which is equipped with a smart resonance-frequency adaptation. The system is able to react to environmental frequency shifts in a completely autonomous way and can be excited in a resonant mode over a large frequency range (150 to 190 Hz). The device was programmed to readjust its resonance frequency every 22 s, and even for large adjustment steps, the recovery time is less than 10 s at an acceleration amplitude of 0,6 g. The effective output-power ranges between 30 and 45 µW, depending on the ambient vibrational frequency. The control-unit in use relies on an ultra-low-power microcontroller, equipped with a look-up table and a learning algorithm. The look-up table allows a very fast and hence energy saving frequency adjustment. With the learning algorithm the control unit is able to keep the look-up table up to date. It can therefore correct inaccurate factory settings and deal with hysteresis, temperature or ageing effects.

INTRODUCTION

Harvesting energy from environmental vibrations with inertial scavengers comes along with one severe restriction: The resonance frequency of the device must match exactly the frequency of the ambient vibrations. If this is not the case, the device will be inefficient and, when a resonator with a high quality-factor is in use, even a tiny mismatch of the resonant frequency will lead to a significant decline of the harvested power. For this reason, current commercial vibration energy harvesters are only used in environments with stable and very common vibration frequencies, like the base frequencies of 50 or 60 Hz from electrical equipment [1].

Since many environments offer vibrations with individually different or even non-constant vibration frequencies, tunable scavengers have attracted more and more attention during the past years [2]. The basic idea is to readjust the resonance behavior in accordance to the environmental conditions. As the resonance frequency of a harmonic oscillator basically depends on the spring constant and the weight of the seismic-mass, and as it results to be difficult to vary the seismic-mass during the operation of the device, most approaches rely on an adjustment of the restoring force. This can be done either by changing the stiffness of the spring material [3,4], or by applying additional restoring forces, e.g. via magnets [5].

The main requirement for any frequency tunable harvester is a low power consumption of the control system. When developing an adaptive energy harvesting system, it is very important to keep in mind that the main purpose of the scavenger is not to power itself, but to supply energy to some useful application, like e.g. a wireless sensor node or a controller. Therefore, any possible measure has to be taken to reduce the power-demand of the tuning mechanism. The power consumption of a frequency tunable scavenger can be split into three parts: The energy required to perform one frequency adjustment step, the power which is needed to maintain a certain resonance frequency and the power used to run the observation of the ambient conditions. The last two points represent the minimum or basic power-draw of the system, since they do not really depend on environmental conditions. A different case is given for the adjustment procedure. The average power consumed here will depend on the rate of environmental frequency shifts and of course on the magnitude of the corresponding adjustment step. The power balance of a frequency tunable scavenger will be positive if the basic power draw is much smaller than the generated power and if the ambient frequency stays constant for at least the time required by the system to recover from the last adjustment procedure.

TUNING MECHANISM

The deployed tuning mechanism relies on the resonance frequency shift obtained when an axial preload is applied to a resonating beam [6]. To apply the mechanical preloads, we use lateral arms connected to the tip of a cantilever beam [7]. The scavenger is made of a triple layered piezoceramic plate (PI-Ceramic). In a first step, the electrodes of the 100 µm thick single-layers are structured with a pulsed Nd:YAG laser. This allows to assign different functions to different parts of the piezoceramics later on. The single layers are then mounted to a stack by gluing. The stack is laser-structured again in order to obtain its final shape [8]. The structure is chosen in such a way that a part of it serves as a piezoelectric energy harvester in a bending mode, while another part is used as a linear actuator (see figures 1 and 2). The device used in this work consists of 2 pairs of opposed cantilever beams. The purpose of the actuator is to interconnect the tips of these opposed cantilever beams and to apply the axial preload to them. The preload will produce an additional moment in the cantilevers, which will ease or harden the deflection of the beam, depending on the direction of the linear actuation. As the additional moment directly contributes to the restoring force of the spring-mass-system, the resonance frequency of the system will be shifted. The whole resonator consists of four springs in form of cantilever beams and one common seismic mass represented by the actuator. To generate an additional

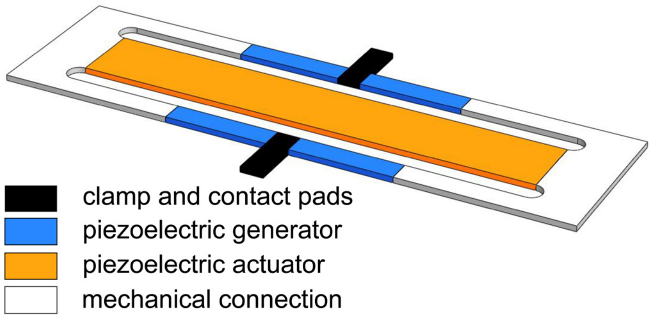

Figure 1: 3-dimensional scheme of the tunable generator.

moment on a cantilever through a lateral arm, it is important to make sure that the deflection-lines of both beams differ as much as possible. With the arm connecting the tips of two opposed cantilever beams, this condition is met very well. Since all relevant parts of the frequency tunable generator are made from the same bulk material, a cost-efficient large-scale production is possible.

HARVESTER CHARACTERISTICS

First, the tunable harvester has been characterized separately on a test rig. The resonance frequency and the optimal power output have been measured with different actuator voltages in order to obtain the correlation function between actuator voltage and frequency (see Fig. 3). The resonance frequency ranges between 215 and 150 Hz for actuator voltages between -30 V and +50 V. The corresponding output power measured with the optimal load resistance ranges between 60 and 90 µW.

Furthermore, the leakage effect on the actuator has been analyzed. With an actuator voltage of 10 V, a leakage current of less than 0.1 nA is measured. This measurement has been done under static conditions, without mechanical vibrations. To make certain that no significant power losses occur under vibrations, we have also analyzed the discharge effects with the device mounted on a shaker. To monitor the

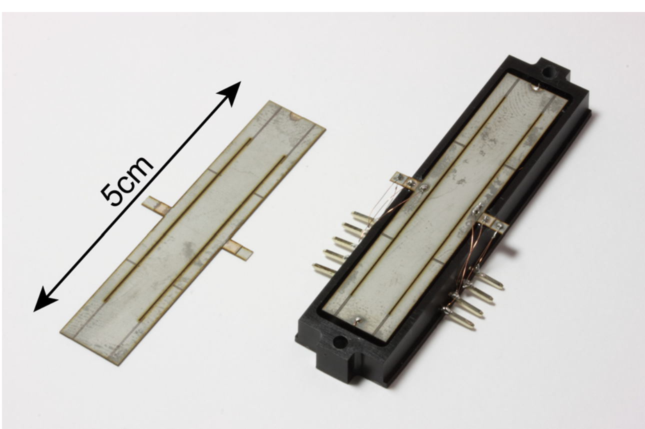

Figure 2: Photograph of the piezoelectric generator before and after being mounted on a polymer-socket. In the center of the structure, the contact pads for the different layers can be seen.

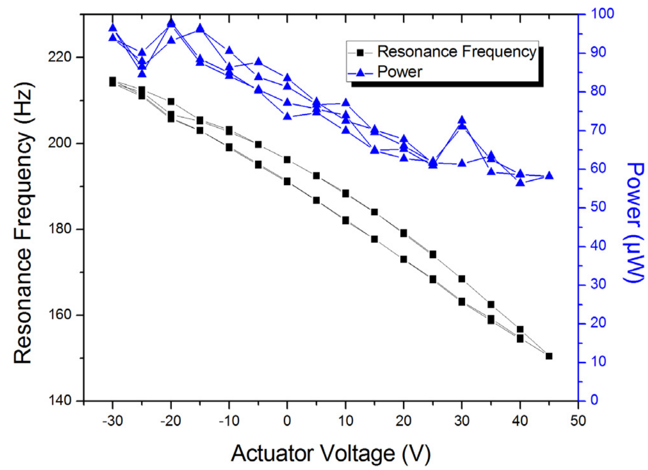

Figure 3: Resonance frequency and output power at the optimal load resistor vs. the applied actuator voltage.

losses, the temporal decrease of the output power has been determined at different frequencies, after isolating the device from the appropriate actuator voltage. Even when starting with high actuator voltages, e.g. at 150 Hz, it takes more than 15 min for the output-power to drop to 50 % of the initial value. These results confirm that a very low power consumption can be established for the retention of a constant resonance frequency.

CONTROL UNIT

The task of the control unit (Fig. 4) is to regularly check the frequency of the ambient vibration and to adjust the resonance frequency of the harvester when necessary. To measure the vibrational frequency, the AC voltage of the harvester itself can be used as input signal. Even when out of resonance, the harvester will vibrate with the excitation frequency. With an analog comparator included in the controller (Atmel XMEGA), the period of this signal can be easily measured, although the signal is affected by the rectifier. With the help of a look-up table, the controller can then choose the appropriate actuator voltage in order to shift the resonance frequency of the harvester to the measured ambient vibration frequency. The required actuator voltages of up to 50 V are directly obtained from a low-power DC-DC converter (LT1615-1). For monitoring purposes, the actuator voltage is scaled with a voltage divider and the scaled value is compared with an internal reference voltage of the controller. As soon as the required actuator voltage is reached, the controller will switch off the DC-DC-converter. Once the actuator voltage is set, all connections to the actuator are electronically disconnected. Especially the feedback-voltage divider needs to be disconnected, because its current draw would be too high, even when using large resistor values.

Using a regulation relying on a look-up table has the important advantage over a feedback-based regulation, that only one measurement needs to be done per adjustment procedure. Since any activity of the controller is power

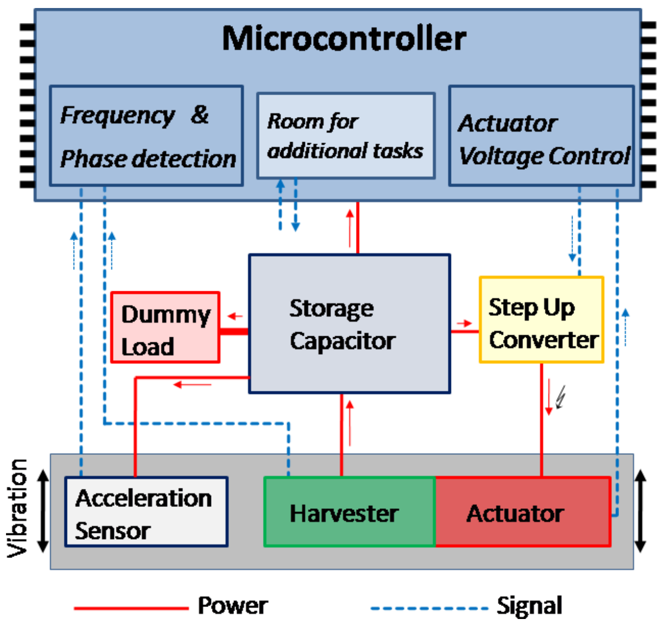

Figure 4: Schematics of the adaptive system.

consuming, the look-up table significantly reduces the tuning effort which is important for a positive power balance. On the other side, the look-up table suffers from its determinism. The contained predetermined parameters need to be correct during the whole lifetime of a device, and at large-scale production the entries of the table would have to be adjusted for every single harvester. As even small production tolerances or temperature shifts during operation can affect the resonance behavior, a predetermined look-up table might not be the optimal solution.

To obviate this inflexibility, the control unit was further equipped with a feedback mechanism. The signal of an independent acceleration sensor (AD-XL327B) is used to determine the phase shift between the motion of the harvester and the motion of the vibrating surface. This allows the control unit to check, whether a frequency adjustment was precise enough or not. If the detected phase shift does not correspond to the resonance condition, the related parameter in the look-up table will be readjusted, i.e. the system "learns" to tune the resonance in a better way. Due to the additional power consumption related to the phase measurements, it does not make sense to create a feedback after every single frequency adjustment step. To avoid unnecessary energy losses, the controller is programmed to generate a feedback after every forth adjustment procedure.

RESULTS

The system has been operated with different control strategies. For the first experiment, a very precise look-up table has been established manually. Fig. 5 shows the power-output of the self-adaptive system in comparison to a resonance curve obtained from the same harvester without control unit. With the adaptive system, the device stays resonant between 150 and 190 Hz resulting in a "resonance plateau" instead of a resonance peak. This plateau is slightly lower than the peak of the non adaptive system, as some power is deviated to the control-unit. Nevertheless, as the microcontroller could also be used for other purposes than just the frequency adjustment, not all of this power must be completely lost. It can further be observed that the effective power output at 150 Hz is lower than at 190 Hz. This difference can be explained with the higher effort made to maintain the higher actuator voltage at lower frequencies.

The second control set-up has been equipped with the learning algorithm and an artificially deteriorated look-up table. Fig. 6 shows the improvement obtained under these circumstances. Using the inappropriate look-up table, the first program exhibits a tremendous power-gap between 160 and 185 Hz. This gap is very well compensated via the learning algorithm. Since the feedback is only generated approximately every 90 s, the system needs a certain amount of time to correct bad values in the look-up table. Fig. 7 shows the learning curve for the worst parameters found at 178 Hz with the given look-up table. The power output increases until the optimal parameters are found. The learning procedure lasted about 8 min in this "worst-case". Once the device has readjusted its look-up table, the optimal parameters will be used immediately in every following adjustment procedure.

POWER BALANCE

The power consumption of the tuning mechanism can be broken down to the different tasks performed by the system. The basic requirement consists of 2 µW consumed during the sleeping period of the microcontroller plus the power consumed for a regular frequency analysis without regulation. To determine the amounts of energy required for the single tasks, the corresponding voltage-drops on the storage capacitor have been examined. With the presented device, 55 to 60 µJ are needed for one determination of the ambient vibration frequency. This analysis takes place every

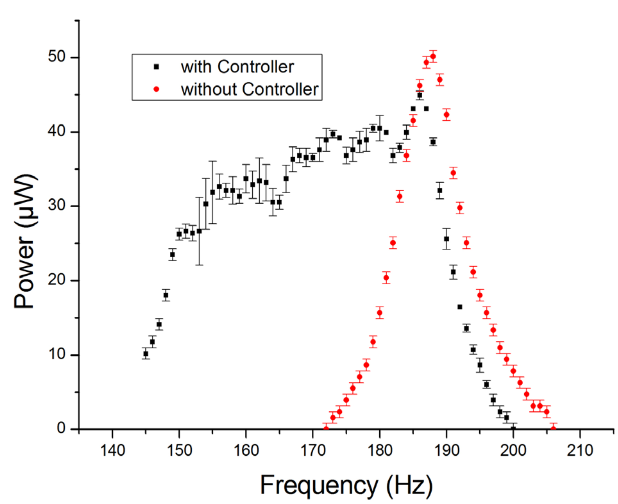

Figure 5: Power-spectrum of the tunable generator, with and without using the control-unit.

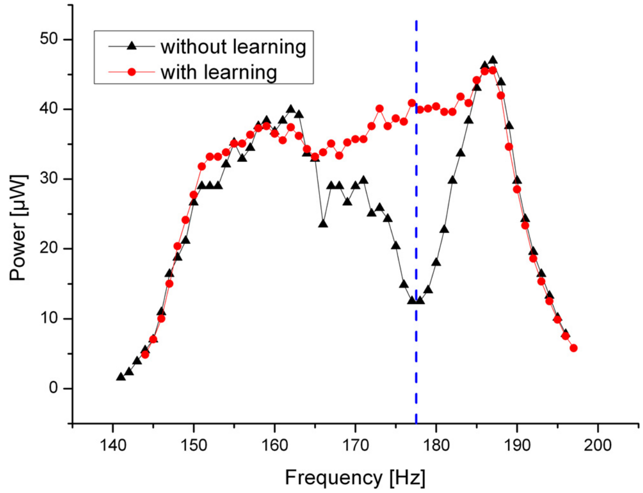

Figure 6: Effect of the learning algorithm, when starting from a "bad look-up-table" (dotted line: see Fig. 7).

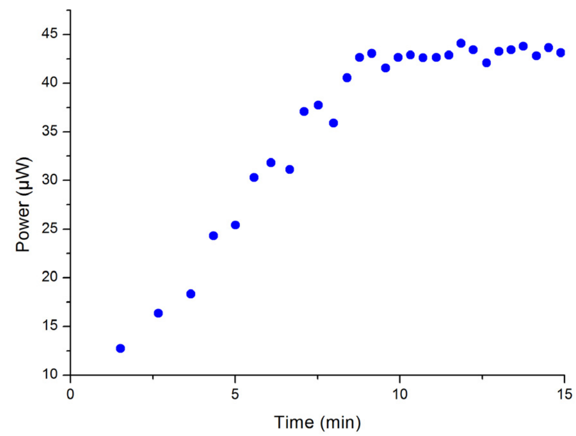

Figure 7: Temporal progress of the learning operation at 178Hz (see Fig. 6).

22.8 s, thus giving an average power consumption of 2.4 to 2.6 µW for the wake-up procedure plus the frequency determination. The power required for the frequency analysis slightly depends on the ambient vibration frequency, as always 6 periods are considered for the frequency determination which results in a longer lasting activity at lower frequencies. Summarizing, the basic power draw of the system amounts to 4.4 µW, when no adjustment needs to be done and no actuator voltage has to be maintained, which is the case at e.g. 190 Hz.

The power consumption of the tuning mechanism will increase as soon as the DC-DC converter comes into play. The energy consumption for one large frequency shift (190 to 160 Hz) amounts to 266µJ. This energy is required to generate the high actuator voltage. How this affects the average power consumption will of course strongly depend on the steadiness of the ambient vibration frequency, which is why no value can be given for the average tuning-power here. Once the tuning is done and the frequency stays steady, the actuator voltage has to be maintained in order to stay resonant. The "worst case" for the presented system at this point is a frequency of 150 Hz, where the maximal reachable actuator voltage has to be kept up. At this frequency, an average power of 8.7 µW is needed to maintain the actuator voltage and to compensate all leakage effects. Compared to the actuator's low loss currents determined before, this value is higher than expected. The losses leading to this relatively high power demand are therefore due to leakage currents in the diodes and transistors connected to the actuator.

CONCLUSION AND OUTLOOK

An energy autonomous frequency-tunable piezoelectric energy harvester has been presented. The actuation required for the tuning mechanism has been done with the same piezoceramic material as the one used for the energy generation. The tuning mechanism has been power-optimized with the result that the largest part of the generated power could be used for an external consumer. The learning algorithm does not only allow to equip a whole production line with the same factory settings, but also enables the device to react e.g. to temperature shifts or ageing effects occurring during operation.

The presented device opens the door to a wide spectrum of further possibilities. With its simple structure, it promises a cost-efficient mass-production and further improvements concerning the frequency-tuning range could e.g. be obtained by modifying the device such that also negative voltages could be applied to the actuator. With more and thinner piezoceramic layers, corresponding frequency shifts could be reached with lower voltages and the tuning range could be further extended.

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