Self-Tunable Vibration Energy Harvester

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Abstract. In this paper we present a small self-tunable vibration energy harvester with an integrated electronic circuit board. The changing of the frequency is realized by a stepper motor which moves an anchor. By moving the anchor the effective length of the cantilever beam is changing and as a result the Eigen-frequency changes. The simulations and experimental results are shown for a proof-of-concept and a designed demonstrator in two configurations with a bandwidth of 12 to 30.5 Hz and 19 to 40 Hz. Depending on several factors the possible tuning resolution is between 0.2 and 2 Hz which allows an efficient energy harvesting in the given frequency range.

1. Introduction
Different methods for tuning the Eigen-frequency of cantilever based energy harvesting structures have been investigated (mechanical, magnetic piezoelectric), each with advantages and disadvantages [1-3]. From literature there is evidence that mechanical methods provide a larger tuning bandwidth than magnetic or piezoelectric methods. However, implementation is a greater challenge. Looking at mechanical methods, two concepts are possible: varying the effective length of a cantilever beam [4] or varying the torque of inertia by a movable secondary mass [5]. A movable mass with actuator components on a vibrating cantilever is not a practical solution for a self-tunable energy harvesting system. Therefore, a mechanical tuning method based on a cantilever structure with a movable anchor is chosen. After theoretical analysis of the concept including simulations, a proof-of-concept setup was realized. Following the experimental characterization a demonstrator was designed, simulated and fabricated. The proposed device stands out from published work in terms of integration level and robustness and aims for low frequency applications.

2. Concept
The concept of the proposed self-tunable vibration energy harvester is depicted in figure 1. A magnetic circuit with an air gap is attached to the end of a cantilever beam. Inside in the air gap of the magnetic circuit a coil is placed, which is fixed on the ground plane. The opposite end of the beam is permanently coupled to a fixed anchor. In addition to the fixed anchor a movable anchor is incorporated into the overall structure. The effective beam length of the cantilever beam is then defined by the position of the movable anchor, which is driven by a threaded spindle and a stepper motor. The movable anchor consists of two sliding blocks with the beam clamped in between. A major challenge is given by the fact, that in horizontal direction the movable anchor has to slide easily driven
by the motor but in lateral direction the movable anchor has to be solidly coupled to the ground plane in order to clamp the beam tightly at the position of the movable anchor.

\[
c = \frac{E \cdot w \cdot t^3}{4 \cdot L_{\text{eff}}^3}
\]  

(1)

\[
f = \frac{1}{2\pi} \sqrt{\frac{c}{m}}
\]

(2)

For each step of the stepper motor \( L_{\text{eff}} \) is changing as a function of the step angle and the thread pitch. By changing \( L_{\text{eff}} \) the spring constant (1) and as a result the Eigen-frequency (2) is changing. The beam width (w), tight (t) and the young’s modulus (E) are constant for every setting. The mass (m) is a combination of magnet mass, iron mass and the fastening frame and also constant. To get a higher accuracy between analytic calculations and experiments an extended version of the formula considering the center of mass [5] was used to calculate the Eigen-frequencies in chapter 3.2.

**Figure 1.** Schematic view of the concept for the self-tunable vibration energy harvester. The tuning concept is based on a movable anchor.

### 3. Implementation

For characterisation of the devices a shaker system (Tira Vib TV 5200) controlled by LabView was used. As shown in table 1 the settings for each experiment is slightly different. The proof-of-concept (poc) experiments were done with a load resistance of 1200 ohm which is close to the internal coil resistance of 1100 ohm. For the demonstrator (demo) the same coils were implemented, but for a better impedance matching a 2200 ohm load resistor was used. To get better results a lower sweep rate was applied resulting in a longer experiment runtime. The proof-of-concept was tested with two different beam widths (15 and 20 mm) and the demonstrator was tested with two different beam thicknesses (0.3 and 0.4 mm).

**Table 1.** Experimental setup for the two devices with two different settings.

| Experiment | \( R_{\text{Load}} \) (Ω) | Sweep Rate (Hz/min) | Sweep Range (Hz) |
|------------|-----------------|--------------------|-----------------|
| poc 15 mm  | 1200            | 80                 | 10-50           |
| poc 20 mm  | 1200            | 70                 | 10-80           |
| demo 0.3 mm| 2200            | 35                 | 5-50            |
| demo 0.4 mm| 2200            | 35                 | 5-60            |

During all experiments the frequency of the shaker and the induced voltage were simultaneously recorded. An acceleration of 0.2g over the whole sweep range was used.
3.1. Proof-of-concept
A first proof-of-concept device was realized by means of a translation stage (figure 2). The moveable anchor is attached to the linear translation unit and was moved in 1 mm steps. The clamping is realized with two aluminum blocks fixed with screws. For better slide characteristics a slide tape (igus tribo-tape) is placed on both parts of the anchor. By changing the torque of the screws a variation of the clamping force is possible.

![Figure 2](image.png) **Figure 2.** First experimental setup with manual translation stage (proof-of-concept).

![Figure 3](image.png) **Figure 3.** Graph showing experimental results from the proof-of-concept setup in relation to theoretical data from simulations.

Experimental results are shown in Figure 3 and compared with simulations done with Ansys mechanical. The cantilever beam has a width of 15 mm and a thickness of 0.4 mm. The length of the beam can be varied between 3 and 20 mm by moving the anchor. As a result, the Eigen-frequency can be tuned from 20 to 45 Hz. Results are also shown for a beam width of 20 mm. In this case the tuning bandwidth is 25 Hz to 58 Hz. In general, simulations predicted higher Eigen-frequencies at shorter beam widths, which is due to the differences in the tightness of the clamping.

3.2. Demonstrator
Based on the proof-of-concept setup a first demonstrator was realized with a U-shaped beam structure and a motorized gear spindle (figure 4). The demonstrator is designed to be robust and flexible allowing modifications to be made by changing different parts. For instance, various stepper motors and gear spindles with different thread pitches can be used. The length change per motor step is then defined by the angle of the stepper motor and thread pitch of the spindle. Depending on the used stepper motor, the thread pitch of the gear spindle and the beam thickness, a resolution of 0.2 to

![Figure 4](image.png) **Figure 4.** First motorized demonstrator with a movable anchor based on a sliding block clamping mechanism. The upper housing and circuit board is not mounted.

![Figure 5](image.png) **Figure 5.** Graph showing the simulated Eigen-frequencies of the demonstrator for different beam thicknesses as a function free cantilever length.
2 Hz is possible. In this paper a combination of stepper motor and thread pitches with a maximum of 49 steps is shown. The beam length is variable between 5 and 30 mm. Both beams of the U-shaped spring element have an effective beam width of 20 mm. By changing the clamping element different beam thicknesses can be verified. To achieve a smooth sliding the material PPS HPV from the company techtron is used.

Analytic calculations in consideration of the centre of mass predict a tunable bandwidth of 16 to 58 Hz for the beam with a thickness of 0.3 mm. As shown in figure 5 the resolution per millimetre movement increases with increasing beam length. To reach a maximum resolution of 1 Hz a movement lower than 0.1 mm per step is required for the frequency range of 16 to 58 Hz. By increasing the thickness of the beam the resolution decreases.

Figure 6. Frequency response of the tunable vibration energy harvester for the 50 different anchor positions with a beam thickness of 0.3 mm (a) and 0.4 mm (b)

With the experimental setup described in the implementation capital two configuration of the demonstrator were tested. The frequency response of each demonstrator is shown in figure 6. With a tuning range of 15.5 to 30.5 Hz for the demonstrator (a) there is a big deviation to the simulation at the upper frequency range. By using the full bandwidth of each tuning step over a voltage limit of 2 V there is a useful frequency range from 12 to 30.5 Hz. The tuning range of the second demonstrator with a beam thickness of 0.4 mm (figure 6 (b)) is 21 to 48 Hz. Compared to (a) the useful bandwidth is 19 to 40 Hz. Both systems have a tuning resolution less than 1 Hz per step in the useful bandwidth. In connection with the bandwidth at each tuning position and the resulting overlapping of the frequency response curves an effective energy harvesting in the whole frequency range is possible.

Table 2. Energy consumption for different stepper motors and driving voltages.

| Shaft pitch | Voltage (V) | Current (mA) | Energy (mJ) |
|-------------|-------------|--------------|-------------|
| 12.7        | 4           | 340          | 81.6        |
| 12.7        | 4.5         | 380          | 102.6       |
| 12.7        | 5           | 424          | 127.2       |
| 25.4        | 4.5         | 370          | 99.9        |
| 25.4        | 5           | 414          | 124.2       |
| 25.4        | 6           | 500          | 180         |
| 25.4        | 6.9         | 570          | 236         |

For a spring mass system with a cantilever beam a strong clamping is very important. The deviations between simulations and experiments are due to the fact that the clamping of the beam is not strong enough. This results in reduced frequencies and nonlinear frequency responses especially at higher frequencies. It is difficult to design a strong clamping and also make a smooth sliding possible. In the presented design are manufacturing tolerances in the linear guidance, the beam clamping, the
position of the motor with the gear spindle and at the fixture point of the cantilever. These tolerances result in a mechanical play.

The operating voltage for the used stepper motors is 6.9 V. To reduce the needed energy for each step lower operating voltages were tested. For all configurations the on-time was 60 ms. By reducing the voltage the current can be decreased, which results in a lower energy consumption. For the full tuning range with the current best setup (12.7 shaft pitch, 4.5 V) 5 J are needed. At a voltage of 4 V (12.7 shaft pitch) and 4.5 V (25.4 shaft pitch) the stepper motor made some step errors, which is a big problem for the electronic circuit because there is no sensor to detect such step errors. After a step error the system needs a calibration. A possible solution for calibrating is to use limit switches at one or both ends of the anchor but it needs a lot of energy to move the anchor only for a calibrating to its end positions. The actually design is prepared for limit switches.

In further development an intelligent algorithm is needed which detects step errors and correct them, use the limit switches and tune the Eigen-frequency with low power consumption. Such an algorithm has to combine with a power management to tune the Eigen-frequency of the vibration energy harvester to the maximum output power in an application with varying excitation frequencies.

4. Conclusion

In this work we presented an energy harvesting system with motorized tuning mechanism. The functionality and feasibility of the concept was demonstrated on the basis of a proof-of-concept and a compact and robust demonstrator. In case of the used cantilever beam a frequency range from 15 to 30 Hz and from 19 to 40 Hz was realized. Depending on the used setup a resolution of 0.2 to 2 Hz is possible.

In further experiments the system will be tested with a power management including a motor controller and a chargeable battery. The battery allows for a system start with initially wrong tuned Eigen-frequency to power the stepper motor for tuning. The capacity of the battery is chosen by the maximum power needed for tuning over the full tuning range. After tuning and generating enough energy for the power management including the loads, the battery will be charged by the energy harvester.

References

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