Verification of Self-Tuning 4DOF Piezoelectric Energy Harvester with Enhanced Bandwidth

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VERIFICATION OF SELF-TUNING 4DOF PIEZOELECTRIC ENERGY HARVESTER WITH ENHANCED BANDWIDTH

L.G.H Staaf, E. Köhler, A. D. Smith, P.D Folkow and P. Enoksson
Chalmers University of Technology, Sweden
E-mail: v96staaf@chalmers.se

Abstract
In this paper, we present an analytical model to predict enhanced bandwidth for a piezoelectric energy harvester with self-tuning, accomplished by a sliding mass. The model predicts that by implementing asymmetry of different piezoelectric cantilever lengths , the bandwidth can theoretically approach 60 Hz. Validation measurements demonstrate an increased 3dB bandwidth up to 21 Hz with 150 mW, by configuration 23/17 mm in open length – providing sufficient power for a ZigBee to continually transmit.

Introduction

Over the last decade, interest for autonomous intelligent wireless sensors (AIWS) has increased tremendously. Accompanying that expanding interest, investigation into powering these sensors has been the subject of increased attention [1-3]. Despite significant research effort, the biggest remaining challenge is substituting a conventional battery solution with a power source that does not need to be replaced. An alternative power source would be to use an energy harvester. To be able to replace a conventional battery solution, an energy harvester needs to be able to deliver sufficient power. Depending on the intended use of the AIWS and its corresponding surroundings, different energy harvesters can be used (such as photovoltaic, thermal and kinetic). In our case, we mainly have a vibration source and therefore a piezoelectric energy harvester solution (kinetic) is chosen. The main problem for a piezoelectric energy harvester is the bandwidth, which is usually quite narrow and makes the harvester ineffective in most real-life applications. To counter this problem, previous works implement an array of cantilevers, with the negative side of increase in size, which grow dramatically for each cantilever added to the harvester [4]. Another solution is to utilize coupled cantilevers in a 2DOF solution where the bandwidth is somewhat broadened [5-6].

In this paper we present a self-tuning piezoelectric energy harvester with enhanced bandwidth that is achieved by a sliding mass. The obtained enhanced bandwidth is based on analytical calculation. The concept for this 4DOF piezoelectric harvester was reported at PowerMEMS 2015 [7], where a maintained voltage output was achieved through a distributed stress over the piezoelectric cantilevers [8]. Further, the devices demonstrated that a sliding mass had a broader bandwidth than if the mass was fixed on the middle beam.

However, the harvester in this work differs from the former by being designed based on predictions of the analytical model. The model suggests that the bandwidth becomes wider by making the harvester asymmetrical via adjusting the stiffness of the piezoelectric beams. Presented is a bandwidth comparison, for symmetric and asymmetric setup, to verify the analytical prediction.

Harvester setup

The harvester contains a top piezoelectric cantilever (MIDE PPA-2014), connected to a back folded middle beam via a coupling. On the middle beam, a sliding mass is placed. The other end of the beam is connected to a bottom piezoelectric cantilever of the same type via a second coupling. The harvester is presented schematically in figure 1. The couplings and middle beam are made of aluminum. Specifications for the couplings, mass and middle beam are in table 1. The length given for the cantilevers and middle beam is the open length, which is the lengths between attachments and couplings.

Analytical model

An analytical harvester model was previously developed based on Euler-Bernoulli theory for homogeneous and isotropic beams with additional point masses [7]. The harvester model is transformed

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to a beam structure using a simple finite element (FE) model. In the present self-tuning system, the first two eigenfrequencies are found to be somewhat close to each other while the eigenfrequency for the third mode is much higher. It is thus imperative that the model adequately captures the two lowest eigenfrequencies. In figure 2, the first mode is presented. In our case, a system using only three beam elements with three-point masses was chosen, resulting in a four DOF problem. By adopting a Guyan reduction of the two nodal rotational degrees of freedom, u_d, the reduced 2×2 equations of motion system for the active nodal displacement DOF, u_a is

$$M\ddot{u}_a + Ku_a = 0. \quad (1)$$

The elements of M and K consist of polynomial expressions in terms of the geometrical and material parameters. Based on these expressions, the two lowest eigenfrequencies and the corresponding eigenmodes are expressed in a closed form involving only algebraic equations.

The analytical model gives a clear prediction that if an asymmetry for the harvester is developed, by altering the length of the piezoelectric cantilevers, the bandwidth for the harvester will be increased. The configuration of analytical model is as follows: top/bottom; 22/22, 23/21 and 24/20. . In figure 3, the difference in bandwidth between symmetric 20/20 (blue line) and 24/20 (green dashed) is presented and configuration the asymmetric 24/20 yields a theoretical bandwidth of 60 Hz

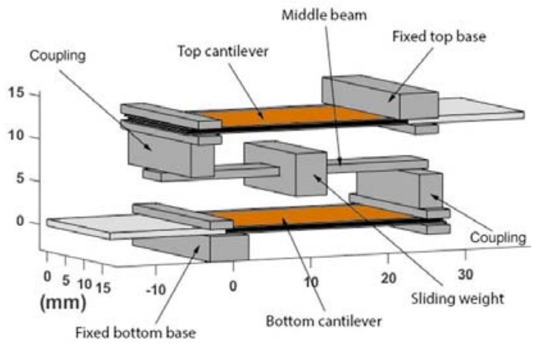

Figure 1, Schematic setup of the harvester

	Weight (g)	Thickness (mm)	Open length (mm)
Total	3.12	-	-
Coupling	1.04	-	-
Sliding mass	0.9	-	-
Middle beam	0.13	0.35	26.5

Table 1, Technical data for the aluminum parts, coupling, middle beam and sliding mass

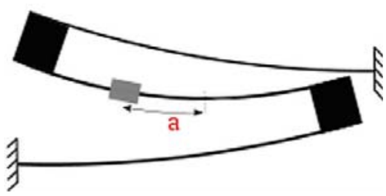

Figure 2, For mode 1, the masses move in the same direction and the position of the sliding mass can be related to the position with zero slope of the middle beam - the distance a, in our case a is close to zero

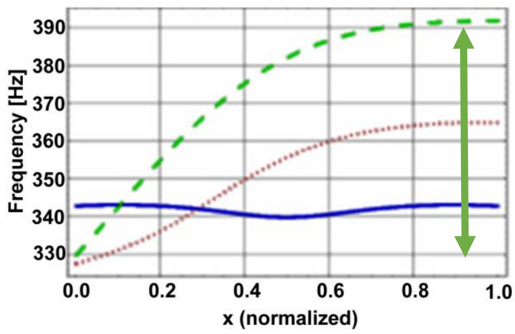

Figure 3, Eigenfrequencies for different positions x of a fixed mass. Upper/lower beam lengths are: 22/22 mm (solid blue), 23/21 mm (dotted red), 24/20 mm (dashed green). The theoretical bandwidth of 60 Hz is marked by the green arrow

Measurement setup

To validate the prediction of the analytical model, the harvester was measured with a symmetric setup and an asymmetric setup. The symmetry chosen is 20/20 and asymmetry 23/17. The length from the model 24/20 could not be achieved due to width restrictions of the coupling. When attached at the outer end, the open length was measured 23 mm with the used the piezoelectric cantilever. The total piezoelectric area is equal for both setups.

In figure 4, the measurement equipment is presented where A) the NI-USB 6210 is used to collect

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data, B) The harvester on shaker table, C) The tone generator which provide vibrations with an applied frequency between 100 – 300 Hz and amplitude of 1g.

Measurement

Before data collection, we swept the frequency several times to mitigate hysteresis in the measurement. While recording, the frequency was increased by 1 Hz at and was not changed until the mass was either stable or moved to a new position on the middle beam. Changes in the mass position occurred rapidly (within 1 to 2 seconds) when the frequency was changed. The RMS Voltage output is presented for the 20/20 and 23/17 case (figure 5) demonstrating that the 20/20 has a higher top output but the 23/17 has a much broader bandwidth. The 20/20 has one peak and the mass did not change position on the middle beam during the frequency sweep while the 23/17 case has two peaks. On the right side of the graph in figure 5, we can see that 20/20 and 23/17 has the same RMS voltage output. This output similarity depends on the mass position of the middle beam (which is the same for the 20/20 and 23/17). Apart from that similarity, we have a narrow frequency range (between 190 and 193 Hz) where the two configurations also have the same output. During this period, both configurations have the mass on same position on the middle beam. Between the two peaks for 23/17 we can see that the mass position affects the harvester in a way that the output is lower than for the 20/20 system. However, in the area left of the peak the mass position for 23/17 affects the system so that it yields a higher output than for 20/20 and gives the asymmetric system a wider bandwidth. The 3db bandwidth (RMS Voltage output) for 20/20 is 11 Hz and for 23/17 it is 21 Hz. The power output for the system above the 3dB bandwidth is over 150 mW (figure 6), which is more than sufficient to power our ZigBee wireless interface.

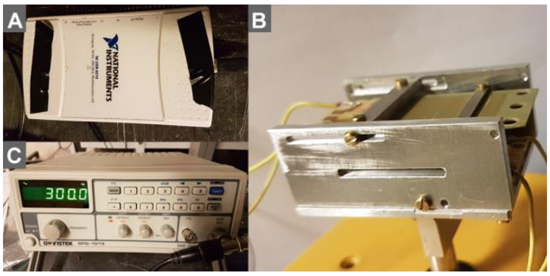

Figure 4, A) Texas Instrument USB-6210, B) The harvester on the shaker, C) Function generator SFG-1013

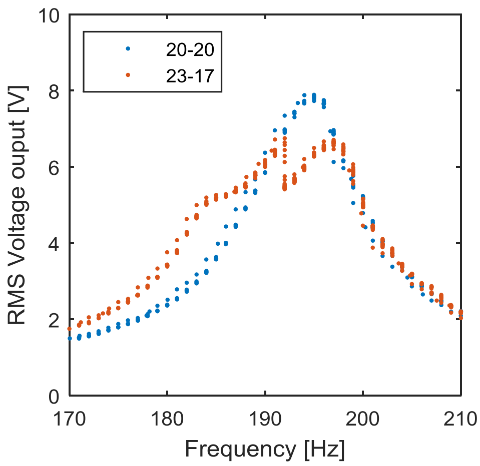

Figure 5, RMS Voltage output for symmetric 20/20 (blue) and asymmetric 23/17 (red)

Bandwidth and power output for real application

For one of our applications on a gas turbine, we provide power for a ZigBee (802.15.4). This particular ZigBee requires 8 mW during startup and 2 mW to be able to send and retrieve signals constantly. Previous measurements with this type of harvester (before the analytical model) demonstrated that we could not provide sufficient power for continuous broadcasting (as seen in figure 7). The power is one critical limit and voltage is the other. To be able to charge a supercapacitor, the voltage needs to be higher than 5.13 V

In our case both 3 dB bandwidth devices (configuration: 20/20, 23/17) are above the critical 5.13 V limit, which is required to maintain power for a ZigBee (802.15.4) equipped with a sensor and transmitting continuously [9]. In figure 6, we can see that the RMS power output has the same signal trend as the voltage output due to maintained total piezoelectric area, with 0.16 W above the critical limit. As seen in figure 5, a frequency step up converter could be used to convert current to voltage effectively achieving even wider bandwidth, with sufficient output for the ZigBee (802.15.4).

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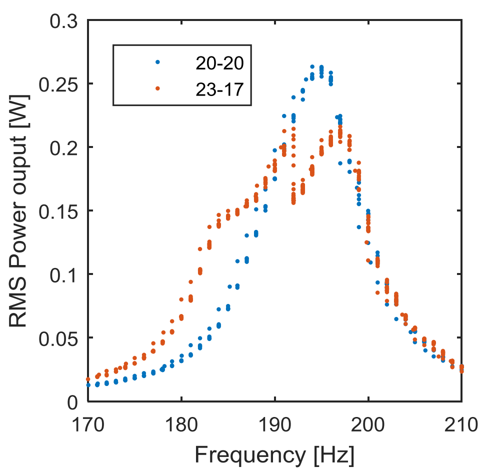

Figure 6, RMS power output for symmetric 20/20 (blue) and asymmetric 23/17 (red)

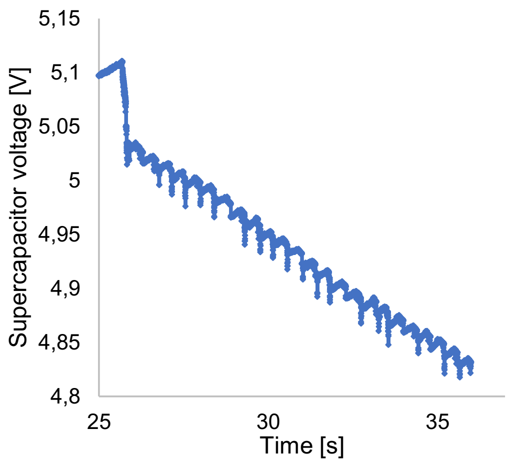

Figure 7, In the graph, measured voltage from a power supply (harvester + supercapacitor) where continuous transmitting performed by a ZigBee on an ex-service Rolls-Royce gas turbine is shown.

Conclusion
A harvester with broad bandwidth and sufficient output is one key to achieve successful autonomous intelligent wireless sensors. Our proposed enhanced harvester has a broad bandwidth of 21 Hz (3dB), which is achieved by an asymmetric setup. The output is slightly lower than for the symmetric setup, but is still above the critical limit (for the used circuitry) for both power (above 2 mW) and voltage (above 5.13 V) within its bandwidth. The prediction based on the analytical model proved to fit well with measurements, where the structure's asymmetric longitudinal change of the piezoelectric beams gives a greater bandwidth of 21 Hz, hencethe asymmetric setup demonstrates an effective method for extending the bandwidth of energy harvesters.

Acknowledgments
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