Smart design selftuning piezoelectric energy harvester intended for gas turbines

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SMART DESIGN SELFTUNING PIEZOELECTRIC ENERGY HARVESTER INTENDED FOR GAS TURBINES

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Abstract. Piezoelectric energy harvesting on a gas turbine implies constraints like high temperature tolerance, size limitation and a particular range of vibrations to utilise. In order to be able to operate under these conditions a harvester needs to be small and efficient and to respond to the appropriate range of frequencies. We present the design, simulation and measurements for a clamped-clamped coupled piezoelectric harvester with a free-sliding weight which adds self-tuning for improved response within the range of vibrations from the gas turbine. We show a peak open circuit voltage of 11.7 V and a 3dB bandwidth of 12 Hz.

1. Introduction

The coming of the internet of things requires that we now develop alternative energy sources to replace or support today's and tomorrow's batteries. Alternative energy sources such as energy harvesters have been focused by many researchers during the past years [1]. Energy harvesters convert ambient energy in our surrounding, like solar irradiation, wind, heat and mechanical vibrations into electric energy. For a gas turbine the main ambient energies are heat and mechanical vibrations. The thermal energy is concentrated to certain areas within the gas turbine, while vibrations are more or less available everywhere, making piezoelectric energy harvesting a viable option. The main challenge for piezoelectric energy harvesting is to maintain a sufficient power output over a broad bandwidth; much research has been done on broadening the harvesting bandwidth [1-2]

In this paper we report on the design, simulation and measurements of a piezoelectric harvester with self-tuning for wider bandwidth and coupled piezoelectric cantilevers to maintain a high power output by extended strain distribution. The harvester is designed to meet the gas turbines specific conditions on size, temperature and frequency. Previous work [3] has shown that by utilizing a distributed stress pattern over the whole cantilever the complete area of the piezoelectric cantilever is used and not only the clamped end, thereby yielding a higher power output. In previous work [4] this distributed stress pattern was observed for a cantilever with one end fixed and the other end coupled to a second (top) cantilever (which showed a stress pattern similar to a single cantilever with one end fixed). In the present design both cantilevers are clamped and coupled at each end, hence using all available piezoelectric capacity to optimize the power output. To extend the bandwidth, passive self-tuning is introduced by a free sliding weight. In previous work a free sliding proof mass has been used on a thin fixed-fixed beam. When the proof mass slides to one end of the thin beam it can get stuck there even if the frequency is changed [5-6]. To avoid this problem we have made our middle beam thicker, in order to lower or remove the impact of the natural frequencies that might force the weight to one end. The movement range of the proof mass has also been limited to prevent the occurrence of it getting stuck at one end.

2. Simulation

The harvester was modelled in the simulation tool COMSOL. Figure 1 shows a schematic image of the harvester; it consists of two piezoelectric cantilevers that are clamped to an attachment at one end.

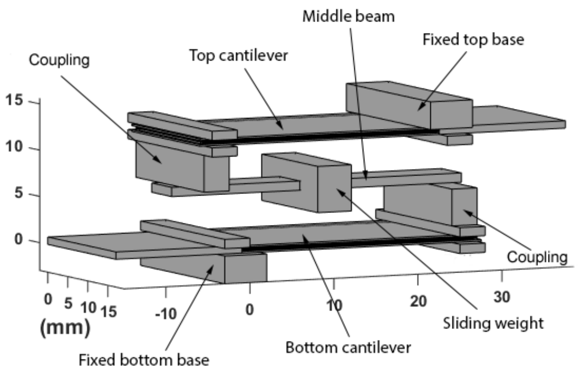

Figure 1. Schematic image of the harvester setup in COMSOL.

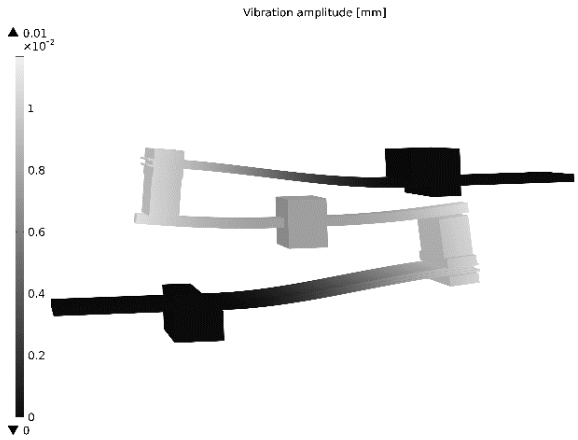

Figure 2. The mode shape at resonance frequency at 380 Hz from simulation

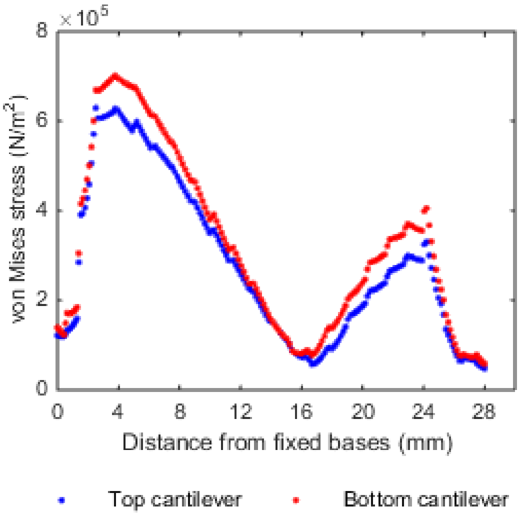

Figure 3. Simulated distributed stress over top and bottom cantilever.

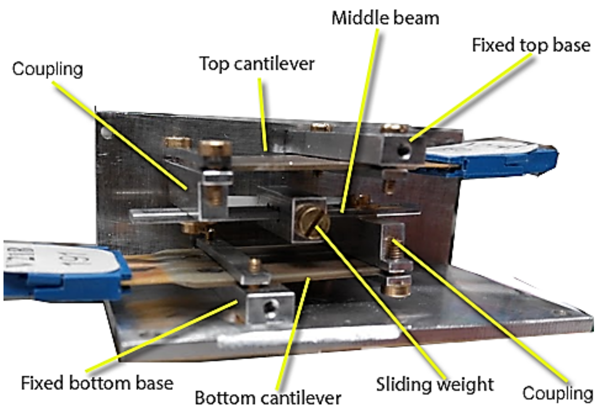

Figure 4. The setup of the harvester, at measurement 1, tuned to 373 Hz

On the other end the cantilevers are attached to a coupling that connects the two cantilevers by an aluminium beam where a sliding weight is placed.

The targeted frequency range is 370 - 380 Hz with self-tuning from the weight. The simulated harvester is tuned to 380 Hz, with a fixed weight at the centre of the middle beam, and the simulation provides the required length of the cantilevers on the real harvester. In figure 2 the mode shape of the resonance frequency mode at 380 Hz is shown. From figure 2 we can conclude that the cantilever attachments and the couplings are not colliding and thus not creating any collision-induced damping.

In figure 3 the stress pattern for the cantilevers is simulated. Both cantilevers have similar stress patterns: higher at the clamped end and less at the coupled end. As shown in previous work [3] the coupling is similar to clamping and a higher open circuit voltage for the piezoelectric cantilever is reached by it utilizing a larger area of stress.

3. Experimental setup

The characterization of the harvester is done on a sinusoidal excited shaker table. The cantilevers electrodes are connected to multimeters measuring the open circuit voltage over the frequency span 330-410 Hz. In figure 4 the harvester assembly is shown. The front wall is removed for a better view from the side. In measurement 1 (M1), figure 4, the cantilevers are 24 mm long and the length of the middle beam is 16 mm. The coupling weight is in total 3.87 g, where the sliding weight is 0.87 g. The active middle beam is 1 mm thick, 3 mm broad and 16 mm long. The natural frequency of the middle beam is 2974 Hz, which is far above our targeted frequency range of 370 – 380 Hz.
In measurement 2 (M2), figure 5, the top and bottom cantilever lengths are 26 mm and 28 mm respectively. The middle beam is 1 mm thick, 3 mm wide and 27.5 mm long. The natural frequency of the middle beam is 1006 Hz, still above our targeted frequency range of 370 – 380 Hz.

4. Result

Table 1. Comparison of measurement 1 (M1) and measurement 2 (M2).

	Primary mode (Hz)	*Open circuit voltage (V)*	3 dB open circuit voltage (V)	*3 dB bandwidth (Hz)*
M1 16 mm beam, sliding weight	373	3.12	2.2	12
M1 16 mm beam, fixed weight	378	3.26	2.3	8
M2 27.5 mm beam, loose sqrew	373	11.2	7.9	10
M2 27.5 mm beam, extremely loose screw	372	11.71	8.28	12
M2 27.5 mm beam, fixed weight	378	11.5	8.13	8

4.1 Measurement 1

The first measurement series was made with 370 - 380 Hz as target frequency. The setup was manually tuned to a resonance frequency of 373 Hz. Even though the movement of the proof mass was visibly much more limited than expected, a small effect could be seen when comparing to a completely fixed weight. In figure 6 the measured result (M1) for the total output with non-fixed and fixed weight with a 16 mm long middle beam is shown for the primary frequency mode of 373 Hz with a 3 dB bandwidth of 12 Hz. The measured open circuit voltage output peaks at 3.1 V and 2.2 V at the 3 dB border. The self-tuned harvester has nearly as high voltage output as the harvester with the fixed weight, but shows a near 50% increase in bandwidth as shown in table 1.

4.2 Measurement 2

From the first measurement we could conclude that the non-fixed weight can increase the bandwidth compared with a fixed weight. Shorter cantilevers are harder to tune than longer, therefore new simulations were performed with longer cantilevers. For the second measurement three parameters were changed, two based on simulation results and one mechanical (a more reliable weight fixture). The middle beam was set to be as long as possible (27.5 mm) due to the current setup geometric constraints as shown in figure 5. In this setup the top cantilever is 26 mm long and the bottom one is 28 mm long. The target frequency was still 370 - 380 Hz; with longer cantilevers and longer middle beam the harvester showed resonance at 372 Hz.
In the second measurement the new weight fixture screw was tested for two different settings; *loose* (-½ screw turn from fixed condition) and extremely loose (unscrewed). For both settings, the weight could be seen to move to different positions when the frequency was changed. By slowly increasing the frequency we could see that after 2-3 seconds at a specific frequency, the weight moved to another

position, where it henceforth remained if the frequency was kept constant. At the start of a measurement sweep the weight was positioned at the middle of the beam. When the frequency reached 357 Hz it moved to the left end (refer to figure 5) and at 368 Hz it started to slide back and forth up to 372 Hz from when it remained stable at the left side. When the frequency sweep was downwards the sliding weight positioned itself accordingly at the same frequency as on the sweep upwards. In figure 6 the open voltage output for the screw settings are compared; it is inferred that a loose screw setting seems preferable.

Compared to the first measurement we can conclude that the second setup had approximately 3.5 times higher open circuit voltage output of 11.7 V (table 1) for the same volume, which might occur from that the natural frequency of the middle beam which is more close to the resonance frequency of the harvester on measurement 2 than on measurement 1. Hence with a lower natural frequency for the middle beam a higher impact on the open circuit voltage might occur. Thinner middle beams with lower natural frequency have to be tested for further evidence of this theory. The bandwidth was the same 3 dB bandwidth range of 12 Hz as in measurement 1.

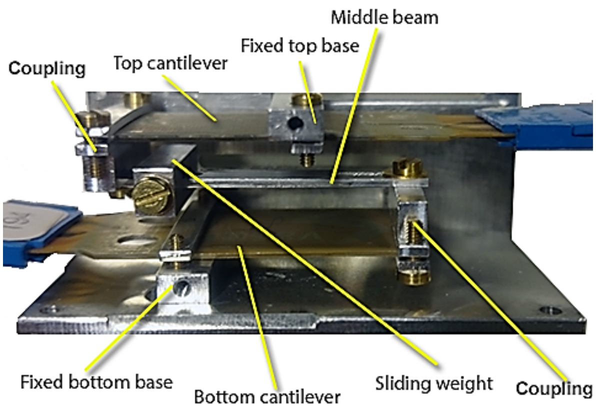

Figure 5. Measurement 2 setup with 27.5 mm middle beam and longer top (26 mm) and bottom (28 mm) cantilevers compared with measurement 1 setup.

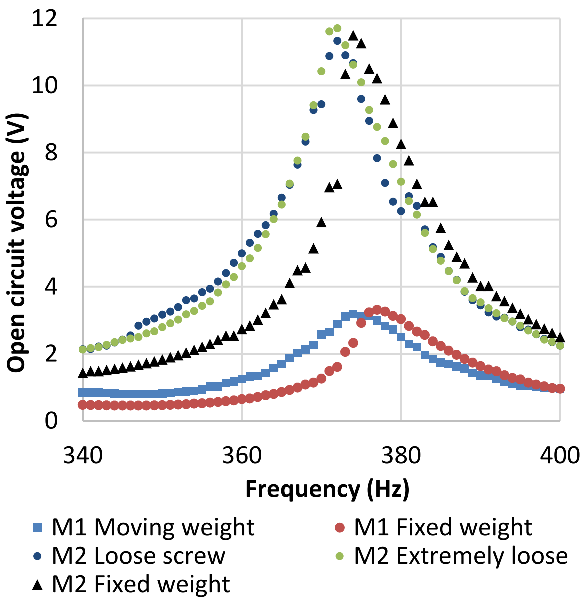

Figure 6. Second measurement (M2) open circuit voltage output with different screw tightness and compared with measurement 1 (M1) which had a 16 mm middle beam and 3.5 times lower output.

5. Conclusion

Our second generation of coupled harvester displayed a bandwidth of 12 Hz and an open circuit voltage of 11.7 V, which is 3.5 times higher, with the same volume, than our first harvester implementation. The higher open circuit voltage might occur from that the natural frequency of the middle beam is closer to the resonance frequency of the harvester on the second measurement. Future harvester improvements are foreseen when tuning 1) the proof mass weight, 2) the stiffness of the couplings and 3) the thickness of the middle beam. Despite improvements remaining to be implemented, the tested harvester demonstrates the bandwidth broadening impact of a passively sliding weight and high open circuit voltage which looks promising for our gas turbine application.

Acknowledgment
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