PERFORMANCE OF A PIEZOELECTRIC ENERGY HARVESTER UNDER VIBRATIONS TAKEN FROM A HELICOPTER

Dibin Zhu*, S. P. Beeby, M. J. Tudor, N. J. Grabham, N. M. White and N. R. Harris
School of Electronics and Computer Science, University of Southampton, Southampton, UK
*Presenting Author: dz@ecs.soton.ac.uk

Abstract: This paper compares performance of a piezoelectric vibration energy harvester, in terms of output power, under different types of vibration. The most common method used to characterize a vibration energy harvester is to excite the energy harvester under a sinusoidal vibration of its resonant frequency and measure the voltage across certain electrical loads. However, in practical applications, the vibration spectrum usually contains multiple peaks at different frequencies. In this research, a piezoelectric energy harvester was tested under vibration taken from a PZL-SW4 helicopter and the charging rate was compared with that when excited with sinusoidal vibration at the resonant frequency.

Keywords: vibration energy harvesting, piezoelectric, helicopter, practical vibration

INTRODUCTION

Vibration energy harvesting, as an alternative energy source for self-powered systems, has drawn lots of attention over the last decade. A vibration energy harvester converts kinetic vibration energy to electrical energy using a transduction mechanism, such as electromagnetic [1], electrostatic [2] or piezoelectric [3] transducers. Such harvesters are usually designed to work at one frequency, i.e. their resonant frequencies, and produce maximum power when the resonant frequency matches the ambient vibration frequency.

To date, the most common method used to characterize a vibration energy harvester is to excite the energy harvester under a sinusoidal vibration of its resonant frequency and to measure the output voltage across certain electrical loads [4]. This is the most straightforward way of evaluating output power of vibration energy harvesters. However, in practical applications, the vibration spectrum usually contains more than one peak at different frequencies. It is important to understand whether vibration peaks at other frequencies will affect the performance of the vibration energy harvester when it only works at one particular frequency. Even so, performance of vibration energy harvesters under complicated practical vibrations is yet to be reported.

In this paper, the performance of a piezoelectric vibration energy harvester under different types of vibration is compared. A piezoelectric energy harvester was tested under vibration taken from a PZL-SW4 helicopter and the charging rate was compared with that when excited with a sinusoidal vibration at the resonant frequency. Details of an energy harvesting block used in the test are presented first, followed by experimental results and discussion.

OVERVIEW

Energy Harvesting Block

Fig. 1 shows a photo of the energy harvesting block. It has dimensions of 55mm×55mm×4mm. The block has a sealed aluminium case that protects the components inside.

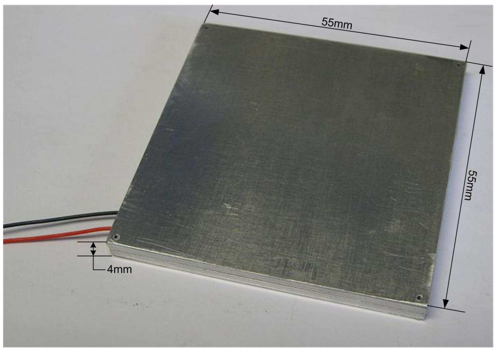

Fig. 1: Overview of a sealed energy harvesting block.

The energy harvester block consists of a thick-film piezoelectric energy harvester clamped to the base and a PCB containing the power conditioning circuit as shown in Fig. 2. The top and base of the block are both 0.5mm thick in the central area, which leaves a space of 3mm for the piezoelectric energy harvester to oscillate.

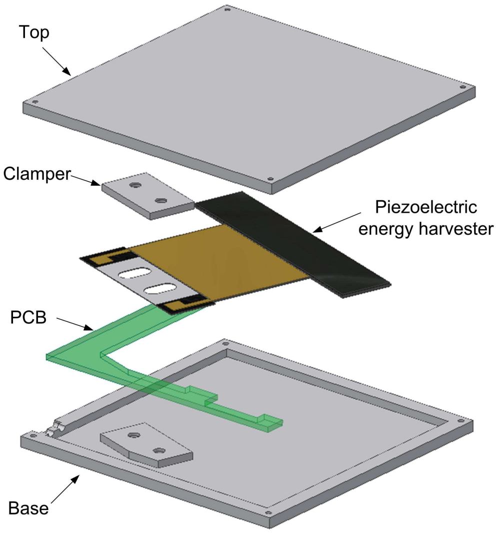

Fig. 2: Components inside the energy harvesting block.

Thick Film Piezoelectric Energy Harvester

Fig. 3 shows the thick-film piezoelectric vibration energy harvester within the energy harvesting block. It has a bimorph structure and was fabricated using screen printing technology. The energy harvester has a T-shape cantilever to reduce its tip displacement. Details of the energy harvester can be found in [5]. Its resonant frequency can be tuned by adjusting the cantilever length to match the vibration frequency before installation. In this application, the resonant frequency of the energy harvester was tuned to around 67.5Hz to match a vibration peak in the vibration spectrum. Detail of the vibration taken from a helicopter will be presented in following section.

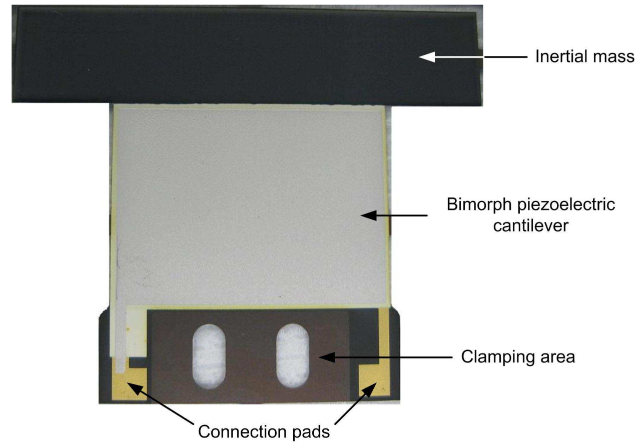

Fig. 3: T-shape bimorph piezoelectric energy harvester.

Power Conditioning Circuit

Fig. 4 shows the power conditioning circuit in the energy harvesting block. The AC voltage generated by the energy harvester is rectified using a bridge rectifier. The rectified DC voltage then charges a storage capacitor.

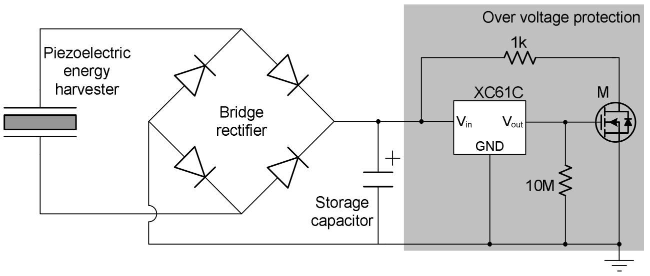

Fig. 4: Power conditioning circuit in the energy harvesting block.

To protect the storage capacitor, an over voltage protection circuit was deployed to limit the maximum voltage across the storage capacitor. A voltage detector, Torex XC61C, was used to measure the voltage across the capacitor. When the voltage across the capacitor reaches the threshold voltage of the detector, the detector outputs a high level which turns on the MOSFET and the storage capacitor is discharged through the 1kΩ resistor. When the voltage across the capacitor is below the threshold voltage of the detector, the detector outputs a low level and the MOSFET is turned off. Thus the over voltage protection is also turned off.

Vibration Spectrum Taken from a Helicopter

Fig. 5 is the vibration spectrum taken from the vertical stabilizer on a PZL SW-4 helicopter [6]. It was taken when the helicopter was flying horizontally at 200km/h and at an altitude of 1000m with an outside air temperature of 10.5^{o}C. The main rotor rotational speed was 103% where 100% = 7.288Hz.

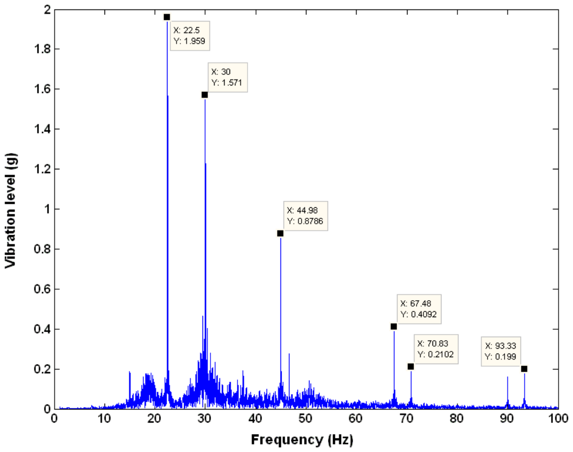

Fig. 5: Vibration spectrum taken from a helicopter.

Table 1 lists all vibration peaks whose amplitude is over 0.2$\boldsymbol{g}$ (1$\boldsymbol{g}$ = 9.8m·s^{-2}).

Table 1: Vibration peaks in the original spectrum.

Frequency (Hz)	**Vibration level (g) (1g = 9.8m·s^{-2})**
22.5	1.96
30	1.58
45	0.88
67.5	0.41
70.8	0.21
93.3	0.2

EXPERIMENT AND DISCUSSION

Experimental Setup

The energy harvester was tested using a Labworks ET-126 shaker with a programmable resistance box and a PC with LabVIEW software controlling the system and collecting the data as shown in Fig. 6.

The time waveform of the vibration taken from the helicopter was first loaded to the PC via a LabVIEW application. The signal generator outputs an arbitrary signal based on the loaded time waveform. This arbitrary signal was then amplified by a power amplifier and drove the shaker to produce the target vibration. An accelerometer is used to detect the acceleration of the vibration produced by the shaker. A LabVIEW program was developed to sample the resulting vibration waveform and to transfer it to the frequency domain using FFT. The energy harvester is bolted securely onto the shaker to minimize the losses in mechanical coupling.

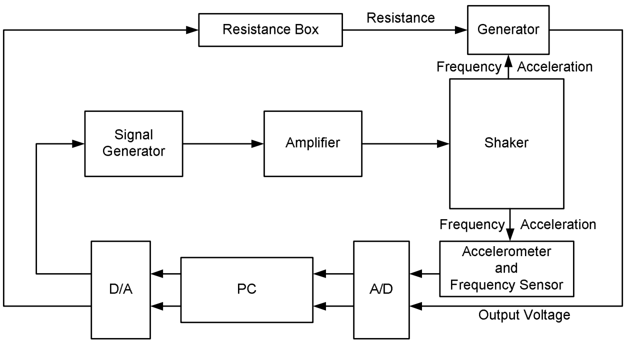

Fig. 6: Block diagram of test platform.

Fig. 7 compares the time waveform of the output from the signal generator and the output from the accelerometer. As expected, it is found that time waveform of the duplicated vibration is very similar to that of the original vibration taken from the helicopter.

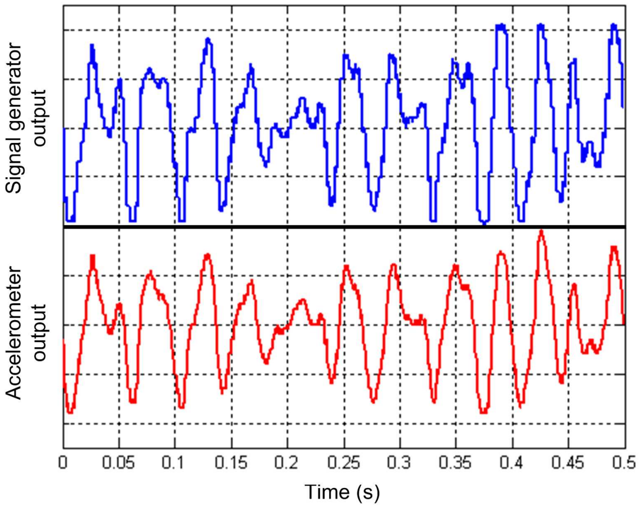

Fig. 7: Comparison of output of the signal generator and output of the accelerometer.

Fig. 8 shows the vibration spectrum of the duplicated vibration. Note that spectrum in Fig. 5 are peak values while in Fig. 8, the acceleration are RMS values.

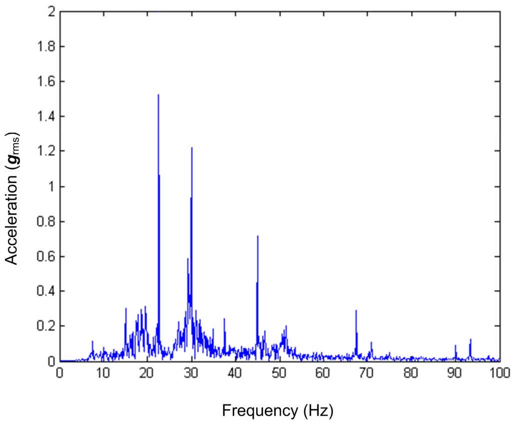

Fig. 8: Spectrum of the duplicated vibration.

Table 2 compares frequencies and amplitude of peaks in the duplicated vibration and the original vibration. It is found that frequencies of the peaks in the duplicated vibration match those in the original frequency closely. Amplitude of the duplicated vibration is slightly higher and lower than that of the original vibration at lower and higher frequencies, respectively. However, the amplitude of the vibration peak at 67.5Hz, which is the resonant frequency of the energy harvester used in the test, in the duplicated vibration is very close to that in the original vibration. Thus, this duplicated vibration is suitable for this research.

Table 2: Comparisons of vibration peaks.

Frequency (Hz)	**Vibration level (g_{rms}) ($1g = 9.8m \cdot s^{-2}$)**	**Target vibration level (g_{rms}) ($1g = 9.8m \cdot s^{-2}$)**
22.5 (22.5)*	1.53	1.39
30 (30)	1.22	1.12
45 (45)	0.72	0.62
67.5 (67.5)	0.3	0.29
70.9 (70.8)	0.11	0.15
93.4 (93.3)	0.12	0.14

*Frequency in the brackets is the target frequency.

Results

Two tests were conducted. In each test, the energy harvester was excited and used to charge one of two storage capacitors (100µF and 90mF respectively). Charging plots were logged for comparison. In the first test, the energy harvester was tested under a sinusoidal vibration of $0.29g_{rms}$ ($1g = 9.8m \cdot s^{-2}$) at 67.5Hz, which matches one of the vibration peaks in the vibration spectrum taken from the helicopter as shown in Fig. 5 and is also the resonant frequency of the energy harvester. The top of the energy harvesting block was removed in this test. In the second test, the energy harvester was tested under the vibration with the spectrum as shown in Fig. 8. Two measurements were taken: when the energy harvesting block was open, and sealed.

Figure 9 and figure 10 show charging plots of a 100µF capacitor and a 90mF super capacitor, respectively.

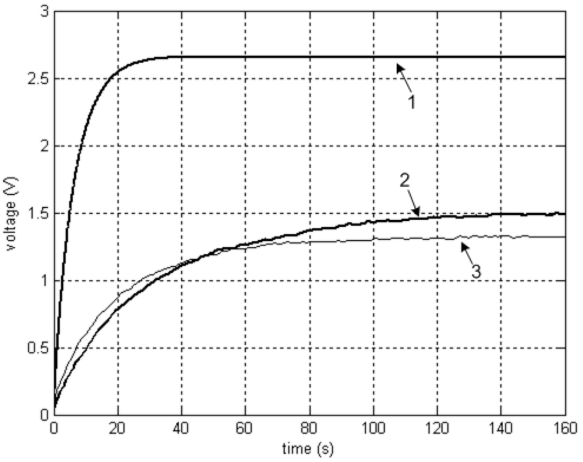

Fig. 9: Charging plot of a 100µF capacitor. (1: Excited at resonant frequency; 2: Excited at practical vibrations, opened block; 3: Excited at practical vibrations, sealed block).

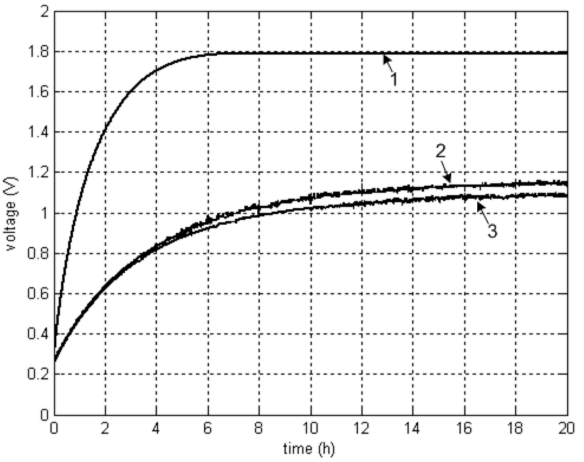

Fig. 10: Charging plot of a 90mF capacitor. (1: Excited at resonant frequency; 2: Excited at practical vibrations, opened block; 3: Excited at practical vibrations, sealed block).

The test results showed that the capacitors were charged more quickly when excited at the sinusoidal vibration than when excited at the practical vibration. Furthermore, when the load capacitance became larger, the final voltage was lower. This is because the resonant frequency of the energy harvester decreases with the increase of the capacitive load. The test results also showed that when the energy harvesting block was sealed, the capacitors were charged more quickly at the beginning but the final voltage was slightly lower than opened devices. This is due to the air squeeze effect. The sealed environment causes the total damping of the energy harvester to increase, which increases the operational bandwidth of the energy harvester, thus the charging rate becomes higher. However, increasing the damping also decreases the maximum output voltage of the energy harvester, which makes the final voltage lower.

CONCLUSION

In conclusion, both output power and voltage of energy harvesters that are designed to work at one frequency will be reduced when excited under vibration with peaks at multiple frequencies. The reason for this is as follows: Although all peaks in the frequency domain are clearly separated and do not interfere with each other, the waveform in the time domain is actually the superposition of sinusoid waveforms with various frequencies. As these waveforms are not always in phase, they may partially cancel each other and thus the output is reduced when excited under vibration with multiple peaks compared to that under pure sinusoidal vibration. Energy harvesters with a wide operational frequency range may be a better solution in such environments. In addition, it is suggested that energy harvesters should be tested under practical vibration to get a better understanding of their performance. Furthermore, the air squeeze effect in an airtight energy harvester could also reduce the performance of vibration energy harvesters. This should be taken into account in future design of vibration energy harvesters and their packaging.

ACKNOWLEDGEMENT

This work is supported by the European Union Seventh Framework Programme (FP7) research project TRIADE (http://triade.wscrp.com/).

REFERENCES

[1] Arnold D P 2007 Review of microscale magnetic power generation *IEEE Transactions on Magnetics* **43(11)** S3940-S3951

[2] Roundy S, Wright P and Pister K 2002 Micro-electrostatic vibration-to-electricity converters *Proceddings of IMECE 2002* S1-S10

[3] Anton S R and Sodano H A 2004 A review of power harvesting using piezoelectric materials (2003-2006) *Smart Material and Structures* **36(3)** S197-S205

[4] Beeby S P, Tudor M J and White N M 2006 Energy harvesting vibration sources for microsystems applications *Measurement Science and Technology* **17** S175-S195

[5] Zhu D, Beeby S P, Tudor M J and Harris N R 2011 A credit card sized self powered smart sensor node *Sensors and Actuators A* 169(2) S317-S325

[6] Stamos M, Nicoleau C, Torah R, Tudor J, Harris N R, Niewiadomski A, Beeby S P 2008 Screen-printed piezoelectric generator for helicopter health and usage monitoring systems *Proceedings of PowerMEMS 2008 (Sendai, Japan, 9th-12th November 2008)*