Broadband electrostatic device for power harvesting

N S Yuksek\textsuperscript{1}, Z C Feng\textsuperscript{2}, and M Almasri\textsuperscript{1}
\textsuperscript{1} University of Missouri, Electrical and Computer Engineering, Columbia, MO, USA
\textsuperscript{2} University of Missouri, Mechanical and Aerospace Engineering, Columbia, MO, USA
almasrim@missouri.edu

Abstract. This paper introduces a prototype energy harvester device with integrated MEMS capacitive plate and two impact oscillators for transferring energy from low frequency structural vibration with varying mechanical spectra to a vibration of a high resonance frequency cantilever. The use of the two impact oscillators not only harvested energy at low frequencies but also had demonstrated exceptionally sufficient and optimum dynamic responses to a broad frequency bandwidth between 13 Hz and 39 Hz, the bandwidth covering wide range of residual vibrations in structures and systems, without reduction in output power. The device was designed with a MEMS capacitor fixed at the free end of an aluminium cantilever clamped at one side, with a high resonance frequency of 605 Hz matched with the single-cavity capacitor, and two cantilevers made of Al sheet with low resonance frequencies of 18 Hz and 25 Hz. The results clearly demonstrates the device’s ability for frequency up-conversion and harvesting power on a wide range from 13 Hz to 39 Hz at 1g excitation.

1. Introduction

Inertial forces are widely used in MEMS power harvesters, charge pumps and voltage step-up converters for energy conversion from unwanted ambient vibrations into electrical energy with high enough voltage level to power up wireless sensors used in construction, security, aviation and biometry. Autonomous wireless sensor networks can be achieved with vibration power harvesters for structural health monitoring in smart buildings and structures. The majority of MEMS energy harvesters are designed to operate at resonance with narrow bandwidth \cite{1, 2}. However, in the real environment, the vibration frequency varies with time, resulting in significant power reduction for resonance operations. Nonlinear energy harvesting devices have been shown to be capable of operating in a broader frequency range and harvesting more power than resonant devices, making them more appropriate for real life applications. To enhance the operational frequency range, researchers have employed solutions by tuning the resonance frequency to match the ambient vibration or broadening the operational bandwidth of the energy harvester \cite{3, 4}. The resonance frequency was tuned by adjusting the stiffness of suspension beams, changing the size of the proof mass or by bidirectional tuning \cite{3, 5}. Bi-stable springs have been used to harden or soften the suspensions to increase the bandwidth of the wideband MEMS electrostatic energy harvester utilizing nonlinear springs \cite{6, 55}, electromagnetic induction energy harvesters \cite{7, 56}, a bistable piezoelectric inertial generator \cite{8, 57}, a wideband micro-electromechanical energy harvesters \cite{9, 58}. Various impact mechanisms were attempted but still resulted in a relatively narrow bandwidth with low power \cite{10-13}. Frequency-up conversion techniques have been used increase the power harvester’s efficiency at low frequency. For example, a periodic single impact between a low frequency driving beam resonator and a single or double high frequency piezoelectric generating beam resonators.
Device Design and Fabrication

The power harvesting device harvests power with a wide bandwidth by transferring the power from low frequency vibration to the high frequency vibration through impact oscillators. The device uses oscillators with low resonance frequencies to convert the energy to a high resonance frequency power harvester through oscillations resulting from intermittent physical contacts between a low frequency oscillator and the power harvester. This technique will enable energy transfer from low frequency structural vibration to power harvester whose natural frequency lies outside the frequency ranges of typical mechanical vibration that the device is designed to harvest energy from. In addition, harvesting low frequency energy is not restricted to the narrow band at the resonance frequency of the impact oscillator. Due to the nonlinearity of the impact oscillator, it has a much broader bandwidth, from its natural frequency to several times of its natural frequency. If the forcing frequency is above the natural frequency when the oscillator impacts on a stiffer structure, it results in a higher “equivalent stiffness” thus a much broader bandwidth than in the absence of impact.

We have designed and built a hybrid macro scale wideband electrostatic power harvester prototype for low frequency vibration (Figure 1). The device consists of a single-cavity MEMS capacitor fixed at the free end of an aluminum cantilever clamped at one side with a length, width and thickness of 63 mm, 13 mm, 3 mm, respectively, with a high resonance frequency of 605 Hz matched with the single-cavity capacitor, and two cantilevers with a length of 34 mm and 50 mm, width of 9.5 mm, 8 mm, and thickness of 0.5 mm, respectively, made of Al sheet vibrating at low excitation frequency, each with a thick impact mass attached at its unclamped end. The low-frequency cantilevers were attached on top of the clamped side of the high frequency cantilever.

![Figure 1. A photo of the macro-scale wideband electrostatic power harvester](image)

One of the two low frequency cantilevers on the macro device was designed to resonate at 18 Hz while the other resonates at 25 Hz within the range of ambient vibration frequency. The metallic impact masses were used in order to reduce the cantilever’s resonance frequency and improve the momentum transfer to the high frequency cantilever. When the power harvester was subjected to a low frequency vibration using a mechanical shaker, the two low frequency cantilevers responded by vibrating at low frequencies with at least one of them vibrating close to its resonance frequency, and thus their thick metallic masses made impacts with the high resonance frequency cantilever repeatedly at two locations. This has caused it along with the MEMS capacitor to oscillate with decaying amplitude at its resonance frequency. After the impact occurs, the absorbed energy by the two low-frequency cantilevers were transferred to the high resonance frequency cantilever and to the single-cavity MEMS capacitor, and then to the electrical domain.

The MEMS capacitors were fabricated successfully using surface micromachining technologies on top of a substrate (Figure 2). Cr and Au layers are sputter-deposited on glass substrate with thicknesses of 50 nm and 150 nm, respectively and patterned. A thin layer of NR-9 3000PY negative photoresist is used for the SiO$_2$ dielectric lift-off process. The first mold for the anchors was prepared with a 10 µm thick layer of AZ 4620 photoresist. The same photoresist layer functions as a sacrificial layer. The photoresist sacrificial layer is cured in a convection oven with an optimized temperature 120 C for 90 minutes and followed by the deposition of another Cr/Au seed layer. A second photoresist mold was patterned on top of the second seed layer to create the top movable plate along with the suspension
beams. The mold was then patterned to provide the movable plates with square holes. The moving plate and suspension beams are grown on the second seed layer by electroplating Ni for a thickness of 10 µm. Magnified optical microscopy image of electroplated Ni plate can be seen in Figure 3. After desired thickness of the material is deposited, the top mold is washed away carefully by solvents. The seed layer is then removed by etching Au and Cr consequently.

Figure 2. Schematics of the MEMS variable capacitor fabrication process by surface micromachining on a glass substrate.

After this step, bottom electrode and trace lines can be seen through transparent photoresist layer.

2. Device Testing

Prior to assessing the fabricated devices, a simple electrical circuit was built to extract the output power generated by the MEMS power harvester. The power source performance was characterized by placing it on a controllable vibration shaker with adjustable vibration frequency and acceleration. The device was connected to a load resistor and the output voltage was measured across a load resistor connected in series with the MEMS capacitor. The voltage was monitored on a PC using LabVIEW and a data acquisition cable through an oscilloscope.

Figure 4. a) Time domain plot of the output voltage across the load resistor. b) The RMS output power as a function of frequency for 1 g excitation acceleration.

An analog accelerometer was used to determine the acceleration at various vibration conditions, and thus calibrate the power harvesting device. The power harvesting devices were characterized by fixing the device on a rigid stage on the shaker. AC signals of different frequencies were applied to the shaker, and the resulting output voltages were measured across a load resistor connected in series with MEMS capacitor, using an oscilloscope and an AC voltmeter. To determine the resonance frequency of the high frequency cantilever, the excitation frequency was swept from 100 to 1 kHz, and the
generated output voltages were measured using a Multimeter. The resonance frequency was observed around 605 Hz for low frequency excitation conditions (Figure 4.a). A typical time domain plot of the measured output AC voltage across a load resistor (100 kΩ) when the device was exposed to an ambient vibration at 25 Hz is shown in Figure 4.a. The plot clearly demonstrates a nonlinear behavior with exponential decay at its resonance frequency of 605 Hz, and the peak to peak signal corresponds to a low frequency vibration of 25 Hz.

This clearly indicates the device ability for frequency up-conversion. To estimate the response bandwidth, the devices were first characterized by sweeping the excitation frequency from 5 Hz to 50 Hz with 1 g of constant acceleration, while the output voltage was measured for each excitation frequency across the load resistor. Initially, with a small acceleration of 1 g, only one impact cantilever with a resonance frequency of 18 Hz responded and made impacts with the high frequency cantilever up to 21 Hz. As the frequency increased further, both cantilevers started to make impact with the high frequency cantilever. As the frequency increased further, the low frequency cantilever stopped hitting the high frequency cantilever beam, and only the second cantilever beam kept hitting the high frequency cantilever beam up to 39 Hz. This has resulted in a wide bandwidth response from 13-39 Hz at 1 g (Figure 4.b). Qualitatively speaking, the oscillator responded with a variable resonance frequency depending on the degree of impact. Therefore, the device had an optimal response over a much broader low frequency. It is noted that two impact masses were enough to cover the frequency range from 13 to 39 Hz at 1 g with a maximum power of 96.2 nW.

References
[1] E. O. Torres and G. A. Rincón-Mora, “Electrostatic energy-harvesting and battery-charging CMOS system prototype,” IEEE Trans. Circuits Syst., vol. 56, no. 9, pp. 1938-1948, 2009.
[2] T. Von Buren, P. D. Mitcheson, T. C. Green, E. M. Yeatman, A. S. Holmes, and G. Troster, “Optimization of inertial micropower generators for human walking motion,” IEEE Sensors J., vol. 6, pp. 28-38, 2006.
[3] D. Zhu, M. J. Tudor, and S. P. Beeby, “Strategies for increasing the operating frequency range of vibration energy harvesters: a review,” Meas. Sci. Technol., vol. 21, no. 2, pp. 1-29, 2010.
[4] S. Roundy and Y. Zhang, “Toward self-tuning adaptive vibration based micro-generators,” Proc. SPIE, pp. 373–384, 2005.
[5] V. R. Challa, M. G. Prasad, Y. Shi, and F. T. Fisher, “A vibration energy harvesting device with bidirectional resonance frequency tunability,” Smart Mater. Struct., vol. 17, no. 1, 2008.
[6] D.S. Nguyen, E. Halvorsen, G. U. Jensen, and A. Vogl, “Fabrication and characterization of a wideband MEMS energy harvester utilizing nonlinear springs,” J. Micromech. Microeng., vol. 20, no. 12, 2010.
[7] B. P. Mann and N. D. Sims, “On the performance and resonant frequency of electromagnetic induction energy harvesters,” J. Sound Vib. vol. 329, pp. 1348-1361, 2010.
[8] S. C. Stanton, C. C. McGehee, and B. P. Mann, “Nonlinear dynamics for broadband energy harvesting: investigation of a bistable piezoelectric inertial generator,” Physica D: Nonlinear Phenomena, vol. 239, pp. 640-653, 2010.
[9] S. D. Nguyen, E. Halvorsen, and I. Paprotny, “Bistable springs for wideband microelectromechanical energy harvesters,” Appl. Phys. Lett., vol. 102, 2013.
[10] S. Moss, A. Barry, I. Powlesland, S. Galea, and G. P. Carman, “A low profile vibro-impacting energy harvester with symmetrical stops,” Appl. Phys. Lett., vol. 97, no. 23, 2010.
[11] K. Ashraf, M. H. Md Khir, J. O. Dennis, and Z. Baharudin, “A wideband, frequency up-converting bounded vibration energy harvester for a low frequency environment,” Smart Mater. Struct., vol. 22, no. 2, 2013.
[12] B. P. Mann and N. D. Sims, “Energy harvesting from the nonlinear oscillations of magnetic levitation,” J. Sound Vib., vol. 319, pp. 515-530, 2009.
[13] N. S. Yuksek, Z. C. Feng, and M. Almasri, “Broadband electromagnetic power harvester from vibrations via frequency conversion by impact oscillations,” Appl. Phys. Lett., vol. 105.11 (2014): 113902.