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SciVerse ScienceDirect
Procedia Engineering 47 (2012) 418 – 421
Procedia Engineering
www.elsevier.com/locate/procedia

Proc. Eurosensors XXVI, September 9-12, 2012, Kraków, Poland

Impact-Enhanced Multi-Beam Piezoelectric Converter for Energy Harvesting in Autonomous Sensors

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Abstract

This work proposes and experimentally validates a piezoelectric vibration energy harvester, which exploits the impact of a central compliant driving beam onto two piezoelectric parallel bimorph beams on flexible steel. At suitable mechanical excitation conditions, the central driving beam impacts the piezo beams and triggers a nonlinear frequency-up conversion mechanism that improves the overall effectiveness, i.e. increases the overall rms output voltage and widens the equivalent bandwidth of the converter with respect to the condition of the noninteracting linear converters.

Keywords: autonomous sensor; impact piezoelectric converter; energy harvesting.

1. Introduction

Most vibration-based generators are spring-mass-damper systems that generate maximum power when the resonant frequency of the generator matches the frequency of the ambient vibration. Different strategies can be employed to increase the operational frequency range of vibration-based generators [1]. One possibility is the exploitation of multi-element harvesters combining the outputs from multiple generators with different frequency responses into a Multi-Frequency Converter Array (MFCA). Alternatively nonlinear effects were investigated [2], with particular regard to bistability [3, 4] created by means of magnets and ferromagnetic materials. Other possibilities are the use of mechanical stoppers [5] or coupled oscillators [6], which are relatively easy to implement but with the main drawback of a decrease in the maximum generated power. Recently, frequency-up conversion techniques which allow to shift low-frequency mechanical vibrations towards the higher resonance frequencies of the converters were investigated using, in particular, solutions based on impact [7].

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doi:10.1016/j.proeng.2012.09.173

2. Impact-Enhanced Multi-Beam Piezoelectric Converter

In this paper an impact-enhanced multi-beam piezoelectric converter for energy harvesting in autonomous sensors is presented. The schematic diagram of the converter is shown in Fig. 1. It is composed of a compliant harmonic steel driving beam with a low resonant frequency (below 25 Hz) sandwiched within two piezoelectric beams (in green) with interposed spacing. Additional masses on the tips of the piezo beams allow the tuning of the resonant frequencies. The mechanical excitation of the base is up-converted to high frequency by the repetitive impact between the driving beam and the piezo beams. The converter has been modeled by equivalent electro-mechanical lumped-element circuits, which have been derived for the driving beam and the top and bottom piezo beams, as shown in Fig. 1. In the equivalent models, x represents the displacement of the base of the beams with respect to an external fixed frame, y_T, y_B and y_D denote the displacement of the free ends of top, bottom and driving beams from their equilibrium position, while d_T and d_B are the distance of the top and bottom piezo beams from the driving beam, respectively. The lumped element m, $1/k$ and R_m with the respective subscripts represent the equivalent mass, elastic compliance and mechanical resistance of the top (T), bottom (B) and driving (D) beams. In the Laplace domain, the force F_y denotes the inertial force acting on each beam due to the acceleration s^2X of the whole converter. The electro-mechanical conversion ratio α and the electrical capacitance C^S are equal for top and bottom piezo beams. The impact among the beams is modeled under the simplifying assumptions of impulsive impact of D on T and B beams, zero engaging time and no effect on D by T and B. This results in additional delta generators F_{DT} and F_{TB}, representing the impulsive forces during the interaction, that only act when distances d_T and d_B are equal to zero with amplitude related to the relative velocity $\dot{y}_{DT}$ and $\dot{y}_{DB}$ of the D beam with respect to T and B beams. Qualitatively, the voltage generated by top and bottom piezo beams after the impact changes from a free response to a resonant decaying response, as shown in Fig. 1.

3. Experimental results

To experimentally validate the proposed architecture, two commercial piezoelectric bimorphs (WAC 3X/18) have been used as top and bottom piezo beams. The beam is a parallel bimorph piezoelectric converter realized on flexible steel with dimensions of (45×19×0.58) mm^3. The typical electrical impedance is a capacitance of 270 nF and a parallel resistance of 20 kΩ, measured with an impedance analyzer HP4194A at 100 Hz. The impact-enhanced multi-beam piezoelectric converter has been excited with a Brüel & Kjær 4808 electrodynamic shaker to obtain constant velocity over frequency. The experimental setup is shown in Fig. 2a with a detailed view of the converter, while the piezo beam adopted is shown in Fig. 2b.

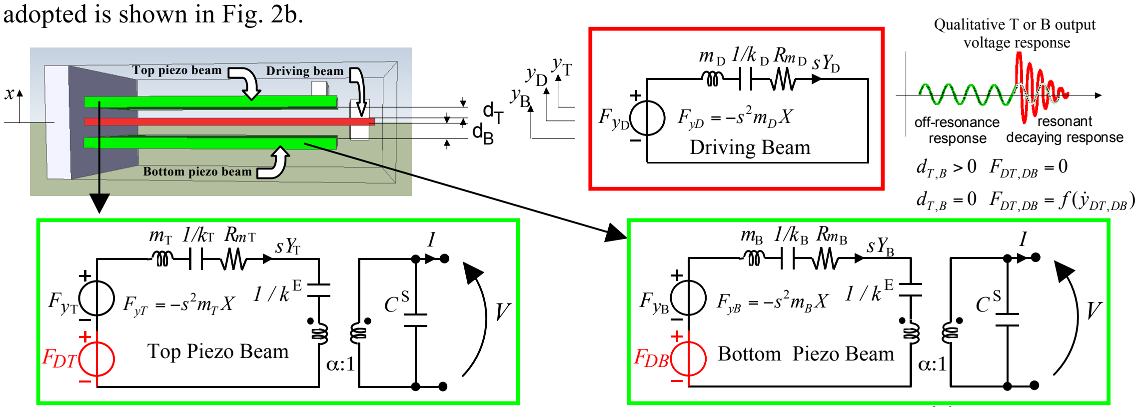

Fig. 1. Schematic diagram of the impact-enhanced multi-beam piezoelectric converter and equivalent electro-mechanical circuits which model the behaviour of the top and bottom piezo beams and the central driving beam.

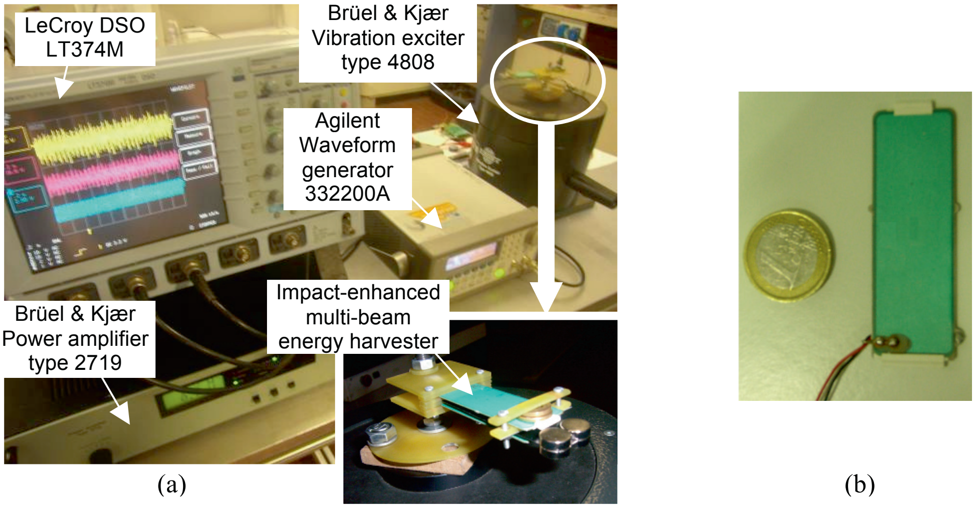

Fig. 2. (a) Experimental setup with a detailed view of the converter. (b) Piezoelectric bimorph used for the top e and bottom beams.

The shaker has been driven by a sinusoidal excitation signal and the open-circuit output voltages from the piezo beams have been measured with a LeCroy LT374 digital oscilloscope. Fig. 3a shows the frequency response of the rms output voltage for the two piezo beams without the interposed driving beam, i.e. in the noninteracting condition. The resonance peaks of the top and bottom beams are at 40 Hz and 65 Hz, respectively. It can be observed that the frequency responses are slightly bent towards the left, due to the structural nonlinearities. The quadratic sum of the rms output voltages has been reported on the same plot, showing that the converter gives best conversion effectiveness when operated in correspondence of either resonant frequencies. Fig. 3b shows the frequency responses of the rms output voltage for the two piezo beams when the driving beam is introduced, i.e. in the interacting condition. As expected, a peak for both the top and bottom piezo beams appears at around 20 Hz, corresponding to the resonant frequency of the driving beam. At parity of mechanical excitation, the quadratic sum of the rms output voltages in the interacting condition is larger over a wider bandwidth with respect to the noninteracting condition.

To validate the realized system under different working conditions, the converter has been excited by a 40-Hz low-pass filtered white noise. In Fig. 4a, the magenta, red, blue and cyan traces represent the excitation signal fed to the shaker power amplifier, the acceleration along the vertical axis of the

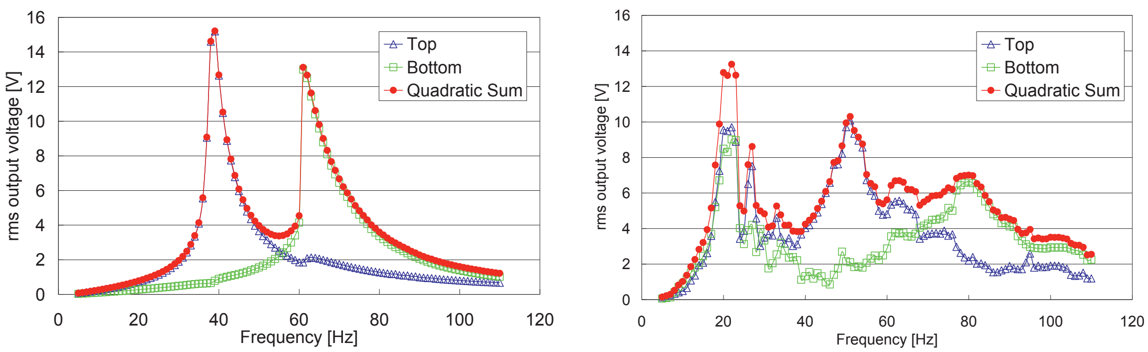

Fig. 3. Measured rms output voltages of top and bottom piezo beams for noninteracting (a) and interacting conditions (b) obtained with different excitation frequencies at constant velocity, with a_{peak} = 1 g @ 50Hz.

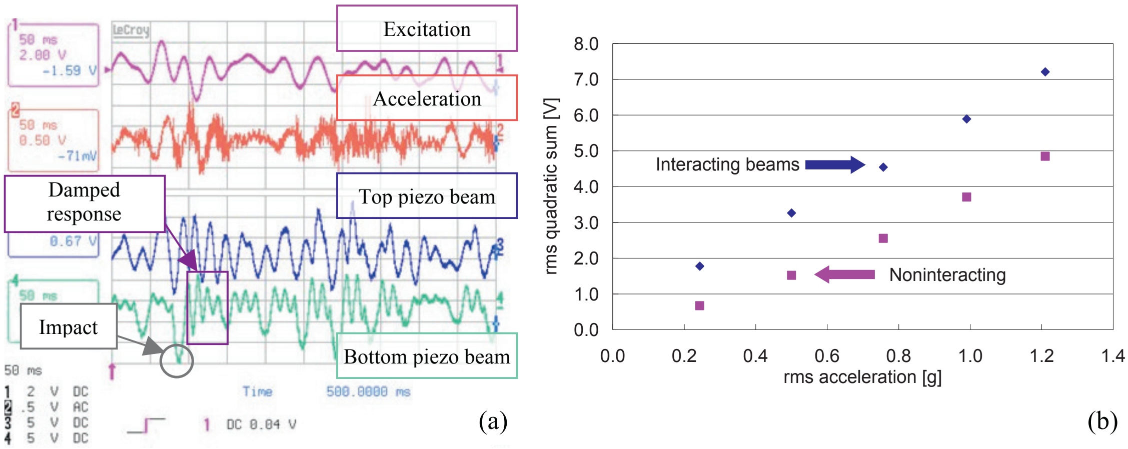

Fig. 4. (a) Typical waveforms of excitation, acceleration and output voltages of top and bottom piezo beams for 40-Hz low-pass filtered white noise excitation. (b) rms quadratic sum of output voltages of piezo beams for interacting and noninteracting conditions obtained at different acceleration levels.

converter measured by an ADXL335 accelerometer, and the output voltages of the top and bottom piezo beams, respectively. The impact between the piezo beams and the driving beam and the subsequent resonant damped response can be clearly identified on the output voltages of the piezo beams. Fig. 4b shows the quadratic sum of the rms output voltages obtained varying the the rms amplitude of the applied acceleration, for both the interacting and the noninteracting conditions. As expected, the quadratic sum for the interacting condition is always larger than for the noninteracting condition, showing the potential benefit of the impact-enhanced configuration over a large range of acceleration levels.

Acknowledgements

The work was partially carried out under the project PRIN2009-2009KFLWJA co-funded by the Italian MIUR.

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