Energy harvesting in a beam system with impacts: experimental studies

Andrzej Rysak, Michael Müller, Marek Borowiec, Jarosław Zubrzycki, Grzegorz Litak

Abstract: We examine energy harvesting in an aluminum beam with a piezoceramic patch subjected to kinematic harmonic excitation and impacts. Due to a mechanical stopper applied and consequently hardening in the spring characteristic of the beam resonator we observed a broader frequency range for the fairly large power output. Due to nonlinearities, the system appeared to be sensitive to initial conditions showing multiple solutions. The occurrence of resonant solution associated with impacts increased efficiency of the energy harvesting process.

1. Introduction

The existence of non-linearities in mechanical systems usually shows complex dynamical responses by a non-trivial dependence of amplitude and frequency, vibration localization, and also by occurrence of multiple solution. This creates unrivalled opportunity to improve the effectiveness of energy harvesting systems in capturing the kinetic energy, through so called broadband frequency effect [1-7]. Corresponding devices of energy harvesting contain mechanical resonators and additional energy transducers for transforming ambient mechanical energy into the electric form.

Such work was continued by Blystad and Halvorsen [8]. The authors of papers [9, 10, 11] studied extensively micro-electromechanical systems and proposed the electrostatic devices for energy harvesting. Additionally, Gu and Livermore [9] presented experimental results of models of energy harvesting devices in which a low frequency resonator impacts a high frequency harvesting resonator. Such experiments demonstrate that the efficiency of the electrical power transfers can significantly be improved.

The present paper continues studies on the non-linear impacting piezoelectric harvesters with stoppers, drawing the approach of broadening the energy harvesting efficiency characteristic demonstrated by authors of [9] and Soliman et al. [12, 13]. In the analyzed real experimental model, the influence of an applied mechanical stopper on the efficiency of the epiezoelectric layers in the moving structure is investigated. Note that impacts of the cantilever into the stopper not only limits vertical displacements but does also change the spring characteristics of the vibrating beam which increases the resonant resonant frequency.

2. Experimental model

The measurements have been performed on a vibration generator TIRAvib TV 50101, which operated in sine mode under controlled conditions. The schematic setup is presented in Fig. **??**a. The beam with attached piezoelectric layers was excited in vertical direction in the vicinity of main resonance. The piezoelectric patch consisted of ten piezoelectric fibers utilizing d_{31}-effect. The fibers were bounded with Elecolit isotropic conductive adhesive and insulated by globe top (epoxy resin).

During the beam vibration, the electric power generated by the piezoelectric loaded the corresponding resistors. The electrical output was measured by means of data acquisition set (DAQ) (see Fig. **??**) as:

$$U_{DAQ} = U_{out}\frac{R_1}{R}, \tag{1}$$

where the ratio R_1/R is the voltage divider presented in Fig. **??**, applied to avoid exceeding the measurement voltage range. In the experiments we used piezoceramic fiber patch.

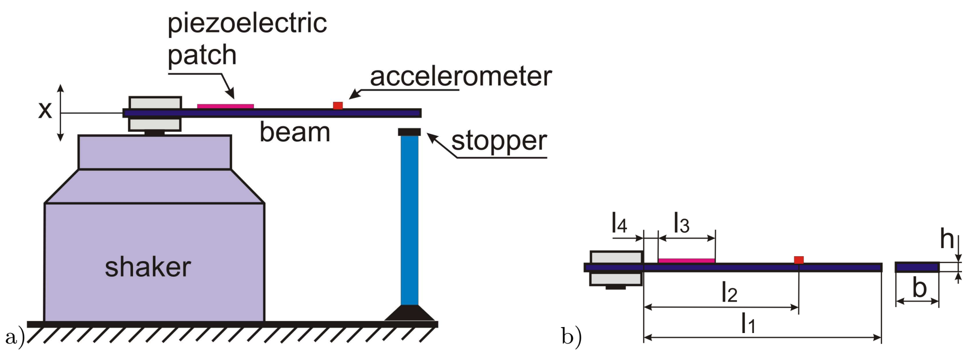

Figure 1. Experimental stand (a), Note the location of the piezoelectric patch, and accelerometer (sensor). Characteristic dimensions of the excited aluminum beam (b). To minimize the risk of fracture of the piezoceramic element we placed the thin layer of rubber on the stopper.

3. Analysis of experimental results

The measurements have been done using two different distances between the fixed stopper and vibrating beam (Fig. 1). The results for two sets are shown in Figs. **??**a and b, by

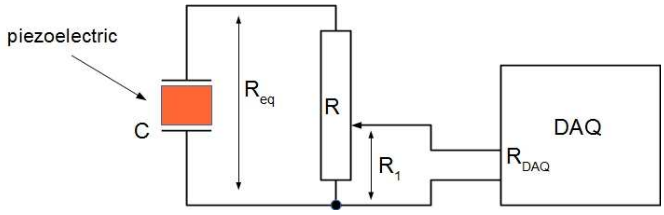

Figure 2. Electrical circuit set with the electro-motive force on the piezoceramic element; the circuit of the voltage divider was used in order to adjust the measured voltage to the range available for the DAQ card.

Table 1. Parameters of the mechanical resonator and electrical circuit.

Symbol and value	Description
$b = 20$ mm	beam width
$h = 1.5$ mm	beam thickness
$l_1 = 163$ mm	beam length
$l_2 = 98$ mm	position of the accelerometer
$l_3 = 12$ mm	the length of the piezoelectric layer
$l_4 = 163$ mm	position of the piezoelectric layer
$R_{DAQ} = 127$ kΩ	internal impedance of DAQ
$R_{eq} = 30,5$k Ω	equivalent load for the attached circuit
$E = 69$ GPa	Young modulus of the beam
$\rho = 2.7$ g/cm^3	density the beam material
$A = 2g$	acceleration amplitude of excitation
$C = 4.9$ nF	capacity of the piezoceramic layler
11.5 mm $\times$ 0.24 mm $\times$ 0.26 mm	dimensions of the piezoceramic fibers

means of resonance curves of gravitation force captured by the accelerometer mounted on the beam. Figure **??**a presents behaviour in case of stopper gap (measured for a motionless beam) beeing 6.5mm, and in Fig. **??**b gap beeing 11mm.

It it easy to notice the difference for increasing gap, when stopper less engaged. Moreover, vibrating the beam with impacts leads to increasing the energy harvesting efficiency through the resonant solution appearing for higher frequencies. Such behaviour manifests in hardening the beam stiffness characteristic and next broadening the reached level of the measured amplitude. The beam was subjected to kinematic periodic excitation with increasing and decreasing frequency sweeps (in Figs. **??**a, b, blue and red lines respectively). On the right hand side of the resonance center we observe at least two solutions indicating resonant

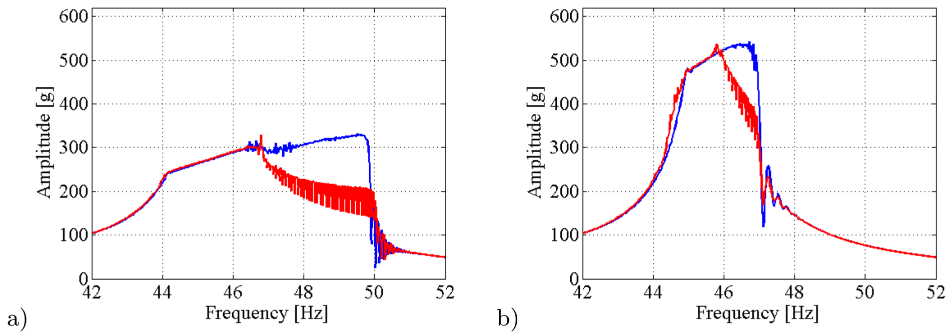

Figure 3. Amplitude of inertial acceleration output versus frequency at different gap sizes between beam and stopper: 6.5mm (a) and 11mm (b). The blue and red lines correspond to up and down frequency sweep, respectively. Note that we limited the discussion to the first mode shape of beam vibration.

(impacting) and non-resonant solutions due to the stopper induced hardening of the effective beam stiffness. Interestingly two solutions (see blue and red lines) are also observed on the left hand side of the resonance center. This looks like stiffness softening originating in the contact between the beam and stopper. Note that this contact was realized through a thin layer of rubber. The broadening in the non-resonant solution branch is presumably caused by the air circulations between macroscopic beam and stopper. Note that it decreases with the increasing distance between the beam and stopper.

Finally, Fig. **??** shows the evolution of the voltage time series along the resonance curve for the gap between the beam and stopper of 11mm (Fig. 3b). The characteristic impact influences are noticeable in Figs. 4b and c. On the other hand Figs. 4d-f correspond to non-resonant solutions.

4. Conclusions

We studied the effect of stopper on vibrational energy scavenging. Decreasing the distance between stopper and mechanical resonator influenced the process of energy harvesting significantly leading to increasing the frequency broadband effect. The evolution of the acceleration and voltage outputs measured along the amplitude-frequency diagram confirms the increase of the vibration amplitude, and consequently, the improvement of the power output in the frequency broad band form. In that region of frequency we noticed multiple solutions by doing up and down frequency sweeps.

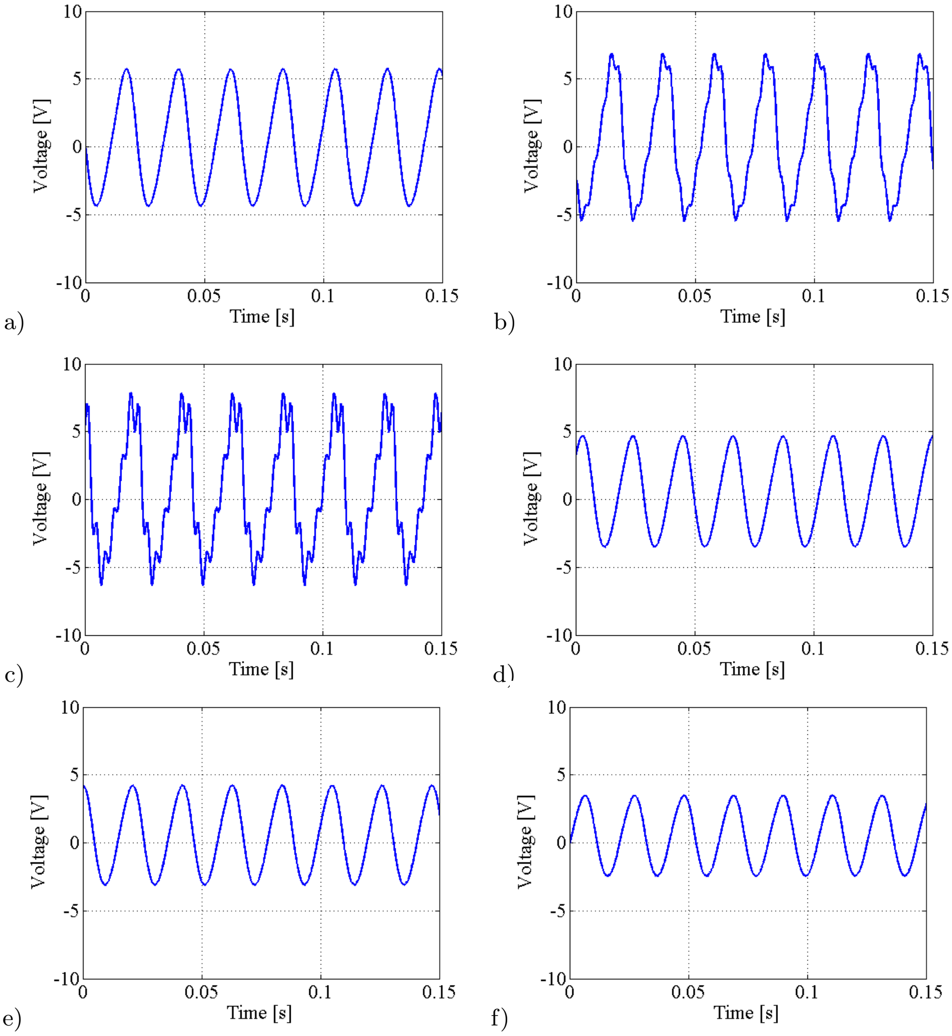

Figure 4. Time series of voltage output measured at the gap size 11mm (case presented in Fig. **??** b). The excitation frequencies for consecutive time series were: (a) $f_{exc} = 44.70$Hz, (b) $f_{exc} = 45.40$Hz, (c) $f_{exc} = 45.86$Hz, (d) $f_{exc} = 46.56$Hz, (e) $f_{exc} = 46.72$Hz, (f) $f_{exc} = 47.06$Hz respectively. The voltage variance (in V^2 units) proportional to the power output for the consecutive cases are following: 12.32 (a), 16.5 (b), 18.33 (c), 8.2 (d), 6.61 (e), and 4.36 (f).

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Andrzej Rysak, Ph.D.: Lublin University of Technology, Institute of Technological Systems of Information, Nadbystrzycka 36, PL-20-618, Poland, the author gave a presentation of this paper during one of the conference sessions (*a.rysak@pollub.pl*).

Michael Müller, Dypl. Eng.: Technische Universität Chemnitz, Institut für Werkzeugmaschinen und Produktionsprozesse, Reichenhainer Straße 70, 09126 Chemnitz, Germany (*michael.mueller@mb.tu-chemnitz.de*).

Marek Borowiec, Ph.D. Eng.: Lublin University of Technology, Department of Applied Mechanics, Nadbystrzycka 36, PL-20-618, Poland (*m.borowiec@pollub.pl*).

Jarosław Zubrzycki, Ph.D. Eng: Lublin University of Technology, Institute of Technological Systems of Information, Nadbystrzycka 36, PL-20-618, Poland (*a.rysak@pollub.pl*).

Grzegorz Litak, Professor: Lublin University of Technology, Department of Applied Mechanics, Nadbystrzycka 36, PL-20-618, Poland (*g.litak@pollub.pl*).