868. Experimental study of coupled dynamic and electric characteristics of piezoelectric energy harvester under variable resistive load

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Abstract. The paper presents experimental study of dynamic and electric characteristics of cantilever-type bimorph piezoelectric energy harvester at the presence of varying resistive loads spanning from short circuit to open circuit conditions. Frequency response measurements of tip displacement and voltage output were performed in a setup with a differential laser Doppler vibrometer. Reported results include resonant frequency, tip displacement, quality factor as well as generated voltage, current and power. It is demonstrated that the magnitude of connected electrical load significantly influences power generated by the harvester as well as other characteristics. The trends in experimentally obtained data are analyzed and reasons behind them are discussed. Conducted experimental study allowed to characterize coupled mechanical and electrical performance of the standard piezoelectric energy harvester with well-defined geometric and material properties under variable electrical loading conditions. Measurement data will be used for verification and updating of the developed finite element model.

Keywords: piezoelectric energy harvesting, load resistance, dynamics, resonant frequency shift, electromechanical coupling, nonlinear softening response, laser Doppler vibrometer.

1. Introduction

Nowadays one may observe a significantly increased interest in the development of wireless sensors and their networks (WSN) due to their adaptability to the wide range of applications (machine condition, health monitoring, tracking security, etc.), ease of deployment and placement in hardly accessible locations. This, in turn, makes a part of research community reviewed in [1] to concentrate on development of the power supply for the WSN nodes, as conventional batteries do not satisfy the requirements of size, long-term continuous power supply, environmental safety and costs. The main aim of the research community is to develop a self-powered WSN node, which would eliminate the most costly issue of battery replacement and/or sudden failure of the node due power run-out.

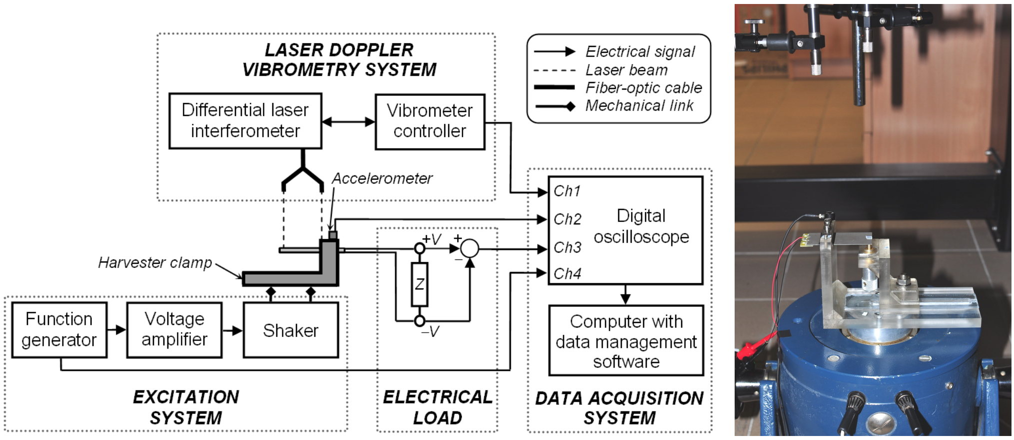
Amongst other possible WSN energy sources (photonic, thermal), harvesting energy from mechanical vibrations employing piezoelectric effect is chosen for this research, as it possesses features of high energy density, good dynamic response and self-contained power generation (i.e. no external energy source is needed for device maintenance). The main issue associated with vibration energy harvesters is their low efficiency [2], as most of the devices produce maximum power only when their resonant frequency matches the ambient vibration frequency and the power output drops notably when these frequencies pass each other, resulting in practical application limits of these devices. To overcome the aforementioned issue, various solutions are suggested [3] including widening the operational bandwidth of devices by increasing their size, shape, and/or configuration; tuning devices to match ambient frequencies;

or joining devices to relatively sophisticated electronic circuits that must transform harvested energy into acceptable electrical energy form. These circuits might consist of capacitors to store energy, rectifiers to convert current from ac to dc, or inductors to increase voltage output of the harvester. As mentioned in [4], usually components of electric circuit are considered to have no influence on the output parameters of the harvester, although in practice, and as demonstrated by the experimental presented in this paper, they are actually impacted by the circuitry elements.

This paper presents experimental study of piezoelectric energy harvester connected to the external resistive load as it is particularly important to clarify underlying physical mechanisms that govern coupled dynamic and electrical behavior of the harvester when it delivers power to an electrical load (i.e. operates under actual operation conditions). The influence of load resistance magnitude is considered for various parameters: mechanical – resonant frequency, quality factor, displacement and electrical – voltage, current, power outputs. It is demonstrated that these values are significantly dependant on the magnitude of load resistance and must be taken into account when predicting efficiency of vibration energy harvesters. Moreover, the measurements performed allow extraction of damping and electromechanical coupling coefficients that are important for numerical modeling of energy harvesters in order to optimize their performance.

2. Experimental setup

Experimental setup, schematically depicted in Fig. 1(a), consists of a piezoelectric energy harvester with connected electrical load and three main systems – excitation, measurement and data acquisition. The main part of the excitation system is an electromagnetic shaker, which is employed to excite cantilever-type energy harvester – piezoceramic bimorph bending actuator PIEZO SYSTEMS T226-A4-503Y (geometric and material properties are given in Table 1), which is fixed in the custom-built harvester clamp made of acrylic glass (Fig. 1(b)). It should be noted that the actual overhang length of the tested cantilever (Fig. 2) is l = 40 mm and is different from the original length (57.2 mm) of this commercial device. Function generator AGILENT 33220A and voltage amplifier KROHN-HITE 7500 are used to control harmonic excitation signal transmitted to the electromagnetic shaker. Single-axis miniature piezoelectric charge-mode accelerometer METRA KS-93 (with sensitivity of $k = 0.35$ mV/(m/s^2)) is attached at the top of the clamp for acceleration measurements at the base of the harvester.



(a) (b)

Fig. 1. Scheme of experimental setup and photo of the tested piezoelectric energy harvester

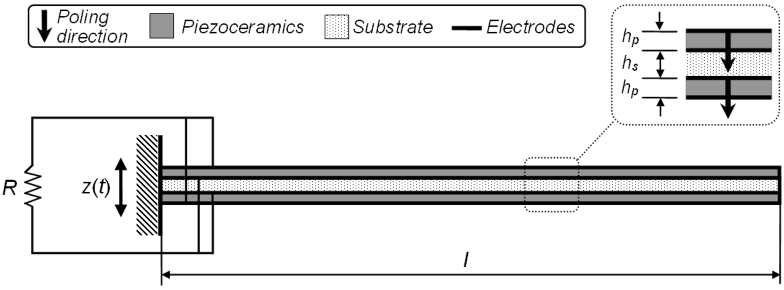


Fig. 2. Configuration of the tested piezoelectric energy harvester

Table 1. Main characteristics of piezoceramic actuator PIEZO SYSTEMS T226-A4-503Y [5]

Dimensions	
Cantilever length, l	40×10^{-3} m
Cantilever width, w	31.8×10^{-3} m
Thickness of substrate layer, h_s	0.14×10^{-3} m
Thickness of piezoelectric layer, h_p	0.27×10^{-3} m
Piezoelectric properties	
Piezoelectric strain coefficient d_{33}	390×10^{-12} m/V
Piezoelectric strain coefficient d_{31}	-190×10^{-12} m/V
Piezoelectric voltage coefficient g_{33}	24.0×10^{-3} Vm/N
Piezoelectric voltage coefficient g_{31}	-11.6×10^{-3} Vm/N
Coupling coefficient k_{33}	0.72
Coupling coefficient k_{31}	0.35
Mechanical properties	
Density	7800 kg/m^3
Elastic modulus $Y^E{}_3$	5.2×10^{10} N/m^2
Elastic modulus $Y^E{}_1$	6.6×10^{10} N/m^2

In order to measure tip displacement (or velocity) of the harvester in the transverse direction, harvester tip and clamp top have small pieces of retroreflective tape attached to enhance laser light collection back into the fiber-optic differential laser interferometer POLYTEC OFV-512, which is connected to vibrometer controller POLYTEC OFV-5000, both comprising the core of laser Doppler vibrometry system. The main advantage of this setup is that registration of relative motion between tip of the harvester and top of the clamp allows measurement of actual tip displacement. Data acquisition system consists of a 4-channel USB oscilloscope (analog-to-digital converter) PICO 3424 that collects signals from the function generator, laser vibrometer, base accelerometer and piezoelectric energy harvester through connected resistive load. Signals from the oscilloscope are forwarded to the computer with data management software (PicoLog 5®, Picoscope 6®).

Tested vibration energy harvester is a brass-reinforced bimorph piezoelectric transducer in quick-mount configuration: its elements are wired for low voltage operation and the bleed resistor mounted on the board protects the transducer and surrounding electronics from transient voltages. Fig. 2 illustrates that piezoelectric layers of the bimorph are poled in the same direction. This configuration requires that each layer of the structure would be accessed individually: two wires are connected to the outside nickel electrodes of relatively negligible thickness, while the others are connected to the center substrate layer (parallel operation mode). Once the harvester is under transverse mechanical excitation, one piezoceramic layer of the structure is stretched, while the other one is compressed and charge is developed in each layer to oppose the imposed strains.

Table 2. Conversion of actual resistance of the connected resistors into effective values taking into account magnitude of input impedance of the oscilloscope

Actual resistance of the connected resistors (Ω)	Effective load resistance acting on the harvester (Ω)
47	47
390	390
1800	1797
3900	3885
4700	4678
6200	6162
15000	14778
56000	53030
100000	90909
510000	337748
3.90×10^6	795918
Open circuit	1.00×10^6

A set of resistors of different magnitude was used in order to create varying electrical loading conditions during frequency response measurements (Table 2). Effective load resistance acting on the harvester was calculated bearing in mind that the input channel of the oscilloscope has an impedance of 1 MΩ, which acts in parallel with the load resistor placed across the piezoelectric layers. The effective load R_{eff} that is actually exerted onto the harvester is influenced by this input impedance of the oscilloscope and is defined as:

$$R_{eff} = \frac{1}{1/R_a + 1/R_{osc}}, \tag{1}$$

where R_a – actual resistance of a resistor, R_{osc} – input impedance of the oscilloscope.

Table 2 lists values of actual load resistance and the corresponding effective values. It should be noted that the maximum load resistance in this case cannot exceed 1 MΩ. Therefore the load resistance used in this experimental study ranges from 47 Ω (close to short-circuit condition) to 1 MΩ (close to open-circuit conditions).

Frequency response measurements of harvester tip displacement and voltage output were performed with the function generator providing swept harmonic excitation within a frequency range of 140-230 Hz and sweep time of 500 s. The same level of acceleration was maintained when changing load resistances in the course of frequency response measurements (however acceleration magnitude fluctuated in the vicinity of 1*g* when sweeping).

The first resonant frequency of the harvester is considered in this experimental study as it corresponds to the practical application conditions of this particular device configuration. Measurement results are discussed in the sections below.

3. Analysis of measurement results

Fig. 3 illustrates experimentally measured frequency responses of tip displacement and voltage output for varying electrical loading conditions ranging from nearly short circuit (s. c.) to open circuit (o. c.). It is observed that increase of resistance leads to higher voltage output, which correlates with reduction in tip displacement amplitude at short-circuit resonant frequency (Fig. 5). Yet at the o. c. resonant frequency tip displacement amplitude increases again and one may note that at the o. c. resonant frequency both tip displacement amplitude and voltage output are amplified as external load resistance increases. Resonant frequency curves in Fig. 3(a) corresponding to low resistance values clearly reveal that the harvester exhibits nonlinear frequency responses with curves being shifted to the left-hand side of the frequency axis.

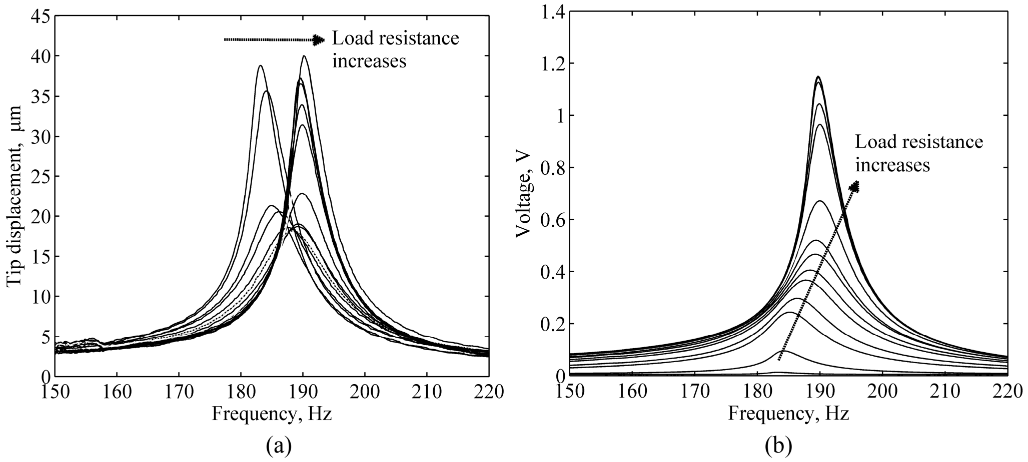


Fig. 3. Measured frequency responses of tip displacement and voltage output for different resistive loads spanning from nearly short circuit to open circuit: (a) tip displacement, (b) voltage output

The reasons for the observed softening behavior are diverse and are associated with a complex interaction of various effects including but not limited to nonlinear damping (due to air drag and material losses), viscoelectroelasticity, nonlinear electromechanical coupling, dielectric effects, etc. Structural displacements were relatively small in these experiments (Fig. 3(a)) therefore it is hardly possible that geometric nonlinearities were induced in this case. These experimental results also demonstrate that the observed nonlinear softening response diminishes with larger resistive loads (corresponding to larger electric fields generated inside piezoceramic layers). This, in turn, suggests that electromechanical coupling, which becomes more prominent with increased electrical loading, counteracts those effects that cause nonlinear softening behavior at lower load resistances (i.e. at weaker electric fields).

Measured tip displacement and voltage output frequency responses in Fig. 3 were subsequently used to derive graphs demonstrating variation of resonant frequency and quality factor (Fig. 4), power output and tip displacement (Fig. 5) as well as voltage and current (Fig. 6) as functions of external load resistance.

The main concern in energy harvesting is the magnitude of generated power, which is directly related to the dynamic response of the piezoelectric transducer. Therefore it is important to examine variation of key mechanical characteristics such as resonant frequency, tip displacement and quality factor during process of power generation.

The resistive load of 47 Ω is very close to the short-circuit conditions for this particular experimental setup, therefore the resonant frequency of 183.2 Hz derived from the measured data may be considered as the fundamental short-circuit resonant frequency f^{sc} of the tested piezoelectric energy harvester. Fundamental open-circuit resonant f^{oc} is measured with the resistive load of 1 MΩ and is equal to 189.9 Hz. The respective 3.7 % shift in resonant frequency is obvious in Fig. 4. It should be mentioned that the magnitude of the observed frequency shift is directly proportional to the square of the electromechanical coupling coefficient calculated in Section 4. This shift in resonant frequencies is attributed to varying electrical boundary conditions: increase of load resistance from s. c. to o. c. condition leads to a change in harvester stiffness since elastic modulus of piezoelectric material increases.

Fig. 4 reveals that quality factor, with the initial value of 33.6 at s. c. conditions reaches its minimum value of 18.4 at the electrical load of ca. 4670 Ω and then gradually increases up to

45.8 at the o. c. conditions. Quality factor is explained as a measure of dissipated mechanical energy of vibrating harvester.

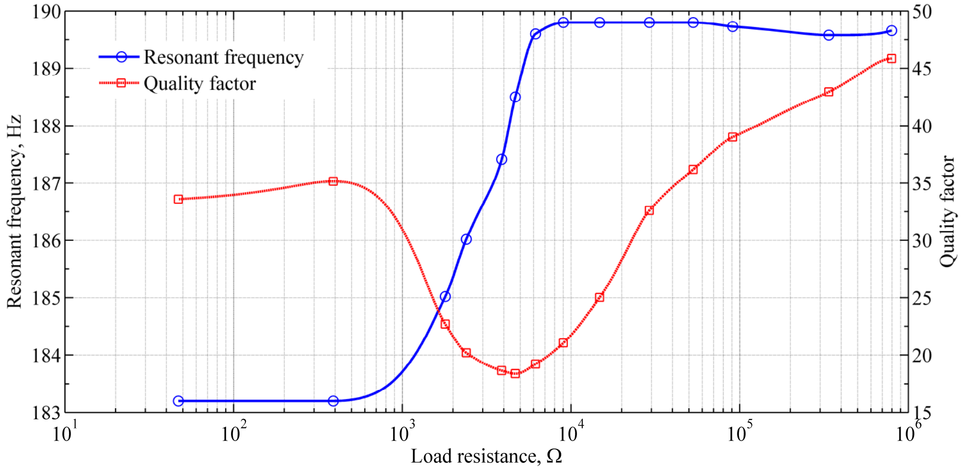


Fig. 4. Resonant frequency and quality factor of the harvester as a function of load resistance

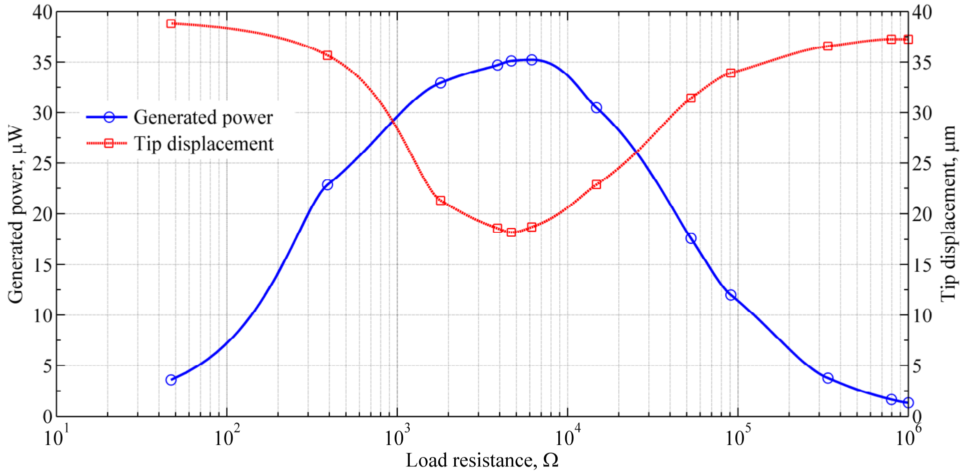


Fig. 5. Variation of power output and tip displacement of the harvester as a function of load resistance

Dissipated mechanical energy may be attributed to characteristics of intrinsic constituent materials and harvester design, thus it is difficult to separate individual damping factors. Yet the efforts are directed to distinguish electrical damping and mechanical damping in the harvester. Electrical damping is associated with the conversion of kinetic energy into electricity and the amount of electrical damping is determined as power consumed in a resistive load, i.e. electrically induced damping is considered as the power consumed in the electrical domain, which is equal to the power removed from the mechanical system. Mechanical damping may be attributed to air and structural damping as well as material losses and thermoelastic effects.

Fig. 5 reveals that vibration amplitude at the fundamental s. c. resonant frequency is attenuated from the value of 38.8 μm as the resistance is increased. It reaches its minimum point (18.2 μm) at the resistance of ca. 4670 Ω and then gradually increases again up to 37.2 μm at o. c. conditions. Attenuated structural response may be explained by the electrically damped motion as in the case of quality factor reduction. A vibrating harvester at s. c. conditions is under mechanical damping only since there is no electrical power consumed. As resistance is increased, mechanical energy is partially transferred to electrical energy. Harvested electrical energy is considered as electrical damping that sums up with the mechanical damping, which finally leads to suppression of cantilever displacement. It is known that electrical effect, called backward coupling, manifests in the harvester, i.e. the feedback is sent from the electrical domain to the mechanical one due to power generation, caused by converse piezoelectric effect. This phenomenon is explained by the theory of piezoelectrics, which are comprised of perovskite crystals with intrinsic dipole moment. Once these materials are strained, direction of polarization among neighboring dipoles becomes unified, producing an electric charge on the surface (direct piezoelectric effect). However, when the feedback is sent from the electrical domain and electrical energy is applied to the poled piezoelectric material, it distorts the orientation of dipole domains, and the overall polarization becomes more random, resulting in mechanical strain (converse piezoelectric effect). Based on this it may be stated that the form of piezoelectric coupling is substantially different from conventional damping mechanisms.

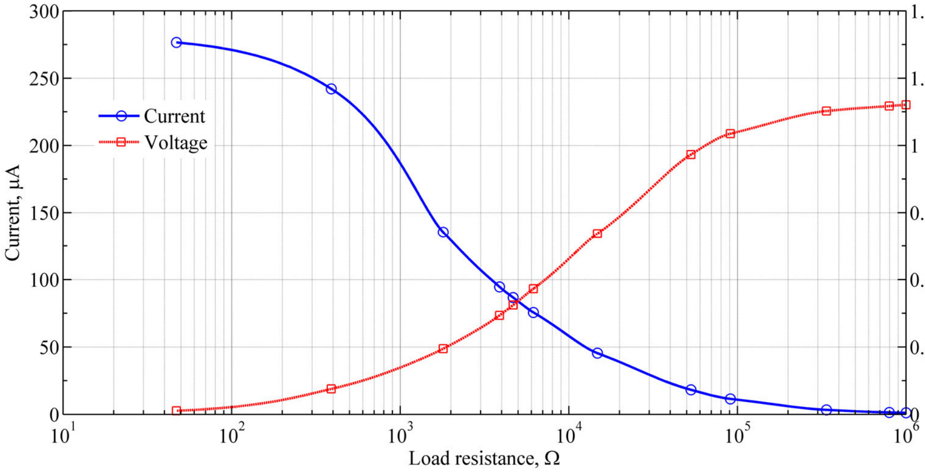


Fig. 6. Voltage and current output of the harvester as a function of load resistance

Electrical outputs of the harvester are also analyzed in order to examine variations of generated electrical current, voltage and power, which subsequently must be considered in optimization process aiming for maximum power output when the harvester is connected to complicated energy harvesting circuits.

Fig. 5 provides a graph of harvested power as a function of load resistances. It is observed that for excitations at the fundamental s. c. and o. c. resonant frequencies, the maximum power output of 36 μW is delivered at the electrical load of ca. 6160 Ω, which may be considered as an optimal value for the considered bimorph cantilever. The resistive load of 47 Ω yields power output of 4 μW at s. c. conditions, whereas the resistive load of 1 MΩ yields 1 μW at the s. c. resonant frequency.

Results presented in Fig. 5 reveal that electrical load corresponding to maximum power output (6160 Ω) does not coincide with the load of minimum vibration amplitude (4670 Ω). This phenomenon is attributed to the nature of electromechanical coupling: vibration amplitude of the piezoelectric transducer will not necessarily acquire its lowest value for the magnitude of electrical load corresponding to the maximum power generation. Thus, it is important to note here that the harvested power is not considered to be directly influenced by the displacement amplitude, but is determined by voltage and external load resistance.

Variations of the electric current and voltage generated by the tested harvester for various resistive loads are plotted in Fig. 6. Voltage amplitude increases monotonically with increasing load resistance from 0 V to 1.15 V, while the current decreases monotonically from 275 μA to 0 μA. The electric current and voltage amplitude curves intersect close to the load resistance of ca. 4650 Ω. It should also be noted that the asymptotic character of voltage and current output variation is observed when the curves approach extreme conditions of load resistance.

4. Derivation of damping and coupling characteristics

Measured frequency responses may be used to extract various damping parameters that will be subsequently employed for the validation of the multiphysics finite element model of the piezoelectric energy harvester. Mechanical damping ratio ζ and Rayleigh damping parameter β are derived from the measured resonant frequency curves.

Firstly, quality factor Q is calculated as:

$$Q = f_r / \Delta f\ , \tag{2}$$

where $\Delta f = f_2 - f_1$ is the bandwidth, which represents the distance between two points on frequency axis where the amplitude is equal to $1/\sqrt{2}$ of the maximum amplitude value.

Quality factor Q is used to derive damping ratio ζ:

$$\zeta = 1/2Q\ . \tag{3}$$

Finally, Rayleigh damping parameter β is calculated as:

$$\beta = \frac{1}{2\pi f_r Q}\ . \tag{4}$$

Following [6], the coupling coefficient k of the system may be determined from the resonant frequencies under open-circuit and short-circuit conditions:

$$k^2 = \frac{(f^{oc})^2 - (f^{sc})^2}{(f^{oc})^2}\ . \tag{5}$$

The coupling coefficient k for the studied harvester was determined to be 0.26. Material data listed in Table 1 indicates that coupling coefficient k_{33} of the piezoelectric material PZT-5A of the bimorph is equal to 0.72, while the one measured for the tested harvester is much lower. This reduction is explained by incorporation of the substrate material in the piezoelectric bimorph configuration as it influences the electromechanical coupling of the complete structure. Moreover, the backward coupling discussed in the sections before is also thought to be mainly influenced by thickness and stiffness of the substrate material.

Conclusions

The paper described experimental setup and measurement results characterizing coupled dynamic and electric performance of cantilever-type piezoelectric energy harvester in bimorph configuration when it is connected to varying resistances, thereby providing electrical loading conditions that range from nearly short circuit to nearly open circuit. The examined parameters include resonant frequency, tip displacement, quality factor, generated current, voltage and power. It was established that measured characteristics are significantly dependant on the magnitude of external load resistance. Major observations of this study may be summarized as follows:

a) Measured tip displacement frequency responses reveal nonlinear softening behavior of the harvester for lower load resistances. The magnitude of the nonlinear response attenuates for larger resistive loads.
b) Measured voltage frequency responses indicate monotonic growth trends with increasing load resistance, ultimately converging to a single o. c. voltage.
c) Resonant frequency of the harvester increases in a nearly monotonic character in a range of ca. 1-10 kΩ, followed by flattening of the curve towards o. c. condition. The resulting frequency shift is equal to 3.7 % when passing from short to open circuit conditions.
d) Non-monotonic variation trend of the harvester structural response manifests with increasing load resistance: passing from s. c. conditions it drops by 53.1 % at the load resistance of 4670 Ω and increases again almost to the initial value at o. c. condition. These results are consistent with measurements of damping: magnitude of load resistance of minimum tip displacement is equal to the resistance that corresponds to the lowest quality factor (4670 Ω).
e) Maximum harvested power constitutes 36 μW and is observed at 6160 Ω, which is considered to be the optimal load resistance for this particular harvester configuration. Power generated at this resistive load is 9 times higher with respect to s. c. case.
f) Mechanical coupling coefficient of the harvester calculated from measurement results is 2.8 times smaller than the one of the piezoelectric material of the commercial bimorph. This reduction is associated with introduction of substrate material and manifestation of effect of backward coupling.

These experimental results will be subsequently used for verification and correction of the developed finite element model of the piezoelectric transducer in order to enable accurate prediction of dynamic and electrical characteristics for different structural designs including vibro-impact configurations aimed at increasing operational bandwidth of the harvester under varying-frequency excitation conditions that are prevalent in the environment.

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