

ANALYZING THE OUTPUT CHARACTERISTICS OF A DOUBLE-CONSOLE PEG BASED ON NUMERICAL SIMULATION

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Abstract. A finite-element simulation of a two-cantilever piezoelectric generator (PEG) is considered. The generator had a bimorph arrangement of piezoelements. Finite element modeling was performed in ANSYS software. The PEG considered is part of an energy generation system, designed to convert mechanical energy from the environment into an electrical energy, with subsequent accumulation. The results of the modal analysis of the first 10 modes of oscillations are present. Harmonic analysis is performed, when damping is taken into account. With the given scheme of electrical connection of PEG elements and various active loads, the results of the output voltage and power for the first four modes are obtained.

Keywords: double-cantilever piezoelectric generator (PEG); finite-element simulation; ANSYS; modal analysis; harmonic analysis; output characteristics.

1. Introduction

In recent years, research has been actively performed on the development of piezoelectric converters of mechanical energy into electrical energy. This type of transducers was called piezoelectric generators (PEGs). The basic information on PEGs, as well as the problems arising at the development stages of energy harvesting devices, were given in review papers [1 – 4], as well as in the fundamental monograph [5].

Depending on the field of application, PEGs of various types have been created, in which a direct piezoelectric effect is used when excitation in the sensitive element is mainly longitudinal (d_{33}) [6 – 9] or bending (d_{31}) [10 – 14] oscillations.

The problem of estimating the energy efficiency of a cantilever type PEG was previously considered in [3, 5, 11, 12, 14]. It has been shown that the output power of PEG depends not only on the electrical characteristics of the piezoceramic materials (PKMs) of PEG sensitive elements, but also on the measurement technique of their output characteristics as well as on the parameters of the electrical circuit [20].

One of the ways to increase the energy efficiency of PEG is to expand the bandwidth of operating frequencies. Usually, a Cantilever type PEG works only on the first mode of oscillation, because the output electrical characteristics of the subsequent modes are small and not of interest for energy harvesting. This, in turn, indicates a narrow band of operating frequencies of PEG cantilever type. In addition, in real working environments, there are often oscillations of arbitrary shape, which are the result of applying oscillations with different frequencies, rather than purely harmonic with one frequency, which are usually used in experiments. Nevertheless, attempts are made to expand the band of PGE operating frequencies of the cantilever type by modifying the classical design and introducing various

engineering solutions into it. This, in turn, not only affects the operating frequencies, but also affects the output electrical characteristics of the generator.

In [15], the authors proposed a so-called embedded cantilever in order to widen the bandwidth of the cantilever type PEG with attached mass. This device had two degrees of freedom, as well as two operating modes of oscillations. The constructive solution consists in using a cantilever, which includes one main cantilever beam and an internal built-in cantilever beam, each of which has piezoelectric transducers. The power, received by the authors, was 1.5 mW for the main beam and 0.8 mW for the internal (enclosed) beam.

In [16], a PEG with multi-cantilever piezoceramic elements was developed, operating at low frequencies. The device consisted of six piezoelectric consoles of different lengths with different masses at their free ends. Researchers have shown experimentally that it can operate at several low resonance frequencies. The maximum power, obtained by this generator was 2.5 μ W, and can be increased by increasing the number of consoles.

In [17], the researchers developed a cruciform piezoelectric generator and investigated its output characteristics. The generator consisted of a thin centrally symmetric cross-shaped elastic substrate and four rectangular piezoceramic elements that were attached to the upper surface of the four blades of the substrate. The exciting force from the oscillation source was applied to the center of the substrate. For the substrate, four types of materials were used: aluminum, copper, brass and stainless steel SUS304. Of all materials, PEG on a SUS304 steel substrate showed the highest values of output voltage (4.42 V) and current (7.83 μ A).

There are several ways of modeling PEG: mathematical model with lumped parameters [8, 14], mathematical model with distributed parameters [7, 9, 14] and finite element model [6,10,18,19]. In this paper, the finite element method will be used, since it is the most convenient for modeling and analysis of structural solutions.

The above brief analysis of known works has shown that the problem of creating an energy efficient construction of cantilever PEG in a whole is not yet solved, although it is quite relevant.

2. Formulation of problem

We analyze the output characteristics of a two-cantilever piezoelectric energy generator having a bimorph structure symmetrically, arranged with respect to the y-axis, to perform a modal and harmonic analysis.

3. Finite element modelling of PEG

Continuous models of composite elastic, electroelastic and electroacoustic medium.

Piezoelectric energy harvesting device is a composite elastic and electroelastic solid, which makes small relative oscillations in the moving coordinate system. Rectilinear vertical motion of the system is given by the law $y(t)$ or, in case of the external force excitation, by $F(t)$ or pressure $\sigma(t)$, according to which the device's base is moving. In these conditions, the initial boundary value problem of linear electrodynamics theory is quite adequate mathematical model, which describes the functioning of such device [21].

In the present paper, we use the linear theory of elasticity and electrodynamics, based on the dissipation of energy, which is realized in the ANSYS software [22], as well as the equations of motion of liquids and gases in the acoustic approximation [23].

For piezoelectric medium, we have:

$$\rho \ddot{u}_i + \alpha \rho \dot{u}_i - \sigma_{ij,j} = f_i; D_{i,i} = 0, \quad (1)$$

$$\sigma_{ij} = c_{ijkl} (\varepsilon_{kl} + \beta \dot{\varepsilon}_{kl}) - e_{ijk} E_k; D_i + \zeta_d \dot{D}_i = e_{ikl} (\varepsilon_{kl} + \zeta_d \dot{\varepsilon}_{kl}) + \vartheta_{ik} E_k, \quad (2)$$

$$\varepsilon_{kl} = (u_{k,l} + u_{l,k}) / 2; E_k = -\varphi_{,k}, \quad (3)$$

where ρ is the density of the material; u_i are the components of the vector-function of displacement; σ_{ij} are the components of the stress tensor; f_i are the components of the vector of the density of mass forces; D_i are the components of the electric induction; c_{ijkl} are the components of the fourth rank tensor of the elastic moduli; e_{ijkl} are the components of the third rank tensor of piezoelectric coefficients; ε_{ij} are the components of strain tensor; E_i are the components of the electric field; φ is the electric potential; ε_{ij} are the components of the second rank tensor of the dielectric constants; α, β, ζ_d are non-negative damping coefficients (in ANSYS $\zeta_d = 0$).

Modeling. The full-scale finite-element PEG model has a two-cantilever structure in the form of a bimorph, symmetrically arranged with respect to the y -axis (Fig. 1a). Thin symmetrical piezoelements are polarized in thickness. The gluing of piezoelements to the substrate is not taken into account. The geometric dimensions of the PEG are shown in Fig. 1a: the substrate has dimensions $l \times b \times h = 120 \times 9.8 \times 1 \text{ mm}^3$, the piezoelectric elements consist of two identical piezoelectric plates, polarized in thickness with dimensions $l_p \times b_p \times h_p = 54 \times 6 \times 0.5 \text{ mm}^3$. The center of the attached mass is fixed at a distance l_m from the clamp of the cantilever. The range of sizes l_m can vary from 65 to 110 mm. In the calculation it was assumed $l_m = 65 \text{ mm}$. The electrical circuit of the PEG connection with the active load is shown in Fig. 1b. The value of the attached mass can vary from 3 to 25 grams. In the calculation, $M = 3 \text{ g}$ was adopted. The material of piezoceramic elements is PCR-7M. The main properties of the PEG structure are also given in Tables 1 – 3 [11]. The generator base was $l_x \times h_z \times b_y = 10 \times 20 \times 20 \text{ mm}^3$.

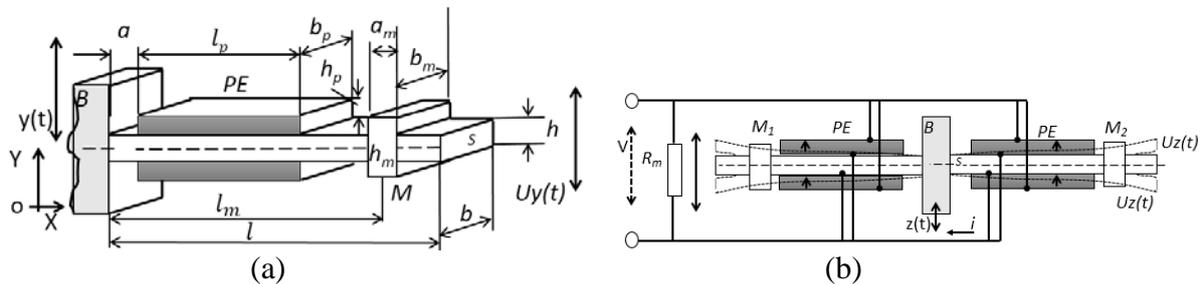


Fig. 1. Electric scheme of compound PEG under active load.

Table 1. Characteristics of the dimensions of PEG elements.

Element	Parameter				
Piezoelement	$l_p, \text{ mm}$	$b_p, \text{ mm}$	$h_p, \text{ mm}$		
	54	6	0.5		
Substrate	$l, \text{ mm}$	$b, \text{ mm}$	$h, \text{ mm}$	$a, \text{ mm}$	
	120	9.8	1	2	
Proof mass	$M, \text{ gr}$	$a_m, \text{ mm}$	$h_m, \text{ mm}$	$b_m, \text{ mm}$	$l_m, \text{ mm}$
	3 – 25	7	6	29.8	65 – 110

Table 2. The elastic moduli C_{pq}^E (10^{10} Pa), piezoelectric coefficients e_{kl} (C/m^2) and relative permittivity $\varepsilon_{kk}^E/\varepsilon_0$ (at room temperature).

C_{11}^E	C_{12}^E	C_{13}^E	C_{33}^E	C_{44}^E	e_{31}	e_{33}	e_{15}	$\varepsilon_{11}^E/\varepsilon_0$	$\varepsilon_{33}^E/\varepsilon_0$
12.5	8.4	8.1	12.1	2.36	-9.0	28.3	17.9	1430	1350

Table 3. Mechanical properties of the structural materials.

No.	Element of PEG	Material	ρ , kg/m ³	$E \times 10^{10}$ (Pa)	ν
1a, 1b	Substrate	fiberglass	1600	0.6	0.25
2a, 2b	Proof mass	plastic	2645	0.3	0.33
3a, 3b	Piezoelements	PCR-7M	7280	–	0.33
4	Base	steel	7700	21	0.33

The model scheme of the PEG structure is shown in Fig. 2a. Positions 1a, 1b show a substrate made of fiberglass; 2a, 2b are the attached masses; 3a, 3b is the piezoelectric element; 4 is the base of the generator.

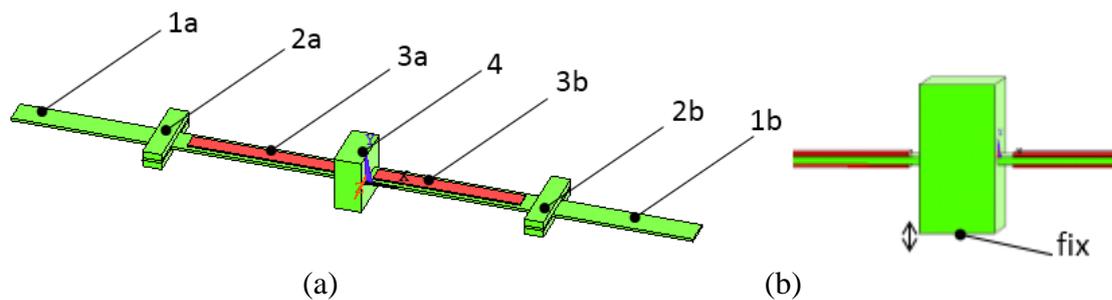


Fig 2. (a) Two-axis PEG model with the location of proof mass at $l_m = 65$ mm; (b) scheme of applying the load to the PEG base.

4. Results of calculations

With the help of the developed FE models in ANSYS software, based on the exact formulation of the problem (1) – (3), modal and harmonic analyses were performed.

Natural frequencies were calculated and their own forms of vibrations PEG. Fig. 3 shows their values and eigen forms of oscillations. The analysis of the first 10 vibration modes shows that 1 – 4, 9, 10 modes correspond to bending oscillations of the structure relative to the vertical y -axis (the vertical axis is shown in Fig. 3). For modes 1 and 2, it is shown that one of the plates is in the region making the maximum oscillation amplitudes, the second plate is in the conditional rest region. Mode 3 is antisymmetric with respect to the y -axis and mode 4 is axisymmetric about the y -axis. Modes 5 and 6 are modes of oscillations in the horizontal plane Oxz i.e. in the plane of the substrate and piezo plates of PEG. Mode 5 is axisymmetric, but mode 6 is an antisymmetric mode of oscillation. Modes 7 and 8 are the torsional modes of oscillations, respectively, of the left and right plates. All modes of oscillation are divided into pairs and each of them lies in the frequency range, which differ by no more than 0.5%.

Harmonic analysis of PEG oscillations with an active load for the first four modes of oscillations is performed. The damping coefficient was assumed equal to $\zeta = 0.031$ and was taken into account by the parameters MP, DMPR, for all 4 types of material properties in ANSYS. The active load was varied within $R = 5 \times 10^3 - 10^6 \Omega$. The analysis of the results is shown in Tables 4 and 5. The dependences of the output voltage and output power of PEG on the value of the active load are shown in Figs. 4 and 5, respectively.

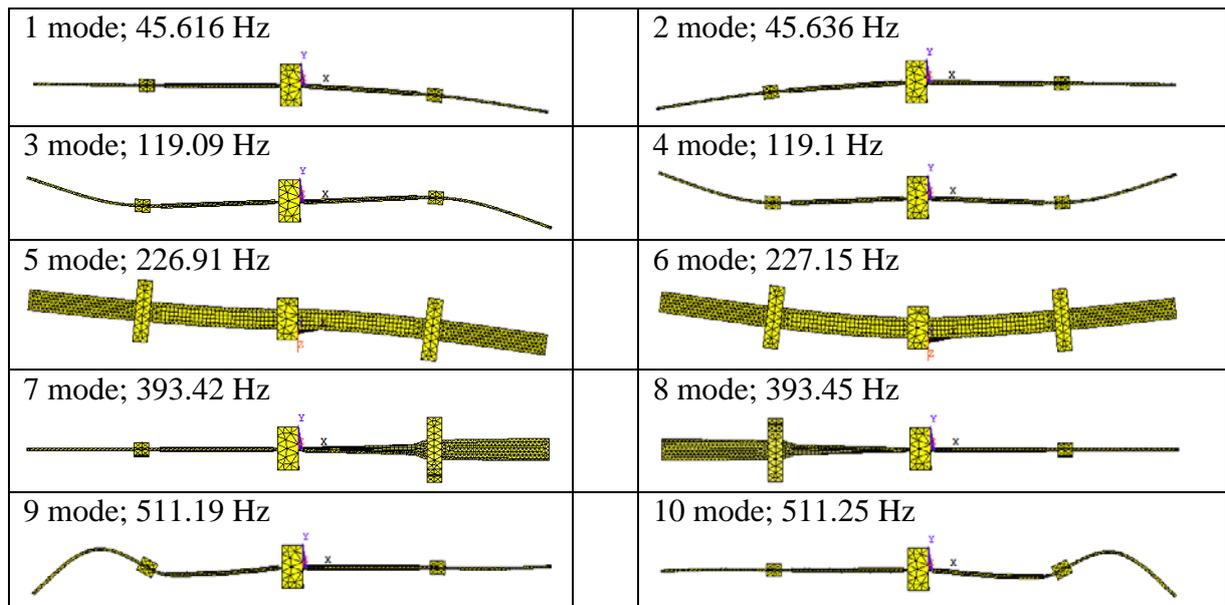


Fig 3. First ten modes of eigen forms of PEG with symmetric fixing of load oscillations.

Table 4. Output voltage of the PEG for location of proof mass $l_m = 65$ mm; results are present for first four modes of oscillation.

Mode	Active load, $R, 10^6 \Omega$						
	0.005	0.01	0.05	0.1	0.25	0.5	1
	Output voltage, U, V						
1	1.66	3.09	8.16	9.48	10.22	10.44	10.54
2	1.70	3.16	8.46	9.89	10.70	10.93	11.04
3	0.76	1.25	1.92	1.98	2.00	2.01	2.01
4	0.76	1.25	1.92	1.98	2.00	2.01	2.01

Table 5. Output power of the PEG when location of the attached mass was $l_m = 65$ mm. The results are given for the first four modes of oscillation.

Mode	Active load, $R, 10^6 \Omega$						
	0.005	0.01	0.05	0.1	0.25	0.5	1
	Output power, $10^{-6} W$						
1	278.1	481.6	669.2	451.9	210.3	109.6	55.9
2	289.2	503.0	720.2	491.7	230.3	120.3	61.3
3	57.7	78.1	37.1	19.7	8.0	4.0	2.0
4	57.8	78.1	37.1	19.7	8.0	4.0	2.0

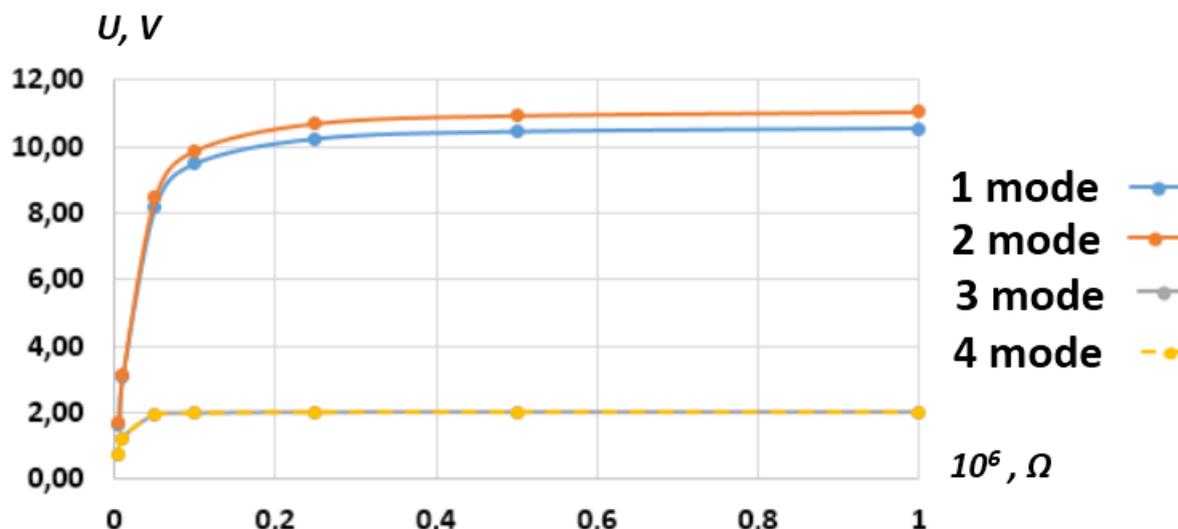


Fig 4. Dependence of output voltage on the load impedance for first four modes of oscillation.

5. Analysis of results

Analysis of the output voltage dependence on the value of active load shows that the voltage rises to a load value of $100 \text{ k}\Omega$. Its value for modes 1 and 2 is 9.48 V and 9.89 V , respectively, with $R = 100 \text{ k}\Omega$. For 3 and 4 vibration modes, it is 1.98 V at $R = 10 \Omega$. With a load of $R = 10^6 \Omega$, the voltage for 1 – 4 modes is 10.54 , 11.04 , 2.01 , and 2.01 V , respectively. Analysis of output power values, given in Table 5, shows that for this construction and fixation of PEG elements at location of proof mass $l_m = 65 \text{ mm}$, the peak values of output power for 1st and 2nd modes of oscillation are achieved with an active load of $R = 50 \text{ k}\Omega$ and are equal to $669 \mu\text{W}$ and $720 \mu\text{W}$, respectively. For 3 and 4 modes, the peak value is attained at $R = 10 \text{ k}\Omega$ and equal to approximately $78.1 \mu\text{W}$.

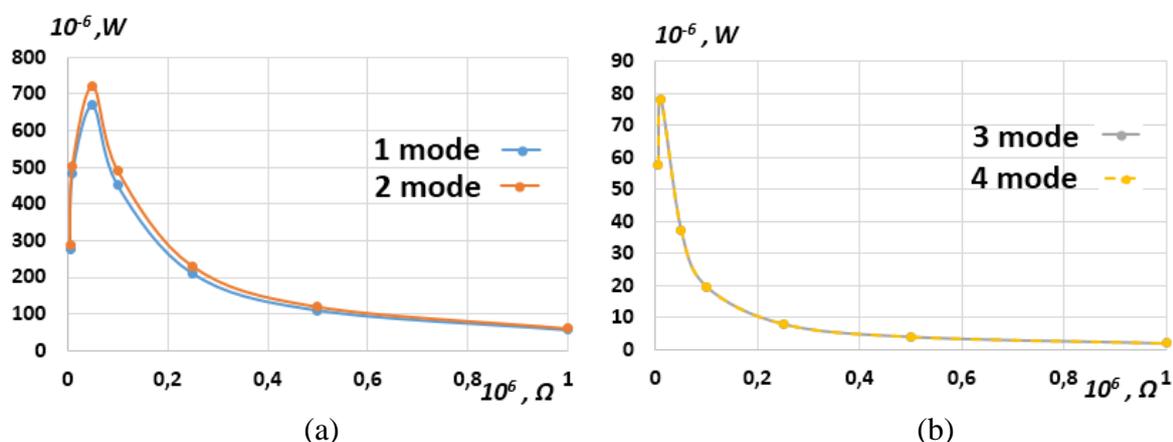


Fig 5. Dependence of output power on load impedance for first four modes of oscillation.

6. Conclusions

By using FE analyses, we simulated a double-cantilever PEG with proof masses having an axisymmetric execution structure. The proof mass was based in the region of the neighboring point of attachment of the piezoelement at $l_m = 65 \text{ mm}$. A modal analysis of the natural oscillations of the PEG was also performed and showed need to use first four modes of oscillations. They have the bending character of the oscillations with respect to the vertical y -axis. For this oscillator model, the resonances were near the circular frequencies $\omega = 45.616 - 45.636 \text{ Hz}$ for the 1st and 2nd modes of oscillations and $\omega = 119.09 - 119.1 \text{ Hz}$ for the 3rd and 4th modes of oscillations. Taking into account these parameters, a harmonic

analysis of PEG oscillations with an active load and taking into account damping for the first 4 vibration modes is performed. The analysis shows that for 1 and 2 vibration modes, the maximum output power is achieved with a load resistance $R = 50 \text{ k}\Omega$ and is $669 \mu\text{W}$ and $720 \mu\text{W}$.

A more detailed analysis of the output power of PEG requires calculation with various values of proof mass, taking into account other properties of the substrate material and the dimensions of the piezoelements.

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