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Finite element analysis of piezoelectric microgenerator – towards optimal configuration

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Abstract

The paper provides results of dynamic numerical analysis of piezoelectric cantilever-type microgenerator intended for wireless MEMS applications. This analysis constitutes an initial phase of ongoing research work aimed at microgenerator optimal design. It is based on beneficial utilization of higher vibration modes, which may offer significant benefits in terms of dynamic performance. Here we report preliminary results of simulations that were performed with a developed 3-D finite element model of the microgenerator that constitutes a bilayer cantilever structure with proof mass at the free end. The structure was subjected to harmonic base excitation by applying vertical acceleration through body load. The resulting characteristics reveal strong dependence of magnitude of generated voltage on design and excitation parameters (frequency, acceleration). Initial findings indicate the necessity to develop microgenerator design with self-tuning of the resonance frequency, i.e. the device should adapt to varying excitation frequency so as to be driven in resonance thereby achieving maximal electrical power output.

Keywords: micropower energy harvesting; MEMS; ambient vibrations; piezoelectric conversion; cantilever; finite element modeling

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1. Introduction

Current advances in microelectronics and microfabrication enabled development of wireless microelectromechanical systems (MEMS) for autonomous sensing applications such as condition-based monitoring of structural health using embedded wireless microsensors. A major limitation in wireless MEMS implementation is related to insufficient amount of energy that is available for the autonomous operation of the units, which are usually difficult to access for recharging. Therefore energy harvesting from ambient vibrations have attracted much attention recently. It is commonly agreed that piezoelectric energy conversion principle is the most promising one, particularly in terms of miniaturization [1-3].

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2. Finite element modeling of piezoelectric cantilever-type microgenerator

The design of piezoelectric microgenerator is selected taking into account its intended applications characterized by low acceleration loading (< 1*g*) and low excitation frequencies (60-200 Hz). These conditions correspond to common environmental vibrations such as those encountered in buildings [4]. Microgenerator configuration based on cantilever with proof mass at the free end is an attractive design solution since it enables the condition of low resonance frequency to be implemented. Fig. 1 provides finite element (FE) model of the microgenerator developed in COMSOL with values of design parameters listed in Table 1. These values are selected so as: a) to achieve fundamental frequency of the structure within the required range of 60-200 Hz and b) to be able to fabricate the microgenerator applying available micromachining technologies. In the proposed microgenerator design the supporting cantilever layer and the proof mass are made of single-crystal silicon, while piezoceramics PZT-5A is used for piezoelectric layer, which is formed on top of the cantilever and is poled along the thickness direction.

The FE model is implemented in piezoelectric application mode of COMSOL. Piezoelectric layer has got electrodes on its bottom and top faces. Due to low thickness the mechanical behavior of the electrodes may be neglected. Their electrical behavior is evaluated by imposing proper electrostatic boundary conditions: the bottom face is grounded, while the top one is set to "Floating potential" condition. For the rest of faces of the piezoelectric layer the condition of "Zero charge/Symmetry" is applied.

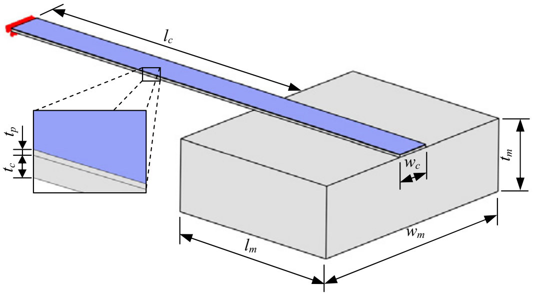

Fig. 1. Finite element model of piezoelectric cantilever-type microgenerator with proof mass at the free end. Zoomed-in area illustrates bilayer structure of the cantilever consisting of supporting layer t_c and piezoelectric layer t_p

Table 1. Values of design parameters of the modeled piezoelectric microgenerator

Description and symbol	Value	Unit
Length of uniform cantilever l_c	2500	μm
Length of proof mass l_m	1500	μm
Width of cantilever w_c	300	μm
Width of proof mass w_m	2000	μm
Thickness of cantilever supporting layer t_c	20	μm
Thickness of piezoelectric layer t_p	5	μm
Thickness of proof mass t_m	600	μm
Young's modulus of cantilever supporting layer and proof mass E_{Si}	200	GPa
Density of cantilever supporting layer and proof mass ρ_{Si}	2330	kg/m^3
Density of piezoelectric material ρ_p	7750	kg/m^3
Poisson's ratio of supporting layer and proof ν_{Si}	0.33	-

Firstly, the model was subjected to modal analysis, which revealed that the fundamental frequency of the structure is equal to 166 Hz. This result was also confirmed by frequency response analysis, which provided amplitude-frequency characteristics of the cantilever tip for different acceleration magnitudes (Fig. 2(a)). During dynamic simulations the model was subjected to harmonic base excitation by applying vertical acceleration through body load equal to $F_z = a\rho$ in each subdomain, where a = Ng (N = 0.1÷1.0, g = 9.81 m/s^2) and ρ is density of the corresponding material (Si or PZT-5A). As an example, Figs. 2(b-c) demonstrate different character of variation of open circuit voltage of the microgenerator during its harmonic base excitation at frequencies of 20 Hz and 500 Hz. Results of frequency response analysis, summarized in Fig. 3(a), indicate that generated peak voltage is directly proportional to magnitude of applied acceleration. It is also obvious that magnitude of peak voltage is considerably higher when excitation frequency of the microgenerator matches its resonance frequency. This suggests the necessity to design microgenerator with self-tuning of the resonance frequency in order the device could adapt to varying excitation frequency so as to be driven in resonance thereby achieving maximal electrical power output.

3. Parametric study

Magnitude of voltage produced by piezoelectric microgenerator is a crucial performance parameter. Therefore it is important to examine the effect of various design parameters on value of output voltage, e.g. thickness of piezoelectric and supporting layers, stiffness of the supporting layer and coverage of the piezoelectric layer.

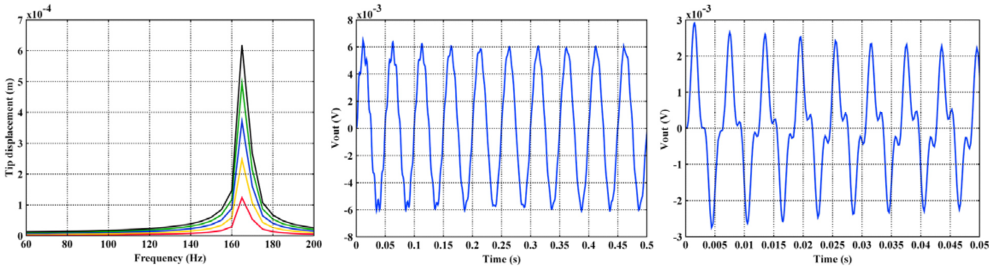

Fig. 2. (a) Amplitude-frequency characteristics of the cantilever tip for various acceleration magnitudes (from bottom to top curve: a= 0.2g, 0.4g, 0.6g, 0.8g, 1.0g); (b-c) Time responses of generated open circuit voltage during harmonic base excitation of the microgenerator with acceleration magnitude of a=0.1g and frequency of 20 Hz (b) and 500 Hz (c)

One of the main tasks during design of a piezoelectric microgenerator is selection of such thickness of piezoelectric layer (with respect to the supporting layer) that would maximize magnitude of generated voltage. Therefore harmonic analyses were performed by varying thickness of the piezoelectric layer from 3 μm to 30 μm (t_c = 20 μm). These simulations were carried out applying harmonic base excitation of a = 0.1g and f = 20 Hz, which is a frequency that is sufficiently far from the resonance. Results provided in Fig. 3(b) indicate that for a given value of t_c there exists an optimal value of t_p which yields maximal generated voltage. In the case of the modeled structure the highest value of open circuit voltage is obtained when the ratio t_c/t_p is approximately equal to 1.43.

Another approach for increasing output voltage is based on possibility to use different materials for fabrication of the supporting layer. Application of materials with larger Young's modulus would enable increasing stiffness of the layer. Silicon was used in above presented simulations. Its Young's modulus E is equal to 200 GPa, however for SiC and SiN$_3$ films E may be up to 380 GPa, for diamond-like carbon (DLC) films – E = 800-900 GPa, for ultrananocrystalline diamond (UNCD) films – E may reach 970 GPa [5]. Thus, harmonic analyses were performed by changing t_c for two materials: silicon and material that is identical to silicon except that its E = 900 GPa (thereby representing a DLC-type material). The reason for adopting such analysis approach was to simulate conditions of variation of stiffness of the supporting layer without modifying other material properties. Results summarized in Fig. 4(a) demonstrate that magnitude of generated voltage can indeed be raised by increasing stiffness of the supporting layer through usage of novel carbon-based thin-film materials with large Young's modulus. However, one should note from the provided plots that this approach should be employed with care since the aforementioned advantage may be achieved only under certain combinations of thicknesses of supporting and piezoelectric layers.

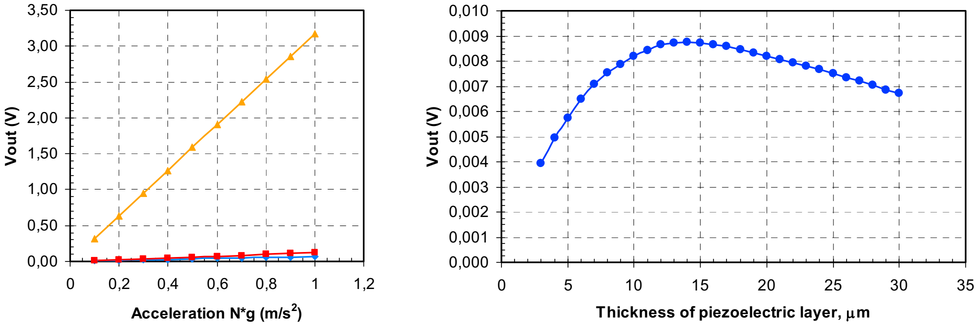

Fig. 3. (a) Peak voltage vs. acceleration during excitation at resonance frequency of 166 Hz (yellow line) and at frequencies of 60 Hz (blue line) and 120 Hz (red line); (b) Open circuit voltage vs. thickness of the piezoelectric layer for the microgenerator under harmonic base excitation

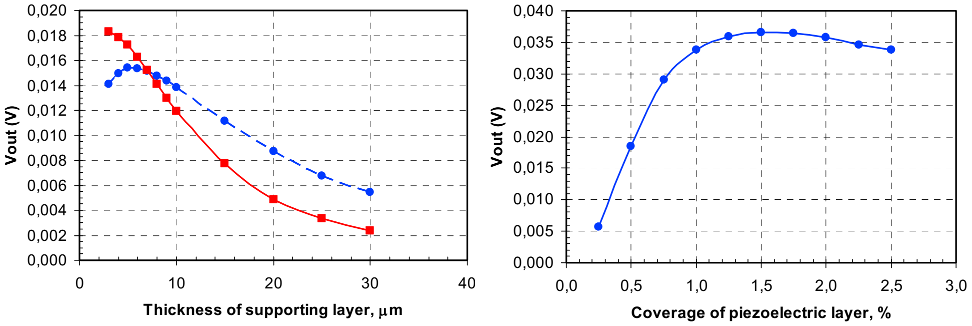

Fig. 4. (a) Open circuit voltage vs. thickness of the supporting layer (blue dashed line – for silicon layer, red solid line – for DLC-type layer) for the microgenerator under harmonic base excitation ($a = 0.1g$, $f = 20$ Hz, $t_p = 15$ µm, $E_{\mathrm{DLC}} = 900$ MPa); (b) Open circuit voltage vs. coverage of the piezoelectric layer (calculated as $(l_p/(l_c+l_m))\times100$, where l_p – length of piezoelectric layer with respect to anchor) ($t_p = 15$ µm, $t_c = 20$ µm)

Another important design parameter is the area of piezoelectric layer that covers the supporting layer. It is natural to expect in the case of cantilever-type microgenerator that output voltage will be affected by length of piezoelectric layer defined from the clamping place since upon vertical displacement of the structure the largest strain is induced near the anchor. Frequency response analyses were performed with the same excitation conditions by varying the length of the piezoelectric layer l_p. The results in Fig. 4(b) reveal that voltage peak is observed when only 1.5 % of the supporting layer is covered with the piezoelectric layer, i.e. when its length from the clamping place is 60 µm.

4. Conclusions

Dynamic numerical analysis of the cantilever-type piezoelectric microgenerator provided the following main results demonstrating influence of ambient vibration and design parameters on output voltage:

- Generated peak voltage is directly proportional to the magnitude of applied acceleration and is considerably higher when excitation frequency of the microgenerator matches its resonance frequency;
- Results indicate that for a given thickness of the supporting layer there exists a particular value of piezoelectric layer thickness which results in maximal generated voltage;
- Magnitude of generated voltage can be raised by increasing stiffness of the supporting layer through usage of novel carbon-based thin-film materials with large Young's modulus.

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