Modeling of Piezoelectric Transducers for Energy Harvesting

R. Emilova, N. Goncharova, B. Ee, R. Konovalov, O. Spirina, V. Tsaplev

Department of Electroacoustics and Ultrasound Techniques
Saint-Petersburg Electrotechnical University "LETI"
E-mails: emilova.roxi@gmail.com
gonchrova9450@gmail.com
ee.boris.eut@gmail.com
rskonovalov.eut@gmail.com
olga.spirina11@gmail.com
valery@convergences-fr.ru

Received: 15.11.2016

Abstract. The paper concerns three different types of piezoelectric transducers for creating energy harvesting devices for small-size radioelectronic devices. Modes of operation of the proposed circuits of piezoelectric transducers are analyzed numerically in the mathematical FEM software package COMSOL 5.1. For a piezoelectric generator of the umbrella type, both numerical and experimental simulations are performed. The load regimes of piezoelements are determined both in the frequency and spatial domains, as well as the frequency dependences of the output voltage for transducers like disk bimorph umbrella-, aeroelastic- and the static-types. It is shown that the matching of the piezoelectric transducer with the load can be coordinated by connecting the piezoelectric elements in parallel to reduce the input resistance of the energy harvesting. The simulation results show the possibility of obtaining rather high voltages at different frequencies, and different designs make possible to use the piezoelectric energy harvesters in various conditions as independent energy sources.

Keywords: energy harvesting, piezoeffect, piezoelectric transducer, mathematical modeling, mechanical stress, strain, output voltage

INTRODUCTION

The design and study of compact piezoelectric energy harvesters now became a very contemporary and important problem, attracting the attention of many scientists and engineers. The interest in this problem is due to the possibility of the prospect of creating different small independent and virtually inexhaustible sources of power for the various autonomous electronic devices. Such sources convert the bargain energy of vibrations that present almost everywhere to the electrical energy and do not require external power sources or do not demand costs for periodic replacement of batteries and their chemical processing [1].

The analysis of numerous works on obtaining electrical energy from vibration for power microelectronic devices shows a significant advantage of piezoelectric method in comparison with the electromagnetic or electrostatic one [2].

The main advantage of the piezoelectric method of energy conversion is large, compared to other methods of conversion, electric power density, and simplicity of design. The range of values of the resulting voltages is much wider than that of all other types of harvesters.

The main disadvantage of piezoelectric method of energy harvesting can be attributed to the large output impedance of the source. However, this disadvantage can be easily compensated by proper choice of the number of piezoelements, or by the proper choice of their connection – parallel or serial. Moreover, this disadvantage can be turned into the advantage. By the proper selection of the number of elements and their connection one can obtain practically any desired output voltage and internal resistance.

Various types of piezoelectric harvesters can be realized using both longitudinal and transverse vibrations, but in most cases they are performed in the form of cantilever beams with piezoelectric elements, one end of which is clamped in the support, and the other is free. To reduce the working frequency range of the piezoelectric bimorph (threemorph) beams a passive load is placed at its free end,

One can conclude, that the piezoelectric method of producing electrical energy is characterized by a high flexibility of choosing its design.

The piezoelectric energy harvester can be placed at any vibrating place, for example fit snugly to the base, or to the element of the building structure or to a floor or to the road surface or to any vibrating surface. As a result of external impact to the piezoelectric element an electric voltage arises at its output, which after rectification can be supplied to the circuit that controls battery charge. Then the energy of the charged battery may be used by the consumer, i.e., used the waste energy of the external impact or vibration of different objects.

All vibrations are of different nature. Accordingly, it is necessary to create a device that can be used effectively under various conditions. In this regard, three types of piezoelectric transducers have been developed: disc – bimorph umbrella-type, aeroelastic and static transducer.

DISK BIMORPH UMBRELLA – TYPE PIEZOELECTRIC TRANSDUCER

Disk bimorph piezoelectric transducer is a cantilevered bimorph piezoelectric transducer, which is vibrating under the influence of external vibrations. Accordingly, alternative electric voltage arises across causing its electrodes due to the direct piezoelectric effect.

It should be noted that "pure bimorph" structure, which is suitable for the construction of the transducer, is not well suited concerning the problem of energy.

Theoretical and experimental analysis shows [3–5], that best design of the piezoelectric harvester must preferably be the "threemorph", rather than "bimorph". That means, that the transducer must contain two piezoceramic plate with an inverted polarization, pasted on the intermediate base metal plate, so that the piezoelectric ceramics must be located in the area of considerable mechanical alternating stresses. However, this increases the thickness of the flexural bimorph piezoelectric element, which in this case goes out of the desired range of vibration frequencies due to the increase of the frequency of its own umbrella resonance. That is why, a rather massive metal ring is glued on the periphery of the round substrate to reduce the frequency of its main resonance.

The piezoelectric transducer (Fig. 1) consists of the round cantilevered plate 1, 110 mm in diameter; the annular mass 3 around the circumference of the plate; and piezoelectric elements 4 on both surfaces of the plate. Each element is made in the form of a thin plate 25 mm in diameter.

To perform a numerical simulation using FEM software COMSOL 5.1 three-dimensional model of bimorph disk piezoelectric transducer of a selected size was created with the necessary parameters and boundary conditions.

The plate oscillates under the action of the externally applied alternated exciting force. The modeling showed, that the offset edges of the plate oscillated harmonically with the amplitude up to 2 mm (Fig. 2).

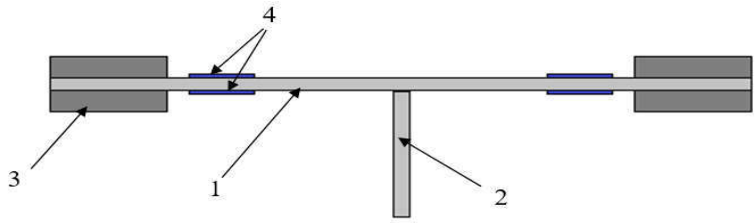

Figure 1. Disk bimorph umbrella piezotransducer:
1 – bronze plate, 2 – leg, 3 – annular mass, 4 – round plate piezoelectric elements

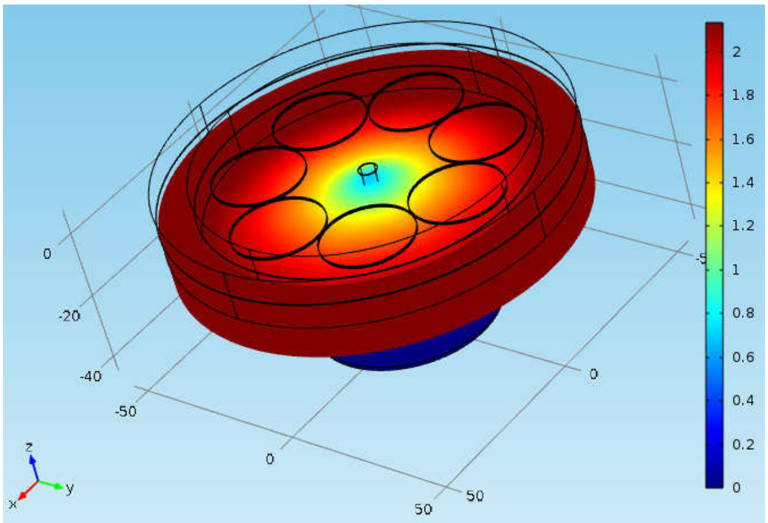

Figure 2. The offset edges of the plate under the action of the external exciting force

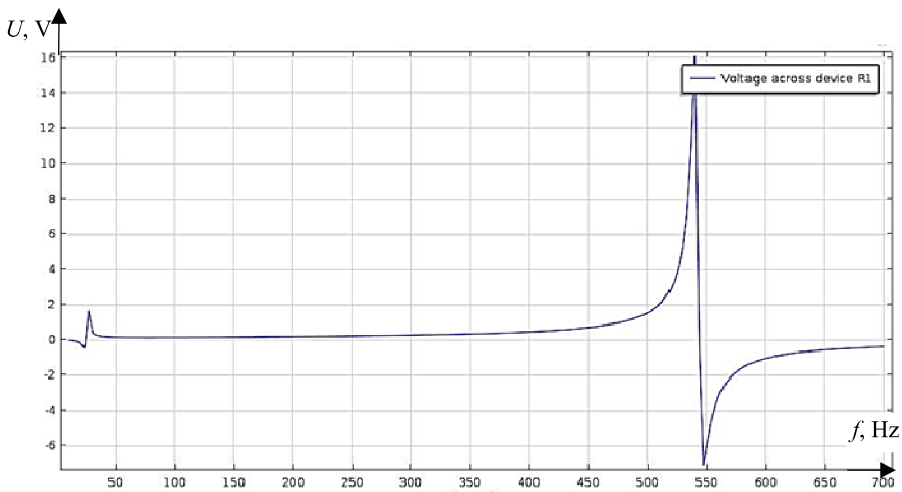

Figure 3. The frequency dependence of the output voltage of the Disk bimorph umbrella piezotransducer

One can see from the curve in Fig. 3, that the output voltage reaches 2 V in the idle mode at the frequency of 46 Hz, and reaches the value of 16 V at the main resonance frequency about 548 Hz. Since the values of the output voltage are complex, the curve is keen.

Modeling of the transducer showed good results. The transducer generated the output electrical voltage up to 16 V in the idle mode. One can obtain better results, if change the settings, sizes, locations of piezoelectric transducers and transducer materials. At this stage of study with the selected parameters the results are optimal.

The usage of this type of bimorph disk transducers for energy harvesting helps to reduce the power consumption by the portable systems of obtaining initial information (electronic devices, sensors, monitoring the state of the environment, etc.) and to provide their autonomous operation for a practically unlimited time due to the energy obtained from vibrations of the environment.

AEROELASTIC PIEZOELECTRIC TRANSDUCER

The turbulent flows that occur in the liquid media or the air around moving bodies, causes flexural deformation of these bodies and flutter. In this context the following aeroelastic model of the piezoelectric transducer was developed [6]. The model provides a rigid wing fastened with a steel rod. On both sides of the end parts of the wing two piezoelectric layers are placed symmetrically from the base of the wing [7]. The wing itself is placed into the air flow, as shown in Figure 4.

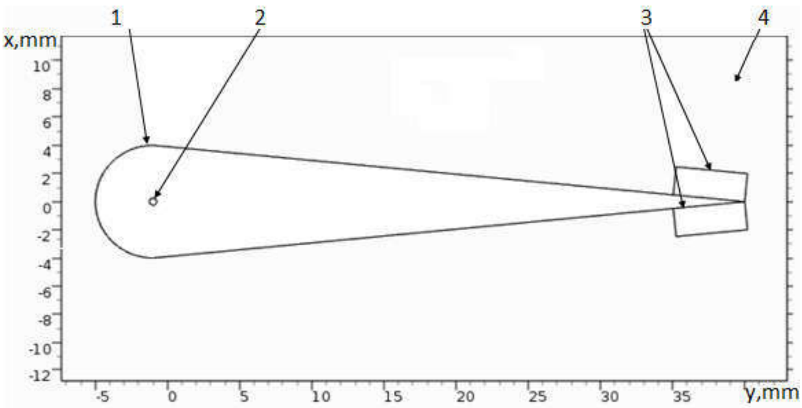

Figure 4. Aeroelastic piezoelectric transducer:
1 – rigid wing, 2 – steel rod, 3 – piezoelectric layers, 4 – environment (liquid or air)

The work of this type of the piezoelectric transducer at different operation modes was simulated by the frequency element method using COMSOL 5.1. The frequency dependence of electric output from the level of mechanical stress is shown in Fig. 5.

The maximum output voltage reaches up to 0.85 at the frequency about 115 Hz. Such changes in the low frequencies range (below 200 Hz) are due to the natural frequencies of the structure model. One can also notice a certain periodical repetitions of the arrival of resonances at frequencies about 300 Hz, 550 Hz, with smaller amplitudes.

Thus, in this paper we analyzed the modes of efficient usage of the energy transducer for the piezoelectric harvester operating in an aerodynamic flow. In the process of mathematical modeling of such piezoelectric harvester with beam-type transducers (the transducers have the form of beams or thick plates) the frequency dependences of the transducer output voltage were determined.

Also the possibility of its usage as a source of electric power when placed in a wind stream, such as air or water. Such an approach is feasible, if put it on the wing of the aircraft, as shown by the simulation results, the generated voltage was more than 0.4 V at the flow velocities over 10 m/s.

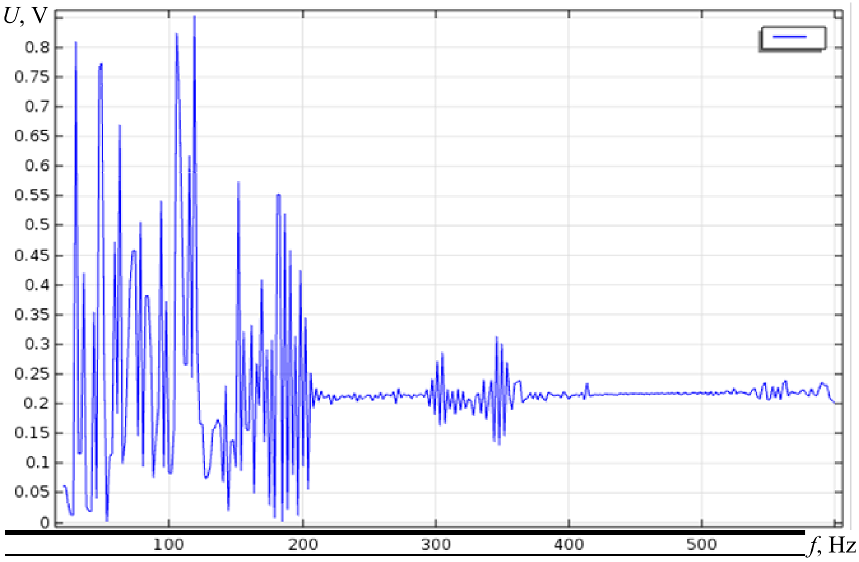

Figure 5. Frequency dependence of generated output voltage of the aeroelastic piezoelectric harvester

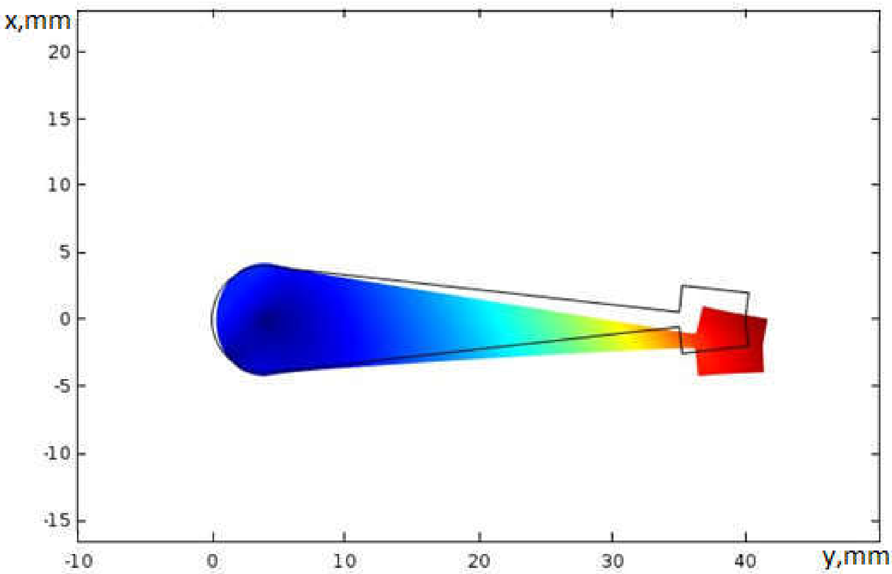

Figure 6. Deformation of the wing (enlarged scale)

Fig. 6 shows an example of deformation of the wing. For the purpose of clarity, the drawing is executed in an enlarged scale.

The static – type piezoelectric transducer

The general arrangement of the static-type piezoelectric transducer for energy harvester is shown in Fig.7). In this figure: 1 – steel plate of 600 mm long, the left end being fixed console – 4. The plate acts as a lever, the load being applied through the hemispherical element 2.

Six piezoelectric PZT elements are assembled in a column – 3. The piezoelement dimensions are: thickness – 2 mm, diameter 30 mm). The piezoelements are connected to better align with the input impedance electrical circuit in parallel. The whole structure is supported on a fixed plate 5.

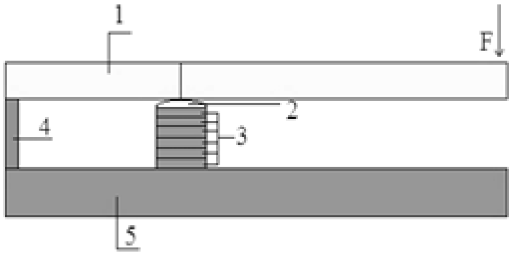

Figure 7. The model of the static-type transducer

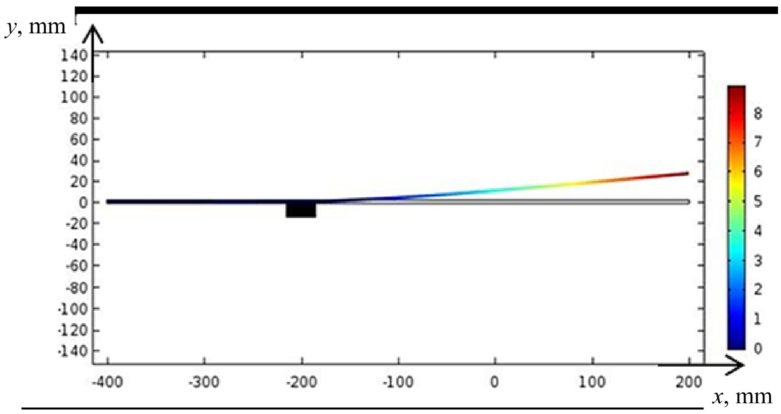

Figure 8. Displacement of the plate

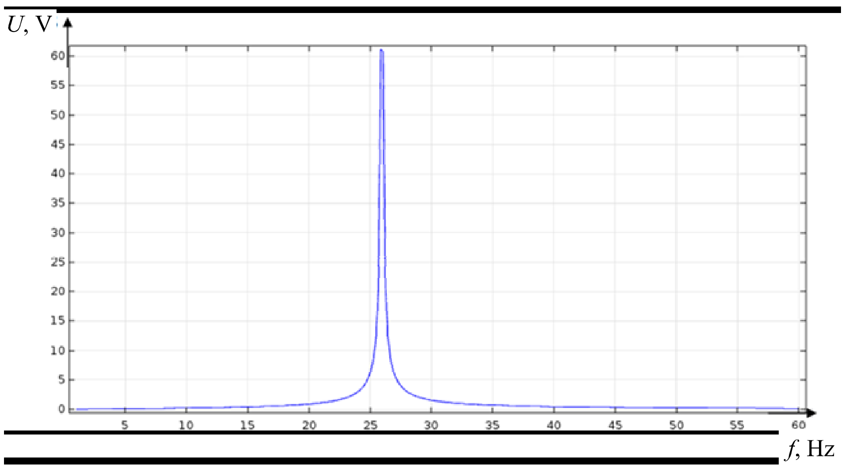

Figure 9. Output voltage frequency response

This type of static generator can be used in different applications. The piezoelectric energy harvesters can be placed at the bottom of some structure that can fit snugly, for example, to the element of the building structure or to a floor or road surface, or to the vibrating surface. One can use it as a power source for lights on the highways, as a low power source for small independent devices, etc.

Numerical modeling [8] has shown that under mechanical load equivalent to the mass of 100 kg, the maximum displacement of the plate was about 9 mm (Fig. 8). The output voltage frequency response is shown in Fig. 9. One can see, that the maximum value of the output voltage may be as much as 60 V.

CONCLUSIONS

Different types of piezoelectric energy sources were analyzed in this paper. The piezoelectric energy harvesters based in these types of piezoelectric transducers are suitable for a great number of electronic devices, sensors, various small appliances as storage elements (batteries). Such devices do not require powerful energy sources, so the piezoelectric transducers are promising.

The simulation results show the possibility of obtaining rather high voltages at different frequencies, and different designs make possible to use the piezoelectric energy harvesters in various conditions as independent energy sources.

Detailed analysis of all possible applications of different types of piezoelectric energy harvesters is far beyond the scope of this work.

The further research will be focused on the study of the influence of the nonlinearity of the piezoelectric ceramic transducers to the properties of piezoelectric energy harvesters.

It should be noted that these types of transducers are based on the usage of commercially available piezoelectric ceramics. They do not require any additional treatment, and they are relatively cheap for production.

ACKNOWLEDGEMENTS

This work has been accomplished as a part of the Ministry of Education and Science of the Russian Federation research assignment "Realization of scientific research (fundamental studies, applied research and advanced developments)". Project code: 2548.

REFERENCES

1. Tsaplev, V., Konovalov, R., & Abbakumov, K. (2015) Disk bimorph-type piezoelectric energy harvester. *Journal of Power and Energy Engineering, 3*(4), 63–68. doi:10.4236/jpee.2015.34010
2. Erturk, A., & Inman, D. J. (2011) *Piezoelectric Energy Harvesting.* New York: Wiley.
3. Cook-Chennault, K.A., Thambi, N., & Sastry, A.M. (2008). Powering MEMS portable devices – a review of non-regenerative and regenerative power supply systems with emphasis on piezoelectric energy harvesting systems. *Smart Materials and Structures, 17,* 043001, 1–33. doi:10.1088/0964-1726/17/4/043001
4. De Marqui Junior, C., Erturk, A., & Inman, D. J. (2009) An electromechanical finite element model for piezoelectric energy harvester plates. *Journal of Sound and Vibration, 327,* 9–25. doi:10.1016/j.jsv.2009.05.015
5. Shu, Y.C., & Lien, I.C. (2006) Analysis of power output for piezoelectric energy harvesting systems. *Smart Materials and Structures, 15,* 1499–1512.
6. Xiang, J., Wu, Y., & Lu, D. (2006) Energy harvesting from the discrete gust response of a piezoaeroelastic wing: modeling and performance evaluation. *Journal of Sound and Vibration, 343,* 176–193. doi:10.1016/j.jsv.2014.12.023
7. Choi, W.J., Jeon, Y., Jeong, J.H., Sood, R., & Kim, S.G. (2006) Energy harvesting MEMS device based on thin film piezoelectric cantilevers. *Journal of Electroceramics, 17*(2–4), 543–548. doi:10.1007/s10832-006-6287-3
8. Kim, S. (2002) *Low power energy harvesting with piezoelectric generators.* PhD diss., University of Pittsburgh. Retrieved from http://d-scholarship.pitt.edu/10228/1/SHKIMA.pdf