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MODELLING AND PRODUCTION PROCESS OF THE ENERGY HARVESTING SYSTEM BASED ON MFC PIEZOELECTRIC TRANSDUCERS

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Abstract: *A* proposal of model of the energy collecting system with Macro Fibre Composite (MFC) transducer is presented. It is one of critical elements of the manufacturing process of the energy harvesting systems. It was created by applying a substitute electric circuit of the piezo element with a resistor connected to its clamps. Using equations of passive electric circuits, the generated voltage was calculated. This model can be used and be very helpful for designers of energy harvesting systems. The proposed mathematical algorithm can be used to estimate power of the system, considering its material and geometrical parameters. It is possible to use it during the synthesis of the energy harvesting systems to choose proper parameters of the piezoelectric transducer taking also into account conditions of the system's exploitation. In this case it could be a useful tool for designers and engineers working with energy harvesting systems.

Key words: Energy harvesting, piezoelectricity, smart materials, modelling, composite piezoelectric transducers.

1. INTRODUCTION

Nowadays energy harvesting is a very popular field of research because electronic devices electronic devices surround us on all sides in the modern world. What is more, contemporary electronic devices could be characterized as systems with low energy consumption and because of that harvesting electric energy from the environment by the device to self-power is very interesting for the designers and engineers. Such solutions could be very important in applications with no possibility to power supply using wire connections or with no possibility to replace batteries. In such systems the possibility to obtain energy from environment during exploitation of the designed system is often the only possible solution. The energy could be harvested using solar systems (photovoltaic elements) but sometimes there is no possibility to use light. In such cases application of energy harvesters based on piezoelectric elements could be an only one solution. Application of materials with piezoelectric properties and using the direct piezoelectric effect allows to generate electricity from deformation of the piezoelectric transducer. Therefore, it is possible to use vibrations to generate electric energy and power supply electronic devices. It is possible to apply new, composite piezo elements in energy recovering systems because their main advantages are that they are flexible, thin, and lightweight transducers that can be easily applied in wide variety of mechanical structures including composite elements.

Paper [14] presents energy harvesting for wide applications of implanted devices, electronic devices, mobile electronics, and self-powered wireless network nodes. The advances of energy recovering using piezoelectricity and electromagnetic phenomenon are presented by authors of this work. Kinetic piezoelectric generators (human-powered and vibration-based devices) and electromagnetic generators (resonant, rotational, and hybrid devices) are reviewed and described. Also, in the work [31] an application of polymers with piezoelectric properties used for harvest electric energy from people walking in a special shoe with the possibility of generating and accumulating the energy is presented.

2. REVIEW OF ENERGY RECOVERY SYSTEMS BASED ON PIEZOELECTRIC TRANSDUCERS AND THEIR MATHEMATICAL MODELS

As it is given by the producer the Macro Fiber Composite (MFC) is the high quality and very thin transducer offering flexibility, high performance, reliability in a non-expensive way [35]. Such elements can be an answer to the problem with applications of classic, monolithic piezoelectric transducers that are fragile and heavy. Composite piezo transducers produced as piezo fibers surrounded in polymer matrix are great solution that can develop piezoelectric technology and take it to a new level by enabling many new applications. Such non-classical piezoelectric transducers are for example active fiber composite (AFC) and Macro Fiber Composite (MFC). Developed, non-classical piezo composites could be applied in a lot of devices, such us structural health monitoring or morphing structures, passive and active vibration control, energy harvesting, [5,10,13,18,25-28,40].

The use of energy harvesting systems from mechanical vibrations by using a simple piezoelectric effect enables the development of extremely innovative power systems, the solutions of which may be even surprising. Very interesting review of the energy harvesting technology from mechanical vibration is presented in paper [15]. Many types of piezoelectric energy recovering systems and piezo materials were investigated in this work. Authors concluded their work by pointing out three problems that limit the wide impact of the vibration-based piezo energy recovering systems: development of high coupling coefficient piezoelectric materials, the energy harvesting systems should be able to maintain under strong vibrations and shocks (for this reason, MFCs transducers, considered in this paper, are such kind of elements that can contribute to the development of this technology) and the last issue marked by the authors in the paper [15] is development of effective electric circuit for energy harvesters.

The overview of the piezoelectric energy harvesting is presented also in [7]. Authors of this paper described device configurations and material operating modes (resonant and non-resonant devices) as well as rotational solutions.

Another review article [29] present an analysis of the latest developments in piezoelectric energy recovering using low profile piezo transducers. Variety of piezoelectric materials is presented, and analytical models are analysed.

A well-known case is the generation of electricity from human walking presented in paper [16]. The system was placed in sports footwear and was able to generate around 100 mW of energy. Electric voltage can be collected from falling drops of water as it is presented in the work [38]. In paper [8] authors present the possibility of obtaining electricity from movement of muscles inside the body. In the paper [9] authors showed that the MFC transducers are good to generate energy from vibration that occurs in the surroundings with no additional mechanical elements necessary to transfer vibrations in the opposition as it is while using monolithic piezo ceramics.

This article discusses the issues related to applications of non-classical piezoelectric MFC transducers in systems for recovering energy from vibrations. A mathematical model of such systems is proposed. Describing the designed technical devices by means of a mathematical model is an essential element and tool which is the first stage necessary to implement it into production. Vibration energy recovery systems are more and more often an indispensable element of modern and innovative technical measures, which are characterized by low electricity consumption, with the simultaneous lack of the possibility of a wired power supply or periodic replacement of the batteries supplying them [3,16,24]. Describing these systems with a correct mathematical model that has undergone the validation process allows, at the design stage, to select parameters (material and geometric) of the elements to ensure its maximum efficiency and proper operation under the assumed operating conditions.

There are a lot of research work concerning with development of mathematical models of energy harvesting systems. Work [30] reports a theoretical model for determination of generated electric power from piezoelectric bimorph transducers in low frequency range far from the piezoelectric resonance. The results of the theoretical model were verified by comparing it with the measured response of a prototype windmill designed for energy harvesting using piezoelectric transducers. The power generation from the piezoelectric bimorphs loaded in the cantilever form as in the case of windmill was modelled using the bending beam theory developed by Timoshenko.

An analytical expression for the optimal power flow from a rectified piezoelectric device is described in paper [22]. An energy harvesting electric circuit is proposed which can achieve this optimal power flow. A brief summation of a background and validation for the piezoelectric power flow theory is contained also in [21]. As it is presented by authors, the electrical characteristics of a vibrating piezoelectric element can be modelled as a sinusoidal current source in parallel with its electrode capacitance.

As it is given by the authors of the paper [1], the expressions derived in paper can be useful in quantifying the harvested power under random vibration. The presented analysis can be used to design energy harvesters subject to random excitation and to provide insight into the physical nature of harvesting when subject to random ambient energy. The pointed out by the authors importance of the presented result is to provide a key to designing harvesters in the more practical case when the ambient vibration is random.

In the paper [12] the analytical method is proposed for cantilever bimorph configurations of ceramic layers with piezoelectric properties. The excitation is caused by the transverse direction translation and a superimposed rotation. Experimental verification of the method was conducted using a cantilever bimorph joined with a tip mass. It was observed that the frequency response functions achieved by the analytical analysis were prediction of the system dynamics.

In the research work presented in paper [36] authors present a model to predict the power generated by a cantilever beam vibration with PZT piezoelectric transducers. As they inform, the model can be applied to a beam with different boundary conditions as well as different layout of PZT transducers. They have verified the model by experiment and proved it is very accurate. In addition, the validation of the model was done using a system with non-homogenous beam's material and a complex PZT layout, what proved that the model can be applied in different mechanical conditions. Authors claimed that the presented mathematical model offers a tool for creating power recovering systems by supporting in defining the size and amount of vibration required to generate the desired energy.

In the paper [34] authors presented results of their research on the fact that power of the energy harvesters depends on the frequency and acceleration of input vibration as well as on the generator's mass, natural frequency, mechanical damping ratio and electromechanical coupling coefficient of the system. The theoretical predictions were validated, and it was proved that there is an agreement with numerical simulations and experimental results.

However, one should remember that there are some independent, external parameters (mainly environmental factors) that can strongly influence on the efficiency of the energy recovering system. One of those parameters is an operation temperature considered for example in works [2,6,11,17,19,20, 32,33,37,39]. Piezoelectric materials can be successfully applied in a lot of applications but the temperature changes effect on the effectiveness of their operation should be considered. In works [2,6,11,17,32] authors indicated that changes of the operating temperature even in the small range can drastically change its efficiency. However, in papers [19,39] one can find that authors present stability of PZT transducers up to 150 Celsius degrees and minor values of composite transducers thermal expansion.

In the work [11] piezo-composites were applied in a tire and examined under simulated rolling conditions. Authors also examined the loss of parameters value in room temperature caused by thermal degradation in elevated temperatures. Changes of piezoelectric constant were small and can be a result of high temperature relaxations in the material. A bonding thickness of PZT patches as well as influence of temperature on the excitation of a cantilever beam was also analysed in the paper [20]. Results of dynamic FEM computations of the piezoelectric–mechanical fields were presented. The research was done with temperatures from −20 up to 50 °C and with adhesive layers up to 200 μm. In work [17] piezoelectric fiber composites (PFCs) were studied when exposed to temperatures in the range between −15 °C and 80 °C. Such transducers are frequently used in aerospace and therefore they are subjected to different temperature values. It was showed that the efficiency of PFCs significantly depends on changes of the temperature.

In the work [6] it was pointed out that piezo materials are used at various temperatures while parameters of materials in the literature are usually designated and described in at room temperature. It leads to inaccurate results of analysis and the inability to optimally design the system. It was shown that electric voltage generated by the harvester increases when loading is increasing and while its temperature is decreasing at the same time. It was noted that at temperature 20°C loading conditions does not affect the generated voltage so this type of piezo material can be effectively used up to this temperature. In temperature range from 50°C up to 300°C properties of transducer change because of depolarization effect so the generated voltage decreases. At temperature 350°C they degrade very rapidly and tending to zero. Also, in [23] the author presented the application of the proposed mathematical model to analyse the temperature changes influence on the energy harvesting effectiveness.

Most of the literature items cited above discuss the systems of energy recovery from mechanical vibrations with piezoelectric transducers attached to a vibrating mechanical subsystem. The proposed mathematical model is a model of a single MFC piezoelectric transducer, which was subjected to axial stretching at a specific frequency. The aim of the author was to develop a model that can be used to verify the influence on the productivity of energy recovery from vibrations of geometric and material parameters only of the piezoelectric transducer used, omitting additional mechanical elements forming the designed system.

3. DEVELOPED MATHEMATICAL MODEL OF THE ENERGY RECOVERING SYSTEM

In the case under consideration, a longitudinally vibrating system in the form of an MFC piezoelectric transducer with a resistor attached to its terminals was analysed. The aim was to develop a mathematical model that allows to determine the value of the electric voltage produced by the piezo element at the terminals of the connected resistor. An important element is the possibility to consider influence of the material and geometric parameters of the applied piezoelectric transducer on the value of the generated voltage. To develop a mathematical model, an electrical substitute diagram of the transducer was introduced, treating it as a source of harmonically variable electric voltage $U_p(t)$ with a specific electric capacity C_p. A substitute diagram of the considered system is shown in Figure 1.

To create the mathematical model of the piezoelectric transducer, well-known constitutive equations were used. The basic constants describing materials with piezoelectric properties are dielectric constant ε_{33}^{T}, piezoelectric constant d_{31} and elastic compliance constant s_{11}^{E}. The upper indicators T and E indicate the value at constant stress or electric field.

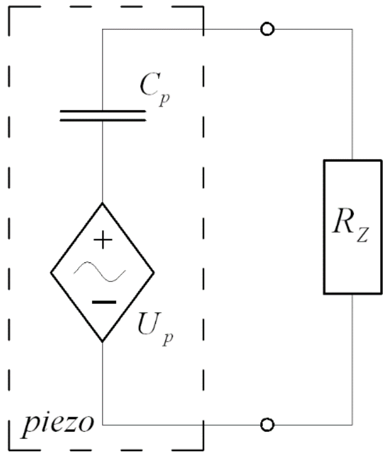

Fig. 1. An electrical diagram of the piezoelectric transducer with the attached resistor

By using these constants piezo materials can be defined by a pair of constitutive equations. They describe relations between mechanical and electrical parameters of transducers [4,28]. Considering loading of the transducer, in the considered case, constitutive equations can be given as:

$$D_3 = \varepsilon_{33}^T E_3 + d_{31} T_1, \qquad (1)$$

$$S_1 = d_{31} E_3 + s_{11}^E T_1, \qquad (2)$$

where D_3, S_1, T_1 and E_3 mean electric displacement, strain, stress, and electric field's intensity in directions of axis defined by the lower indices. The subscripts of the piezoelectric constant show that it defines the relationship among the stress of the transducer in direction of the axis 1 while the electric field is in direction of the axis 3 [4, 28].

The piezoelectric transducer equation, with the attached resistor, was obtained based on the method of linear electrical circuits analysis. The piezo element was treated as an electric charge source that has a specified electrical capacity. So, the whole system was described as a RC electric circuit with zero initial state (the capacitor was not pre-charged) [27]. When the harmonic voltage $U_P(t)$ is generated because of the deformation of the piezo element, a transient state appears in the system. Using equations of alternating current circuits analysis, corresponding to Kirchhoff's law the electric circle can be obtained:

$$R_Z C_P \frac{\partial U_C(t)}{\partial t} + U_C(t) = U_P(t), \qquad (3)$$

where R_Z is the resistance of the joined resistor, C_P is the electric capacity of transducer, and $U_C(t)$ is the voltage on the electrodes of the capacitor. The generated electric voltage is a result of deformations and can be described as:

$$U_P(t) = \frac{Q(t)}{C_P}, \qquad (4)$$

where $Q(t)$ is the electric charge. The stress of the piezo element can be calculated from the equation (2) and introduced to the equation (1). After ordering it was obtained:

$$D_3(t) = \frac{d_{31}}{s_{11}^E} S_1(t) + \varepsilon_{33}^T \left(1 - \frac{{d_{31}}^2}{s_{31}^E \varepsilon_{33}^T}\right) E_3. \qquad (5)$$

Equation (5) considers the change in time of electrical displacement which is a result of time-varying deformation of the system. The electrical displacement is electric charge per the surface area. The surface area of the electrodes in the considered transducer was defined as an area of the piezo-element active part multiplied by a copper fiber volume fraction $V_E = 0{,}190$ [39]. The intensity of the electric field is considered as a ratio of a voltage to the transducer's thickness. The electric charge is depending on time, so the generated voltage can be described as:

$$U_P(t) = AS_1(t) + BU_C(t), \qquad (6)$$

where:

$$A = \frac{V_E l_P b_P d_{31}}{C_P s_{11}^E}, \qquad (7)$$

$$B = \frac{V_E l_P b_P \varepsilon_{33}^T}{C_P h_P}\left(1 - {k_{31}}^2\right), \qquad (8)$$

$${k_{31}}^2 = \frac{{d_{31}}^2}{s_{11}^E \varepsilon_{33}^T}. \qquad (9)$$

k_{31}^2 is the electromechanical coupling constant, which describes the efficiency of transforming mechanical energy into electric energy or electric energy into mechanical energy [28]. Equation (6) defines the generated voltage assuming uniaxial, homogeneous deformation. Therefore, in the considered system with the RC circuit it could be written down:

$$U_P(t) = U_C(t) + U_R(t), \qquad (10)$$

where $U_R(t)$ is a drop of the voltage on the connected resistor. Assuming the total resistance of the considered system is equal to the resistance of resistor R_Z, the voltage drop can be described as:

$$U_R(t) = \frac{U_P(t)}{\sqrt{{R_Z}^2 + \left(\frac{1}{\omega C_P}\right)^2}} R_Z. \qquad (11)$$

By substituting the relation (6) to (11), this voltage drop can be defined as the function of the piezo-element deformation:

$$U_R(t) = \frac{AR_Z}{BR_Z+(1-B)\sqrt{R_Z{}^2+\left(\frac{1}{\omega C_P}\right)^2}} S_1(t) \qquad (12)$$

In Table 1 parameters of the considered system are presented. Using them in the equation (12), the voltage peak value on the resistor was calculated.

The developed mathematical model was validated during the laboratory tests described in [23]. In the experiment, the active length of the piezo element was reduced to 50 mm due to the need to mount it in the jaws of the vibration generating machine. During the tests, a resistor with a resistance of 94 *kΩ* was attached to the MFC. The system was excited with a frequency of 1.5 *Hz* and the maximum operational tensile strain was 2000 *ppm*. At that time, a very good agreement of the obtained results of the mathematic modelling of the system with the measurements performed on the laboratory stand was demonstrated. The obtained waveforms of the electric voltage generated at the terminals of the attached resistor are shown in Figure 2. The results of analytical and experimental tests are juxtaposed.

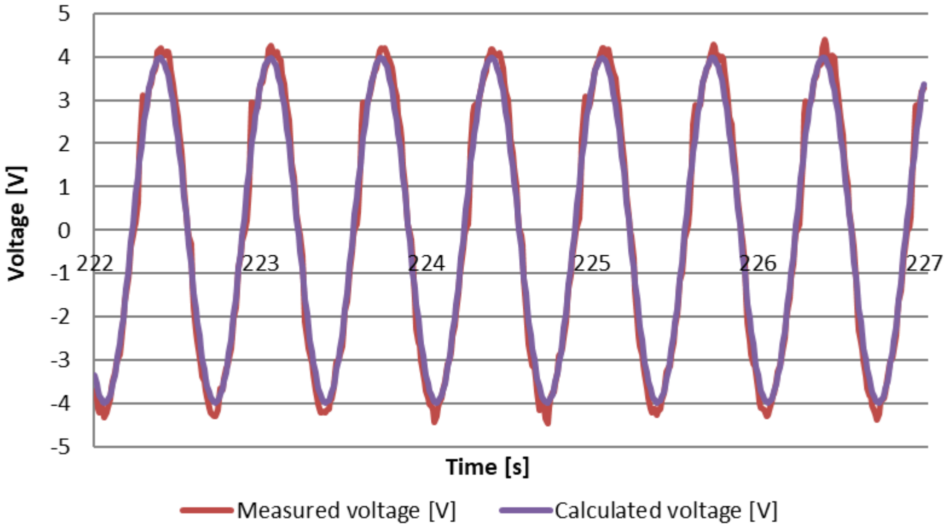

Fig. 2. Voltage drop on the resistor calculated analytically juxtaposed with the course obtained during laboratory measurements

Table 1. Parameters of the MFC8514P2 transducer

Description	Notation [units]	Value
Active length of the MFC	l_{MFC} $[mm]$	85
Active width of the MFC	b_P $[mm]$	14
Thickness of the MFC transducer	h_{MFC} $[mm]$	300
PZT fibers thickness	h_P $[\mu m]$	127
Capacitance	C_P $[nF]$	138
Copper fiber volume fraction	V_E $[dimensionless]$	0.19
PZT fiber volume fraction	V_P $[dimensionless]$	0.824
Piezoelectric constant	d_{31} $\left[\frac{pC}{N}\right]$	-1.7E+02
Elastic compliance constant	s_{11}^E $\left[\frac{m^2}{N}\right]$	16.4E-12
Dielectric constant	ε_{33}^T $\left[\frac{F}{m}\right]$	1.504E-08

In the considered case, the load connected to the voltage source in the form of a PZT transducer is resistance and does not contain reactance, the value of the effective power can therefore be determined from the relationship:

$$P = \frac{U^2}{R}, \qquad (13)$$

where U is the RMS value of the voltage generated by the transducer. The calculated power of the energy harvesting system from mechanical vibrations in this case was therefore 85.1 μW.

Table 2. Types and geometric parameters of standard MFC P2 transducers [35]

Model	Active length $[mm]$	Active width $[mm]$	Active surface area $[mm^2]$
M0714-P2	7	14	98
M2807-P2	28	7	196
M8503-P2	85	3	255
M2814-P2	28	14	392
M8507-P2	85	7	595
M8514-P2	85	14	1190
M5628-P2	56	28	1568
M8528-P2	85	28	2380
M8557-P2	85	57	4845
M8585-P2	85	85	7225

Using the proposed mathematical model, it is possible to estimate the power of the designed electric energy recovery system from mechanical vibrations. Figures 3 and 4 show the determined values of the effective voltage and power of the system in the case of using different sizes of MFC piezoelectric transducers offered as standard models by the manufacturer, listed in Table 2. These transducers have the same material properties, however, due to the different dimensions, they have different active surface area. The graphs show the obtained waveforms as a function of the active surface area and assuming different values of the transducer's vibration frequency.

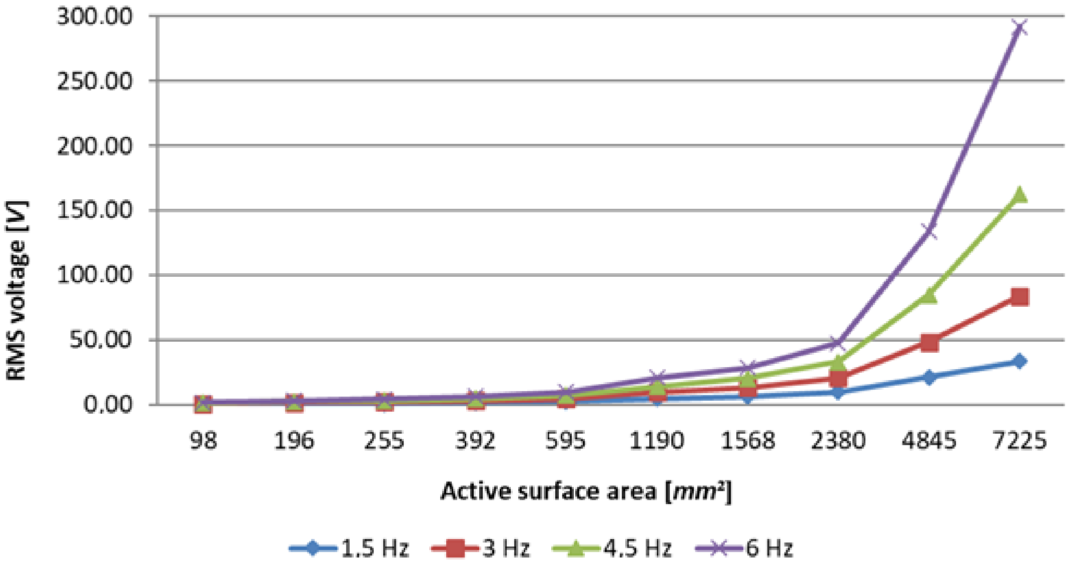

Fig. 3. Analytically determined RMS voltage as a function of the excitation frequency and the active surface area

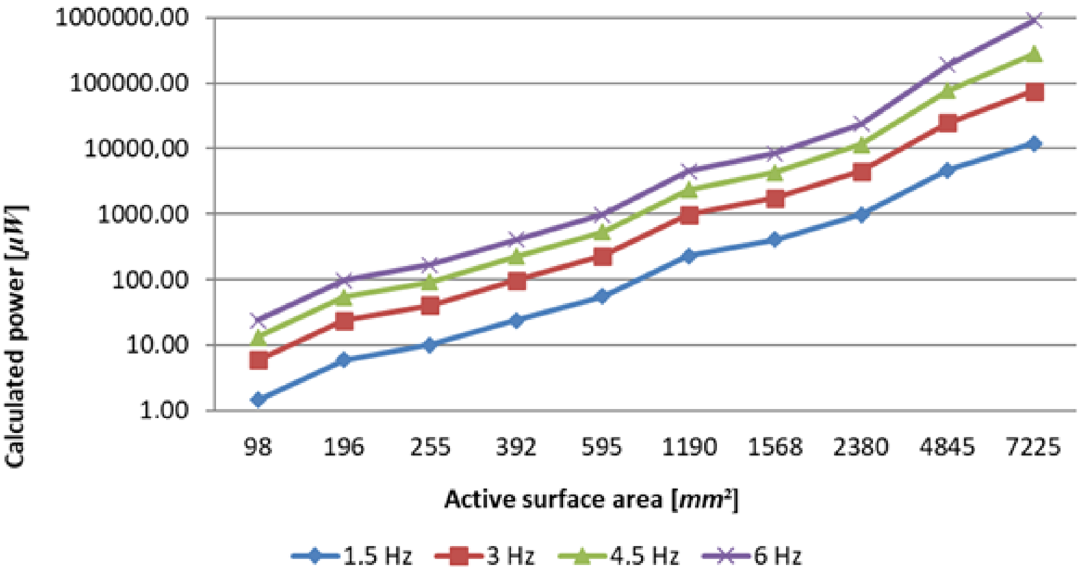

Fig. 4. Analytically determined power of the EH system as a function of the excitation frequency and the active surface area on a logarithmic scale

The strong dependence of the efficiency of the designed vibration energy harvesting system on both the active surface area of the transducer and the frequency of its excitation is clearly visible. Of course, using the proposed mathematical model, one can determine the impact of other parameters of the piezoelectric transducer on the efficiency of electric energy recovery from vibrations, such as material properties or the transducer maximum operational tensile strain. The analysis of these parameters will be considered in further works, and the obtained results will be verified during tests in laboratory conditions.

4. PRODUCTION PROCESS OF THE ENERGY HARVESTER BASED ON MFC'S

MFC transducers are commercially available as ready-made piezoelectric transducers in the form of thin, flexible films. These transducers are a patented

NASA invention that has been commercialized. The transducer is made of piezo-ceramic bars with a rectangular cross-section, placed between the layers of electrodes and polyimide foil. The electrodes used in the transducer are attached in such a way that they form an interdigitated system. Thanks to this design, the transducer is a ready-to-use, durable element that can be used, among others, in systems for energy recovery from mechanical vibrations. Numerous solutions of this type of systems are known, in which piezoelectric transducers are attached to the surfaces of vibrating mechanical systems or integrated with them by laminating them in a composite structures.

In this paper production process of an energy harvester with MFC transducers integrated with composite panel is presented. The harvester consists of four MFC transducers type M8514P2 laminated between layers of the composite panel. The system is made of a glass fabric with a weight of 600 g/m^2 and a twill weave. In the first step, pieces of glass fabric of the required dimensions were cut out, securing the cut edges with tape. The prepared piece of glass fabric is shown in Figure 5.

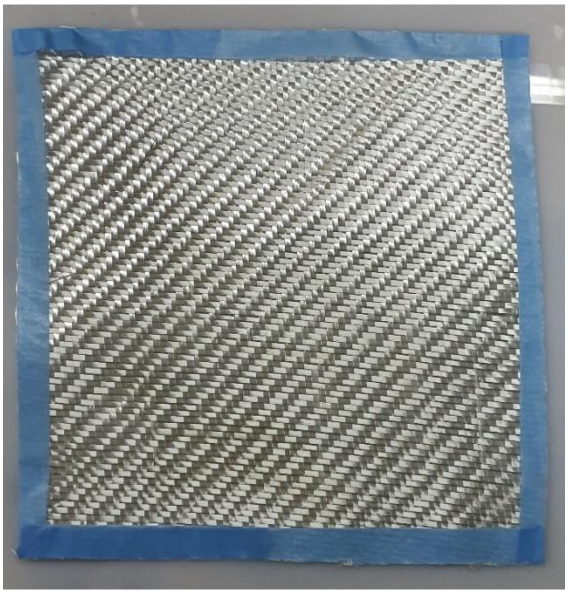

Fig. 5. A prepared piece of glass fabric

In the described system of recovering electric energy from vibrations of the composite panel, which in the discussed case is a mechanical subsystem excited to vibrations, six layers of glass fiber cloth are turned at 90 degrees relative to the previous layer of the composite panel.

Piezoelectric transducers were laminated between the 3rd and 4th layers of glass fiber cloth as shown in Figure 6. The matrix used was the Ig700 epoxy resin and the hg700 hardener mixed with each other in a mass ratio of 100/30. The gelation time of the created composite was about 70 minutes. To eliminate the possibility of air bubbles in the composite and to ensure proper saturation of the fabric with resin, mechanical pressure was applied. A ready-to-use composite panel containing MFC piezoelectric transducers is shown in Figure 7.

Fig. 6. Piezoelectric transducers during the process of lamination between the 3rd and 4th layers of glass fiber cloth

Fig. 7. A ready-to-use composite panel containing MFC piezoelectric transducers

The produced composite panel should be cut to the required final size and installed in the target workplace.

The developed solution is an intelligent structure that can serve both as a system for obtaining electricity from mechanical vibrations, and a structure whose dynamic parameters can be controlled with the use of piezoelectric transducers laminated in it. The applied MFC converters can also be used as sensors measuring structure vibration parameters in real time, and the generated signal can be processed by the control system. Based on the measurements made, the control system can power the other transducers in such a way to damp vibrations of the structure. This action is known as active vibration damping.

5. CONCLUSIONS

Systems that enable powering electronic components wirelessly and without the need to charge or replace batteries are becoming a more and more commonly used solution in modern technical systems. Numerous studies are carried out to improve this type of systems and improve their energy efficiency, as shown in the presented literature review. Efforts are made to improve the properties of the piezoelectric transducers themselves, as well as the effectiveness of the electronic systems cooperating with them. The development of this field of technology opens new possibilities for designers, as well as enables the use of mechanical energy accompanying many processes in a controlled and efficient manner, while in the previous solutions this energy was lost.

The first and basic tool for designing and manufacturing this type of systems, however, is their modelling and examination of the impact of individual parameters on their effectiveness. Therefore, the development of an appropriate mathematical model significantly reduces the need to conduct a series of laboratory tests and prototypes, which is time-consuming and costly. The proposed mathematical model enables analytical estimation of the effectiveness of the designed system of electric energy recovery from mechanical vibrations with the use of piezoelectric transducers. Using the proposed tool, it is possible to select the material and geometric parameters of the transducer necessary to achieve the planned performance of the system. The developed mathematical apparatus was validated by carrying out tests in laboratory conditions [23]. High compliance of the obtained results has been demonstrated, as well as the fact that the proposed mathematical model can be developed to consider the environmental conditions of its operation on the productivity of the energy recovery system. The proposed tool will therefore be further developed and tested to facilitate the design and production of modern technical means in which the energy of mechanical vibrations is recovered and used.

The presented technology to produce composite elements with integrated piezoelectric transducers confirms the large possibilities of using composite piezoelectric transducers in modern intelligent structures. The advantages of modern transducers in the form of flexible and thin foils allow for their full integration with the created structure and creates new possibilities of their applications. The presented technological process of production of this type of systems is not complicated, and the proposed mathematical model allows to design the system in such a way as to achieve its maximum efficiency and estimate the energy efficiency of its operation as a system for recovering energy from mechanical vibrations.

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