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GENERATING OF ELECTRICITY FROM MAGNETOELECTRIC COMPOSITE WITH USE OF CHANGES IN DIRECTION OF MAGNETIC FIELD VECTOR

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Summary:

Paper shows study on the magnetoelectric composite material placed in an external magnetic field with changing magnetic field vecotr. An experimental setup for investigation of magnetoelectric properties of magnetostrictive-piezoelectric material was prepared. The hybrid structure is made of magnetostrictive composite (based on Terfenol-D) and piezoelectric material. Experimental results shown the response of prepared hybrid material to the rate of changes of direction of magnetic field vector. Investigation were mainly focused on possibility of generating of electric power from prepared material. It was found that the prepared hybrid material exhibits magnetoelectric effect in the case of work when direction of magnetic field vector was changing. This effect might be use in Energy Harvesting applications.

Keywords:

SMART materials, Energy Harvesting, magnetostriction, active materials, Terfenol-D

INTRODUCTION

Currently, the research on new materials exhibiting cross effects, coupled by the mechanical and magnetic fields are directed to combine these materials with other materials which exhibit completely different properties. The most promising of these additional materials tend to be those which are characterized by an electric properties. Usually in the literature a combination of these two kind of materials is known as hybrid material. They can be characterized by the capability to work under the influence of various external factors. Most of these new materials are based on polymer matrices. Polymer-based magnetoelectric (ME) materials are one of the most interesting, challenging and innovative materials and thus these materials are in a field of interest of many research centers.

Due to the unique properties of ME materials, it is believed that in the near future, the gap between basic research materials and real applications will be filled. Materials exhibiting magneto-electric effect are sort of bridge connecting the magnetic and electrical properties [4, 9, 13]. The interest in applications of ME materials is increasing due to their potential applications in areas such as data storage, multi-state memory, sensors, actuators, transformers, gyros, microwave devices, optical waves, diodes, and other [2, 5, 6 10, 11]. In order to positively match the technological requirements of these and other applications, a strong ME effect at room temperature has been obtained from multiferroic (MF) composites, which is generally obtained by combining piezoelectric and magnetostrictive components [3].

In this paper a study on the magnetoelectric effect observed in the magnetostrictive-piezoelectric composite material is presented.

1. THEORY

Multiferroic materials with the coexistence of at least two ferroic orders have recently drawn increasing interest due to their potential applications as multifunctional devices. Among these materials, the coexistence of ferroelectricity and ferromagnetism is highly desired. But only this coexistence is not enough; of most importance is to require a strong coupling interaction between two ferroic orders. In multiferroic materials, the coupling interaction between the different order parameters can produce additional functionalities, such as a magnetoelectric (ME) effect. From the view of material constituents, multiferroic ME materials can be divided into two types: single-phase [1, 7, 12, 14, 15] and composite [11, 13,].

Different from what happens with the single-phase ME materials so far available at room temperature, the larger design flexibility of MF composites allows the introduction of multifunctional properties. In those materials the coupling interaction between the piezoelectric and magnetostrictive components produces magnetoelectric response several orders of magnitude higher than those in single-phase ME materials.

The ME effect in such composites results from the cross interaction between the piezoelectric and magnetostrictive phases in the multiferroic ME composite, whereas the sum and scaling properties denote the average or the enhancement of effects which are already present in the constituent phases [11]. In this way, composites can be used to generate an ME response from the combination of materials which themselves do not allow the ME phenomenon [5].

Once a magnetic field is applied to the composite, strain in the magnetostrictive phase is induced. This cause the deformation of the piezoelectric material, which undergoes a change in electrical polarization. In an analogous way, the reverse effect can occur: when an electric field is applied to the composite, strain is induced in the piezoelectric phase which is transmitted to the magnetostrictive material, which occurs in a change of the material magnetization.

2. MATERIAL

In this chapter, materials that were used to prepare a hybrid ME material are shown. The main properties that allowed us to use these materials to prepare ME samples are presented.

2.1. Piezoelectric material

The principle of work of piezoelectric materials is well known and is based on relocation of electric charges under mechanical deformation. This physical phenomenon works also in opposite way it means that change in the electric charge causes mechanical deformation of this kind of material. At present, material such as PMN-PT single crystals exhibits the best coupling coefficient in d_{33} mode. This coefficient qualifies the efficiency of energy conversion between electric and mechanical one. Unfortunately these type of piezoelectric materials is expensive and highly brittle. Thus, for our investigations we choose PZT oxide ceramics, which also exhibit a good coupling coefficients.

PZTs can work along several modes, each of them can be characterised by its own coupling coefficient. In the case of bulk PZT materials we can distinguish two modes such as d_{33} and d_{31}. We are talking about first one of these modes d_{33} when the strain of material and its polarization are in the same direction. The second mode d_{31} is define when the strain and polarisation of the material are orthogonal. Similar comparison can be done for a thin discs or layers made of PZT. However in the case of thin disc we can define d_t and d_p modes. If the strain is normal to the plane of the piezoelectric disc the d_t mode is defined and when the strain is in the radial direction the d_p mode is defined. Scheme of each mode is shown in Figure 1.

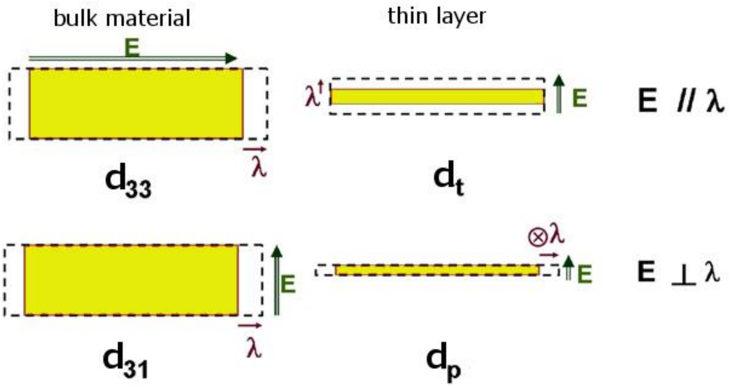


Fig. 1. Scheme of modes for bulk PZT material and thin layer

Source: Lafont T., Gimeno L., Delamare J., Lebedev G. A., Zakharov D. I., Viala B., Cugat O., Galopin N., Garbuio L., Geoffroy O.: Magnetostrictive–piezoelectric composite structures for energy harvesting, Journal of Micromechanics and Microengineering 22 (2012), p. 6

For this investigation it was decided to use commercially available material which was supplied by Smart Material company. The P1 type of micro fiber composite (MFC) was chosen. This type of material is made up of PZT-5 microfibers (130 × 150 μm^2), encased between two Kevlar/Kapton sheets and polarized along their length. The P1 type of MFCs are utilizing the d_{33} effect for actuation and they elongate up to 1800 ppm if operated at the maximum voltage rate of -500 V to +1500 V. The P1 type of MFCs might be used as a very sensitive strain sensors. Figure 2 shows a principle of work of P1 type of MFC material in the case of d_{33} mode.

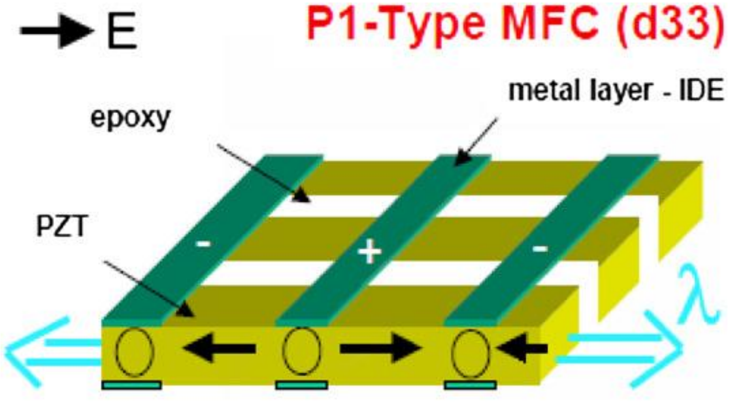


Fig. 2. P1 type MFC working in d_{33} mode

Source: Lafont T., Gimeno L., Delamare J., Lebedev G. A., Zakharov D. I., Viala B., Cugat O., Galopin N., Garbuio L., Geoffroy O.: Magnetostrictive–piezoelectric composite structures for energy harvesting, Journal of Micromechanics and Microengineering 22 (2012), p. 6

2.2. Magnetostrictive material

Magnetostriction as the phenomenon could also be defined as a change in material dimensions caused by a change in its magnetic state. Most often, the magnetostrictive materials change their dimensions as a result of a change in magnetic field applied to them, as well as a change of their magnetic properties under applied load.

In this study, the magnetostrictive composite also referred to as GMMc is used. It was made by combining the epoxy resin and the GMM material (Terfenol-D) powder. At first, the epoxy resin Epolam 2015 (from Axons Technologies company) was mixed with the curing agent. Next, the appropriate amount of Terfenol-D powder (Gansu Tianxing Rare Earth Functional Materials Co., Ltd.) was added, with particle size of about 5-300µm.

The manufacturing procedure consisted of intensive mixing of all the ingredients until their complete homogenization. The mixture was then vacuum vented, poured into the dedicated cylindrical containers and subjected to the initial polarization. After that, the material was again vented in the vacuum chamber to eliminate the air introduced during the mixing stage.

Additionally, in order to prepare magnetostrictive composite with high amount of Terfenol-D particles it was necessary to remove the excess of resin, which was in the mixture after the initial procedure. For this purpose, pre-prepared mixture was poured into a container, one end of which was secured by a filter with high density and an aluminum rod (Figure 3). Containers prepared in such a way were placed between the grips of a hydraulic testing machine MTS, wherein the second end of the container was protected in the same way as the first (Figure 3b). Then the mixture which was in a container, was subjected to compression by means of aluminum rods. Squeezing of the mixture allowed to empty the containers of excess of the resin, which was possible thanks to the half-permeable filters that allowed the free flow of resin, and prevented the escape of the powder particles from the containers (Figure 3c). In order to ensure a uniform value of Terfenol-D volume fraction in the composite, each sample was subjected to the same pressure. Prepared in this way samples were left in the testing machine for 8 hours, until initial resin curing process was over. Then, after the time allowed for initial binding, the prepared sample was removed from the testing machine and placed for 24 hours in a furnace in order to achieve full bonded matrix and then it was removed from the container.

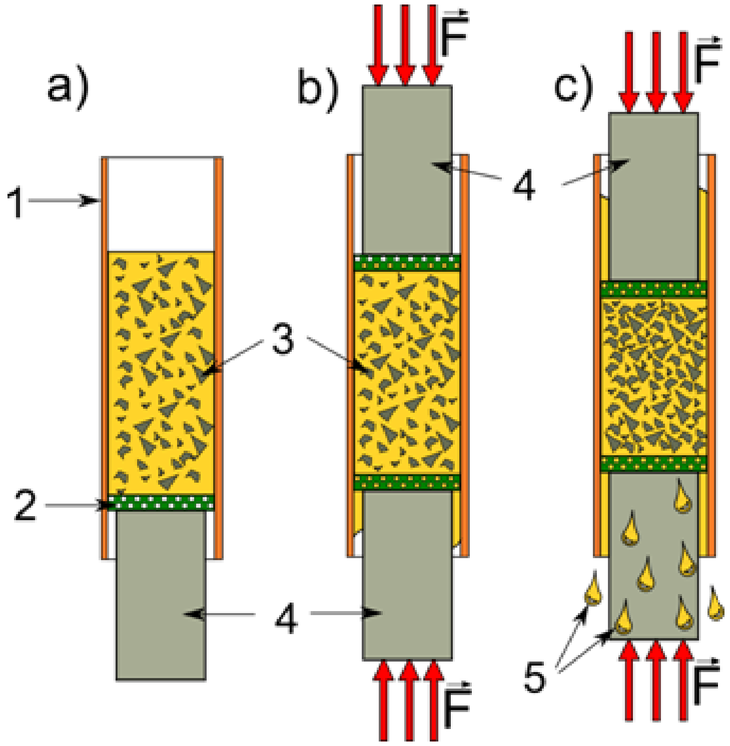


Fig. 3. Methodology for preparing composite samples with a high volume fraction of Terfenol-D particles, where: 1 - container, 2 - filter, 3 - mixture, 4 - aluminum rods, 5 - excess resin

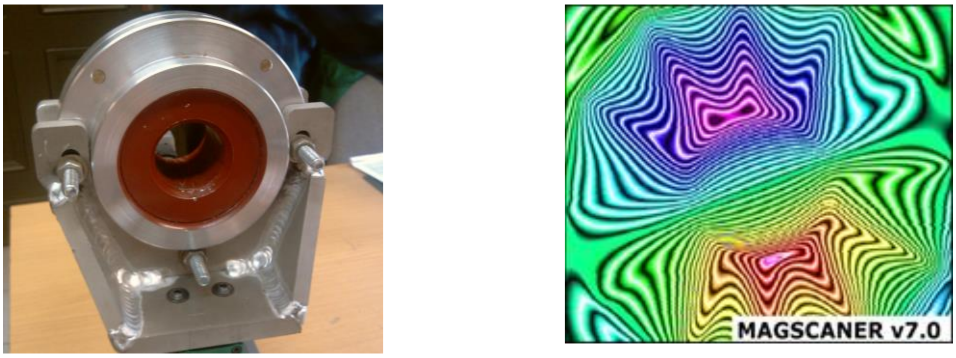
Source: own elaboration

3. EXPERIMENTAL RESULTS

An experimental setup for investigation of properties of magnetostrictive-piezoelectric material is presented. The influence of changes of magnetic field vector direction on the strain of magnetostrictive phase and response of piezoelectric material is shown.

In order to conduct a study which main goal was to determine the effect of a change of the direction of the magnetic field vector on the deformation of the hybrid material (magnetostrictive part) and the voltage value obtained from a piezoelectric material it was necessary to prepare a novel experimental setup.

In order to obtain intended goal it was decided to use so-called Halbach array as a source of magnetic field (Figure 4a). In this array, the magnetic field has strictly defined direction, what can be clearly seen in Figure 4b. In this figure the map of magnetic field distribution around the Halbach array is presented. The magnitude of the magnetic field inside the Halbach array was on the level of 1 T. Due to its characteristics Halbach array allows to easily change the direction of the magnetic field vector around the object in its interior, while ensuring the constancy of the value of this field.



a) **b)**

Fig. 4. Halbach array: a) real image of Halbach array, b) map of magnetic field distribution around Halbach array

Source: own elaboration

The construction of the hybrid material needed to allow to place it inside of the Halbach array. Unfortunately, due to relatively small dimension of the area inside the Halbach array it was impossible to use large amount of magnetostrictive and piezoelectric materials.

Prepared hybrid sample consisted of small piece of piezoelectric materials, which was placed between two layers of magnetostrictive material. View of the sample is shown in Figure 5. In order to perform the deformation (strain) measurements it was decided to use conventional strain gauges, which were placed in a such way that allow to measure strain in many directions.

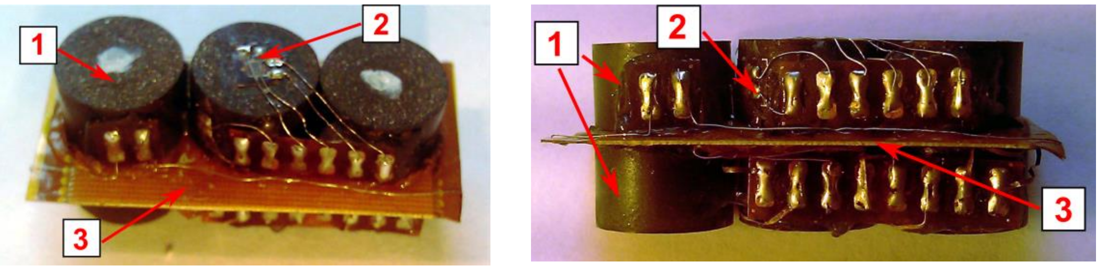


Fig. 5. View of the magnetostrictive-piezoelectric sample, where: 1 – magnetostrictive composite, 2 – strain gauges, 3 – piezoelectric material

Source: own elaboration

Prepared sample was placed in an aluminum housing (Figure 6), which was used to provide the appropriate pre-stress to the hybrid material. Additionally the housing needs to provide to keep constant position relative to the Halbach array.

In order to test the effect of the rate of change of the magnetic field vector on the response of the material, the study was conducted in two stages. Firstly the quasi-static examination was performed. During this test the Halbach array was rotating in steps.

At first the zero position of the array was determined. In a zero position the direction of field lines was perpendicular to the sample surface. After determination of zero position a Halbach array started to rotate around the sample. The rotation increments was 15 degrees at 20 second intervals. It allowed to determine the response signals from the strain sensors taking into account fact that change of magnetic field might have influence on the obtained result.

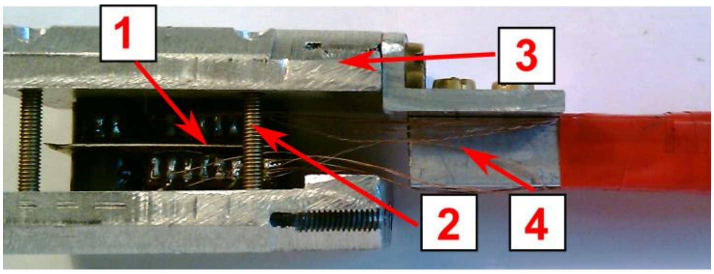


Fig. 6. Hybrid composite material placed inside aluminum housing, where: 1 – sample, 2 – screws, 3 – aluminum housing, 4 – signal wires

Source: own elaboration

During the measurement the Halbach array performed one full turn (360o). The measurement results are shown in Figures 7 and 8. Figure 7 shows the results obtained for the strain sensors placed between the piezoelectric and magnetostrictive material, so it can be assumed that the deformation of both materials was similar. It is clearly visible that the greatest deformation of the material was obtained when the magnetic field vector was acting on the side of the sample (it was parallel to the piezoelectric material).

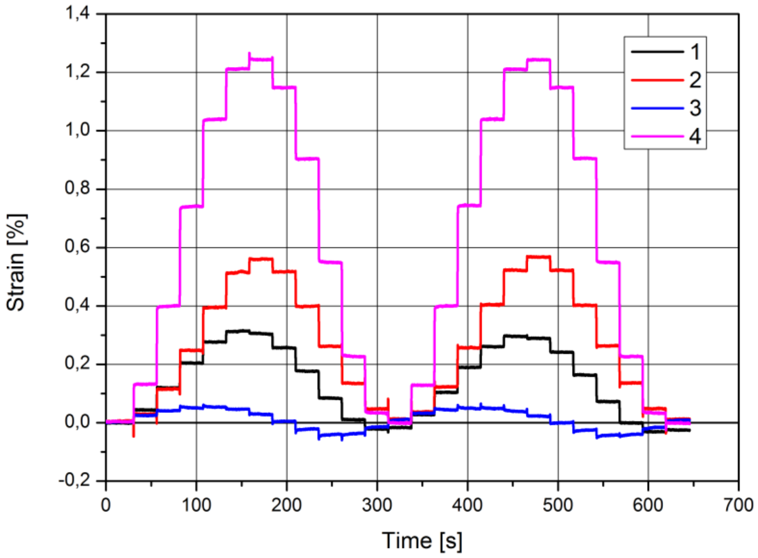


Fig. 7. Change in a signal from strain gauges during quasi-static measurements

Source: own elaboration

Additionally, Figure 8 shows the induction of a voltage signal from the piezoelectric material. It is seen that during the whole measurement there are no changes in the value of electrical voltage. The lack of voltage changes was connected with the low rate of change of the magnetic field vector.

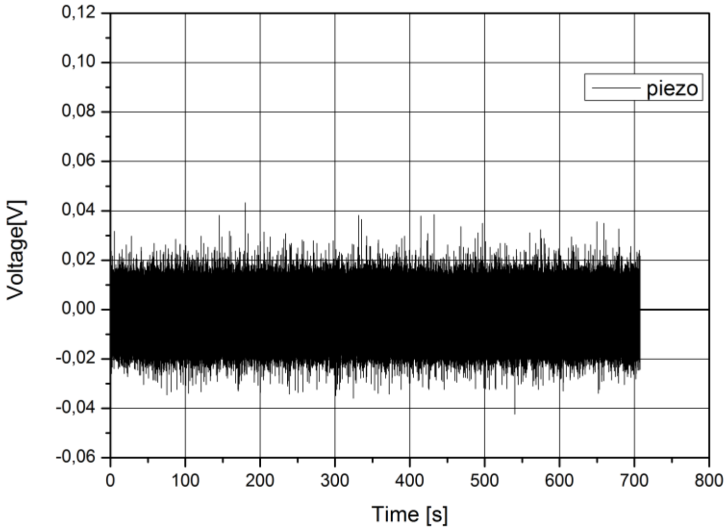


Fig. 8. Voltage signal from the piezoelectric material during quasi-static measurements

Source: own elaboration

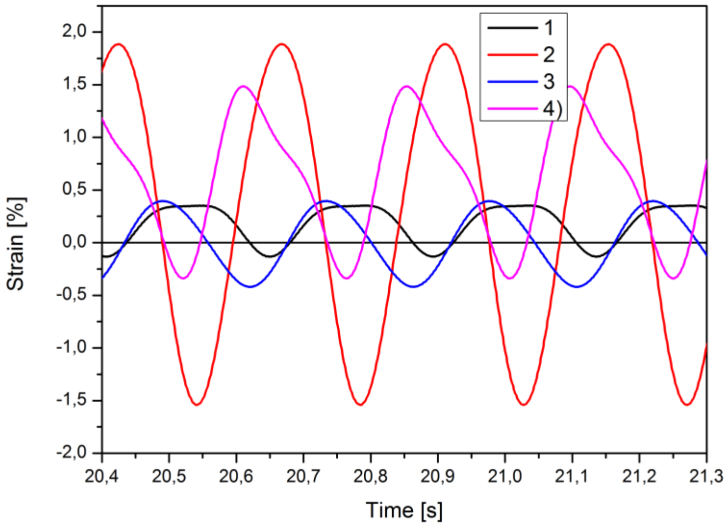


Fig. 9. Change in a signal from strain gauges during cyclic measurements

Source: own elaboration

Further studies have been made for cyclic changes in the direction of the magnetic field vector. The measurement consisted in rotating the Halbach array around the sample with varying frequency. In Figures 9 and 10 are shown the results obtained from the measurements of the changes of direction of the magnetic field at frequency of 5 Hz.

Similarly as before for the measurement of quasi-static firstly the deformation of the material under the influence of an applied magnetic field is presented (Figure 9). The obtained results show the sinusoidal nature of the changes, which was to be expected. Just like it happened in the case of quasi-static measurements in the case of cyclic one, the maximum deformation of the material obtained when a magnetic field vector applied to the material was acting from the side of the sample.

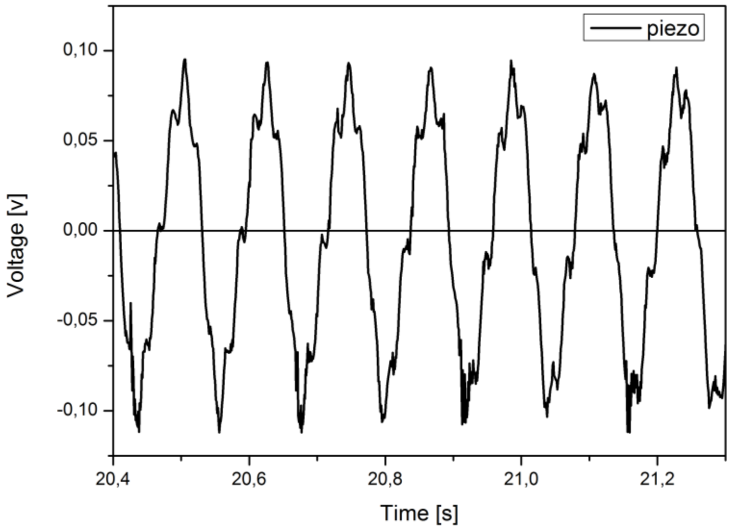


Fig. 10. Voltage signal from the piezoelectric material during cyclic measurements

Source: own elaboration

In Figure 10 the signal received from the piezoelectric material is shown. In a contrast to the quasi-static measurement during the cyclic measurements there was noticed a change of voltage value of the piezoelectric material. The voltage obtained from the piezoelectric material at the frequency of changes in the direction of the magnetic field of 5 Hz was 0.2 V (peak to peak). On the basis of these results, we can conclude that, the rate of change of direction of the magnetic field vector, affects the voltage value obtained from the piezoelectric part of the hybrid material. Additionally it can be said that with the increase of the frequency of these changes the ME effect should also increase.

CONCLUSION

The paper presents the results of research on the developed hybrid composite material. Using a special test stand, the operating principle of produced composite material was presented.

Based on the obtained results, it was found that the prepared composite material exhibits magneto-electric effect in the case of work in a variable direction of magnetic field vector. However, results also shown that the amount of the voltage obtained from the piezoelectric material is highly connected with the rate of magnetic field vector direction changes. Additionally it was found that polarization of both magnetostrictive and piezoelectric elements of hybrid materials also influences the magnetoelectric effect.

The results can be the base for further research over the properties of this new group of SMART materials, especially for applications in a field of Energy harvesting. Even though the voltage obtained from the piezoelectric material was relatively small it still might be use as a power source for low power electric devices.

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BIOGRAPHICAL NOTE

Rafał MECH – PhD Eng. title obtained in year 2015 on Mechanical Faculty of Wroclaw University of Science and Technology, Assistant Professor at Department of Mechanics, Materials Science and Engineering, Mechanical Faculty, Wroclaw University of Science and Technology; The main areas of his interest are: SMART magnetic materials, measurements of basic physical properties of materials, energy harvesting as a power source for small power devices. Author of 58 works including of 15 journal articles and 5 book chapters, cited 36 times.

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