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The actuator based on a magnetostrictive composite working in the feedback loop

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ABSTRACT

The paper presents an actuator based on a coil placed in the casing, with specially prepared connection rods. The construction allows installation of the fiber Bragg grating sensors inside the coil. It allows to measure deformation of the composite that is located in the core of the coil. Thanks to the signal generation with use of DASYLab software, it is possible to precisely control the frequency, value of amplitude excitation and to send the signal to the system with use of the measurement card. The main goal of the experiment is to keep constant value of deformation, by means of a feedback loop with use of PID control, and to change the initial conditions of the test by change of the external force. The system is designed to return to the initial settings by appropriate control of the intensity of magnetic field, and thus the deformation of the sample.

1. INTRODUCTION

One of the materials exhibiting so-called Giant Magnetostriction effect is Terfenol-D (Schwartz, 2002; Engdahl, 2000). Thanks to its unique properties, the material allows the conversion of magnetic field energy into mechanical energy, using magnetostriction effect. The effect is reversible and allows conversion of the mechanical energy into magnetic energy using Villari's effect (Kaleta and Lewandowski, 2007; Kaleta, et al., 2007). Therefore Terfenol-D is widely used in a variety of applications such as: construction of actuators, sensors and so-called energy harvesters. Unfortunately, despite of the many advantages, solid material has also a significant drawbacks. The most important are the presence of strong eddy currents as a result of cyclic loading at high frequency of work (Kendall and Piercy, 1996) and low tensile strength of the material. In order to eliminate those drawbacks, researchers are trying to produce a new materials, such as polymer composites containing powdered Terfenol-D (Ching, et al., 2006, Duenas, 2000; McKnight, 2001; McKnight, 2002). This new approach, involves examining whether those new types of composite materials may be used in similar applications as the solid material. Investigation of the magnetomechanical

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Note: Copied from the manuscript submitted to "Smart Structures and Systems, An International Journal" for presentation at ASEM13 Congress properties of vibration exciter (actuator), containing magnetostrictive composite with Terfenol-D particles, for variable values of the magnetic field around the magnetically active element, including the operations of the actuator in the feedback loop was the goal of this work.

2. MATERIAL

In the study a magnetostrictive composite was used(hereinafter referred to as: GMM composite). It was prepared in the Institute of Materials Science and Applied Mechanics at Wroclaw University of Technology. The composite was made by combining an epoxy resin and a powder of Terfenol-D powder (GMM material). The first step the was introduction of the hardener to the epoxy resin. The next step addition a properly measured amount of Terfenol-D powder with a grain size of 0-300μm (according to the manufacturer: Gansu Tianxing Rare Earth Functional Materials Co., Ltd.). The shape and size of the grains is shown in Fig. 1.

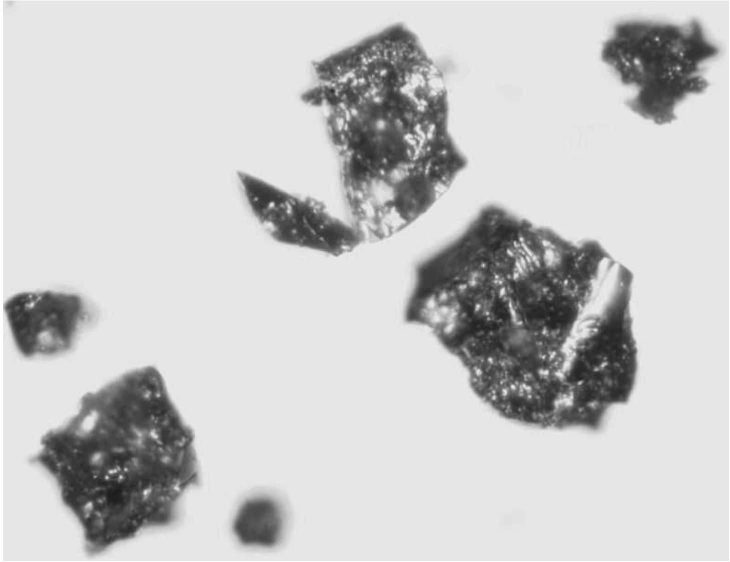

Fig. 1 Terfenol-D powder – image from a light microscope.

The image shows that the powder particles are of different size, their shape is irregular, and their edges are sharp. Two types of curing agents were used in order to optimize the time of initial setting of the resin (about 40 minutes). The manufacturing procedure shown in Fig. 2. It consists of an intensive mixing of the ingredients until their complete homogenisation. The mixture was subjected to the several venting processes, and then poured into cylindrical containers and pre-polarized by inserting the sample between the permanent magnets. After that it was subjected to the one more venting process.

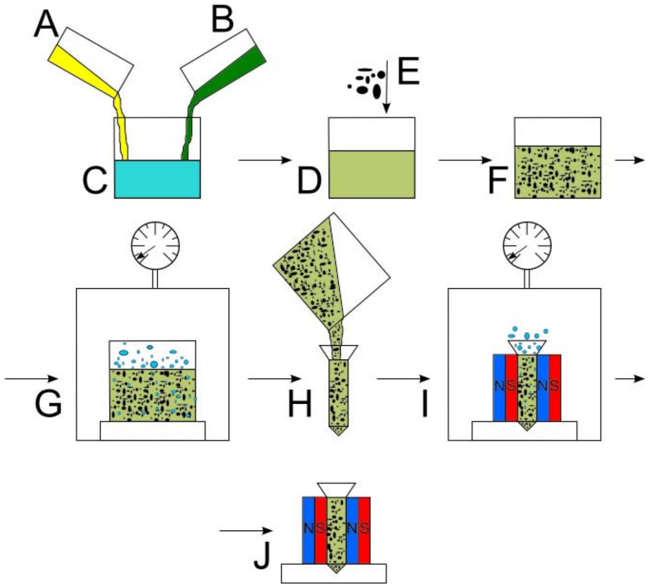

Fig. 2 Scheme of the consecutive processes in the manufacturing of the magnetostrictive composite (Mech 2008).

Due to the fact that authors wanted to obtain a composite sample with a high volume fraction of giant magnetostrictive material powder, it was necessary to develop a new methodology for the preparation of composite samples. Diagram presented in Fig. 3. presents the three stages of new preparation method of composite samples with increased volume content of powder Terfenol-D.

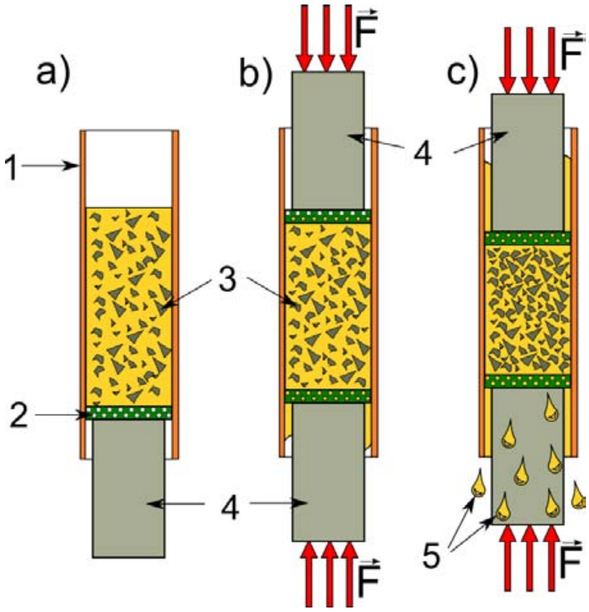

Fig. 3 Methodology for the preparation of samples with a high volume fraction of Terfenol-D powder, where: 1 - the container, 2 - filter, 3 - particle mixture, 4 - aluminum rods, 5 - excess resin.

In the case of the preparation of samples with a higher content of the powder in the mixture, it was necessary to remove excess resin from the mixture after the initial procedure. For this purpose the mixture was poured into a container, where one end was sealed with a filter with high density and an aluminum rod (Fig. 3). Containers prepared in such way were placed between the grips of a universal testing machine MTS, wherein the top end of the container was protected in the same way as the bottom one (Fig. 3b). Then the mixture in a container, was subjected to compression by means of aluminum rods. Squeezing of the mixture allowed removed of the excess of the resin from the container. It was possible thanks to the half-permeable filters that allowed the free flow of resin, and prevented the escape of particles from the containers (Fig. 3c). In order to ensure uniform value of Terfenol-D volume fraction in the composite, each sample was subjected to the same pressure. Thus prepared samples were left in the testing machine for 8 hours, until initial resin curing process was finished. Then, after that time sample was removed from the testing machine and placed for 24 hours in a furnace in order to full bond the matrix material. In the end it was removed from the container.

Additionally, during the manufacturing process an anisotropy was introduced to the composite samples. It was obtained by the application of magnetic field parallel and perpendicular to the main axis of the sample (Kaleta, et al., 2009).

Furthermore, in order to make sure that the composite sample will be working properly inside the core of an actuator, the faces of the samples were tuned, so that adhere perfectly to the metal rods of the actuator. This procedure prevents the degradation of the sample during investigations.

3. CONSTRUCTION OF AN ACTUATOR

During the process of selecting the geometry of the actuator, authors decided use know-how gathered during previously performed computer simulations. To achieve the goal authors did not to restrict in any way the maximum value of the displacements obtained during test. The only limitation was the maximum value of the magnetic field used to stimulate the material. It was assumed that the actuator together with the system will operate most of the time at a specific value of DC power, which necessitated the use of open housing design. This solution was chosen due to the fact that when the system is powered by the longer time with a DC power, the electromagnet coil generates a lot of heat. The heat should be as soon as possible dissipated. The main component of the system was the magnetostrictive composite material with Terfenol-D powders, which was obtained in the way described in previous part. Visualization of a parametric model of the actuator is presented in Fig. 4. One can noticed, that its structure is not very complex, however it allows to obtain high values of the magnetic field and provide easy access to the core of the device. Two plates, top and bottom, made of ferromagnetic material are the main elements of the actuator housing. They are intended spread uniformly the magnetic field and to prevent excessive loss of magnetic field inside the coil. Thus authors decided to use square plates, that allowed to preserve symmetry. In addition, four middle elements with a cylindrical shape made of a ferromagnetic material were used. The shape of these connectors has been conditioned by the fact that in the case of parts with sharp edges, the concentration of the magnetic field appears on those edges. Therefore it impedes the free flow of the magnetic field and may cause disturbances in propagation of the magnetic field around the coil. A cylindrical shape of connectors allows more uniform distribution of the magnetic field, and limits losses. Additionally, the number of connecting elements was chosen to ensure a secure and stable connection between the two plates of the housing, while preserving as many open spaces, as possible. This solution results in a sufficiently large heat radiation area for cooling of the coil. Due to the fact that, the actuator will work in applications, where different displacement values will be required, it was necessary to increase the external dimensions of the actuator, including housing. However, it should be noted, that the construction is compact and simple.

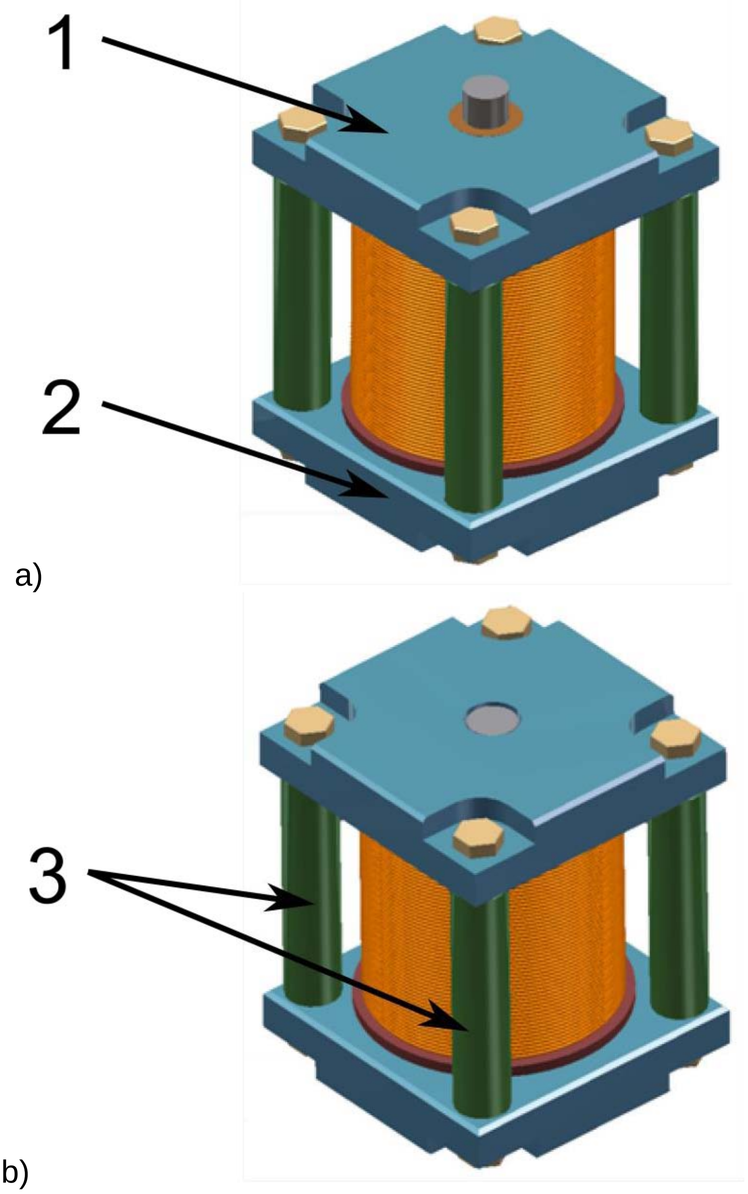

Fig. 4 Model of the actuator: a) top view, b) bottom view. 1 - upper housing plate, 2 - lower housing plate, 3 - connection elements.

During the designing process of the actuator system, authors decided that it should meet the following requirements:

- provide a compact and simple construction,
- ensure an electric and magnetic safety of the user and the whole construction,
- provide an easy access and replacement of the sample,
- allow to control the value of the pre-stress on both solid and magnetostrictive composite material,
- ensure easy installation procedure on the test rig or in the case of potential applications,
- provide an easy control of entire system.

In Fig. 5, the parametric model of the actuator together with components is presented. Among the components of the actuator, one can find a sleeve made of bronze, which was located at the top of the housing. The reason for usage of such element is to reduce the potential friction that could occur between the upper rod of the actuator and the upper plate, during operations of the system. Note that even though the elements which will ensure alignment of magnetostrictive material are used, even a small deviation from the vertical position of the sample could cause friction between the active element and the top of the housing. This might cause a highly reduction of the parameters of the actuator and what is more, it would influence the ability to control the device with use of feedback loop. In addition, (what is not shown) the interior of the housing is protected by the elastic ring, whose main task is to ensure the pre-stress, that can be adjusted by its lowering connecting rods. The possibility to adjust pre-stress is very important due to its influence on the obtained magnetostriction value. The results of the influence of pre-stress on the magnetostriction value will be presented later in this paper.

As the source of the magnetic field a magnetic coil was chosen, as it allows relatively long time of work at a constant DC current level, ensuring, at the same time, the slowest growth of the temperature. Thank to such solution, it was possible to ensure the longest preservation of the optimum operating parameters. Due to the characteristics of the GMM material test of the system can be performed for small value of the magnetic field, which should be approximately 200kA/m. Because of the predicted specification of the working characteristic of the system, it was decided that the system responsible for the preliminary magnetization of the sample will affect only the initial increase of the magnetic moment in the material. Therefore, the control of the system allow increase of the current value what cause deformation of the material only in one direction, regardless of the phase of the magnetic field generated in the coil.

In addition, the measurement of the deformation of the actuator's core, made of the giant magnetostrictive material it was decided to implement the fiber Bragg grating sensor (Blazejewski, et al., 2011). This solution made it possible, to increase the accuracy with which it is possible to control the actuator and neutralized the effect of the electromagnetic field on the control of the device. It significantly helped during preparation of the control algorithm. The use of fiber optic sensors has forced additional changes in the design of the actuator, so that it was possible to mount fibers directly into the core of the actuator. At the same time, it made it easier to measure deformation of the sample.

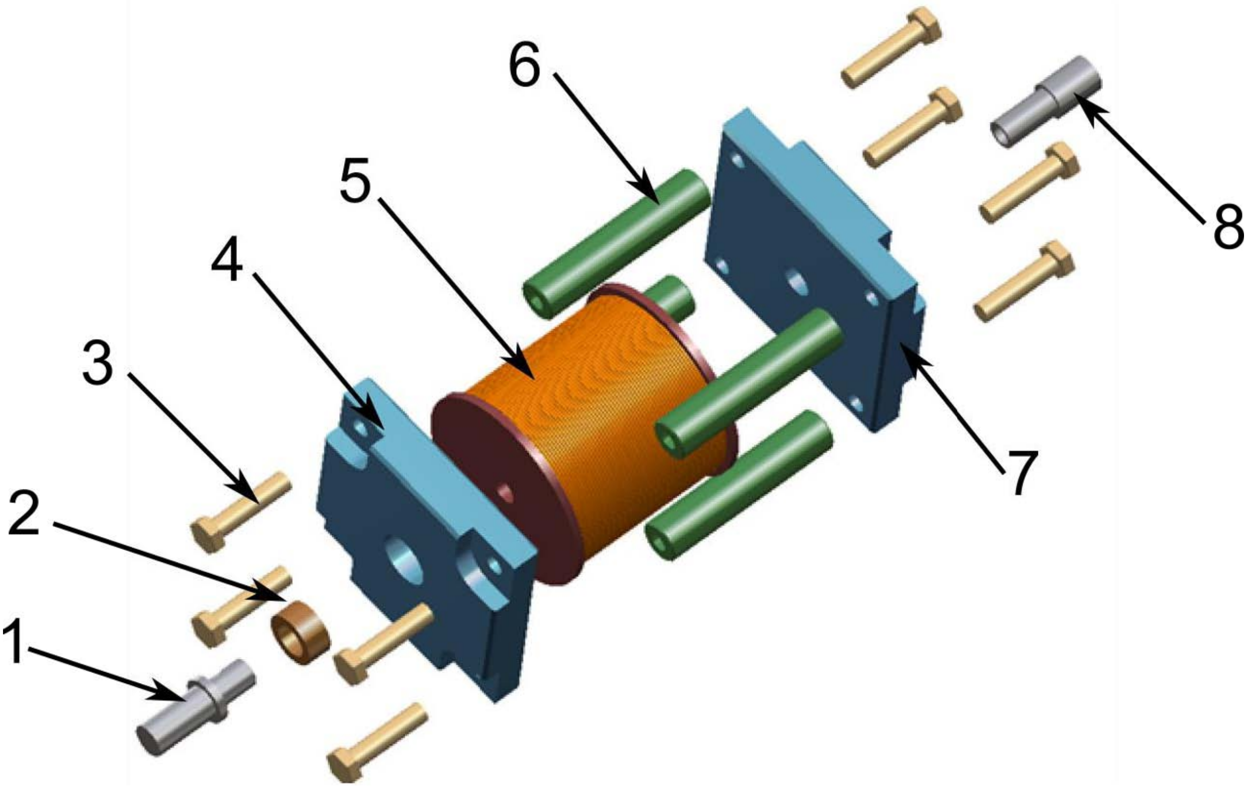

Fig. 5 The actuator model components: 1 - upper rod (actuator), 2 – bronze sleeve, 3 - bolts, 4 - upper housing plate, 5 - coil with composite core, 6 - connection elements, 7 - bottom housing plate, 8 bottom rod.

4. TEST RIG

Goal of the testing was to obtain the quasi-static and cyclic properties of the actuator and check possibility of feedback loop control of the actuator. The cyclic tests means that during the test there is an alternating deformation of the composite core inside the actuator, which is caused by stimulating the magnitude of the magnetic field in the frequency range from 1 to 20Hz. For each test a change of deformation of the composite core, at the corresponding values of the magnetic field, were recorded. Obtained data allowed determination of the maximum value of magnetostriction, depending on the method of stimulation.

The study consisted of determining changes in the magnetic field with the use of triaxial Hall probe and deformation of the sample with a fiber Bragg grating sensors. Additionally, during the investigations the value of the pre-stress applied to the composite core, was changed. This solution was proposed to check whether the value of the pre-stress affects the value of obtained magnetostriction. In addition, during the study it was checked, whether the proposed deformation control algorithm of the magnetostrictive core was valid and able to control the system working in the feedback loop. In such system the controlled value is the value of magnetostriction. Fig. 6 shows a schema of the experimental system of the actuator's feedback loop.

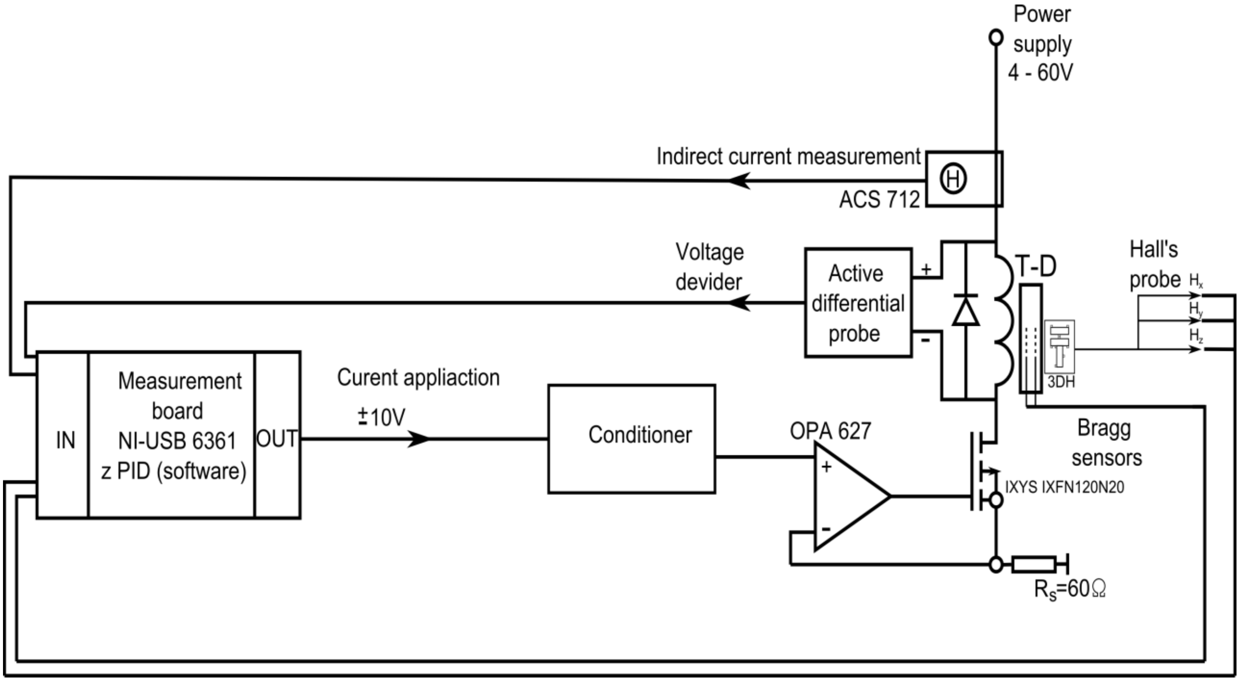

Fig. 6 Scheme of high power vibration exciter with a giant magnetostrictive composite core, that can be controlled using PID controller.

5. RESULTS

First effect of the use of different values of pre-stress on the composite core with Terfenol-D powder, on the value of obtained magnetostriction was tested. Fig. 7 presents the results of maximum obtained values of magnetostriction for composites with high volume fraction of Terfenol-D powder and various initial polarization. It can be clearly noticed, that with the increase of the value of pre-stress, there was an increase in the value of magnetostriction. Based on the received results for the range of the pre-stress' used during the study it was found that the best results are obtained for the composite material with an initial polarization perpendicular to the main axis of the sample. Based on these results, it was decided that this type of material will be used in further studies with use of actuator system.

In Fig. 8 and 9 are shown the results obtained, respectively, for quasi-static tests and for research at the alternating magnetic field in the actuator system, where the working frequency of was 1Hz. Comparing the two graphs it can be seen that the value of the magnetostriction obtained for the same value of the magnetic field is similar.

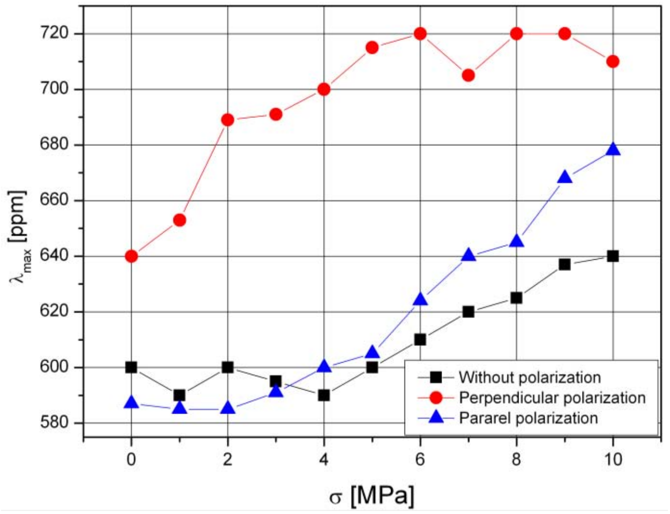

Fig.7 Change of the magnetostriction value Δλ depending on the intensity of the pre-stress in the quasi-static test.

What is more, it should be noted that in the case of measurements made for the variable magnetic field, (Fig. 9) it presents the change of magnetostriction only for negative values of the magnetic field. This result is related to the limitation of the measurement system. Characteristics of the electrical system used in the test rig prevented the "transition" by point zero, therefore, the measurements started from the zero value. It should be noted, that this limitation does not affect in any way the possibility to compare the results from both investigations: quasi-static and cyclic. It is possible because of the magnetostrictive core, which was used in those tests, is characterized by the effect of magnetomechanical parity, which means that the size of the magnetostriction must be the same for the same magnetic field value regardless the phase of the magnetic field, as it is presented in Fig. 8.

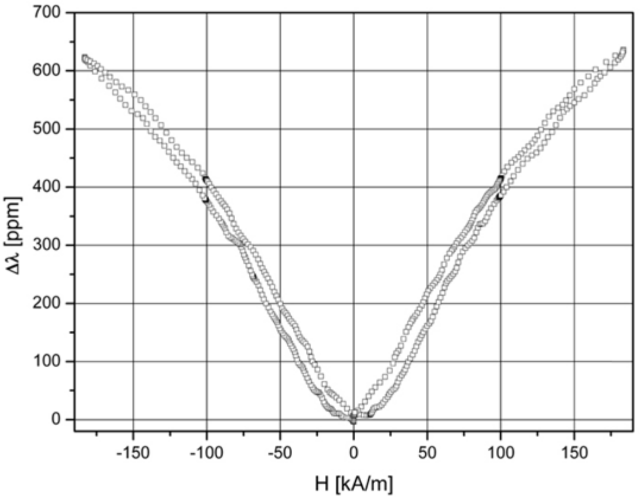

Fig. 8 Change of the magnetostriction value Δλ depending on the intensity of the magnetic field in the quasi-static test.

It should be also noted that both graphs presented were taken for the same value of pre-stress of the composite core (1MPa). It is clear that in the case of low frequency operations, the obtained magnetostriction value is close to the value obtained in the case of quasi-static test. It allowed to carry out the tests, with the feedback loop system, that can be performed, as well, for low frequencies. Thanks to the fact, that at low frequency of work there is only a small deformation effect of the material, it was possible to simplify the control algorithm of feedback loop and therefore, the entire system.

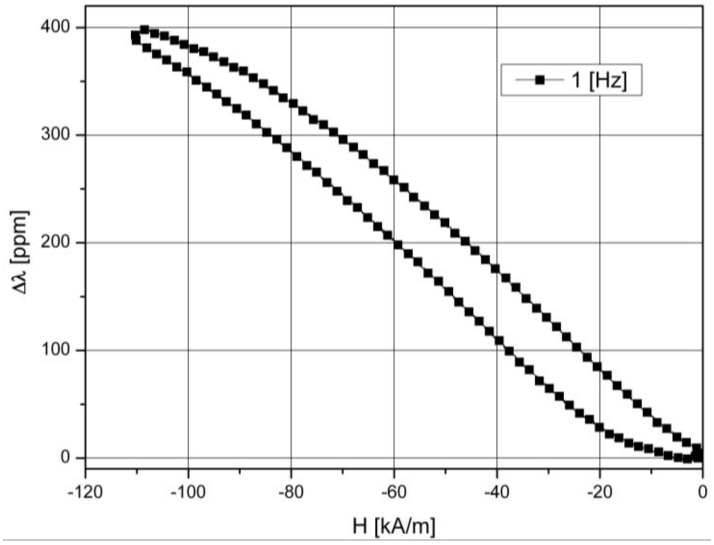

Fig. 9 Change of the magnetostriction value Δλ depending on the intensity of the magnetic field in the cyclic test, at 1Hz frequency.

In the following figures a comparison of the performance of the actuator in the case of application of the feedback loop system, and without such a system is presented. Subsequent numbers in the graphs correspond to the following steps during the test:

- 1 – start of the measurement and application of magnetic field,
- 2 – loading of the actuator (load 20kg) (blue dashed line),
- 3 – unloading of the actuator (red dashed line).

Fig. 10 presents the result of deformation of the material in actuator, when the feedback loop system was off. The actuator was loaded with the weight of 20kg. It is clear that under the influence of the applied load the value of the received magnetostriction has decreased and thus, the active rod. Such rod, which can be used e.g. for control in various applications, did not keep its position.

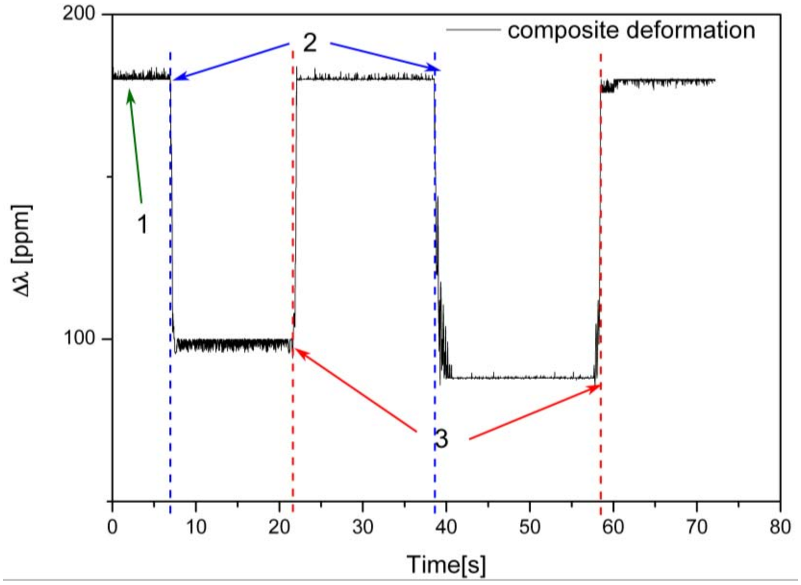

Fig. 10 Deformation of the magnetostrictive rod without a feedback loop system.

Moreover, in the case of the system without the feedback loop, the value of the magnetic field did not change during the experiment, as it is shown in Fig. 11. Following response of the actuator can be predicted.

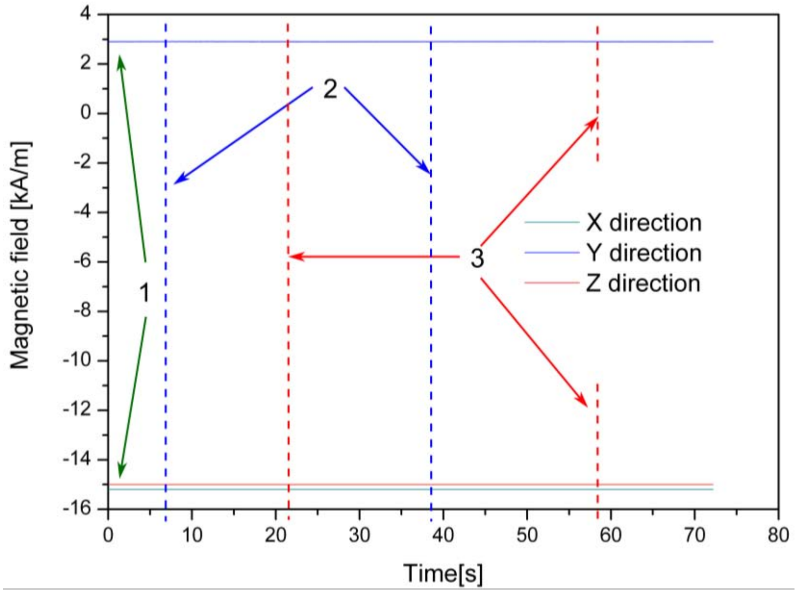

Fig. 11 Changes in magnetic field inside the coil without feedback loop system.

The following figures 12 and 13 presents the results obtained for the system where feedback loop was on. The control of this system took place on the basis of the values read from the fiber Bragg grating sensors. Control algorithm was executed using the DASYLab software. Signal was sent to the actuator system with the help of National Instruments measurement card. At the same time all changes in the system were recorded using the same measurement card. Thus it was possible to control the system using the value of the current inflicted on the actuator coil, allowing to maintain a constant predetermined value of magnetostriction, regardless of the load. In Fig. 12 results of deformation of the magnetostrictive material can be seen when the load of 20kg was placed on the actuator. The oscillation of the strain of the sample is clearly seen, that was recorded using optical fiber sensor. This effect was caused by the use of PID controller in order to receive once again the same values of strain, as the one set at the beginning of the experiment.

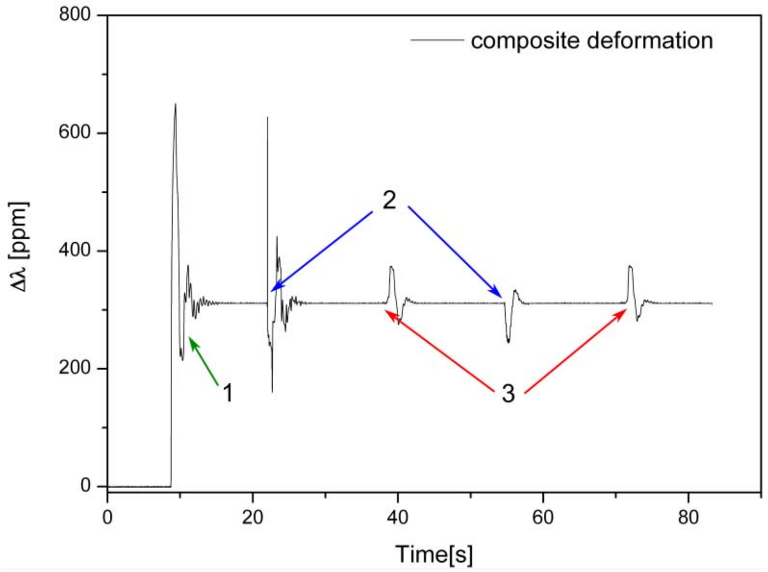

Fig. 12 Deformation of the magnetostrictive rod with a feedback loop system.

In addition, in Fig. 13, changes in the value of the magnetic field during the same test were presented. The results show changes in magnetic field recorder by each of three Hall sensors placed inside the actuator coil. Measurement direction of Hall sensors are as follows: X direction along the main axis of the sample, Z direction towards the sample and Y direction on the outside of the sample (Fig. 14). Similarly as in the results of the deformation of the sample, it can be clearly noticed that oscillation at places indicated by numbers on presented figures from 10 to 13. This result is caused by the characteristics of the PID controller.

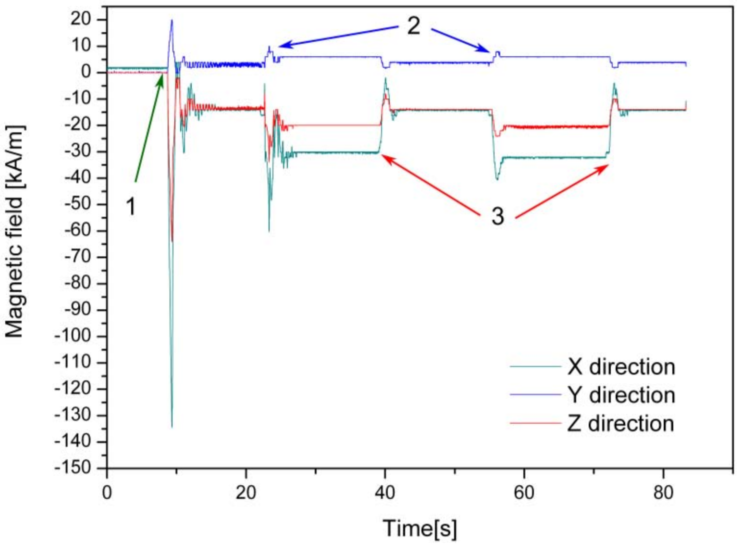

Fig. 13 Changes in magnetic field inside the coil with feedback loop system.

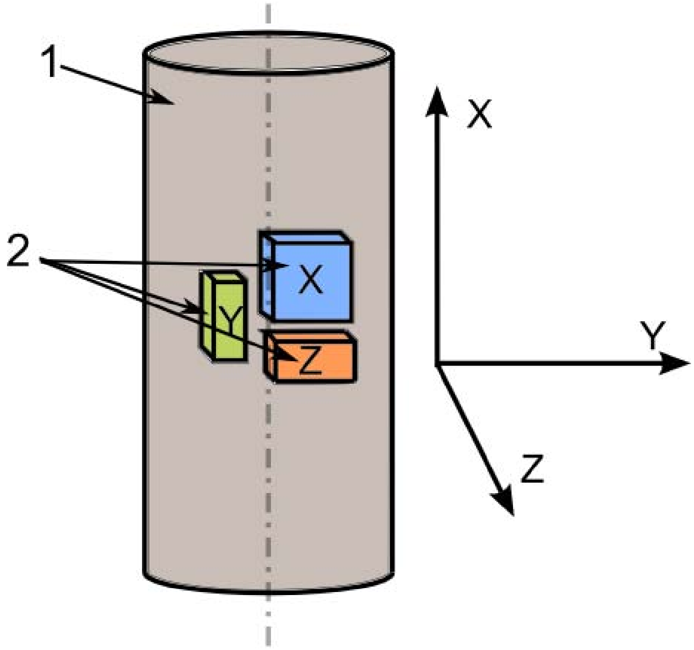

Fig. 14 Measurement direction of Hall's sensors attached on the sample: 1 – sample, 2 - sensors.

6. CONCLUSIONS

Research has shown that for very low frequency of work (1Hz) vibration exciter equipped with a composite core with Terfenol-D particles, present no significant differences between the magnetostriction obtained for the same value of magnetic field strength for both tests carried out in a quasi-static and cyclic manner. What is more, the tests carried out at the same values of the pre-stress shown that it does not change the value of magnetostriction of the composite material regardless of the test method (quasi-static or cyclic).

Moreover, it has been shown that it is possible to actively control a displacement of an actuator, which is based on magnetostrictive composite core, with a feedback loop system. Control of such system is based on the changes of a value of the intensity of the magnetic field around a composite core. In addition, through the use of fiber optics strain sensors, the measuring system made it possible to simplify control of the deformation of the material. Of course there is still a necessity of further development of this system to improve its parameters, however at this stage it can be said that it can be used in many different application.

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REFERENCES

Blazejewski, W., Gasior, P. & Kaleta, J. (2011). Application of Optical Fibre Sensors to Measuring the Mechanical Properties of Composite Materials and Structures, Advances in Composite Materials - Ecodesign and Analysis, 978-953-307-150-3, InTech.

Ching Yin Lo, Siu Wing Or, Helen Lai Wa Chan., (2006) Large Magnetostriction in Epoxy-Bonded Terfenol-D Continuous-Fiber Composite With [112] Crystallographic Orientation. IEEE TRANSACTIONS ON MAGNETICS, **42**.

Duenas T. A., Carman G. P., (2000) Large magnetostrictive response of Terfenol-D resin composites, Journal of Applied Physics, **87**, ss. 4696-4701.

Engdahl G. (2000), Handbook of Giant Magnetostrictive Material, San Diego, Academic Press.

Kaleta J., Lewandowski D., (2007) Inelastic properties of magnetorheological composites: I. Fabrication, experimental tests, cyclic shear properties, Smart Materials and Structures, 16, 5, ss. 1948-1953.

Kaleta J., Lewandowski D., Zietek G., (2007) Inelastic properties of magnetorheological composites: II. Model, identification of parameters, Smart Materials and Structures, 16, 5, ss. 1954-1960.

Kaleta J., Lewandowski D., Mech R., P. Gąsior P. (2009), Magnetomechanical properiteis of Terfenol-D powder compo-sites. Solid State Phenomena Vol. **154** ss. 35-40.

Kendall D., Piercy A. R. (1996), Terfenol-based materials with reduced eddy-current loss for high frequency applications, Ferroelectrics, Volume **187**, ss. 153-161.

McKnight G. P., Carman G.P., (2001) Large magnetostriction in Terfenol-D particulate composites with preferred [112] orientation, Proc. SPIE Vol. **4333**, Smart Structures and Materials 2001: Active Materials: Behavior and Mechanics, Christopher S. Lynch; Ed.,ss. 178-183.

McKnight G. P., (2002) [112] Oriented Terfenol-D Composites, Praca doktorska: UNIVERSITY OF CALIFORNIA Los Angeles.

Mech R. (2008). Examining the magnetomechanical properties of composites on the basis of powders of giant magnetostrictive materials (in Polish), master thesis, Wroclaw University of Technology.

Schwartz M. (2002) Encyclopedia of Smart Materials, John Wiley & Sons.