Chapter 4

Development of Resonators with Reversible Magnetostrictive Effect for Applications as Actuators and Energy Harvesters

Jerzy Kaleta, Rafał Mech and
Przemysław Wiewiórski

Additional information is available at the end of the chapter

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Abstract

This chapter presents the methodology of designing and testing wideband actuators and energy harvesters which can be treated as one device called a mechanical resonator. In order to obtain described effects, the magnetostriction phenomenon was used. This effect enables the construction of resonators in selected frequency bands, including the ultrasonic range. Cores made of giant magnetostrictive materials (GMM) were used for the construction. Considerable attention was given to composite cores to reduce the weight of pure Terfenol-D. The influence of the volume fraction of Terfenol-D powder, the size of its grains, and the direction of polarization on the value of magnetostriction in a wide frequency band were investigated. The magnetostriction of composite cores and solid Terfenol-D samples was also compared. The structure and the use of magnetostrictive cores containing a combination of NdFeB magnets and pure Terfenol-D are also presented. An important issue was also the development of our own methodology of magnetostriction testing, including the use of fiber optic sensors (Fiber Bragg Grating sensors, FBGs), Hall's sensors, and the original measuring system for magnetic field visualization (Magscanner). The chapter also discusses several own designs of actuators and energy harvesters, including shock harvester, resonant harvester, and energy transmission system.

Keywords: magnetomechanical cross-effect, smart magnetic materials, magnetostriction, Terfenol-D, magnetostrictive actuators, frequency response, energy harvesting, harvesters

1. Introduction

Materials called/classified as smart materials (SM) have already formed a large group of new construction materials. The phenomenon of smart materials is based on the fact that their main properties, expressed as a physical unit (i.e., mechanical field), depend on some other unit (i.e., magnetic, electric or temperature field). Therefore, in the description and application of these materials, cross effects are the crucial factor. A significant group of SM is materials that present their main application characteristics based on magnetic stimulation (smart magnetic materials, SMM). The following materials should be mentioned as the representatives of the group: magnetorheological, giant magnetostrictive and magnetoresistive, magnetocaloric, shape memory magnetically activated, etc. It means that the diverse properties of SMM—including, for example, viscosity, shape, stiffness, temperature, electric resistance, color—can be modified with use of magnetic stimulation. In this chapter, the possibilities of using one of SMM groups, namely giant magnetostrictive materials (GMM), are presented.

The following subjects are described in this chapter:

- Development of the concept of GMM actuators in terms of applications as a vibration exciter or active vibration damper.
- Application of the inverse magnetostriction effect (called Villari-effect) for energy harvesting devices
- Preparation methods of composite magnetostrictive rods: GMM composite (GMMc): as magnetic active cores
- Application of fiber Bragg gratings (FBG) technique in online measurement of the magnetostriction level in strong magnetic field environment
- Testing method of resonators cores using impact as energy harvesting power sources for the standard microcontroller dedicated to wireless nodes
- Construction of high-power actuator with a real-time PID magnetostrictive regulator to compensate self-thermal effect

2. Magnetostrictive mechanical resonators and their applications

The main goal described in this chapter is to develop a methodology for designing and testing broadband resonators. This methodology should offer a better understanding of both actuators and energy harvesters, including those working alternately as one device. One of the most important issues to solve is obtaining mechanical resonance in a wide frequency band, which would allow the use of resonators in any mechanical construction.

It turned out that one of the materials exhibiting the so-called giant magnetostriction effect is Terfenol-D [1, 2], which might be very useful in solving this particular issue. Thanks to its unique properties, the material allows the conversion of magnetic field energy into mechanical energy, using a magnetostriction effect. The effect is reversible and allows the conversion of mechanical energy into magnetic energy using the Villari effect. Therefore, Terfenol-D is widely used in a variety of applications such as construction of actuators [3–5], sensors [6], and so-called energy harvesters [7].

Unfortunately, despite their numerous advantages, solid materials also have significant drawbacks, among which the most important ones are as follows: the presence of strong eddy currents as a result of cyclic loading at high frequency of work [8], and low tensile strength. In order to eliminate these drawbacks, researchers are trying to produce new materials, such as polymer composites containing powdered Terfenol-D [9–14].

2.1. Actuators based on Terfenol-D

The Department of Mechanics, Materials Science and Engineering has been associated with the area of magnetic SM since the early 1990s. The first research related to this type of materials was mainly related to liquids, especially magnetorheological fluids. However, in subsequent years, this interest became more and more widespread, and as a result, a few years later, a great deal of attention was also paid to other materials, including the so-called giant magnetostriction. As it was mentioned before, Terfenol-D is a representative of such materials. The first work related to the research on this material allowed the design and manufacturing of the actuator whose core was the solid Terfenol-D. **Figure 1** shows one of the earliest magnetostrictive actuators called "singing table" which was designed by the authors.

Although the actuator presented in **Figure 1** was used mainly as a demonstration object, it allowed to show how the magnetostriction phenomenon works in an accessible way. Based on this first construction, the actuator construction was improved and modified in such a way that it could serve as an executive element in a prototype research stand. A new type of actuator made it possible to damp the vibrations of the construction with the use of counter vibration. Thanks to this, the vibrating wave of the opposite phase was adjusted to the natural

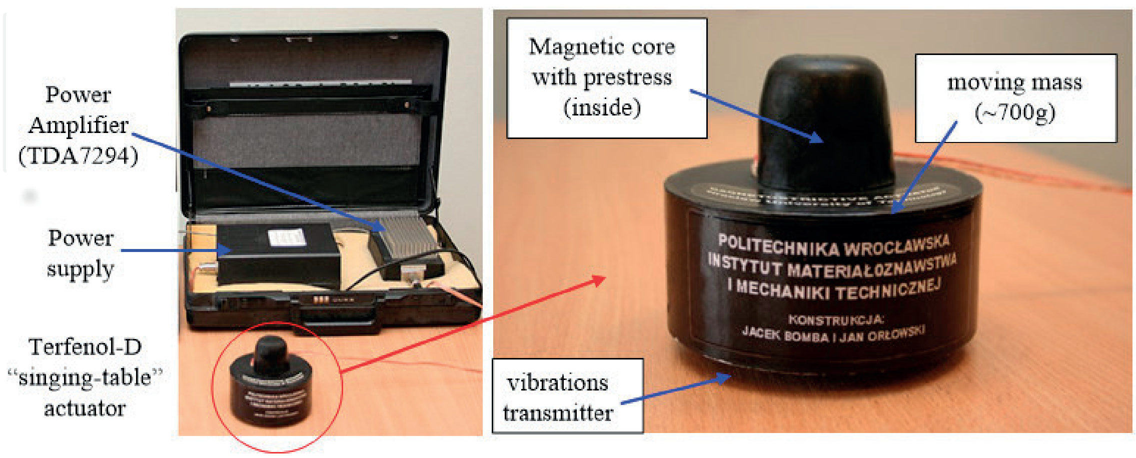

Figure 1. Vibration exciter system (singing table) as the first step taken by the authors' team to magnetostrictive technology [15].

vibrations of the structure, which caused the damping of vibrations and ensured the stability of the entire structure. **Figure 2** presents the second type of a Terfenol-D-based actuator dedicated for dumping mechanical vibrations in a low-frequency band (50–1000 Hz) [15].

2.2. Reversible effect actuators selected for energy harvesting

Energy harvesting (EH), in primary sources known also as power harvesting or energy scavenging, is a set of methods allowing to generate electrical energy using surrounding sources, such as mechanical, thermal, solar and electromagnetic energy, salinity gradients, etc., for example, [7]. Generally, the goal is using sources commonly available in the environment (so called background energy) which are undesirable and usually are suppressed (e.g., noise, impact and mechanical vibration of devices and constructions, electromagnetic smog, frictional and combustion heat as well as heat obtained as a result of electric current flow and engine cooling) or commonly available (solar light, wave energy, salinity differences, biochemical processes in, e.g., plants) and also related to human biology (motion, body heat, etc.). Currently, it is assumed that EH can be an effective source of "cost-free" (apart from installation costs) power supply for low power devices (e.g., electronic devices, sensor systems). It is assumed that in the future vast harvester networks will also be used as large power energy sources.

Magnetostrictive harvesters and actuators are constructed using physical cross effects based on magneto-mechanical phenomena. It is assumed that even in terms of low power and efficiency (albo: in the case of low power and efficiency techniques) they can be a valuable source of power supply. In low-power techniques, it is assumed that harvesters work as typical power supplies that are connected by a wire to a microprocessor subsystem (μC) which after supplying power sends data wirelessly to a unit receiving and processing information according to its operation algorithm (program code).

The principle of EH is to create a new concept of voltage generators which will use cross effects including the magneto-mechanic one. The assumption is that even though EH using the magneto-mechanical effect can provide only small powers or efficiencies, they can become valuable sources of energy. Special attention has been paid to this issue for the last few years in the biggest research institutes all over the world, especially in the USA and quickly developing Asian countries. The energy harvesting concept together with the development of

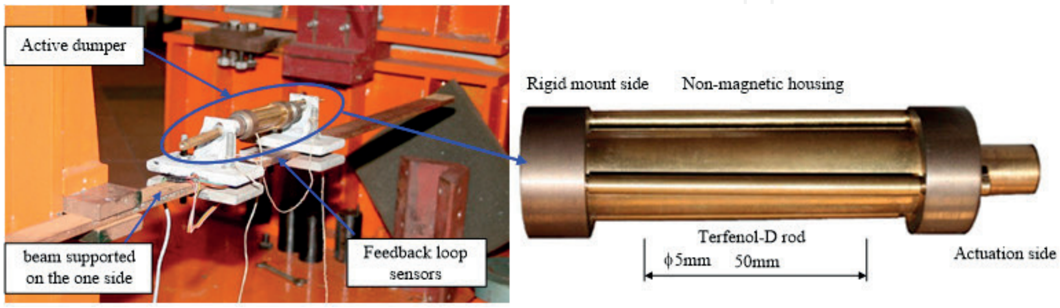

Figure 2. View of actuator as a part of the active dumping vibration system of calibrated mechanical beam [15].

energy recovering devices' (harvesters) development belongs to the field of alternative and renewable energy.

Taking into account the physical phenomena occurring during the energy exchange process, the construction and principles of work, and environmental conditions in a specified working area, harvesters (as sources with different electrical characteristics) can be divided into three groups:

- DC voltage harvesters (e.g., harvesters based on the thermoelectric effect),
- AC voltage harvesters (e.g., harvesters based on the Faraday effect or so called piezoelectric patches),
- Shock harvesters (e.g., harvesters with a magnetostrictive core).

In order to be able to design electrical circuits for harvesters, the knowledge of their working characteristics is mandatory. Only the ones based on the thermoelectric or photovoltaic effect can generate DC voltage. Those which regain energy from vibrations, magnetostrictive, piezoelectric or based on the Faraday effect are the sources of AC voltage. The scope of research related to energy harvesting conducted by the authors of the chapter is shown in **Figure 3**.

Harvesters supplied with energy from impacts [16] are a completely different type of devices. Electric energy generation lasts only for a very short period of time when it comes to the impulse power supply although its current amplitude is extremely high. Harvesters "supplied" with a mechanical shock generate various voltage outputs. However, they are considered devices characterized by strong current impulse and additional frequencies generated in

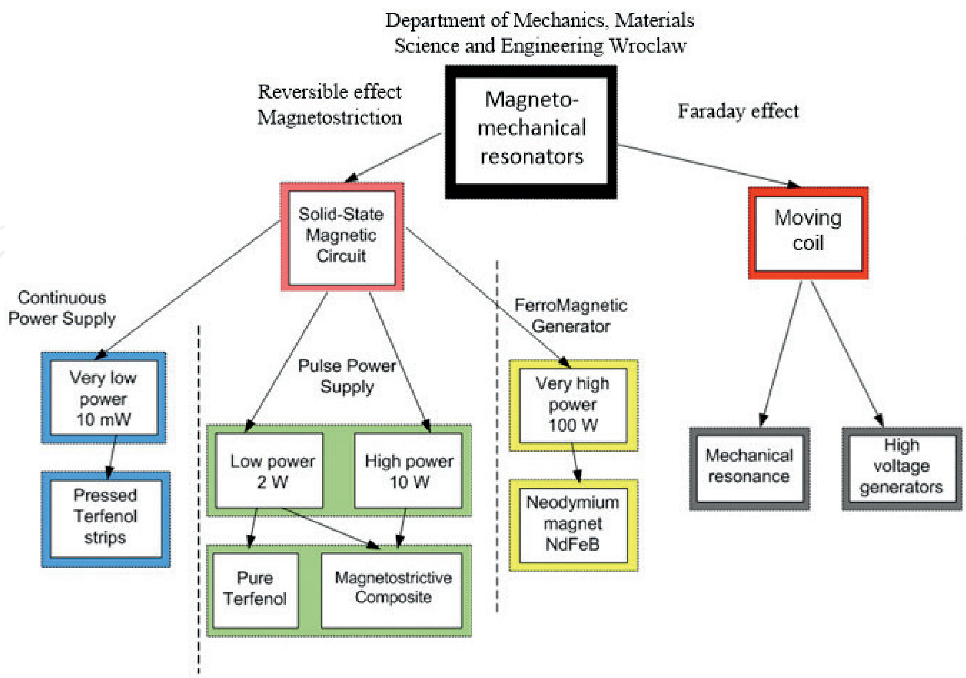

Figure 3. Structure of evaluating energy harvesting methods.

the signal which occur as a result of resonance in the core-coil system. In this chapter, a new method of electrical current generation due to the demagnetization of neodymium magnets in the circuits with magnetostrictive core is also presented.

Currently, a particular type of generators is harvesters from the explosive-driven ferromagnetic generators (EDFMG) group. They generate the electromagnetic wave that occurs due to the instant demagnetization of a magnet caused by a mechanical shock which results from an explosion or another strong force impulse. In this moment, the magnet loses its magnetic properties, generating a strong impulse magnetic field in its surroundings. During the impact, even the total destruction of a magnet is possible; however, the amount of energy that is generated on a coil is huge and it is sufficient to charge high-voltage capacitors with a substantial amount of electric energy.

The new concept of the harvester was developed based on the idea of a ferromagnetic generator (FMG) in which strong magneto-mechanical phenomena occur, including the demagnetization of strong neodymium NdFeB magnets in order to generate electric current due to a mechanical shock. One of the construction priorities was to standardize particular sizes and parts, so every single element of the harvester could be easily exchanged and disassembled. **Figure 4** presents the parts of the harvester.

It has to be remembered that the estimated efficiency value of the transformation between the mechanical shock, which occurs during the demagnetization of the neodymium magnets, and the electric current is about 0.2%. That is why, the main challenge is to improve power transformation. The so-called pulse power supply harvester constructions are shown in **Figure 5**.

2.3. Use of actuator-harvester circuits to power up wireless network system

Harvesters which in their principle of work use cross effects are more frequently based on magneto-mechanical phenomena. It is assumed that even in the case of low power and efficiency; they can be a valuable source of power supply.

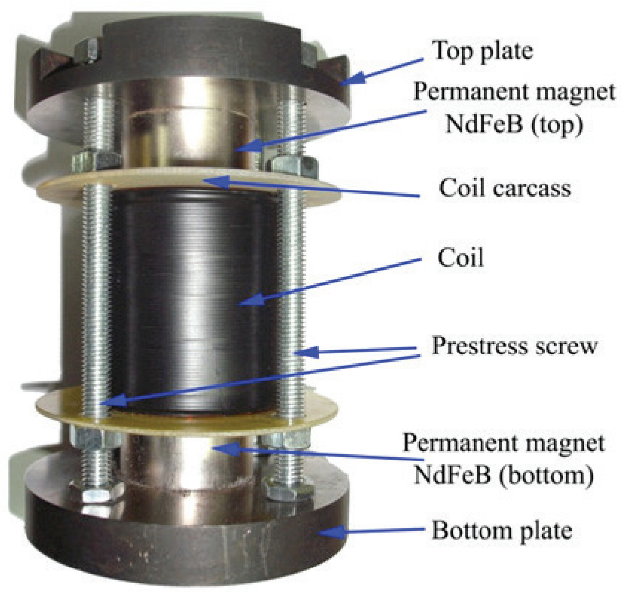

Figure 4. View of a shock harvester with description of its elements [16].

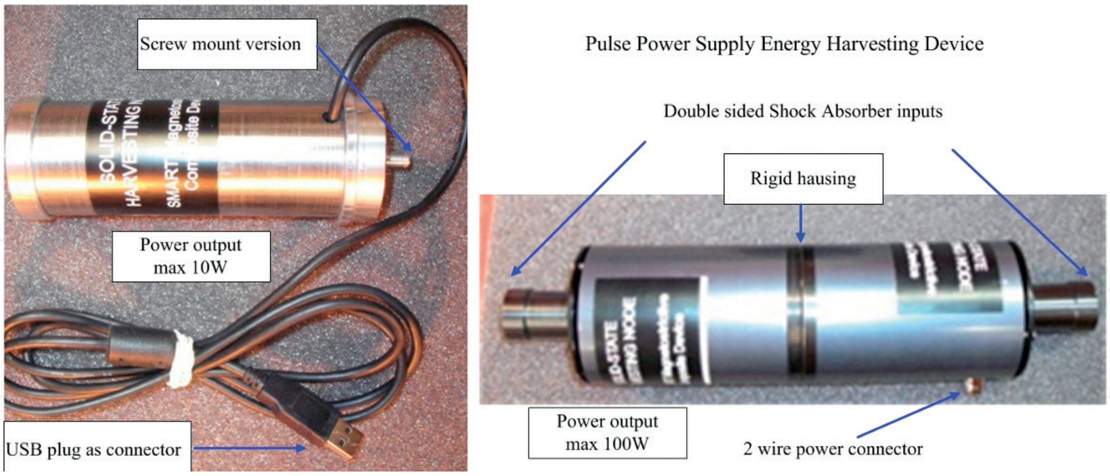

Figure 5. View of solid-state harvesters based on GMMc diameter of ϕ=5 mm (left) and ϕ=10 mm rod (right) for tactical grade versions of 10 W devices.

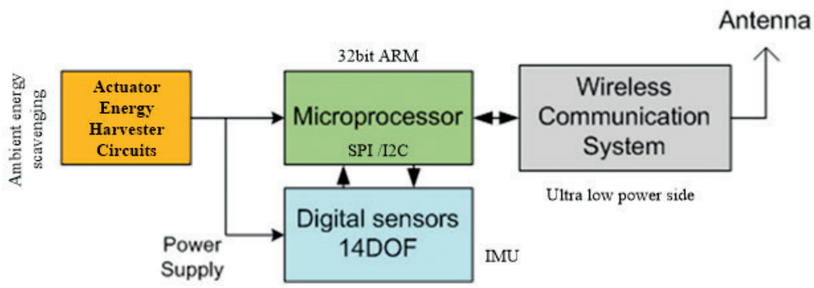

Figure 6. The structure of a wireless harvesting system with a 14 DOF block [17].

A multinode harvesting structure can be used in structural health monitoring (SHM) applications to recover electric power from wasted energy generated mostly from vibrations. Magnetic harvesters might also be used as a power source in SHM systems which monitor large mechanical structures. Our latest system presents this solution. It uses 14 MEMS sensors with designated 14 degrees of freedom (DOF) (3D accelerometer, 3D gyroscope, 3D magnetometer, barometric pressure sensor, microphone, temperature T, humidity R, light intensity). The structure of the system is shown in **Figure 6**. The software designed by the authors allows to monitor the parameters provided by 14 sensors via a webpage or in a service mode. The software is designed to support such systems as an ADIS16488 module and other components of the most precise IMU (Analog Devices iMEMS 2016). In order to process the data received from the 14 DOF sensors, which includes not only measuring the certain physical value but also monitoring the level of recovered energy, proper microprocessors had to be chosen (an important factor here is power consumption).

Figure 7 shows three typical sources of low-frequency energy harvesting: mechanical shock wave (**Figure 7A**), low-frequency mechanical resonance (**Figure 7B**) and energy transmission through ultrasonic resonant vibrations (**Figure 7C**). A properly selected conditioning circuit provides the harvesting system with useful current and voltage capabilities. The creation of a wireless node to measure certain physical quantities and to monitor the level of recovered energy requires the selection of an appropriate hardware platform, such as a microprocessor and a wireless transmission system. The use of SM in wireless power transmission turned out

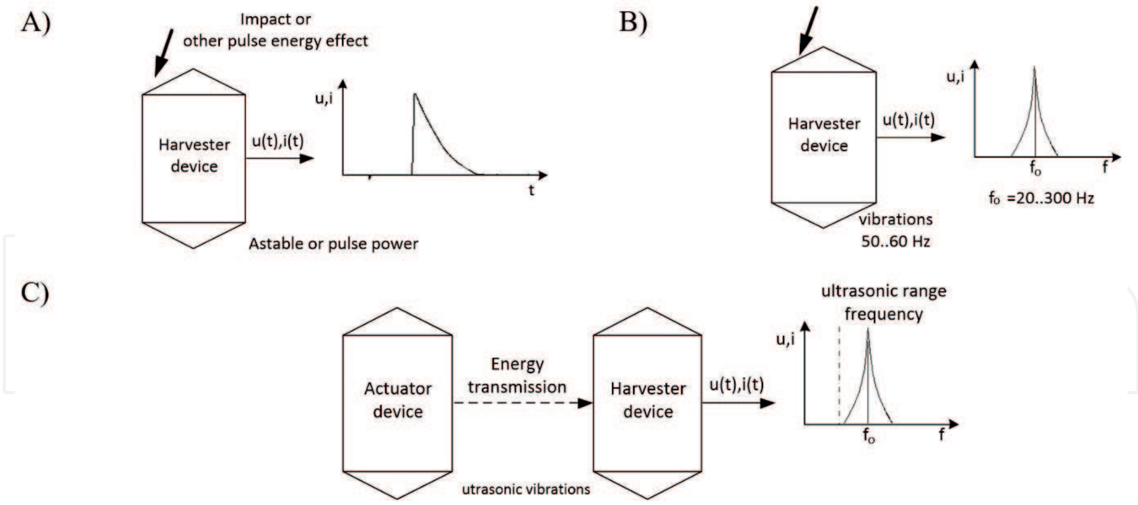

Figure 7. Energy harvesting sources and their power requirements: (A) mechanical impact, (B) low-frequency mechanical resonance and (C) energy transmission by ultrasonic vibration [17].

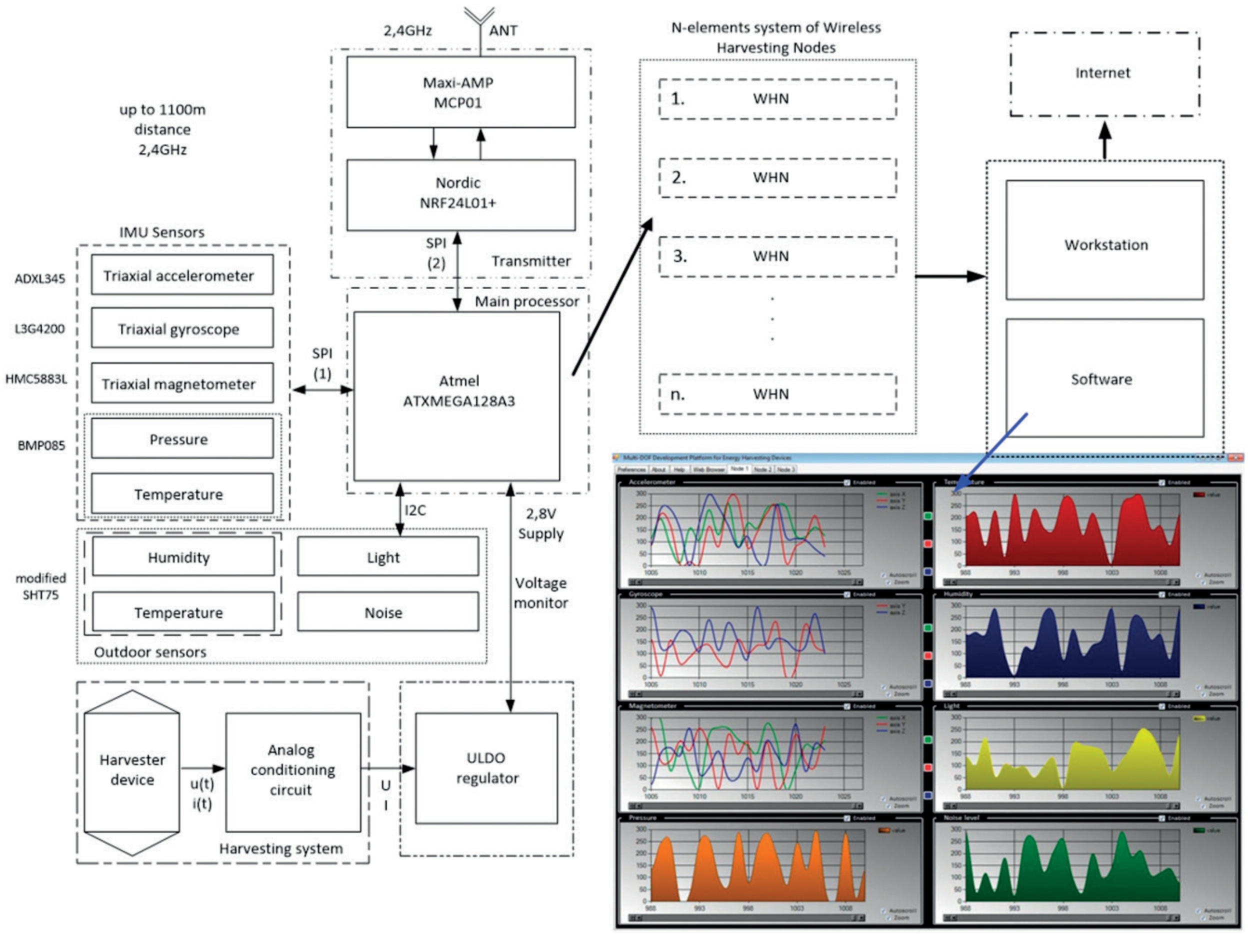

Figure 8. Prototyping of multi-DOF wireless sensors platform: Main communication station and Multi-DOF software [17].

to be effective. For this purpose, Smart Ultrasonic Resonant Power System (SURPS), a system for simultaneous power and data transmission, was developed. It ensured transmission through various media (solid, liquid) and with various transmitter-receiver configurations [17].

After matching the sensor-microprocessor configuration with a suitable energy harvester, the whole packets, together with a wireless communication system, were placed in the nodes. Due to the fact that every node is equipped with the same wireless communication system, different types of sensors can be easily substituted or put together by the user, thanks to the dedicated software shown in **Figure 8**.

A properly selected conditioning circuit provides the harvesting system with a certain current and voltage output. The creation of a wireless node to measure certain physical quantities and to monitor the level of recovered energy requires the selection of an appropriate hardware platform, such as a microprocessor and a wireless transmission system.

3. The idea of the composite rod in the wideband actuator and energy harvester

Bearing in mind the justifiability of limiting the use of solid Terfenol-D in the construction of magnetostrictive resonators, two solutions are presented below, namely the use of a GMM composite core and—in Chapter 4—a core consisting of a neodymium magnet and Terfenol-D.

3.1. The preparation of GMM composite

Referring to price of Terfenol-D which is a relatively expensive material, a device which would not require this material would be adequately cheaper. The brittleness of pure Terfenol-D can be replaced with a composite material [7].

A prospective application area for Terfenol-D, which is a typical representative of the GMM group, is (electric) energy harvesting from, for example, mechanical vibration systems [18, 19]. However, some of the applications of this material are restricted due to eddy current loss at a high frequency. In addition, it has some drawbacks, such as intrinsic brittleness accompanied by maximizing the fraction of the brittle, Laves phase. The magnetostrictive composite materials have been developed as an alternative way to overcome both the eddy current loss and intrinsic brittleness since 1990.

The main advantages of magnetostrictive composites based on a nonmagnetic polymer matrix and containing Terfenol-D powder particles are as follows:

- reduction of solid Terfenol-D’s drawbacks (eddy currents at higher operating frequencies and its brittleness limiting its use under, for example, tensile stress [1, 20], whereby its application range is significantly extended,
- new potential applications in, for example, (SHM) composite materials and structures (tagging) [21].

Therefore, the main goal of this research was to investigate the magnetostriction of a field-structural composite with Terfenol-D particles. The composite should replace the solid Terfenol-D rods in an actuator or a damper. It was decided to closely examine the effect of the (perpendicular, parallel, without polarization) direction of composite polarization and different frequencies of magnetic field stimulation. The results were compared with those obtained for solid Terfenol-D samples with the same geometry.

In the study, a magnetostrictive composite was used (hereafter referred to as GMMc). It was prepared in the Department of Mechanics, Materials Science and Engineering at Wroclaw University of Science and Technology. The composite was made by combining an epoxy resin and Terfenol-D powder (GMM material).

- The first step was introduction of a hardener to the epoxy resin.
- The next step was the addition of a properly measured amount of Terfenol-D powder with a grain size of 0–300 μm (according to the manufacturer, Gansu Tianxing Rare Earth Functional Materials Co., Ltd.).

Specimens presented in this work contain 70% of Terfenol-D particles volume fraction, and they have different polarization directions. For each case, the particles and resin were homogeneously mixed together and deaerated. Moreover, one of the samples was polarized perpendicular, and others were polarized parallel to the main axis of the specimen. This effect was obtained by using permanent magnets and coil during a composite curing process, respectively.

The container with the mixture was placed between two magnets or inside a coil and after that it was placed on an MTS hydraulic pulsator, where samples were pressed with a force of 10 kN for 4 h until the preliminary resin binding started. This process allowed to reduce the excess of epoxy resin from samples and to obtain a high volume fraction of Terfenol-D particles. The schemes of these processes for perpendicular and parallel polarized specimens are shown in **Figure 9A** and **Figure 9B**, respectively. Additionally, one of the specimens was cured without any source of a magnetic field.

After 24 h preliminarily cured specimens were placed in an oven at 70°C for another 24 h to ensure the full cure of the epoxy resin. Samples produced in this way contain a small portion of pores, which confirms the good connection of powders with resin. The polymer material provides a good magnetic insulation of the Terfenol-D powder grains and prevents its oxidation.

3.2. Experimental determination of GMMc parameters

To determine if the polarization applied during the curing process to the manufactured composites made any changes in the magnetization of specimens, the magnetic scans of their surfaces were made (**Figure 10A** and **Figure 10B**). The scans were obtained with the use of the innovative system of Magscanner described in [23]. The results show clearly that there is a difference between the manufactured specimens with different types of polarization. The magnetization layout along its main axis for the parallel polarized specimen (**Figure 10A**) is even as evident, as the one contrasted with the parallel polarized specimen (**Figure 10B**). This confirms that polarized samples preserved the direction of the desired magnetization.

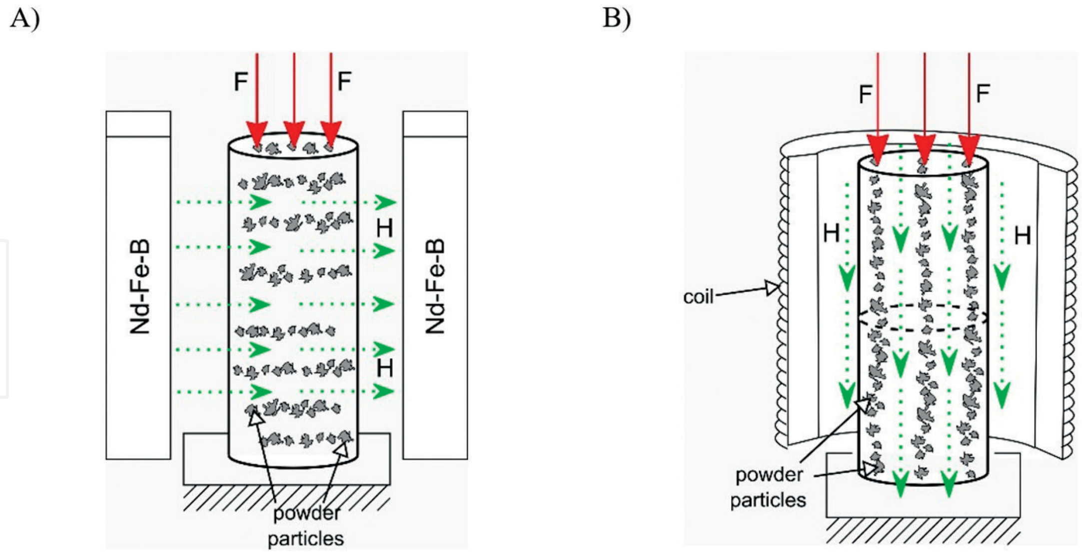

Figure 9. Schema of perpendicular (A) parallel (B) polarization to the main axis of the sample during curing process. F—direction of force during curing process, H—direction of magnetic field during curing process [22].

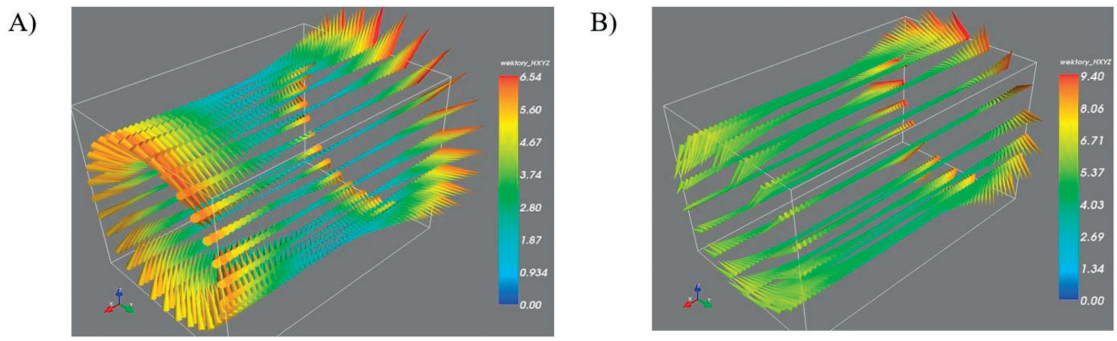

Figure 10. 3D magnetic vector fields around perpendicular (A) and parallel (B) premagnetized Terfenol-D composites [22].

The experiments methodology involving the quasi-static measurements of the magnetostriction of the produced composites and the measurements made for different magnetic field frequencies is shown later.

The magnetic field strength acting on the magnetostrictive composite was dependent on the strength of the current in the coil. The magnetic field was generated by an adjustable power supply unit (0–30 V, 20 A). The magnetic field strength range H was limited by the magnetic circuit and amounted to 0 ÷ 168 kA/m. The measurement was conducted with the use of the Hall's sensor (placed inside the coil), for both positive and negative H values to check the evenness of the phenomenon in the composite samples. Sample displacement $\Delta\lambda$ was measured using the innovative method of fiber Bragg grating (FBG) sensors. In this way, the influence of the electromagnetic field on the results was eliminated. The FBG method is described in more detail in [24]. The strain sensors were placed directly on the specimens, as shown in **Figure 11**. One of the sensors was placed along the main axis of the specimen while the other one was attached to the sample circumference. The aim of such a sensor arrangement was to

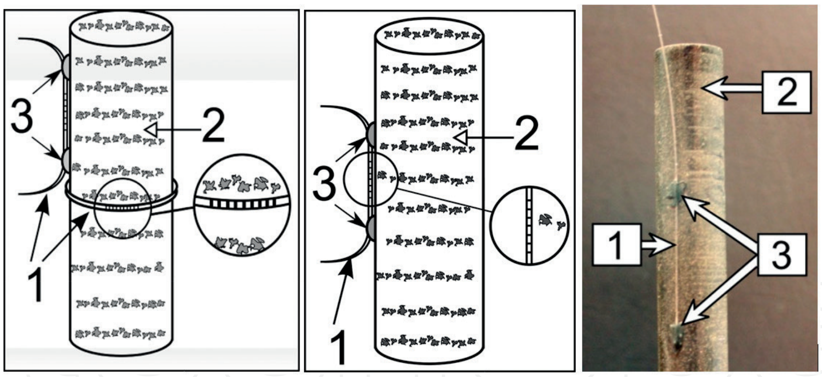

Figure 11. Arrangement of the strain sensors on a sample: 1—Sensors, 2—Specimen, 3—Glue [22].

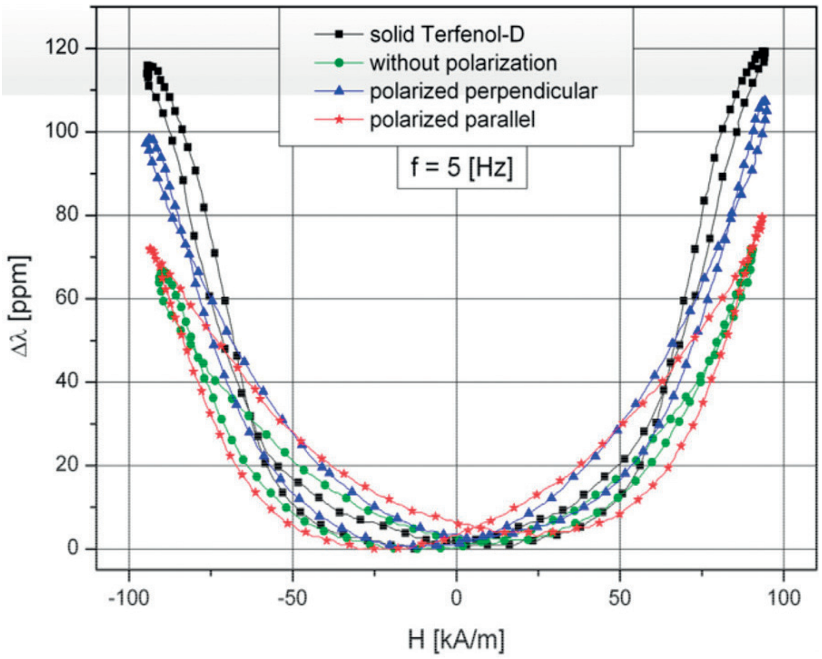

Figure 12. Comparison of magnetostrictive dependence from magnetic field intensity H, at frequency f = 5 Hz, for composite specimens and solid Terfenol-D [22].

check whether the volumetric magnetostriction occurs in the material apart from the linear magnetostriction.

In addition, changes in the value of the magnetic field during the same test were presented in **Figure 12**.

4. Designing of magnetostrictive core for solid-type resonators

In this chapter, the problem of cores built with neodymium magnets and Terfenol-D and impulse power supply for the microcontroller is discussed.

4.1. Coupling of NdFeB magnets and Terfenol-D in the resonator core

The idea of the Top Core Coil Magnet (TCCM) actuators and reversible harvesters appeared in the Department of Mechanics, Materials Science and Engineering laboratories. The basic model of unique TCCM system is shown in **Figure 13**. The model called TCCM is a construction combining four major elements: Top whose role was to transfer shock to the core, Coil, Magnet and Core which determines the processing energy of impact (obtained from the Top part) into electricity. The TCCM harvester is the simplest form of the implementation of the harvester based on the core placed in the coil with a fairly large number of coils in the magnetic field of the NdFeB magnet. Low rigidity and low resonance frequency at the moment of impact describe the system without the prestress.

The range of measurement and devices used to perform the testing of actuator/harvester response is presented below:

- IXFN20N200, MOSFET by IXYS, a fast transistor for linear motor was used to provide the speed of a defined value for moving aluminum frame
- Encoder strip coupled with a reader by Sharp Company, path measurement system of 720 dpi resolution;
- Hi-speed, Hi-power linear motor-dumper up to 20 N hammer used to provide impact energy;
- PZT sensor used to measure force signal in the place of mounting;
- (TMS320C6701 DSP) Hunt Engineering Heron System by Texas Instruments, with GFLOPS performance at a clock rate of 167 MHz, used for high-performance DSP programming. It possesses the operational flexibility of high-speed controllers and the numerical capability of array processors. The processor has 32 general-purpose registers of 32-bit word length and 8 highly independent functional units;
- The Heron HEPC8 Module Carrier Board is a PCI form factor module carrier board supporting up to four Heron modules which can be multiplied. HEPC8 provides 32-bit first-in, first-out (FIFO) buffers between each module slot and the other module slots on the board for data transfer between Heron modules;
- Laser switch by Balluff Company used to trigger the start of acquisition;
- PicoPower Evaluate System v0.8 2010, PicoPower Processor Development Platform by the Institute of Material Science and Applied Mechanics of WrUST, designed in the Institute as the main testing system;
- Capacitors by EPCOS Company of 2.2uF.

The scheme of the test stand for the shock test TCCM harvesting system based on a high-speed linear motor is shown in **Figure 14**.

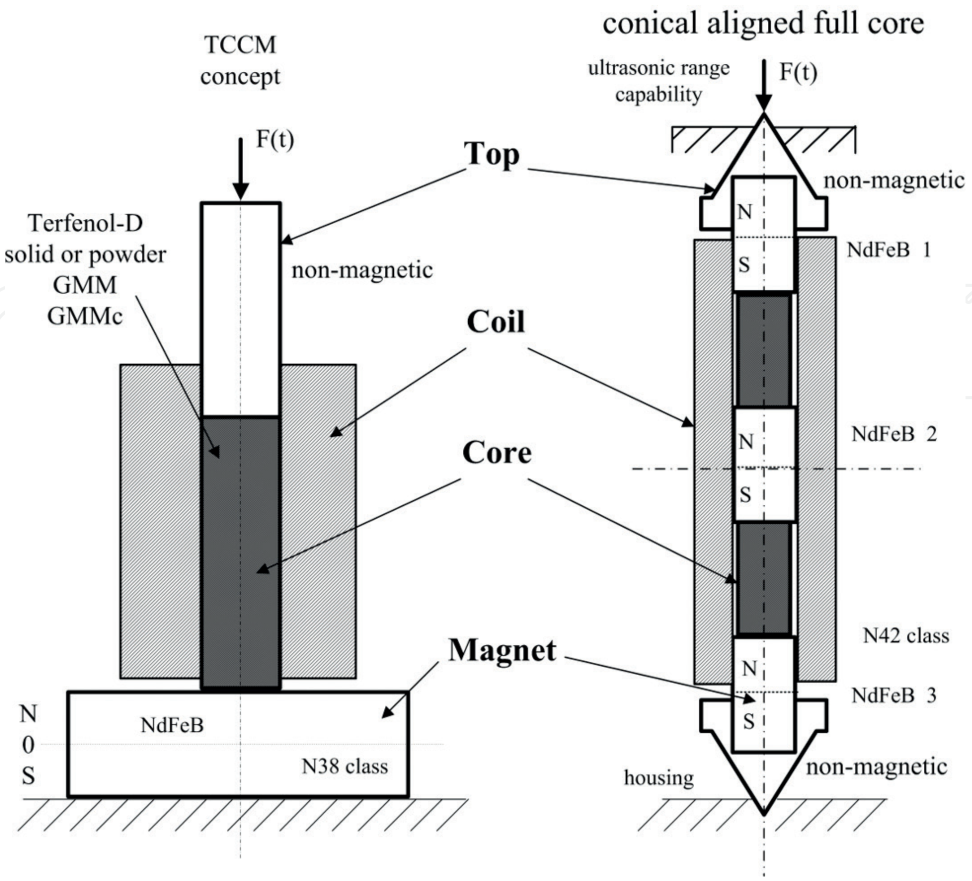

Figure 13. Scheme of the magnetostrictive core used as reversible effect resonator in energy harvesting devices [16].

The TCCM device was fixed with a PZT sensor in the horizontal orientation on a nonmagnetic, hard surface. In the main axis of the device, at the distance of 80mm was the aluminum hammer. Its speed accelerates to a defined value due to the fast linear motor transistor MOSFET. The speed of hammer was measured with an encoder strip coupled with a reader. The energy of impact was controlled by weights attached to a linear motor moving element. The maximum weight that could be used to accumulate energy is 2 kg. Due to the small size of a harvester, a beater load of 0.5 kg was used. The high reproducibility of the hammer speed and run-off place of the transistor MOSFET were obtained for that test stand, which resulted in the stability of impact energy E_k.

The shock force was applied to the TCCM device and, as a result, the impulse response of system was registered, as shown in **Figure 15**. Upon the analysis of this signal, the waveform was divided into phases. The first phase occurs before the strike, where the increase in voltage is present as a result of the motion of ferromagnetic hammer in the neodymium magnet's magnetic field. After the strike moment, wave motion passing through the top and the core to the neodymium magnet occurs and creates a string change of the magnetic field of the system, which causes the induction of the voltage resulting from the mechanical resonance frequency of the TCCM harvester.

Only the top and coil materials have an influence on the resonant frequency. The wave that passes through the material inside the coil either circulates repeatedly in the steam-core-magnet system or comes out of the harvester if the magnet has contact with the other surface,

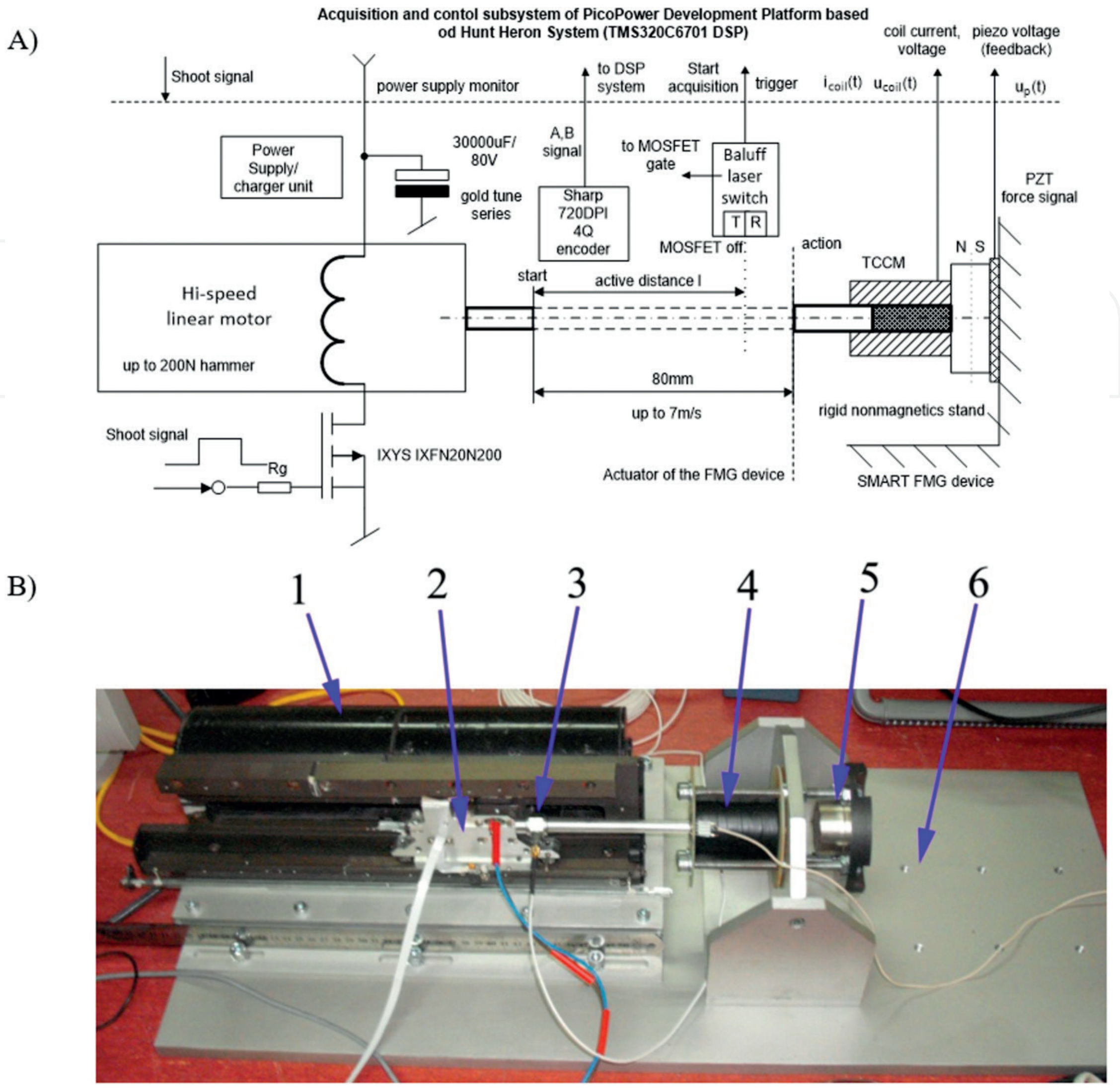

Figure 14. The schema of test stand to determine magnetostrictive core parameters (A): (1) linear motor, (2) movable trolley of a linear motor, (3) piezoelectric force sensor, (4) inductor, (5) NdFeB magnets used for constant magnetic field generation around the inductor, (6) base plate with the inductor position regulation. View of the test stand (B) [16].

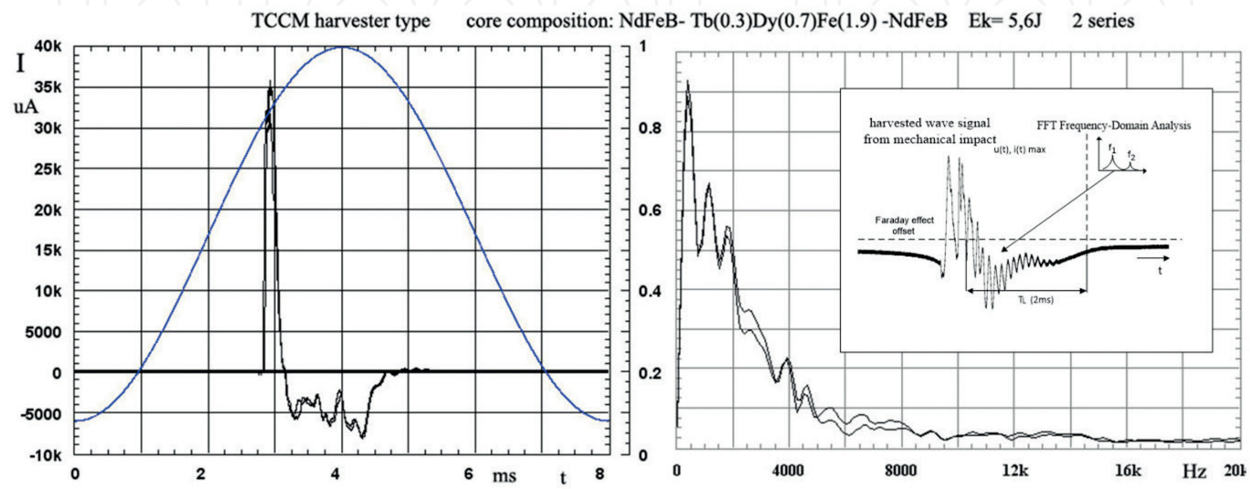

Figure 15. The current coil measurement for bulk Terfenol-D and its FFT plot.

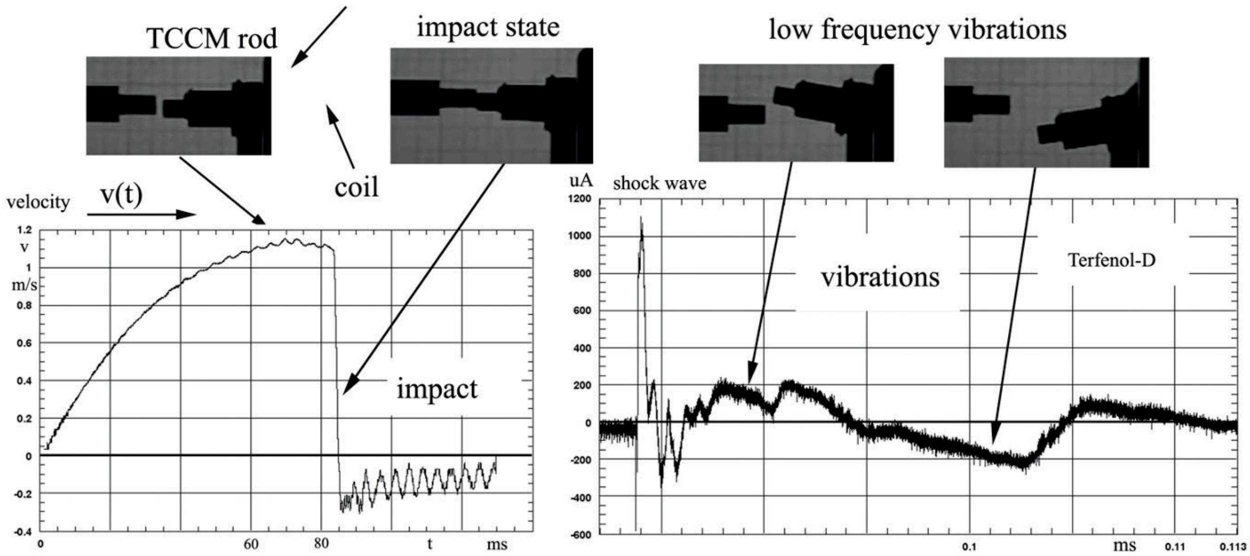

Figure 16. Photo series of mechanical impact correlated with velocity and pulse output voltage graphs.

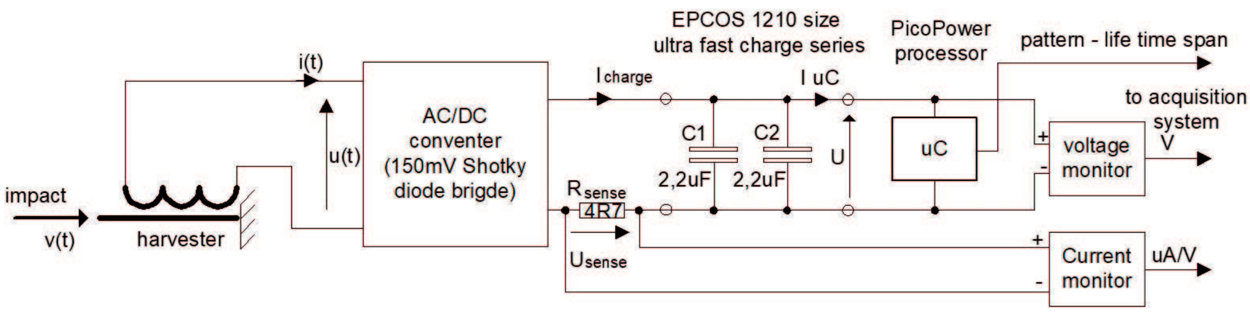

Figure 17. Supply current and voltage measurement scheme for detect life time span of powered μC [16].

but it is not transferred to this coil. The crucial effect in the operation of the top-coil-magnet system is the mechanical resonance effect of that system under impact. In **Figure 16**, the hammer impact chart of the TCCM harvester with correlated photos is shown.

In the TCCM type of Energy Harvester construction the calibration of prestess cores is not as critical as in vibrations exciter device. The prestress is obtained in the first phase of impact where the main maximum useable signal occurs. The significant increase in current and voltage occurs at the moment of the resonance frequency of the system. The value of this voltage depends on the number of turns in the coil when the same impact energy is applied.

4.2. Practical aspect of pulse power supply

The idea of a working harvesting device was not to supply continuous power for the microcontroller, but to provide a strong enough current pulse to quickly charge a high-capacity capacitor, see **Figure 17**. These capacitors were chosen in such a way that the processor voltage did not exceed 5.5 V. The role of the capacitor is very important, and hence, special capacitors which are able to capture the impulse current within a few dozen μF must be used.

As the practical application of the pulse power supply (PPS), the acquisition of lifespan of an ATMEL microcontroller based on the primary node was chosen. The ATMEGA48V system was used as a low-power processor. It is one of the most common microcontrollers in industrial applications. It could be started at a voltage level of only 1.8 V. It was powered by a DC of 1.8– 5.5 V, as an AC/DC system transducer on the rectifier used Schottky diodes. The signal acquisition and the control of the test parameters of the harvesting device, the AC/DC rectifier, a microprocessor and a base station were provided by a dedicated system.

In **Figure 18**, the current consumption by the system capacitors -μC type recorded as a reduction in voltage on measuring resistor R_{sense} = 4.7 Ω is presented. In the first phase, there is a very strong increase in current due to the initial charge on C1 and C2 capacitors (**Figure 17**), which are very heavy load on the signal generated by the harvesting device, followed by a decline in current consumption, given that it has not yet started μC. The "life time" algorithm of the program allows the microprocessor to send more than 50 pulses in a voltage range from U_{max} = 5 V to U_{min} = 1.8 V, which can be described as about 3 ms of μC life. By selecting various sources of the mechanical extortion obtained values of the microprocessor, one can cause pulses to rise up to 200 and the life time to extend to 8 ms. Based on the results, it can be found that an energy harvesting device (EHD) was developed. EHD is able to supply a popular microcontroller which realizes its code throughout the life of 3 ms from small impact energy E_k = 0.25 J. The core of this device was made of Terfenol-D powder.

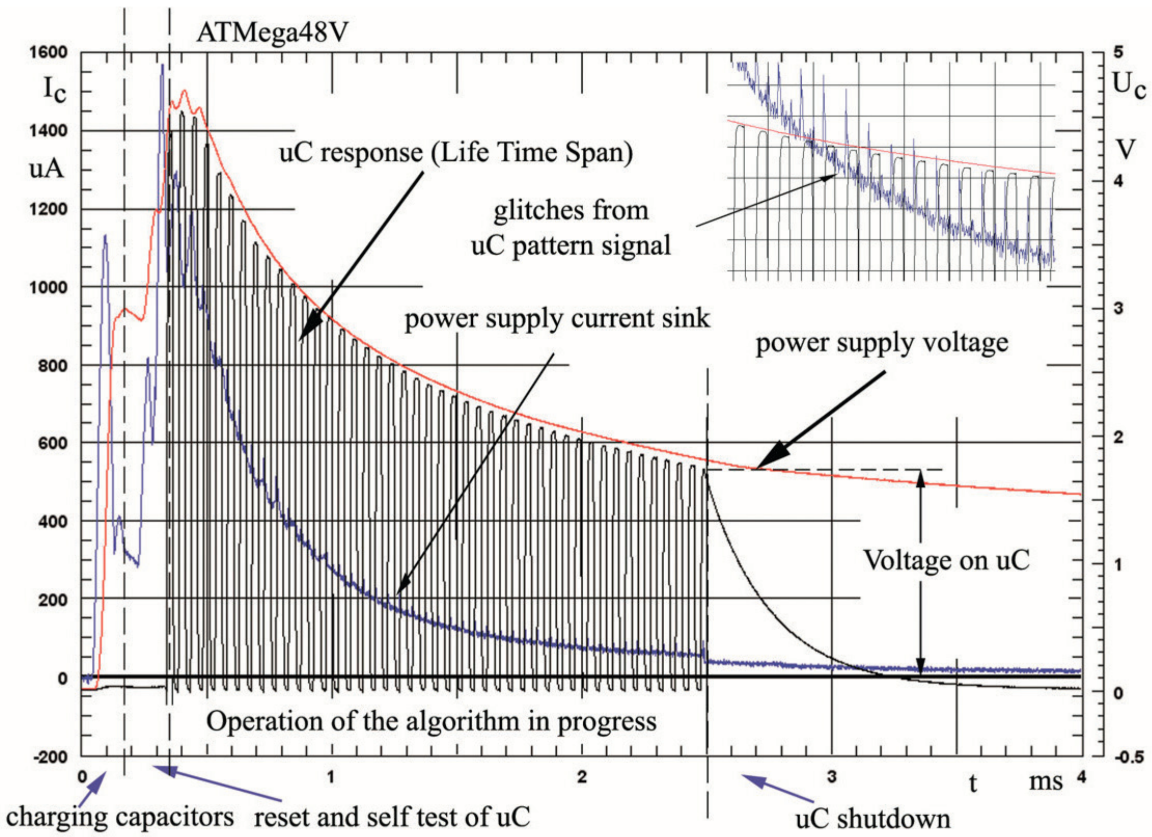

Figure 18. Life time span of microcontroller\circuit powered from energy harvesting device induced at low impact energy E_k = 0.25 J [16].

5. Construction of high-power wideband actuator

5.1. Design of classic magnetostrictive actuator dedicated for mechanical vibrations in selected frequency range

During the process of selecting the geometry of the actuator, the authors decided to use know-how gathered during previously performed computer simulations. To achieve the goal, they did not restrict the maximum value of the displacements obtained during test in any way. 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 DC powered for a longer time, the electromagnet coil generates a lot of heat. The heat should be dissipated as soon as possible. The main component of the system was the magnetostrictive composite material with Terfenol-D powder which was obtained in the way described in the previous part. The visualization of the parametric model of the actuator is presented in **Figure 19**. It can be observed that its structure is not very complex; however, it allows to obtain high values of the magnetic field

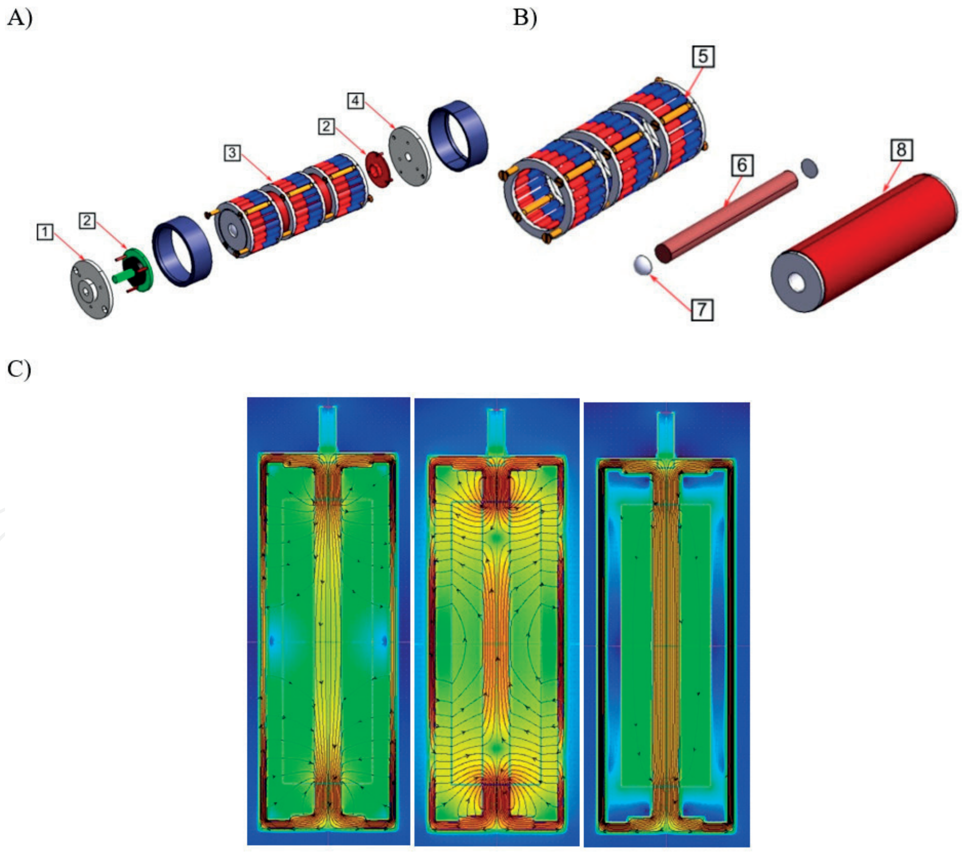

Figure 19. Construction of the basic type of magnetostrictive actuator for acoustical frequency band applications (A), magnetic core structure (B), simulations of magnetic field around magnetostrictive core and actuator body (C). Components define: 1-front cover, 2-rod centering alignment, 3-magnetic core, 4-back cover, 5-outer NdFeB ring, 6-GMM(c) rod, 7-alignment tip, 8-coil [22].

and provides 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 to spread the magnetic field uniformly and to prevent the excessive loss of the magnetic field inside the coil. Thus, the authors decided to use square plates which 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 was 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 the propagation of the magnetic field around the coil. The cylindrical shape of the connectors allows a more uniform distribution of the magnetic field and limits losses. Additionally, the number of connecting elements was chosen in such a way that they 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 the 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 its housing. However, it should be noted that the construction is compact and simple.

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

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

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 the usage of such an element is to reduce the potential friction that could occur between the upper rod of the actuator and the upper plate during system operation. It should be noted that although the elements which ensure the 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 high reduction of the parameters of the actuator and, what is more, it would influence the ability to control the device with the use of a feedback loop. In addition, the interior of the housing is protected by the elastic ring (which is not shown) whose main task is to ensure the prestress, that can be adjusted by lowering the connecting rods. The possibility to adjust prestress is very important due to its influence on the obtained magnetostriction value. A real construction of the actuator is shown in **Figure 20**.

5.2. High power actuators with magnetostriction feedback

Based on results described in the previous part of this chapter, a specific coil was chosen for the new type of actuator (**Figure 21**). This coil allows a relatively long time of work at a constant DC current level, and at the same time ensures the slowest growth of temperature. Due to the characteristics of the GMM material, the system test can be performed for a small value of the magnetic field which should be approximately 200 kA/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 in the magnetic moment of the material. Therefore, the control of the system allows to increase the current value, which causes the deformation of the material only in one direction, regardless of the phase of the magnetic field generated in the coil.

In addition, due to the necessity to measure the deformation of the actuator core made of a GMM, it was decided to implement the Fiber Bragg grating sensor. This solution allowed to increase the accuracy thanks to which it was possible to control the actuator and neutralize the effect of the electromagnetic field on the control of the device. It significantly helped during the preparation of the control algorithm. The use of fiber optic sensors forced additional changes in the design of the actuator which allowed to mount fibers directly into its core. At the same time, it was easier to measure the deformation of the sample.

The goal of testing was to obtain the quasi-static and cyclic properties of the actuator and check the possibility of using the feedback loop control of the actuator. The use of 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 20 Hz. For each test, a change of deformation of the composite core, at the corresponding values of the magnetic field, was recorded. The obtained data allowed to determine 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 a triaxial Hall probe and the deformation of the sample with a Fiber Bragg grating sensors. Additionally, during

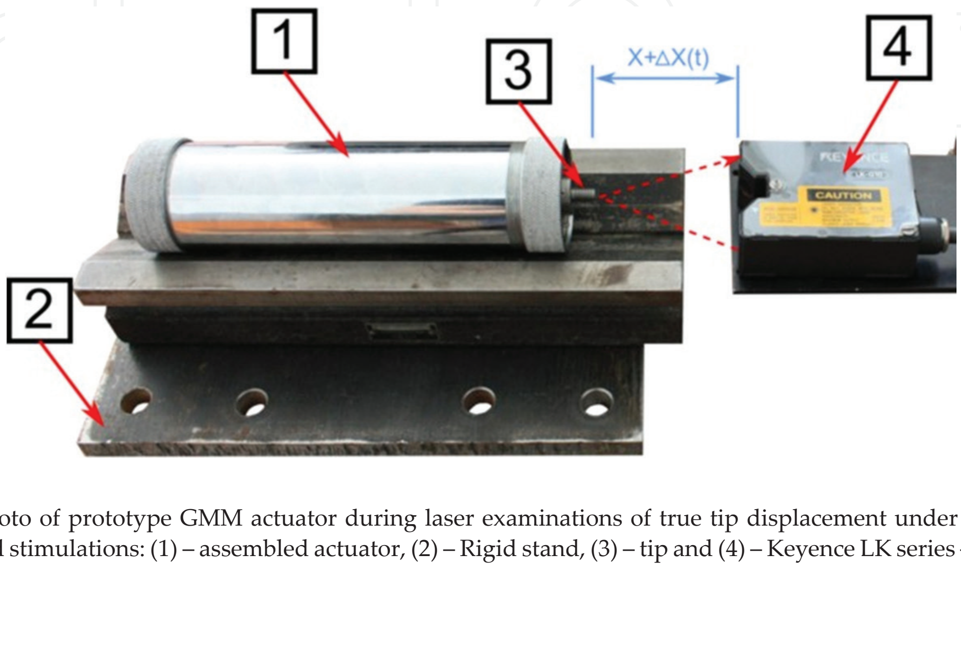

Figure 20. Photo of prototype GMM actuator during laser examinations of true tip displacement under programmed magnetic field stimulations: (1) – assembled actuator, (2) – Rigid stand, (3) – tip and (4) – Keyence LK series – laser sensor.

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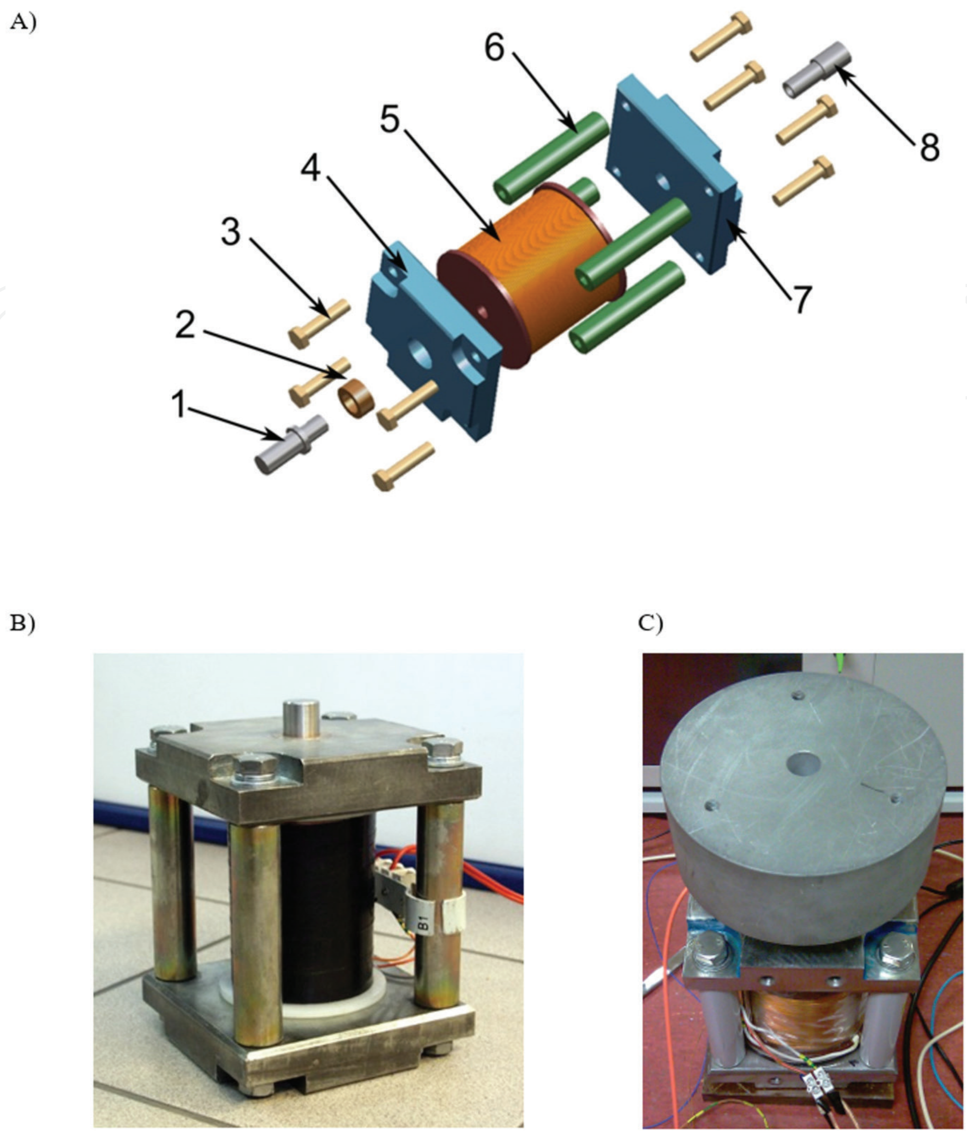

Figure 21. The high power actuator: model components (A): (1) – upper rod (actuator), (2) – Bronze sleeve, (3) – bolts, (4) – upper housing plate, (5) – coil with composite core, (6) – connection elements, (7) – bottom housing plate and (8) – bottom rod , the higher frequency version (low induction coil) (B), version with FBG and magnetic sensors for regulators of vibrations applications (C) [25].

the investigations the value of the prestress applied to the composite core was changed. This solution was proposed to check whether the value of prestress 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 a system, the controlled value is the value of magnetostriction. **Figure 22** shows the schema of the experimental system of the actuator feedback loop.

The same values of the pre-stress showed that it does not change the value of the magnetostriction of the composite material regardless of the test method (quasi-static or cyclic). In the following figures, a comparison of the performance of the actuator in the case of the application of the feedback loop system and without such a system is presented. The 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 200 N) (blue dashed line),
3. unloading of the actuator (red-dashed line).

Figure 23 presents the result of the deformation of the material in the actuator when the feedback loop system was off. The actuator was loaded with the weight of 20 kg. It is clear that under the influence of the applied load the value of the received magnetostriction decreased so did the active rod. Such a rod which can be used, for example, for control in various applications, did not keep its position. Moreover, in the case of the system without the feedback

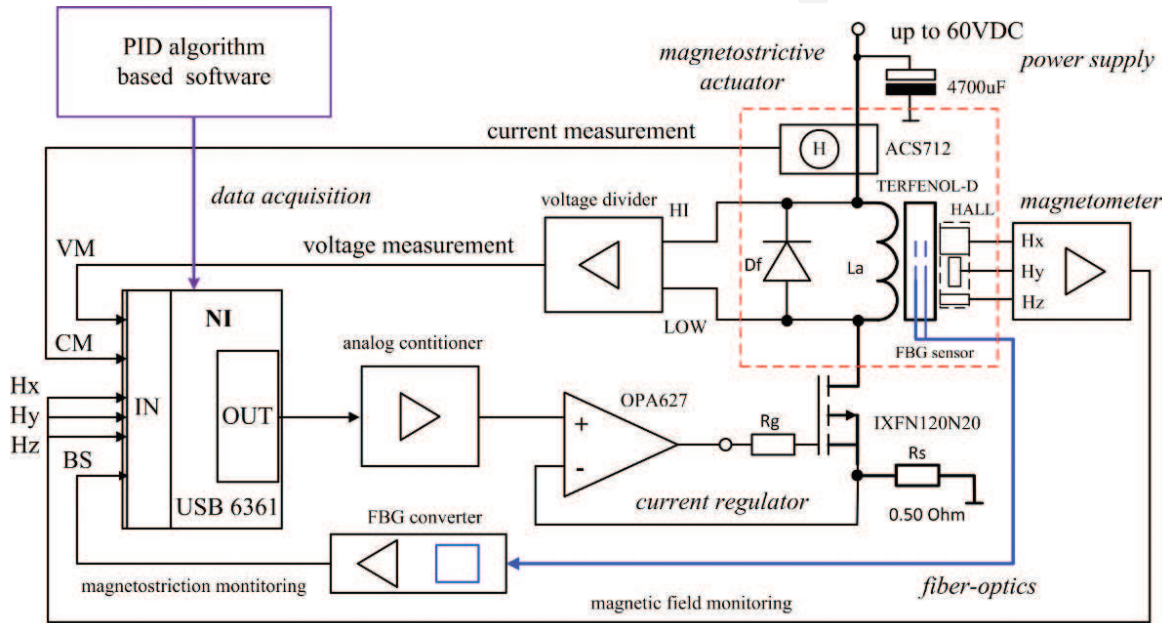

Figure 22. Schema of high power GMMc vibration exciter core that can be controlled using PID controller.

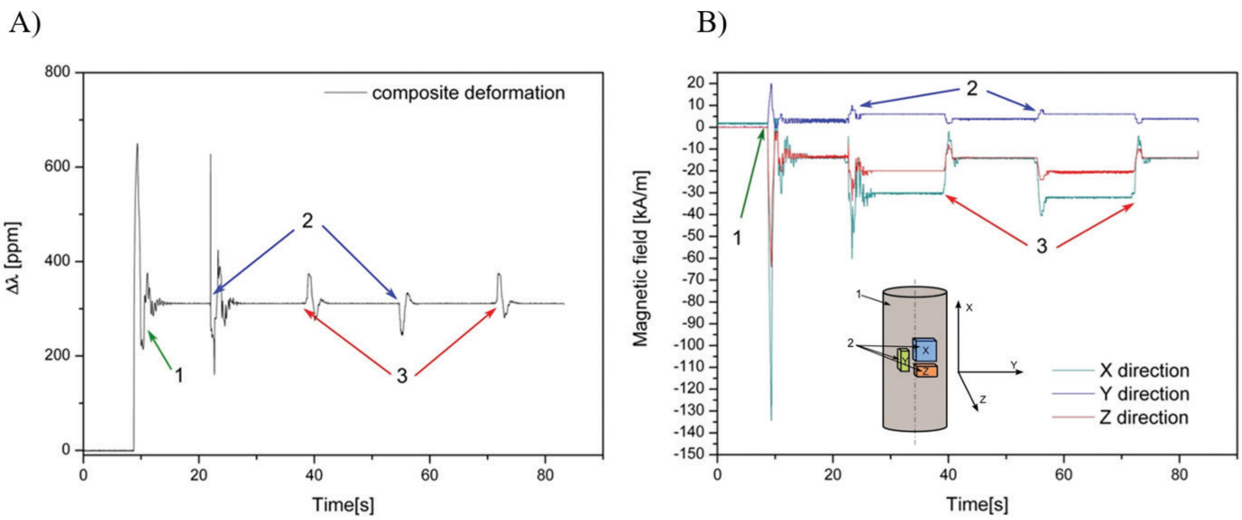

Figure 23. Deformation of the magnetostrictive rod with a feedback loop system (A), tri-axial magnetic field measurement using hall sensors attached to the sample: (1) – Sample, (2) – Sensors (B) [25].

loop, the value of the magnetic field did not change during the experiment, as it is shown in **Figure 23A**. This response of the actuator can be predicted.

The results show changes in the magnetic field recorder shown by each of the three Hall sensors placed inside the actuator coil. The measurement direction of the Hall sensors are as follows: X direction along the main axis of the sample, Z direction toward the sample and Y direction on the outside of the sample (**Figure 23B**).

Table 1 summarizes the most important parameters of the high power actuator.

The frequency response of the high power actuator is shown in the **Figure 24**.

Moreover, it is shown that it is possible to actively control the displacement of an actuator which is based on the magnetostrictive composite core with a feedback loop system. The control of such a system is based on the changes of the intensity value of the magnetic field around the composite core. In addition, through the use of fiber optics strain sensors, the measuring system made it possible to simplify the control of the deformation of the material. Certainly, it is still necessary to further develop this system to improve its parameters; however, at this stage one may say that it can be used in many different applications.

1.	Maximum DC current with forced cooling	10 A continuous, up to 80°C
2.	Maximum real power	400 W, 30% duty cycle
3.	Static displacement of tip as a unit step	More than 50 μm, 1 kN load
4.	Static impedance	3.8 Ω with terminal connections
5.	The range of permissible loading force	5 kN, only compression
6.	Useful frequency range	0–500 Hz

Table 1. The main operational parameters of the actuator (**Figure 21C**).

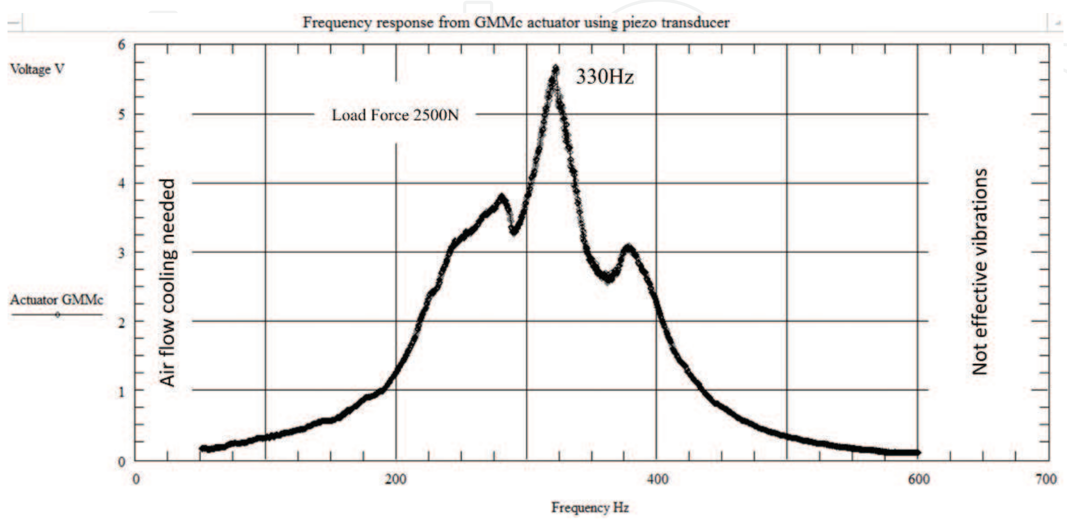

Figure 24. Frequency response of the high power actuator with FBG magnetostriction feedback.

6. Conclusions and final remarks

The chapter presents the design and test methodology of wideband magnetostrictive resonators, that is, actuators and energy harvesting devices. Detailed conclusions are presented below:

- The magnetostriction phenomenon as magnetomechanical cross-effect enables new concepts of the research methods for designing of effective actuators utilizing mechanical vibrations in a selected frequency band, even in an ultrasonic range.
- Similarly to piezo transducers, magnetostrictive cores allow to create sensor-actuator reversible devices. The choice whether the transducer is a sensor or an actuator is dictated by the amount of active material. In the smallest scale, even a sensor can be used as an actuator.
- The concept of a mechanical resonator has been introduced, which can be understood as an actuator or an energy harvester. A wideband actuator and a harvester can be the same device.
- By evaluating the effects of polarization direction, it was found that composites with perpendicular polarization show the highest magnetostriction value in comparison to the others, such as parallel polarized and the ones without polarization in the entire frequency range. What is more, at higher values of frequencies the response of the composite material was comparable with monolithic Terfenol-D, and this is why it can be suggested that the composite material provides the basis for applying it in actuating devices.
- The measurement of the deformation of the actuator core was carried out with implementation of the Fiber Bragg grating sensor. This solution allowed to increase the accuracy of measurements and neutralized the effect of the electromagnetic field on the results.
- The magnetostriction of the GMM composites achieved in this work can be further improved by more accurate fabrication parameters, especially by the investigation of polarization and differences in the volume fraction of particles. Moreover, research on different matrixes as binders could show if the behavior of a matrix-powder connection will have influence on the properties of these materials.
- Magnetostrictive cores based on NdFeB magnets and pure Terfenol-D or its replacement composites were designed and verified on the real constructions of devices. Testing methods and dedicated systems have been developed for applications both as a wideband actuator or as an energy harvesting device.
- The described method of energy transformation allows the usage of mechanical shock to generate the electric current. The current signal frequencies spectrum, generated in a coil due to the wave movement, is determined by the magnetic resonance frequency. This fact allows the selection of a specific harvester depending on the working environment frequency.
- The authors design and prototype various groups of harvesters, mainly with the magnetic core (“Pulse Power Supply”), for use as power supplies which are capable of producing tens of watts in a few milliseconds.

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Author details

Jerzy Kaleta*, Rafał Mech and Przemysław Wiewiórski

*Address all correspondence to: jerzy.kaleta@pwr.edu.pl

Department of Mechanics, Materials Science and Engineering, Wrocław University of Science and Technology, Wrocław, Poland

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