Applications of piezoelectric MFC type transducers in mechatronic measurement systems - the impact of a mechanical subsystem damage on a system operation

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Abstract. The work include a report of research works concerning applications of non-classical piezoelectric transducers in mechatronic measuring systems. Composite piezoelectric transducers called Macro Fiber Composite (MFC) are considered. Characteristics of considered transducers were made, indicating their advantages and disadvantages, as well as the results of carried out laboratory tests are presented, in which MFC transducers were used as sensors for mechatronic measurement systems. A series of laboratory tests was carried out on the created laboratory stand to determine the impact on the measured values of damage of the mechanical subsystem on which the MFC-type piezoelectric transducer was glued. Results of measurements are presented and analysed in relation to different applications of the piezoelectric MFC sensors.

1. Introduction
Piezoelectric materials are finding an increasing number of applications in modern technical devices due to the number of advantages that this type of intelligent materials is characterized by. One of these advantages is the ability to directly convert both electricity into mechanical work by a piezoelectric transducer powered by alternating voltage (inverse piezoelectric effect), and the ability to generate an electric charge under the influence of mechanical loads to which the transducer will be subjected (simple piezoelectric effect). For this reason, piezoelectric transducers can be used both as actuators and driving elements, as well as sensors. The progressive development of materials with piezoelectric properties is aimed at improving their efficiency of energy transformations underlying the operation of piezoelectric transducers. Starting from the classic ceramic transducers, e.g. PZT type, where the disadvantages limiting the field of their potential applications are the fragility of the transducers and their large mass, in the course of research and scientific work, flexible and highly efficient composite transducers were developed. These types of transducers include piezoelectric films. An example of this was the development of composite piezoelectric transducers. In 1996, the American Langley Research Center invented cheap, innovative piezoelectric composite transducers designed, among others, to control vibrations, noise and deviations in structural composites of beams and panels, as well as to recover electrical energy from mechanical vibrations. The developed piezoelectric transducers are called Macro Fiber Composite (MFC) and they have the form of a thin, flexible piezoelectric film. In 2002, MFC transducers were commercialized as a licensed and patented invention, which is constantly improved and adapted to the specific needs of customers and new applications. NASA initially developed...
piezoelectric film to develop and improve aircraft structures by using MFC film in aircraft wings and helicopter rotor blades. MFC piezoelectric film consists of rectangular piezoelectric ceramic rods, placed between polymer layers containing electrodes that transfer voltage directly to piezoelectric rods (their thickness does not exceed a few tenths of a millimetre) [1,2]. As a result of powering the piezoelectric transducer from an external source, the following: tensile, bending or torsion of the transducer is possible. It is also possible to use MFC films in systems for recovering electrical energy from mechanical vibrations [3,4].

As a part of the author's research on MFC piezoelectric transducers, issues of modelling and application using both simple and inverse piezoelectric effect were discussed. This paper presents selected proposals for the application of MFC transducers in mechatronic measuring systems, as well as the limitations and disadvantages of such systems that should be considered during their design. Also results of a series of laboratory tests that were carried out to determine the impact on the measured values of damage of the mechanical subsystem on which the MFC-type piezoelectric transducer was glued are presented. Mechatronic systems are characterized by a synergistic combination primarily of mechanical, electrical and IT engineering, which leads to the development of modern technical means [5,6]. This article, in chapters 2 and 3, presents a review of the subject literature and a synthetic description of previously published research results, which aims to introduce the reader to the most important elements of the considered issues. Chapter 4 presents, however, unpublished results of preliminary research on the analysis of the impact of mechanical subsystem damage in the proposed measuring system based on the use of MFC piezoelectric transducers on the effectiveness of its operation. The thesis was summarized by drawing conclusions based on both, previously published studies and the results of the latest research.

2. Applications of MFC transducers in mechatronic measurement systems

In the research and development project regarding the modernization of the body of freight wagons, the idea of operation of the technical condition supervision system for modernized freight wagons was proposed. The paper [1] presents issues regarding the use of piezoelectric films to monitor the technical condition of freight wagons during their operation. The results of laboratory tests that were carried out on a freight car model created on a scale were presented. The possibility of detecting changes in the technical condition of the wagon based on the analysis of its dynamic response was determined. The research consisted in measuring the dynamic response of the model while driving. To measure the vibrations of the supporting structure of the model, a piezoelectric Macro Fiber Composite (MFC) transducer was used, which was glued on its surface. A series of tests was carried out on the model without load and with load, as well as with obstacles located on one or both rails. The waveforms obtained were analysed. The conducted works were aimed at verifying the possibility of inferring about the state of the examined object based on measuring its response to dynamic excitations and the possibility of its separation from noise, which is the result of its work in normal operating conditions. It was shown that it is possible to infer about the technical condition of the tested object based on signals generated by properly placed piezoelectric sensors, affixed on the wagon components. As a part of the work, measurement points on the created freight wagon model were selected, and a series of tests was carried out. Tests carried out on the created laboratory stand showed the effectiveness of the proposed method. It is possible to analyse and interpret the electric voltage signal generated by piezoelectric film stuck on the surface of the tested object in order to infer its condition. Papers [7-8] present the results of tests and verification of system assumptions carried out on real objects. During these tests, MFC transducers were glued to structural elements of a standard freight wagon and the voltage waveforms generated by them during the observed rides in the conditions of operation of the wagon close to standard operation were recorded. At the current stage of research, the recorded waveforms were used to excite vibrations of elements of a modernized freight wagon box equipped with composite panels. By measuring the dynamic response to given excitation, the possibility of detecting the presence or absence of elements of the modernized plating was determined. The subject of further work will be the
construction of a prototype freight wagon with modernized shell plating and conducting long-term operational tests of the plating damage detection system.

Systems based on piezoelectric transducers applications are also used in railway transport and issues related to the study of the dynamic response of both railway rolling stock and railway infrastructure are the subject undertaken by a lot of researchers. Dynamic loads generated during the passage of railway trains are deleterious to the infrastructure, such as bridges or buildings located near tracks, as well as people staying in them. There is however the possibility of their use in systems for condition monitoring of infrastructure components [9-14]. Also important are issues of protection of building against vibration generated by the ground and underground rail transportation as well as protection and minimizing the impact of vibrations on both passengers and persons in the buildings surrounding the railway line [10].

An interesting idea of piezoelectric films application is also an innovative system for traffic supervision and detecting and alerting about collisions presented in paper [15]. The purpose of the research was to conduct theoretical and experimental research in the field of analysing the dynamic response of road infrastructure elements, such as protective barriers, soundproof screens, lighting elements, etc., to extortion caused by ongoing traffic. The implementation of research tasks was aimed at acquiring new knowledge in the field of phenomena occurring during the propagation of vibration energy, generated by passing vehicles, on infrastructure elements, and the possibility of measuring the dynamic response of these elements using glued MFC piezoelectric foils, as well as analysing the received signals for their use in modern surveillance systems.

There are known methods for measuring vehicle speed, traffic intensity and controlling traffic lights, implemented through embedded sensors in the form of induction loops or piezoelectric sensors, which also allow measuring the weight of passing cars. Such solutions, however, require interference with the surface, which makes it impossible to install them without impeding traffic or incurring high costs. In the proposed solution it is possible to carry out this type of tasks by measuring the dynamic response of road infrastructure elements located directly in the vicinity of the road gauge. To this end, experimental research was conducted, in which the hypothesis was verified. The measurements of the dynamic response of protective barriers were carried out on the highway. The sensors were glued on the elements of the protective barrier that separates the lanes in opposite directions and is located on green belt. In order to perform the measurements a mobile voltage signal acquisition system station was constructed. To build up the system and for the data acquisition equipment and software from National Instruments were used. Four of the MFC piezoelectric films were connected with the measuring card NI-9215. Then the measuring card was installed in the module cDAQ-9191. The measurements were carried out simultaneously with the recording of the passing vehicles with the camera. Recorded video was then compared with the voltage waveforms generated by the piezoelectric transducers in order to analyse and interpret the results.

By analysis of signals received during each of the tests, it was found that the profile belt is too susceptible element. Numerous spikes of the generated signal voltage were observed reflecting not passing of any vehicle. These signals resulted from weather conditions (wind) and were not results of a vehicle movement. Most precisely the vehicle passing is reflected by the waveform generated by the piezoelectric film mounted on the pillar. Passing of a vehicle of weight over 3,5 tons moving along right and left lanes of the road as well as passing of a vehicle of weight up to 3,5 tons moving along the left lane of the road can be easily detected. Signals generated by all transducers were also affected by vehicles travelling in the opposite direction on the road lanes separated by a green belt.

An important advantage of this kind of system is the assembly of its components to existing elements without violating the road surface and the retention of the traffic. The system will also have a very low demand for electricity, which also can be met using renewable energy sources such as solar, wind and even recovery of electric energy from mechanical vibrations using piezoelectric elements making up the system. On the other hand, there are also a few problems that must be solved. The impact of the vehicles going along the opposite road lane as well as the possibility to detect light vehicles driving on the right lane can be solved by a proper distribution of sensors. In the presented work sensors were glued on the elements of the protective barrier that separate the lanes in opposite directions and is located on green
belt. The mentioned problems should be solved by distribution of sensors on all protective barriers (external barriers and barriers on the green belt). Waveforms generated by all sensors in the system can be then filtered and juxtaposed in order to correctly infer the type, location and direction of movement of vehicles. It will be the aim of the author’s future work.

3. Reliability of measuring systems based on the use of MFC piezoelectric transducers

When developing the concept and designing mechatronic systems in which MFC piezoelectric transducers are used as sensors, the possibility of disturbing the measurements by various external factors should be considered. These may include fluctuations in the system's operating temperature, electromagnetic disturbances or improper performance or damage to the layer connecting the transducer to the mechanical subsystem [16]. For this reason, studies about the impact of electromagnetic disturbances as well as changes in their operating temperature on the effectiveness of MFC piezoelectric transducers were carried out [17-20].

During the study of the impact of electromagnetic disturbances presented in paper [17] during laboratory tests two Macro Fiber Composite (MFC) piezoelectric transducers were used. Both were glued on the surface of the cantilever beam made of aluminium alloy. The first one was used for vibration excitation. It was connected to the high voltage amplifier supplied by the wave generator. Harmonic electric voltage was applied to the transducer to generate harmonic excitation of the beam. The beam was excited by the MFC transducer with frequency equal to 7.1 Hz. It was the first natural frequency of the beam. In the case of excitation with the first natural frequency it was possible to obtain the highest values of the beam deflection amplitude. It was very important to obtain the maximum value of the electric voltage generated by the second MFC transducer which was used as a sensor of the beam’s deflection. According to the beam harmonic vibrations the MFC sensor generates harmonic electric voltage. This electric voltage was measured using NI 9191 CompactDAQ Chassis equipped with C series voltage input module. During the tests, the influence of conducted disturbances on the transmission wire between sensor and the measure module was examined. The EM-clamp consisting of a tube of split ferrite rings of two different grades, which can be clamped over the cable under test in a non-invasive way was used in order to introduce disturbances into the system. The MFC sensor was connected to the measuring equipment using shielded wire but during the measurements the shield was connected as follows:

- disconnected on the both ends of the wire,
- connected only to the MFC transducer (to the negative potential wire), while the second end of the shield was disconnected,
- connected only to the NI 9191 chassis (to the ground connection on the module housing), while the second end of the shield was disconnected,
- both ends of the shield were connected properly (to the negative potential wire of the MFC transducer and to the ground connection on the module housing of the NI 9191 chassis).

During measurements the disturbances were generated on the transmission wire with agreement to the generated by the testing system signal with frequency from 150 kHz up to 20 MHz. The frequency of the disturbance was changed with the step of 100 kHz at every 3 seconds. What is more the signal of disturbance was modulated with the frequency 2 Hz. It could be noticed that the proposed measuring system was sensitive to the influence of conducted disturbances. Only by application of shielded wire as the transmission wire and proper connection of the shield on both ends of the wire, the influence of conducted disturbances can be eliminated. In case of improper connection of the shielding, the results of measurements are affected by the signal of disturbances. It is very important to take it into account during measurements carried-out using proposed system based on the Macro Fiber Composite sensors.

In the paper [18] the temperature fluctuation during the device operation was tested. Laboratory tests were conducted on laboratory stand equipped with universal mechanical testing machine (Instron Electropuls 10000) and thermal chamber. During the tests samples were subjected to cyclic extortion
simulating the operation of the system in various environmental conditions by forcing changes in system operation temperature with constant conditions of its excitation. The terminals of the tested piezoelectric transducer were connected to an external resistor (placed outside of the thermal chamber) and an electric voltage drop on it was recorded. An experimental analysis of the impact of changes in the working temperature of the tested system on the efficiency of electricity generated by the used MFC piezoelectric transducer was done. The test was carried out by measuring the values of the voltage drop on the connected resistor during the temperature changes of the piezoelectric transducer in the range from -30 to +70 Celsius degrees. The useful working range given by the manufacturer is from -35 to +85 Celsius degrees [2]. The tests were carried out with a temperature gradation every 10 °C. The piezoelectric transducer was heated at a given temperature for 10 minutes and then subjected to 500 load cycles by harmonically variable force with a frequency of 1.5 Hz. The laboratory stand was controlled using an extensometer, ensuring a constant deformation value of the transducer at the maximum level of 2000 ppm. A significant effect of temperature change on the voltage drop value on the resistor connected to the tested MFC piezoelectric transducer was observed. There was a decrease in the voltage peak value by more than 50% along with the temperature increase in the analysed range from -30 to +70 degrees Celsius. Such an important change translates directly into the efficiency of the energy recovery system from mechanical vibrations exposed to variable temperature operating conditions. One of the reasons for the decrease in the efficiency of the system as the temperature rises may be the change in the dielectric constant value of the material with piezoelectric properties, which is applied to the tested composite transducer. Conducted tests in laboratory conditions proved that temperature changes could significantly affect the efficiency of the energy harvesting system based on Macro Fiber Composite applications. By providing a constant value of deformation of the tested sample by using an extensometer to control movement of the machine jaws and providing a constant frequency, identical excitation parameters of the tested sample were ensured during all research tests. Only temperature changes could have influence on the obtained results.

4. Research on the impact of a mechanical subsystem damage on a system operation

To determine the impact on the measured values of damage of the mechanical subsystem on which the MFC-type piezoelectric transducer was glued, a series of laboratory tests was carried out on the created laboratory stand. The laboratory stand, shown in figure 1, consisted of the following elements:

- Tabor WW5064 25MHz 4-Ch Arbitrary Waveform Generator,
- High voltage amplifier HVA 1500/50,
- NI-cDAQ-91911-Slot, Ethernet and 802.11 Wi-Fi CompactDAQ Chassis with the measuring card NI-9215,
- Personal computer with LabVIEW software.

Composite samples made of carbon fiber in an epoxy resin matrix with dimensions of 200x40 mm and a thickness of 1 mm were tested. During the tests, the samples were clamped in the jaws of the vice, and two MFC M8514P1 type piezoelectric transducers were glued on their surface. One MFC transducer was used to excite the vibration of the tested sample and during the tests it was powered by a harmonically variable voltage signal of a given frequency and amplitude, generated by the W5064 generator and amplified by the HVA 1500/50 high voltage amplifier. The second of the MFC transducers was used as a sensor, and the value of the electric voltage generated by this transducer as a result of its deformation was measured using the NI-9215 measurement card and recorded using the NI-cDAQ-9191 measurement module in LabVIEW software.
Three samples were tested. The first of them had no damage (sample number 1 in figure 2), while the other two were damaged by making incisions in them. In the case of the first of the damaged samples, the incisions were irregular (sample number 2 in figure 2), while the second damaged sample had damage in the form of regularly spaced incisions of equal depth spaced evenly and running perpendicular to the sample axis (sample number 3). Damages were made to obtain changes in dynamic characteristics of the tested samples relative to the undamaged sample and to determine their impact on the values of the electric voltage generated by the MFC piezoelectric sensor.

During the first stage of tests, the frequencies of natural vibrations of individual tested samples were determined by inducing them to vibrations using a signal in the form of noise. Signals generated by the MFC piezoelectric sensor were recorded and analyzed using Fast Fourier Transform. This way the first natural vibration frequency of the samples was determined. Then individual samples were excited to vibrate by supplying the piezoelectric transducer using harmonically variable signals with the frequencies equal to the determined first natural frequencies of the tested samples. At the same time, signals generated by the MFC piezoelectric sensor were recorded and the peak value generated by the sensor was determined. The results of the tests are listed in table 1.
Table 1. The peak voltage values generated by the tested samples depending on the excitation frequency.

|                  | Sample 1 | Sample 2 | Sample 3 |
|------------------|----------|----------|----------|
| Natural frequency| 25.2 Hz  | 22 Hz    | 21.2 Hz  |
| Excitation frequency 25.2 Hz | 1.05 V  | 0.60 V   | 0.45 V   |
| Excitation frequency 22 Hz     | 0.65 V  | 2.52 V   | 2.20 V   |
| Excitation frequency 21.2 Hz     | 0.48 V  | 2.11 V   | 3.03 V   |

The obtained results indicate a significant impact of mechanical subsystem damages, on the surface of which MFC type piezoelectric sensors was glued, on the generated values of measurement signals. These differences result from changes in dynamic characteristics and the natural frequency of the tested samples as a result of their damage. The introduced damages caused changes of dynamic susceptibility of the samples and thus translated into higher values of deformation of the sensor glued on their surface. Higher vibration amplitude of individual samples in the range of their resonance frequency caused higher voltage peaks generated by the piezoelectric sensor. There is a visible increase in the value of voltage generated by the MFC sensor in the case of damaged samples relative to the sample without damage, resulting from their greater susceptibility and higher vibration amplitude.

5. Conclusions
The literature review, tests and measurements proved that Macro Fiber Composite piezoelectric transducers can be successfully used as sensors. They can easily be glued on the surface of tested elements and structures, as well as laminated in composite elements. What's more, they can be easily protected against weather conditions. However, as it was shown during the research on the impact of electromagnetic disturbances and changes in operating temperature, it should be remembered that the values of the electric voltage generated by the proposed sensors may be disturbed. Therefore, these changes should be considered during the design and construction process of mechatronic systems in which piezoelectric films are used. Omission of these phenomena can lead to incorrect measurements and incorrect operation of the system.

The tests carried out on composite samples made of carbon fiber in an epoxy resin matrix also indicate a high sensitivity of the measuring system based on the use of a piezoelectric sensor in the form of a MFC film glued on the surface of a vibrating mechanical subsystem on its damages and thus changes in dynamic characteristics. Any mechanical damage causes a change in the frequency and amplitude of vibration of the tested system and thus directly translates into the values of voltage generated by the piezoelectric sensor glued on the surface of the tested element. Therefore, the conducted research indicates that this type of sensors can be successfully used in systems for monitoring the technical condition of various technical means, including primarily elements made of composite materials. Such a solution was proposed in the case of testing the technical condition of composite panels used as the sheathing of boxes of modernized freight cars [1,8]. However, when measuring the vibration parameters of road infrastructure elements to detect the passage and collision of vehicles in vehicular traffic any damage and changes in the dynamic characteristics of the elements on which piezoelectric measuring sensors will be glued can lead to disturbances in the operation of the traffic monitoring system. Changes in the dynamic characteristics of the element on which the measurement is made can lead to a significant change in the signal generated by the MFC piezoelectric sensor and thus be misinterpreted, for example, as a vehicle collision. This phenomenon is extremely important in relation to the reliability and effectiveness of the proposed mechatronic road traffic supervision system and should be considered when selecting the elements on which the measuring sensors will be mounted and potential changes in their dynamic characteristics should be anticipated. These changes may be the result of exposure of system components, among others, to changing weather conditions, corrosive wear, mechanical damage
and many other factors that should be foreseen and, if possible, reduce their impact on the designed measuring system. To this end, further research is required both in laboratory conditions and in real operating conditions to which the elements of the designed mechatronic measuring system based on the use of sensors in the form of piezoelectric films are subjected.

6. References

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