

SHM SYSTEM BASED ON IMPEDANCE MEASUREMENTS

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Summary

The paper presents the results of laboratory testing procedure applied for the SHM system developed at AGH-UST Department of Robotics and Mechatronics, Poland. Experimental setup has allowed for the measurement of electromechanical impedance with piezoelectric transducers bonded on an aluminum panel. In the paper there are presented the principle of nondestructive testing based on the impedance measurement, the description of developed SHM system and the results of performed experiments. It is shown how local changes introduced into the panel properties influence measured electromechanical impedance.

Keywords: SHM, piezoelectric transducer, electromechanical impedance.

SYSTEM MONITOROWANIA STANU KONSTRUKCJI DZIAŁAJĄCY W OPARCIU O POMIARY IMPEDANCJI

Streszczenie

Artykuł przedstawia wyniki testów laboratoryjnych przeprowadzonych dla systemu monitorowania stanu technicznego konstrukcji opracowanego w Katedrze Robotyki i Mechatroniki AGH w Krakowie. Zbudowane stanowisko pomiarowe umożliwiło pomiar impedancji elektromechanicznej za pomocą przetworników piezoelektrycznych przytwierdzonych do aluminiowej płyty. W artykule opisano metodę realizacji nieniszczących testów bazujących na pomiarach impedancji, przedstawiono opracowany system monitorowania oraz wyniki uzyskane w przeprowadzonych eksperymentach. Przedstawiono wpływ lokalnych zaburzeń własności płyty na zmierzone wartości impedancji elektromechanicznej.

Słowa kluczowe: monitorowanie stanu konstrukcji, przetwornik piezoelektryczny, impedancja elektromechaniczna.

1. INTRODUCTION

Structural Health Monitoring (SHM) systems stand for a class of applications of non destructive testing (NDT) dedicated for continuous monitoring of the condition of mechanical constructions [1-3]. SHM is usually carried out with the results of measurements performed in arrays of sensors which are permanently installed on monitored construction, first of all in critical localizations. SHM applications characterize the integration of sensors and actuators, the use of smart materials and the ability of data processing inside monitored structures. SHM has been proposed and developed in order to reduce the costs of maintenance activities by swapping from scheduled to health based inspections. Moreover procedures of data processing applied in SHM help to predict remaining life time for monitored structure.

Applications of SHM can be divided into two groups. First group is defined as global SHM and allows for damage detection with the assessment of characteristics measured for a whole structure, e.g.

acceleration of vibrations. Local SHM, in turn, is based on the measurement of structure properties performed for a certain region only, e.g. with local excitations done with piezoelectric transducers (PZT). One of the most known technique used to monitor the condition of mechanical properties is SHM based on the measurements of electromechanical impedance. It takes the advantage of electromechanical coupling utilized in PZT and therefore allows for both excitation of the vibration in the PZT vicinity and structural response measurement performed for the frequency range from 10 kHz up to 500 kHz. Measured frequency characteristics of impedance are used to track local perturbations of mechanical properties resulting from incipient and then growing damage.

Emerging application areas of SHM determines the necessity of continuous development of monitoring systems including both hardware and software contribution. The effort is put to increase the quality of monitoring process by improving the sensitivity to incipient damages as well as to prevent from false alarms. On the other hand the reduction

of energy consumption, installation and maintenance costs may be a key issue when designing a new SHM system.

The paper is organized in the following sections: section 2 describes SHM based on impedance measurements, section 3 presents developed SHM system, the experimental setup and obtained results of laboratory tests are presented in sections 4 and 5 respectively, final section 6 covers summary and concluding remarks.

2. IMPEDANCE BASED SHM

Impedance based SHM stands for the assessment of condition of mechanical structure performed with the measurements of electromechanical impedance. Frequency characteristics of impedances are determined with PZT bonded on monitored structure. Due to introduced electromechanical coupling there is possibility of both activating the mechanical vibrations in a structure and then the measurement of its response. The inference on presence of damage is carried out by the comparison between yielded frequency characteristics. There are possible two configurations applicable for the measurements of electromechanical impedance:

- Point Frequency Response configuration (shown in Fig. 1); It assumes that only one PZT is used which simultaneously acts as both actuator and sensor. The drawback of the application is however reduced emission of vibration power and sensitivity of the measurement because of the compromise on the electromechanical characteristics of PZT which is expected to be both effective actuator of vibration and sensitive sensor. The electromechanical impedance is determined with the voltage and current measured directly for PZT, i.e. as in the case when common electric impedance is determined, and can be found by the following equation:

$$\underline{Z} = \frac{V_{IN} - V_{OUT}}{\frac{V_{OUT}}{R}} \quad (1)$$

- Transfer Frequency Response configuration (shown in Fig. 2); The configuration determines the use of two PZT for separate excitation and measurement. The advantages of described approach are: the increase of measurement sensitivity and vibration energy transmitted into structure resulting from the fact that each of used PZT can be separately chosen accordingly to the task it accomplishes. The main drawback is however the increase of number of bonded PZT and more complex control electronic circuit which must contain additional systems including charge amplifiers. Electromechanical impedance is calculated as follows:

$$\underline{Z} = \frac{V_{IN}}{\frac{V_{OUT}}{R}} \quad (2)$$

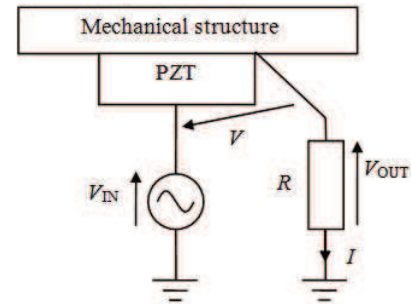


Fig. 1. Point Frequency Response configuration

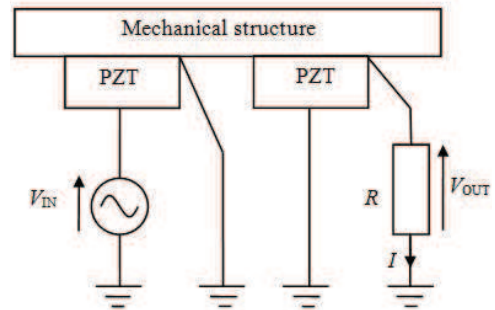


Fig. 2. Transfer Frequency Response configuration

For both configurations during measurement the structure is excited to locally vibrate for the range of high frequencies. Therefore it is feasible the inference on damage presence even though its size is small. High frequency measurement characterizes significant sensitivity to local changes in mechanical properties of monitored structure. It results from the fact that this changes mostly interfere with high frequency normal modes characterizing small wavelengths, i.e. of damage size. There must be noted however that impedance based SHM may be effectively performed only within the vicinity of mounted PZT, i.e. with distances of millimeters and centimeters rather than meters [4].

For the quantitative assessment of the differences between baseline and current impedance characteristics the following exemplary damage indexes (DI) may be applied [1,5]:

$$DI1 = \sum_{i=1}^n |(\operatorname{Re}(Z_{0,i}) - \operatorname{Re}(Z_i))(\operatorname{Re}(Z_{0,i}))^{-1}| \quad (3)$$

$$DI2 = \left(\sum_{i=1}^n ((\operatorname{Re}(Z_{0,i}) - \operatorname{Re}(Z_i))(\operatorname{Re}(Z_{0,i}))^{-1})^2 \right)^{1/2} \quad (4)$$

$$DI3 = \sum_{i=1}^n \left((\operatorname{Re}(Z_{0,i}) - \operatorname{Re}(Z_i))(\operatorname{Re}(Z_{0,i}))^{-1} \right)^{1/2} \quad (5)$$

$$DI4 = 1 - \left((n-1)s_0s \right)^{-1} \cdot \sum_{i=1}^n \left(\left(\operatorname{Re}(Z_{0,i}) - \operatorname{Re}(Z_0) \right) \left(\operatorname{Re}(Z_i) - \operatorname{Re}(Z) \right) \right) \quad (6)$$

where: $Z_{0,i}$ and Z_i are respectively referential and current values of impedance for i -th frequency step, Z_0 , s_0 and Z , s - are mean values and standard deviations of referential and current impedances, n stands for the number of considered frequencies.

Impedance based SHM characterizes application versatility dealing with both the type of monitored mechanical structure and the construction material. Most known applications of described type of SHM are [6-11]: bolted and screw joints, welded and spot-welded joints, glued joints, pipelines and railroad tracks, performed for metallic and composite materials, concrete and reinforced concrete.

3. DESCRIPTION OF DEVELOPED MONITORING SYSTEM

Impedance based SHM has been applied in developed monitoring system. The overall structure of the system is presented in Fig. 3.

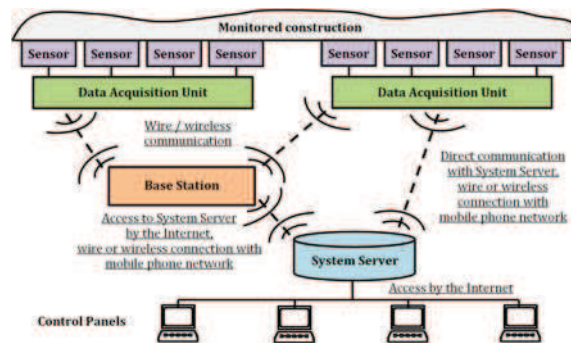


Fig. 3. Structure of developed SHM system

The system consists of Data Acquisition Units (DAU), Base Stations and System Server which enables for the connection with Control Panels. DAU and Base Stations are localized in the area of monitored structure. The main task of DAU is to check the condition of the construction by the impedance measurements performed with mounted PZT. DAU also allows for data processing and can calculate DI accordingly to implemented algorithms. Used DAU is presented in Fig. 4. It is possible to connect up to 16 sensors to each DAU considering that both Point and Transfer Frequency Response configurations are possible. For the measurement of impedance in Transfer Frequency Response configuration it is possible to choose any pair of actuator-sensor amongst all connected PZT. The data which is gathered in DAU is sent to Base Station or directly to System Server by either wire or wireless connection. All the information is stored in

System Server and can be acquired at any time with Control Panels. Control Panels are mobile or desktop computers which have access to the Internet and already installed SHM system software. The configuration settings of the whole system can be reprogrammed remotely. The measurements can be triggered automatically according to programmed time intervals or manually with Control Panels.

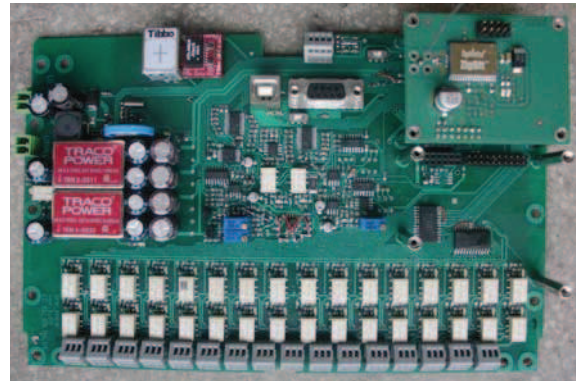


Fig. 4. Data Acquisition Unit

Applied analog electronic path enables for the impedance measurements up to 100kHz. The environmental conditions can be assessed with additional temperature and humidity sensors. The variation of mentioned above two parameters should be assessed as it significantly influences the frequency characteristics determined for electromechanical impedance [12].

In the system there are possible several communication techniques to enable for the data transfer between all system components. Between DAU and Base Station there have been implemented the following communication technologies: wireless (ZigBee and WiFi) and wire connection with the Ethernet protocol. The data connection between Base Station and System Server can also be possible either as wire, i.e. by the Internet, or by using mobile phone network infrastructure (GSM technology). For applications where there is a direct communication between DAU and System Server, i.e. applications which do not require Base Stations, applicable communication techniques are the same as previously mentioned for the connection between Base Station and System Server. DAU may work either independently or create a network.

Elaborated system may work properly for wide ranges of parameters describing the environmental conditions: at the temperature from -40°C up to $+85^{\circ}\text{C}$ (from -20°C up to $+50^{\circ}\text{C}$ for the system equipped with additional high capacity accumulators) with humidity up to 100%. Used housings allow for industrial applications and ensure the protection compliant with IP66 protection level [13]. All wire outlets from housing boxes are insulated.

DAU is supplied with accumulators optionally equipped with photovoltaic panels used to extend the operating period without any maintenance activity.

The other system components are powered by external voltage 230V/50Hz. Base Station is equipped with uninterruptible power supply.

4. EXPERIMENTAL SETUP

To verify the properties of developed monitoring system a series of experiments have been performed on a freely suspended aluminum plate panel. Examined object has been equipped with four piezoelectric patches made of PIC151 material (PI Ceramic) permanently bonded using epoxy glue. Dimensions of used PZT are 10 mm, 10 mm, and 0.3 mm.

Two locations of the damage introduced to the structure have been considered. In the first case the damage has been placed in the equal distances between the transducers. In the second case in turn it has been moved towards PZT number 4. Damage has been simulated as an additional mass and stiffness. Thick steel washers in two different sizes have been attached to the panel using wax to induce local changes in the dynamical properties of the structure. Dimensions of the tested object and damage localizations are presented in Fig. 5, the experimental setup is shown in Fig. 6.

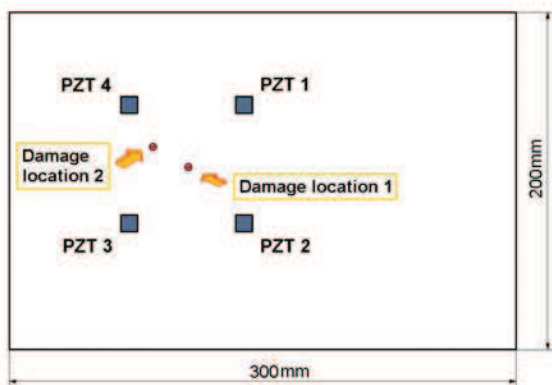


Fig. 5. Dimensions of monitored structure and damage location

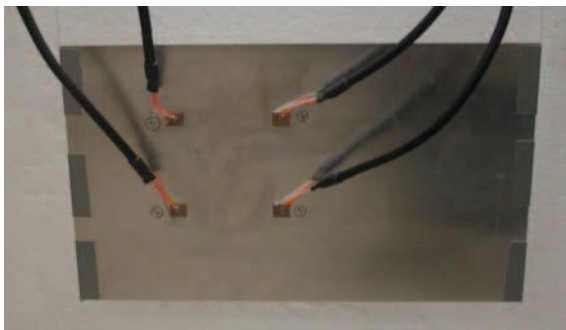


Fig. 6. Experimental setup

Two sets of baseline measurements have been performed for the undamaged structure to check the repeatability of experiments and to determine initial values of damage metrics. Next, damage has been introduced and the measurements have been repeated for the same frequency ranges.

5. RESULTS OF EXPERIMENTS

As an outcome of experiments a set of electromechanical impedance plots has been obtained. Both Point and Transfer Frequency Response functions have been evaluated for all piezoelectric transducers working as actuators and sensors. The measurements have been performed for the frequency range from 24 kHz up to 28 kHz with a frequency step equal 10 Hz. Relatively small frequency step has been chosen to ensure sufficient resolution of the measurements due to high modal density of the structure for chosen high-frequency range.

The exemplary results obtained for Point Frequency Response configuration for PZT no. 1 and no. 3 are shown in Fig. 7 and 8 respectively. It can be seen that appearance of the damage causes shifts of the resonance peaks and changes of their amplitude. Shown impedance modules have been directly calculated with raw values received from impedance analyzer data registers without any data scaling. Therefore no unit is added in plots.

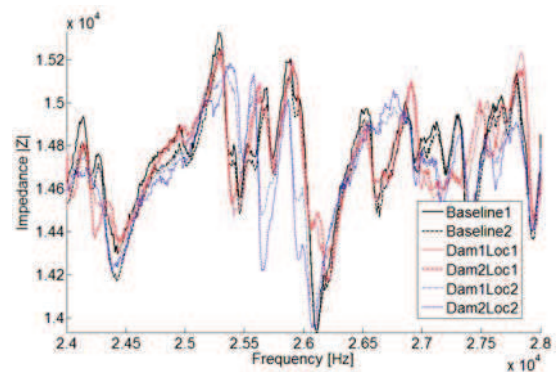


Fig. 7. Impedance plots obtained for transducer no. 1 – Point FRF

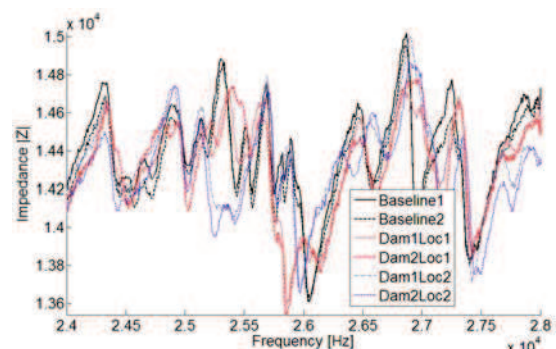


Fig. 8. Impedance plots obtained for transducer no. 3 – Point FRF

The values of damage metrics calculated on the basis of recorded impedance data for the failure placed in location 1 are presented in Fig. 9. For all PZT monotonic relationships between damage size and the value of DI have been obtained. In case of second damage location the proportions between metrics calculated for different damage sizes remained similar.

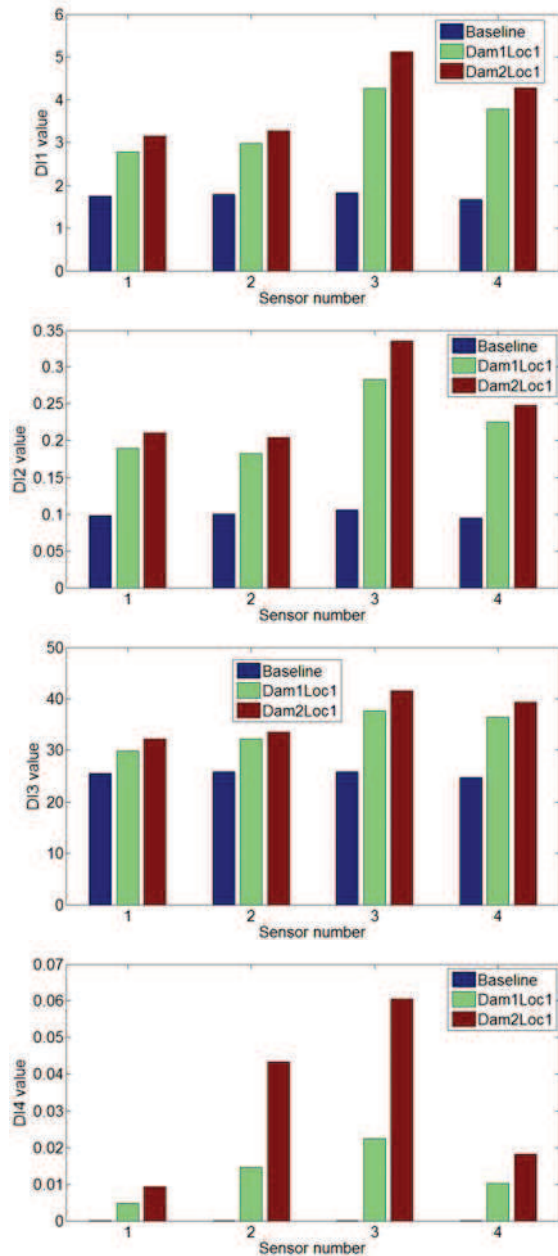


Fig. 9. Damage indexes calculated for Point FRF of the electromechanical impedance – damage location 1

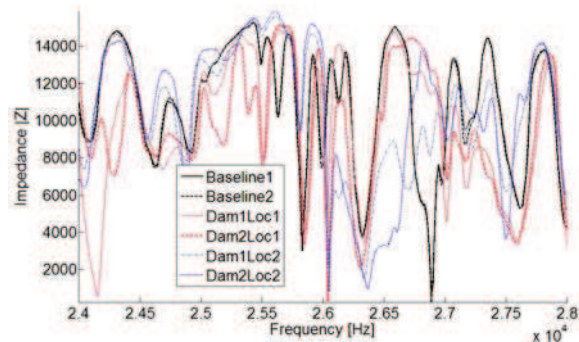


Fig. 10. Impedance plots obtained for transducer no. 2 – Transfer FRF

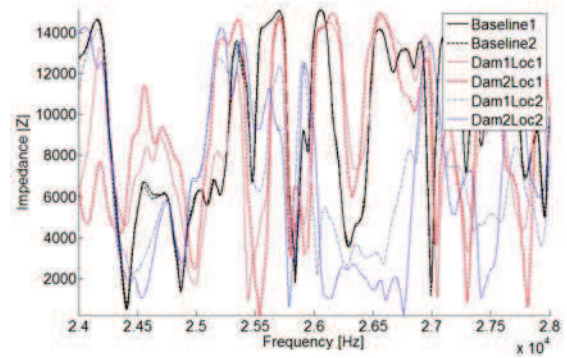


Fig. 11. Impedance plots obtained for transducer no. 4 – Transfer FRF

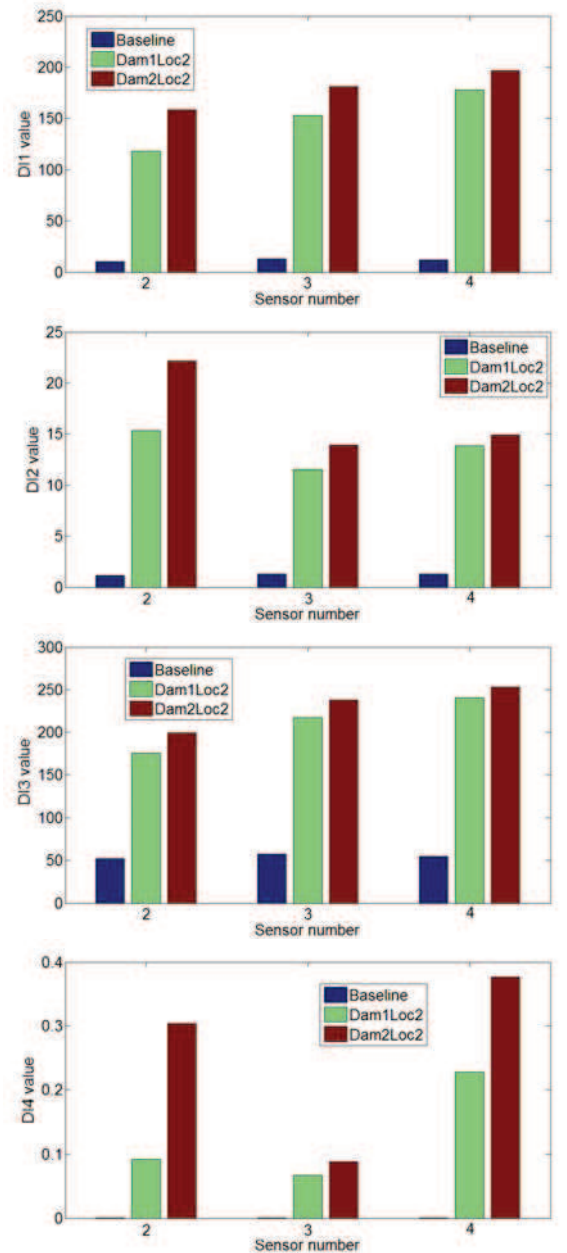


Fig. 12. Damage indexes calculated for Transfer FRF of the electromechanical impedance – damage location 2

Selected impedance plots evaluated for Transfer Frequency Response configuration are shown in Fig. 10-11 for PZT no. 1 acting as an actuator and transducers no. 2 and 4 working as sensors. Corresponding DI for exemplary damage location 2 are presented in Fig. 12. In all considered cases the greatest differences between particular failure sizes were observed for the statistical metric DI4. Moreover better repeatability for impedance baseline signals has been found for Transfer FRF case.

In accordance with obtained experimental results a conclusion can be made that tested application of impedance based SHM allows to detect a presence of the damage in mechanical structure and track its growth.

6. SUMMARY, CONCLUDING REMARKS

In this paper a conception of SHM system based on electromechanical impedance measurements is presented. The results of experiments performed using developed hardware show that described measurement method is sensitive to incipient and growing damage. Due to found its properties impedance based SHM is a promising technique for local monitoring of mechanical constructions.

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BIBLIOGRAFY

- [1] Park G., Inman D.J.: *Structural health monitoring using piezoelectric impedance measurements*. Phil. Trans. R. Soc. A, 365, pp. 373-392, 2007.
- [2] Giurgiutiu V.: *Structural Health Monitoring with Piezoelectric Wafer Active Sensors*. Elsevier Academic Press, Amsterdam; Boston, 2008.
- [3] Klepka A., Ambroziński Ł.: *Selection of piezoceramic sensor parameters for damage detection and localization system*. Diagnostyka, 4, 56, 2010.
- [4] Sun F.P., Chaudhry Z., Liang C., Rogers C.A.: *Truss structure integrity identification using PZT sensor-actuator*. Journal of Intelligent Material Systems and Structures, 6, pp. 134-139, 1995.
- [5] Rosiek M., Martowicz A., Uhl T., Stępiński T., Łukomski T.: *Electromechanical impedance method for damage detection on mechanical structures*. Proceedings of 11th IMEKO TC 10 workshop on Smart diagnostics of structures, Krakow, October 18-20, 2010.
- [6] Ayres J.W., Lalande F., Chaudhry Z., Rogers C.A.: *Qualitative impedance-based health monitoring of civil infrastructures*. Smart Materials and Structures, 7, pp. 599-605, 1998.

- [7] Chiu W.K., Koh Y.L., Galea S.C., Rajic N.: *Smart structure application in bonded repairs*. Composite Structures, 50, pp. 433-444, 2000.
- [8] Fasel T.R., Sohn H., Park G., Farrar C.R.: *Active Sensing using Impedance-based ARX Models and Extreme Value Statistics to Damage Detection*. Earthquake Engineering & Structural Dynamics Journal, 34, 7, pp. 763-785, 2005.
- [9] Park S., Inman D. J., Yun Ch-B.: *An outlier analysis of MFC-based impedance sensing data for wireless structural health monitoring of railroad tracks*. Engineering Structures, 30, pp. 2792-2799, 2008.
- [10] Tseng K.K., Wang L.: *Smart piezoelectric transducers for in situ health monitoring of concrete*, Smart Materials and Structures, 13, pp. 1017-1024, 2004.
- [11] Wait J.R., Park G., Farrar Ch.R.: *Integrated Structural Health Assessment using Piezoelectric Active Sensors*, Shock and Vibration, 12, 6, pp. 389-405, 2005.
- [12] Park G., Kabeya K., Cudney H.H., Inman D.J.: *Impedance-based Structural Health Monitoring for temperature varying applications*. JSME International Journal, Series A, 42, 2, 1999.
- [13] The international standard IEC 60529 Degrees of protection provided by enclosures (IP Code)



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