An Overview of Electromechanical Impedance Method for Damage Detection in Mechanical Structures

M. ROSIEK, A. MARTOWICZ and T. UHL

ABSTRACT

This paper presents an overview of research performed at the AGH University of Science and Technology in the field of the electromechanical impedance method for damage detection in mechanical structures. A theoretical background on the described method is made in the first part of the paper. Next, results of numerical analyses of the electromechanical impedance for simple mechanical structures are shown. Afterwards an outcome of laboratory measurements performed with developed structural health monitoring system based on the electromechanical impedance phenomenon is presented. Finally, results of tests of the monitoring system in environmental conditions are discussed.

INTRODUCTION

One of the structural health monitoring techniques is based on the measurements of the electromechanical impedance. It utilizes piezoelectric transducers, mainly made of piezoelectric ceramic as actuators and sensors. Due to the presence of the electromechanical coupling in the piezoelectric transducer, its electrical impedance is directly related to the mechanical properties of the host structure and is named the electromechanical impedance [1,2,3]. Variations of dynamical parameters of the structure, i.e. as a result of damage, influence the measured impedance plots, which in turn can be used for damage assessment. This paper briefly introduce the work done at the AGH University of Science and Technology in the subject of the electromechanical impedance based structural health monitoring.

Mateusz Rosiek, Adam Martowicz, Tadeusz Uhl, AGH University of Science and Technology Department of Robotics and Mechatronics, Al. Mickiewicza 30, 30-059 Krakow, Poland

DEFINITION OF THE ELECTROMECHANICAL IMPEDANCE

The complex electrical admittance of the piezoelectric transducer $\underline{Y}$, which is the inverse of the electrical impedance $\underline{Z}$, depends on mechanical impedances of the monitored structure $\underline{Z}_s$ and the piezoelectric transducer $\underline{Z}_a$ according to the following equation [1,2,3]:

$$\underline{Y} = j\omega a\left[\underline{\varepsilon}_{33}^{T} - \frac{\underline{Z}_s}{\underline{Z}_s + \underline{Z}_a} d_{31}^{2}\, \underline{Y}_{11}^{E}\right] \tag{1}$$

where: a is the geometrical constant of the piezoelectric transducer, d_{31} is the piezoelectric strain coefficient, $\underline{Y}_{11}^{E}$ is the complex Young's modulus, and ε_{33}^{T} is a complex dielectric constant of the PZT material evaluated at zero stress.

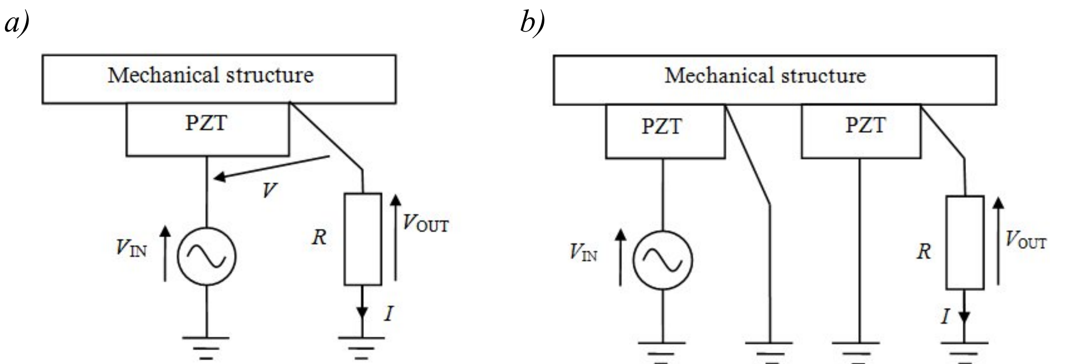


Figure 1. Methods of measuring electromechanical impedance: point Frequency Response Function (a), transfer Frequency Response Function (b).

Two methods of measuring the electromechanical impedance are presented in Figure 1. In the first case the point Frequency Response Function of the impedance is evaluated with the use of one PZT transducer acting simultaneously as an actuator and a sensor (Figure 1a) [2,4,5].

The second possibility is to measure a transfer Frequency Response Function with the use of two piezoelectric transducers placed in different locations in the structure (Figure 1b) [4,5]. The values of point and transfer impedance characteristics can be evaluated using the following equations:

$$\underline{Z} = \frac{\left(\underline{V}_{in} - \underline{V}_{out}\right)R}{\underline{V}_{out}} \tag{2}$$

$$\underline{Z} = \frac{\underline{V}_{in}\, R}{\underline{V}_{out}} \tag{3}$$

To qualitatively asses the changes of registered impedance plots, the following damage metrics can be used:

$$DI1 = \sum_{i=1}^{n} \left| \frac{\mathrm{Re}\left(\underline{Z}_{0,i}\right) - \mathrm{Re}\left(\underline{Z}_{i}\right)}{\mathrm{Re}\left(\underline{Z}_{0,i}\right)} \right| \tag{4}$$

$$DI2 = \sqrt{\sum_{i=1}^{n}\left(\frac{\mathrm{Re}(\underline{Z}_{0,i}) - \mathrm{Re}(\underline{Z}_i)}{\mathrm{Re}(\underline{Z}_{0,i})}\right)^2} \tag{5}$$

$$DI3 = \sum_{i=1}^{n}\sqrt{\left|\frac{\mathrm{Re}(\underline{Z}_{0,i}) - \mathrm{Re}(\underline{Z}_i)}{\mathrm{Re}(\underline{Z}_{0,i})}\right|} \tag{6}$$

$$DI4_q = \left(1 - \frac{1}{n-1}\frac{\sum_{i=1}^{n}\left(\mathrm{Re}(\underline{Z}_{0,i}) - \mathrm{Re}(\overline{\underline{Z}}_0)\right)\left(\mathrm{Re}(\underline{Z}_i) - \mathrm{Re}(\overline{\underline{Z}})\right)}{s_0 s}\right)^q \tag{7}$$

where $Z_{0,i}$ and Z_i are respectively the referential and the current value of the electromechanical impedance for i-th frequency, Z_0, s_0 and Z, s are the mean values and the standard deviations of referential and current impedances, n is the number of considered frequencies and q is the order of the damage metric. Damage index DI2 is the Root Mead Square Deviation (RMSD) [6,7], while DI4 is a statistical metric known as Cross Correlation [8]. Metrics DI1 and DI3 are proposed by the authors of this paper [9,10].

NUMERICAL SIMULATIONS

The first stage of the research comprised simulations of the electromechanical impedance for simple structures with use of the Finite Element Method (FEM). In order to perform numerical analyses finite element models of freely suspended aluminium beam and cantilever steel beam were created in ANSYS software (Figure 2) [9].

Piezoelectric transducers were modeled using 3D-finite elements, which fully incorporate the phenomenon of electromechanical coupling present in the PZT material. The models were considering also a thin layer of epoxy adhesive. The damage was modeled as a vertical notch with its depth varying from 1mm to 4 mm (denoted in the Figures 3 and 4 as damage cases Dam1, Dam2, Dam3 and Dam4).

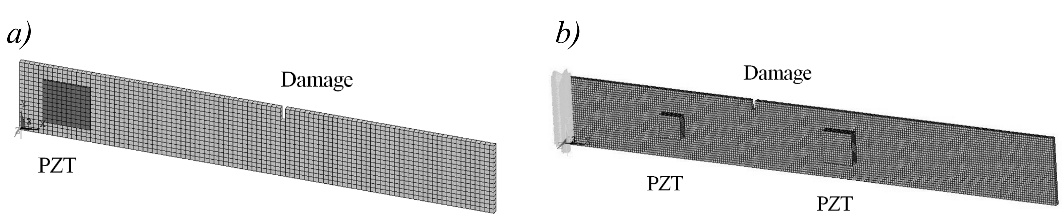


Figure 2. Finite element models of the simply suspended aluminium beam with one PZT patch (a) and cantilever steel beam with two PZT transducers (b).

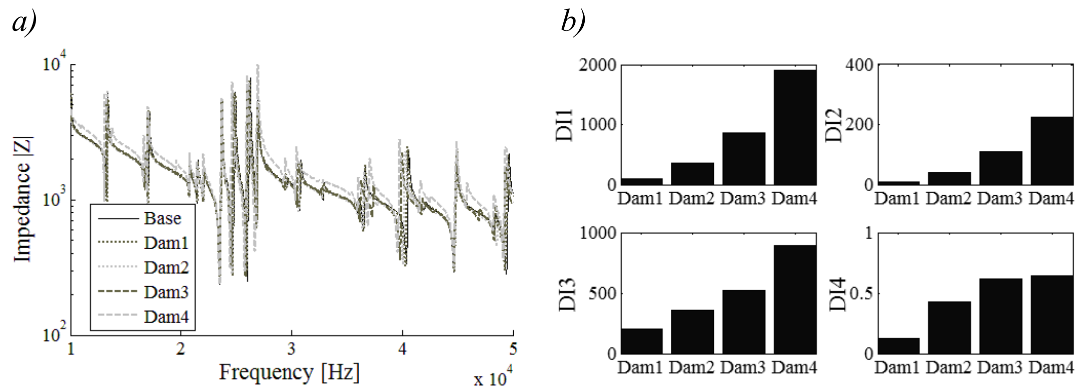


Figure 3. Point Frequency Response Functions simulated for the aluminium beam (a), damage indexes calculated on their basis (b).

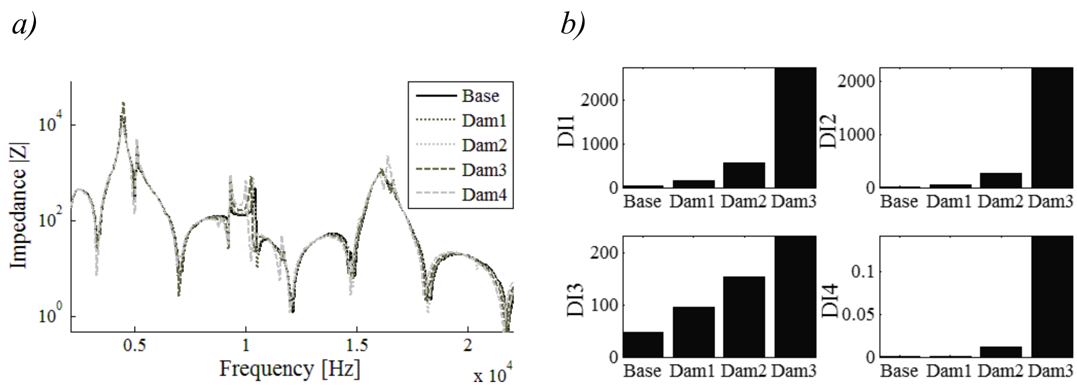


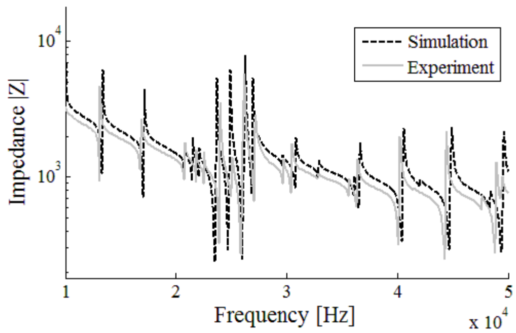
Figure 4. Transfer Frequency Response Functions simulated for the steel beam (a), damage indexes calculated on their basis (b).

Coupled-field harmonic analyses were carried out in order to generate the point and transfer impedance plots for both healthy and damaged constructions. Growing fault caused a shift of most of resonance peaks towards lower values of frequencies (Figure 3a and 4a). It was a result of increased compliance of the structure when the notch was introduced. For all tested damage metrics a monotonic relation was observed between the damage index value and notch size (Figure 3b and 4b).

LABORATORY MEASUREMENTS

Beams with bonded PZT transducers described in the previous paragraph were next subjected to the laboratory tests. The aim of the investigation was to verify the accuracy of the modeling technique chosen to simulate the dynamical behavior of the discussed structures. Agilent 4395A and Analog Devices AD5933 impedance analyzers were used to perform the measurements. Impedance plots obtained from experiments were compared with the simulations and there was a good agreement between numerical and experimental data (Figure 5).

a) b)



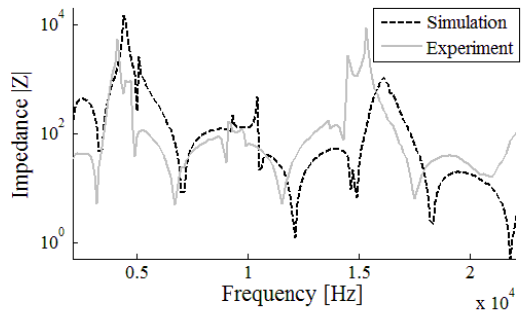
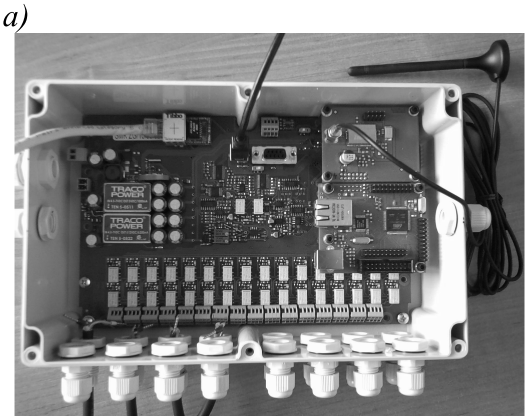


Figure 5. Comparison between simulated and experimental point (a) and transfer (b) Frequency Response Functions obtained for the examined beams.

On the basis of numerical analyses and preliminary laboratory measurements a structural health monitoring system has been developed. The main hardware component of the system is Data Acquisition Unit (DAU) shown in Figure 6a. The device is capable to measure both point and transfer Frequency Response Functions of the impedance in a frequency range up to 100 kHz. Several DAU can be connected into a network to cover all necessary points of larger structures. Data gathered by the DAU is afterwards send to the system server using wire or wireless transmission techniques. Detailed description of the developed monitoring system can be found in [10].

a) b)



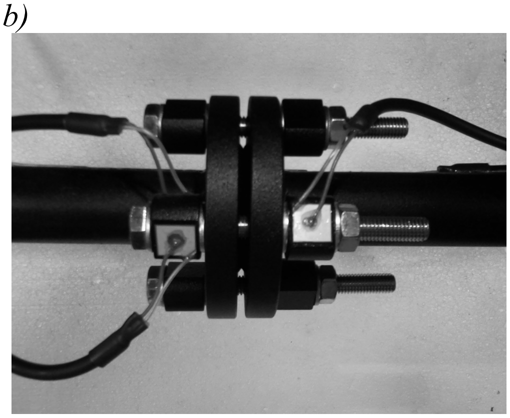


Figure 6. Data Acquisition Unit used for measurements (a), section of a pipeline with mounted steel washers with bonded PZT patches (b).

A more complex structure tested in the laboratory with the use of developed DAU was a section of a pipeline connected with four screws and nuts (Figure 6b) [10,11]. The object was equipped with special type of steel washers with bonded PZT transducers placed between screw heads, pipe flanges and nuts [12].

Damage was introduced in the structure by loosening one of the screws after evaluating baseline impedance plots measured for the object in a healthy state (all screws tightened with torque equal 20Nm).

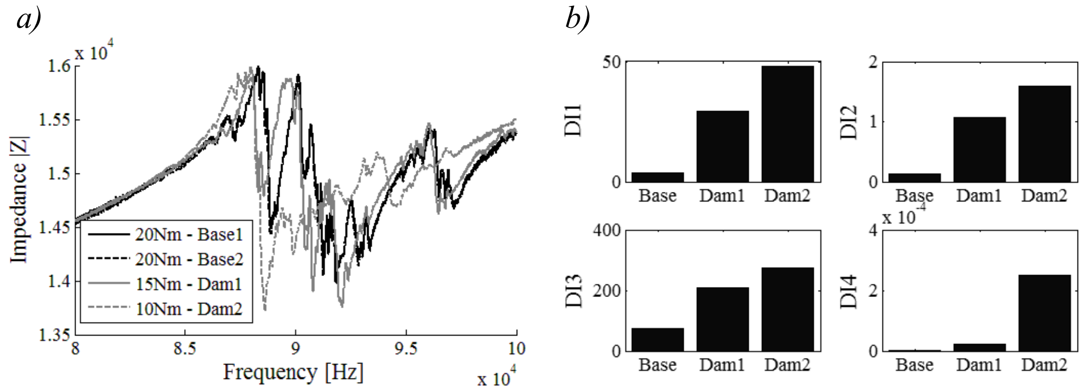


Figure 7. Point Frequency Response Functions measured for the pipeline section (a), damage indexes calculated on their basis (b).

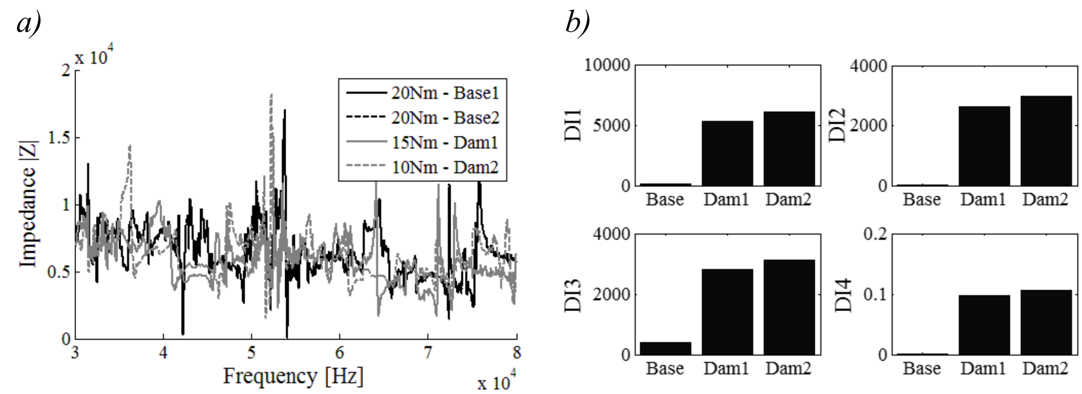


Figure 8. Transfer Frequency Response Functions measured for the pipeline section (a), damage indexes calculated on their basis (b).

Figures 7 and 8 show the acquired point and transfer Frequency Response Functions and calculated on their basis damage metrics. Obtained results confirm the ability to detect loosening of a screw in the joint. However, it should be noticed that in some cases use of damage indexes for damage assessment may be misleading for relatively large defects (i.e. lack of the screw) due to the large structural changes that can occur in the construction.

EXPERIMENTS PERFORMED IN ENVIRONMENTAL CONDITIONS

To test the usability of the developed SHM system to detect damage in engineering structures in environmental conditions, a series of measurements was carried out on jet planes withdrawn from operational use.

One of the tested object was a riveted engine housing shown in Figure 9a. Two MFC d31 piezoelectric transducers, marked as P1 and P2, were bonded to the inner side of the monitored structure near the construction node (Figure 9b). In order to introduce the damage to the structure, a notch was made between rivets R2 and R3, which corresponded to damage case Dam1. The notch was afterwards deepened (Dam2) and lengthened to the rivet R1 (Dam3).

a) b)

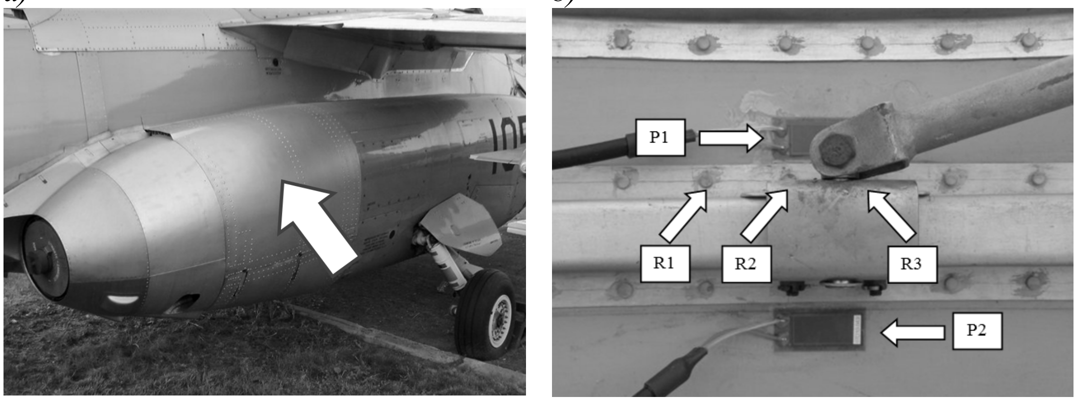


Figure 9. Monitored aircraft component (a), inner side of the riveted engine housing with visible MFC transducers (b).

a) b)

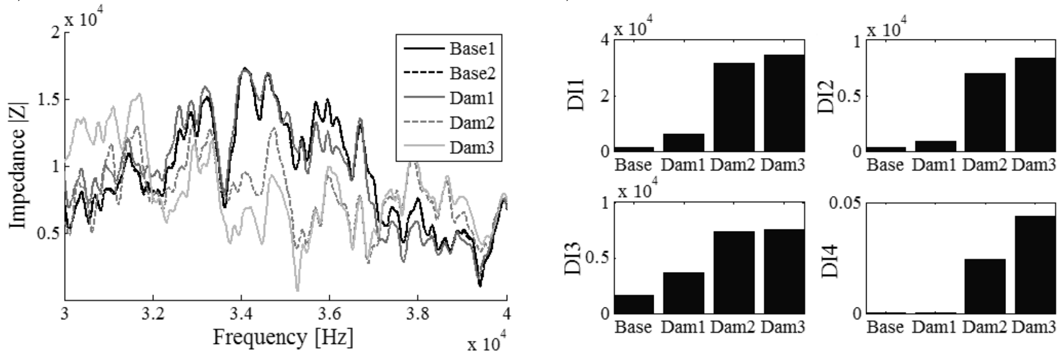


Figure 10. Transfer Frequency Response Functions measured for the engine housing (a), damage indexes calculated on their basis (b).

Obtained from the experiments transfer impedance plots and calculated on their basis damage metrics are presented in Figure 10. It can be seen that significant changes in the amplitude of the resonance peaks can be observed in the registered impedance characteristics with presence of the damage (Figure 10a).

CONCLUSIONS

The work presented in this paper has shown, that the electromechanical impedance based damage detection is a promising method for the state assessment of mechanical structures, however it should be treated as qualitative rather than quantitative technique.

With the use of damage index approach it is difficult to determine the size and location of the fault. Thus, it is important to properly distribute the piezoelectric transducers in the monitored structure, by placing them in the areas in which the occurrence of damage is most likely.

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