ELECTROMECHANICAL IMPEDANCE METHOD FOR DAMAGE DETECTION IN MECHANICAL STRUCTURES

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Abstract

Non-destructive measurements of an electromechanical impedance allow for the effective assessment of the state of mechanical structures. Piezoelectric transducers, which are distributed in monitored construction, introduce coupling between mechanical properties and directly measured electric entities. Therefore incipient mechanical damage can be detected and its growth followed. The changes of mechanical properties are found with the comparison between plots of impedances measured for both original healthy system and the system which is operating in a current state. This paper presents the results of Finite Element analyses performed for a cantilever aluminium beam with bonded piezoelectric transducer. Modelled structure was excited to vibrate at high frequency range and electromechanical impedance plots were obtained from the harmonic analysis. Vertical notch was introduced in the beam and the damage metrics were used to asses qualitative changes in structural properties of the system. The numerical results were confirmed experimentally using laboratory equipment. With obtained numerical and experimental results there has been introduced the idea of a Structural Health Monitoring (SHM) system.

Introduction to electromechanical based measurement

Amongst a number of applications of Non-Destructive Evaluation (NDE) there are Structural Health Monitoring (SHM) techniques based on the measurement of electromechanical impedance. Monitoring of material integrity can be performed with piezoelectric transducers bonded to mechanical structure [1,2]. Transducers are powered with alternating voltage and change their frequency characteristics of electrical impedance accordingly to fluctuations of mechanical properties of monitored structure. Appearing damage causes local change of stiffness and damping properties which in turn modifies plots of impedance [4,5,6]. It can be achieved since the feature of electromechanical coupling in piezoelectric transducer is present. Therefore measured electric impedance of the transducer is commonly called as electromechanical impedance. For the range of linear relationship between mechanical and electrical properties of the piezoelectric material the following matrix equation can be formulated [7]:

$$\begin{bmatrix} \mathbf{S} \\ \mathbf{D} \end{bmatrix} = \begin{bmatrix} \mathbf{s}^{E} & \mathbf{d}_{t} \\ \mathbf{d} & \boldsymbol{\varepsilon}^{T} \end{bmatrix} \begin{bmatrix} \mathbf{T} \\ \mathbf{E} \end{bmatrix} \tag{1}$$

where: $\mathbf{S}$ - vector of mechanical strains, $\mathbf{T}$ - vector of mechanical stresses, $\mathbf{E}$ - vector of electric field, $\mathbf{D}$ - vector of electric displacement field, $\mathbf{s}$ - matrix of mechanical compliance, $\mathbf{d}$ - matrix of piezoelectric strain constants, $\boldsymbol{\varepsilon}$ - matrix of electric permittivity. Indexes E and T are used for the entities measured with electrodes connected together and at zero stress respectively. Operator t stands for the transposition. Equations which define $\mathbf{S}$ and $\mathbf{D}$ describe respectively direct and converse piezoelectric effects. Converse effect allows for the excitation of vibrations in monitored structure since applied alternating voltage makes the transducer deformed. Direct effect in turn enables the measurement of electromechanical impedance as already vibrating structure influences measured frequency plot.

Usually a group of transducers is distributed to cover critical localizations in mechanical structure. Data acquisition units gather data measured with transducers, perform data processing and finally create reports on the state of monitored construction. It is based on the information whether assumed thresholds for damage indexes are exceeded. The measurements of electromechanical impedance are performed within the range of frequency 10kHz – 500kHz [4,5]. The range of high frequencies enables for high sensitivity to incipient damage as it disturbances local normal modes of small size. Moreover the results of such measurement can therefore be independent from external operational loads, i.e. low-frequency excitations from rail and road vehicles. However damage detection can be effective only within neighboring area of transducer localizations.

The process of damage detection is performed with the comparison between impedance plots obtained for healthy system as well as for its current state [3]. There has been defined a number of damage indexes, including based on statistical data, which are used to assess the growth of damage. Some exemplary ones are introduced in the following sections.

Fig. 1a presents commonly applied electric circuit which is used for the electromechanical measurements.

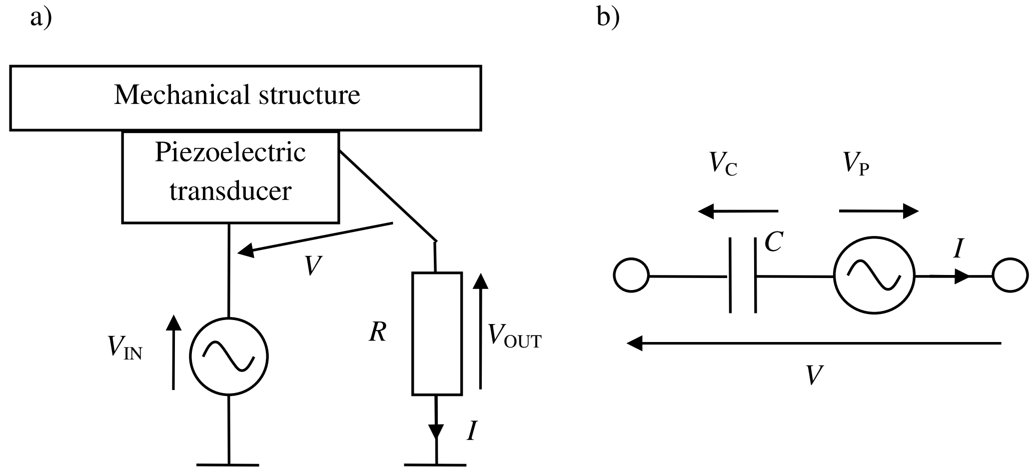

Fig.1. Scheme of electric circuit used for measurement of electromechanical impedance (a), resultant model of piezoelectric transducer (b)

The electric circuit consists of the following elements connected in a series: power supplier – electromotive force V_{IN}, piezoelectric transducer and referential resistor R. Electromechanical impedance Z_{E} is found with the formula:

$$Z_{\mathrm{E}} = \frac{V}{I} = \frac{\left(V_{\mathrm{IN}} - V_{\mathrm{OUT}}\right)}{V_{\mathrm{OUT}}/R} = R\left(\frac{V_{\mathrm{IN}}}{V_{\mathrm{OUT}}} - 1\right) \tag{2}$$

The current I is indirectly measured with the referential resistor R. Voltage V measured on the transducer can be calculated with known voltages V_{IN} and V_{OUT}. The piezoelectric transducer can be substituted with the series connection of capacitor C and electromotive force V_P as shown in fig. 1b. Indirectly measured voltage V depends on the value of V_P generated in piezoelectric transducer accordingly to direct piezoelectric effect. Hence any change of mechanical properties caused by damage finally influences Z_{E}.

Description of numerical model

For numerical analyses the finite element model of freely suspended aluminium beam has been created in ANSYS software. The model is presented in fig. 2. The size of finite elements used in the mesh has been assumed to equal 0.5 mm.

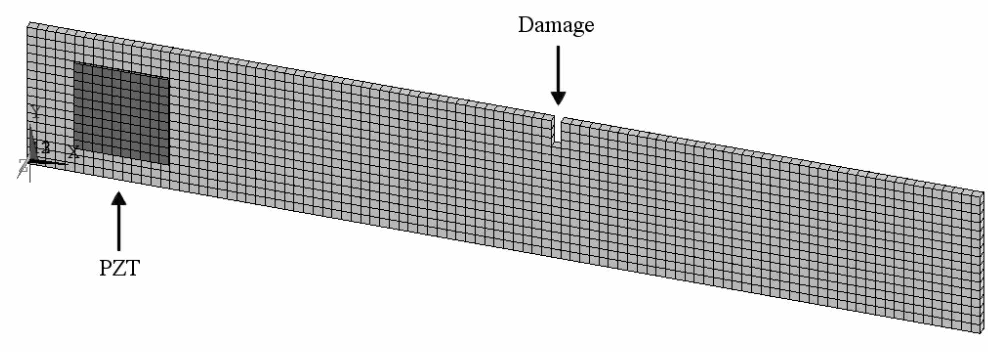

Fig. 2. Finite element model of analyzed structure

The dimensions of the beam were: 100mm, 16mm and 1mm. A simple piezoelectric transducer of sizes 10mm, 10mm and 0.3mm, made of the material PIC151 following the specification of PI Ceramic has been bonded to the beam to allow the electromechanical impedance evaluation. The transducer was located 5mm far from the beam end in its left hand side. The model was considering also a thin layer of epoxy adhesive.

All components of the model were build with 3D and 20-node parabolic finite elements. Elements used to model transducer additionally considers the feature of piezoelectric coupling. Additional FE elements were enabled for the introduction of electric circuit, i.e. voltage source and referential resistor. The alternating voltage with the magnitude of 1V has been applied to power electric circuit. The resistance of referential resistor was equal 100Ohms.

The damage in the model has been introduced as a 1mm wide incision with varying depth - from 1mm to 4mm. The damage was localized 55mm far from the left vertical edge of the beam. Non-central localization of the incision has been assumed not to disturb the node lines of the fundamental bending and plate mode shapes of the beam. As reported in the literature mentioned above case could cause problem with correct interpretation of the size of damage [8].

Numerical analyses

Multiphysics harmonic analyses have been performed with elaborated finite element model to generate the frequency plots of electromechanical impedance for both healthy construction and with introduced damage (Fig. 3).

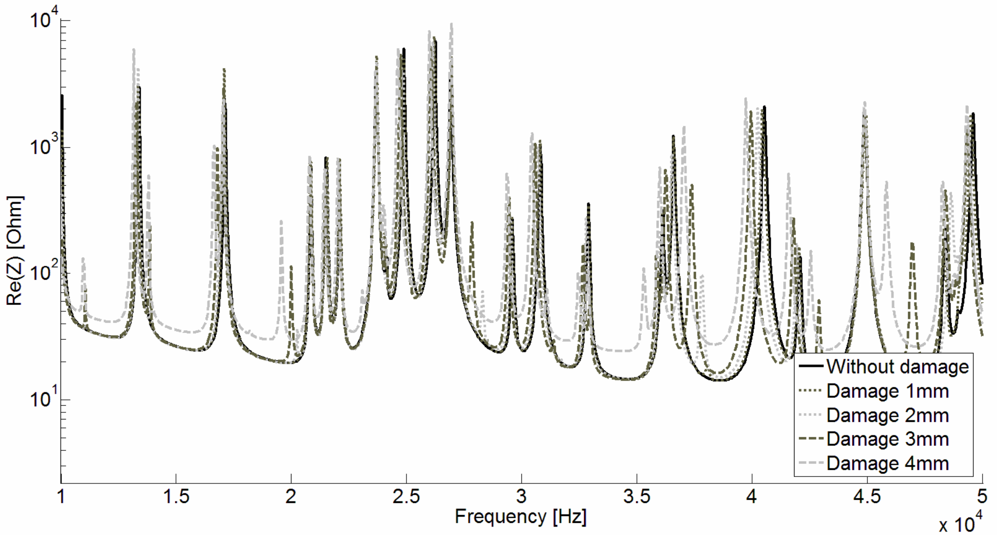

Fig. 3. Real part of simulated electromechanical impedance

The real part of electromechanical impedance has been considered since it is more sensitive to changes of monitored mechanical properties [1]. Growing damage causes shift of most of resonances towards lower values of frequencies. It results from increasing compliance of the structure when incision is introduced. Moreover for the largest damages new resonance peaks are observed because of significant structural changes.

To monitor the size of damage the following damage indexes have been taken into account:

$$DI1 = \sum_{i=1}^{n} \left| \left(\mathrm{Re}\left(Z_{0,i}\right) - \mathrm{Re}\left(Z_i\right)\right)\left(\mathrm{Re}\left(Z_{0,i}\right)\right)^{-1} \right| \tag{3}$$

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

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

$$DI4 = 1 - \left((n-1)s_0 s\right)^{-1} \sum_{i=1}^{n} \left(\left(\mathrm{Re}\left(Z_{0,i}\right) - \mathrm{Re}\left(Z_0\right)\right)\left(\mathrm{Re}\left(Z_i\right) - \mathrm{Re}(Z)\right) \right) \tag{6}$$

where: $Z_{0,i}$ and Z_i -respectively referential and current value of impedance for i-th frequency, Z_0, s_0 and Z, s-mean values and standard deviations of referential and current impedances, n-number of considered frequencies. Fig. 4 presents values of damage indexes calculated for all sizes of introduced incision.

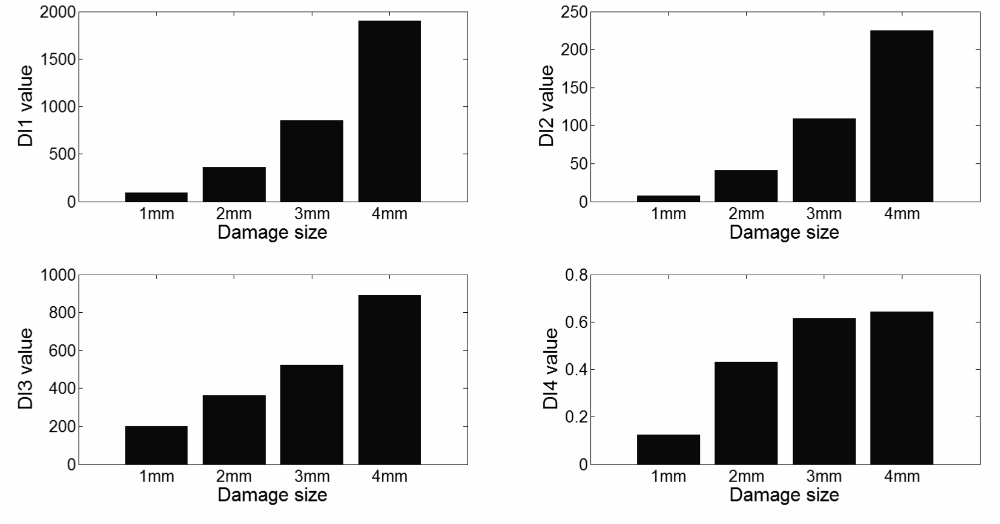

Fig. 4. Relations between depth of incision and damage indexes – numerical results

For all tested damage indexes there have been obtained monotonic relations between their values and depth of incision. This observation justifies the effectiveness of the assessment on the propagation of damage introduced in monitored construction.

Experimental verification

For the mechanical structure mentioned previously experimental measurements of electromechanical impedance have been performed using high precision HP/Agilent 4395A Impedance Analyzer. Fig. 5 presents results obtained for the aluminium beam in the same frequency range as for the simulations.

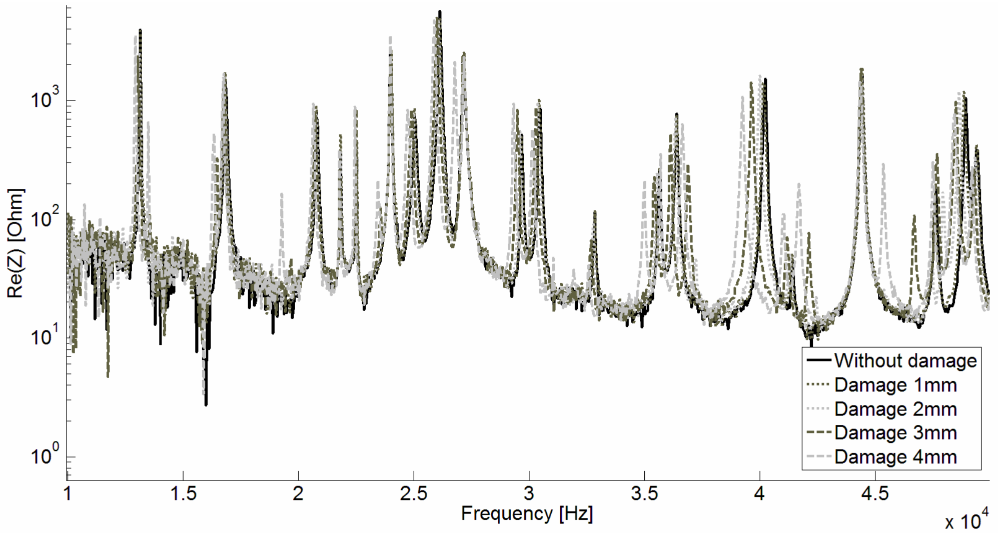

Fig. 5. Real part of measured electromechanical impedance

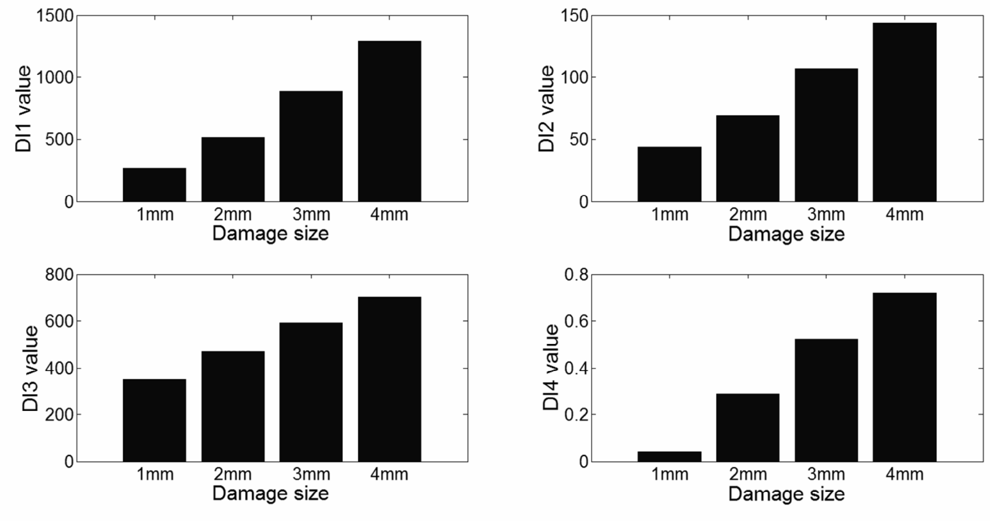

Fig. 6. Relations between depth of incision and damage indexes – experimental results

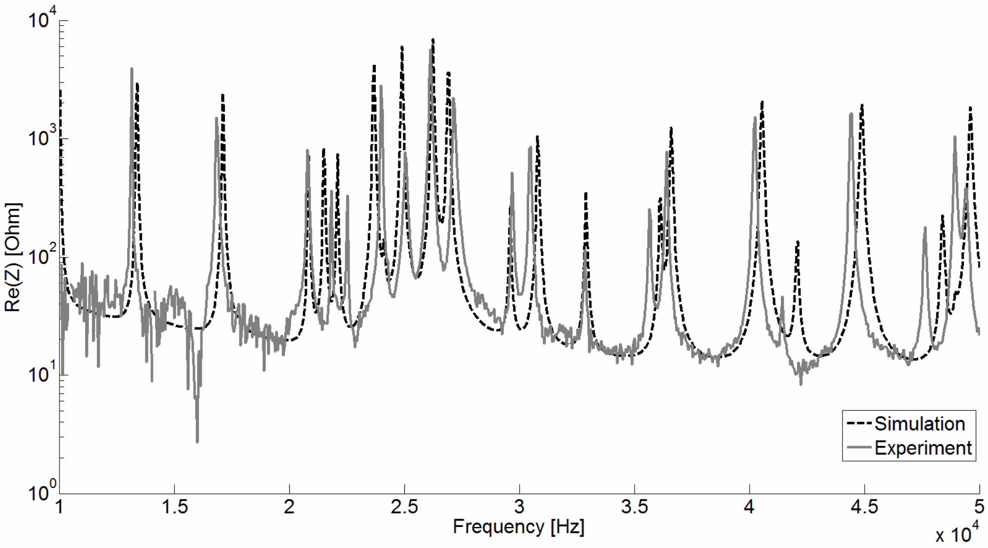

Fig. 7. Comparison between numerical simulations and experimental results for healthy structure

Analogically to the results of FE analyses growth of damage size causes the increase of values of the damage metrics. Impedance plots obtained from experiments were compared with the simulations and there was a good coincidence between numerical and experimental data. Some minor changes in resonance peaks and amplitudes can be observed due to the fact that FE model was not updated after performing the measurements.

Summary and concluding remarks

In this work a utilization of electromechanical impedance measurements for damage detection in mechanical structures was introduced. Numerical results were compared with experimental data and good agreement was reached between simulations and measurement. It was proven, that impedance based technique can be used successfully in structural health monitoring, however this method should be treated as qualitative assessment rather than quantitative one.

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