# SIMULATION OF STRUCTURAL DAMAGE AND ITS DETECTION BY METHOD OF ELECTROMECHANICAL IMPEDANCE

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**Abstract.** The purpose of this article is to evaluate more details the effect of opening / closing of a fatigue crack to the electromechanical impedance (EMI) of the system "piezoelectric transducer / host structure The mentioned effect was investigated in the frequency range of 20-40 kHz and it is particularly significant to all component of the EMI and especially to the resistance PZT. It is established that the effect of opening / closing mainly affects the capacitance of PZT that due the change of piezoceramics relative permittivity under mechanical load. The result of the study is the base of some procedure of fatigue crack detecting by the EMI method. The developed model of EMI of 'host structure – PZT' allows to solve main problems of the SHM system designing and optimizing of its parameters.

## Introduction

The guided Lamb wave technology (LWT) is one of the most effective means of structural damage detection in the thin-walled structural elements of aircraft. Its application for structural health monitoring (SHM) of aircraft is very perspective [1, 2]. Usually monitoring procedure requires that there is known initial state of a structural element, so called 'baseline'. Comparison of a current state with baseline is the general principle of damage detection using LWT. But the mechanical load and environmental exposure leads to a degradation of the monitored structural element, and the sensor of SHM system, built into the structure.

It means that the reliability of detection of structural damage can be higher, if the rule of the structure assessment is based only on the current information. It can be derived from some phenomena that enable to give directly the contrast of structure behavior in two different states of the structure. In particular, the effect of a fatigue crack opening/closing in the monitored structural element may be used as such phenomenon for effective ultrasonic examination. It is caused by the difference in the features of ultrasonic waves at the closed crack (in the unloaded state) in comparison with an opened crack (in the loaded state). Note that the effect of crack opening/closing was reliably fixed in the number of research [3-8]. Comparison of the ultrasound wave intensity of interaction with the opened and closed fatigue crack is the main effect investigated in these research.
The purpose of this pater is to evaluate more details the effect of opening / closing of a fatigue crack to the electromechanical impedance (EMI) of the system "piezoelectric transducer / host structure".

In ultrasound non-destructive inspection the concept of electromechanical impedance (EMI) was used primary in [9-14]. Since this time the several authors used the EMI method for structural health monitoring. Many examples of application of EMI method can find in fundamental monographs [1, 2]. The effect of structural damage is associated with the changes of dynamic properties of a structure and can be effectively defined in the frequency ultrasound. Many ways of the EMI interpretation were proposed. Theory, different solutions, equipment, technology of this method is well discussed in many works. Recent achievements description in this area can find in review-articles [15, 16].

A large number of EMI models have been developed [17-24]. New type of the EMI model and its application for aircraft structural health monitoring (SHM) was developed in articles [25,26]. There was obtained an expression of the electromechanical impedance common to any dimension of models (1D, 2D, 3D), and directly independent from imposed constraints. The modal analysis of the system "host structure - PZT" dynamic response is the basic tool of this model. The final EMI equation is:

$$Z(\omega) = \frac{1}{i\omega C}\left[1 + \frac{k_{31}^2\omega^2}{\left((1-\nu)-2\frac{E}{E\prime}\nu\prime^2\right)Ah}\Phi(\omega)\right]^{-1}, \qquad (1)$$

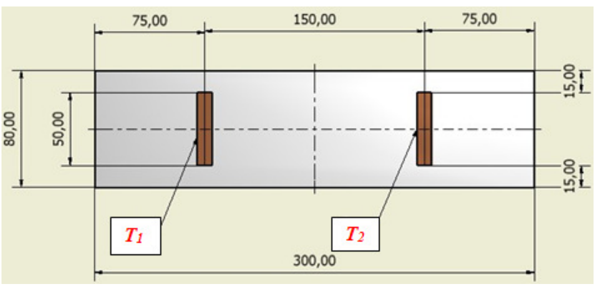
where

$$\Phi(\omega) = \sum_{k=1}^{\infty}\frac{\int\left[(\epsilon_{1k}+\epsilon_{2k}+2\nu\prime\epsilon_{3k})+\frac{d_{33}}{d_{31}}\left(\nu\prime(\epsilon_{1k}+\epsilon_{2k})+\frac{E\prime}{E}(1-\nu)\epsilon_{3k}\right)\right]dW\int\rho(\xi)(\xi-\xi_C)U_k(\xi)dW}{M_k(\omega_k^2-\omega^2)},$$

$k_{31}^2 = \frac{d_{31}^2}{\varepsilon_{33}s_{11}}$ is the electromechanical coupling coefficient, $s_{11}$ is the component of mechanical compliance at zero field, $\varepsilon_{33}$ is the dielectric constant at zero stress, and $d_{31}$ is the induced strain coefficient, i.e., mechanical strain per unit electric field, $E$ and $E'$ are the elasticity modulus, and $\nu$ and $\upsilon'$ are the Poisson ratios of transverse isotropic material of PZT, $C = \varepsilon_{33}\frac{A}{h}$ is the capacitance, $A$ and $h$ are the electrodes area and the thickness of PZT, $\epsilon_{jk} = \frac{\partial U_{jk}}{\partial x_j}$, $(j = 1,2,3)$ and $\boldsymbol{U}_k(\boldsymbol{x})$ and $\omega_k$ is $k$-th mode shape and frequency.

## Experimental study: main results

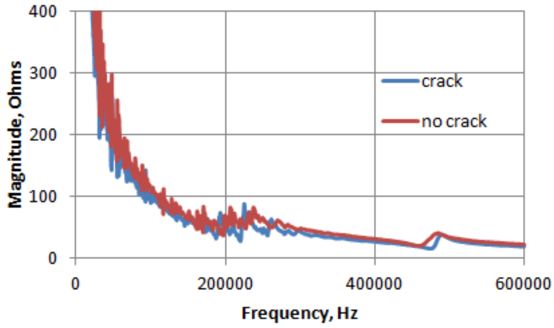
Experimental study of the effect of the crack opening / closing to EMI performed using a rectangular sample 80x300 mm of 1.15 mm Al sheet (Pic. 1). For fatigue crack initiation the 4 mm hole was drilled in centre of a sample. Cyclic load 12/4 kN and 10 Hz was performed using 100 kN hydraulic test machine Instron The sample were equipped by two piezoceramics transducers PIC151 0.5x10x50mm (***T1*** and ***T2***).



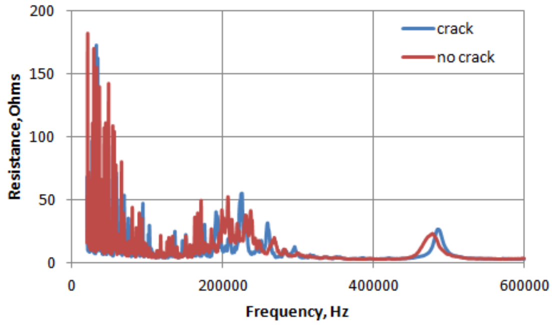

Pic.1. Test sample of Al2024-T3 1mm sheet

During the fatigue testing periodically the cyclic loading was interrupted for ultrasound response and EMI measurements under static loading / unloading up to a maximum load of 12 kN. Sample No. 1 had a central hole with a diameter of 4 mm and not subjected to fatigue tests. Sample No. 2 after fatigue testing has a central fatigue crack length of 40 mm (including a 4 mm diameter central hole for the initiation of a fatigue crack. Each sample was loaded tensile axial static load from zero to 12 kN in increments of 2 kN and stops for measuring electromagnetic radiation. The EMI measurements were performed using the C60 device (Cypher Instrument) in the frequency band from 20 to 600 kHz. The device also gave information on the electric capacity of the transducer in the frequency range of 20-40 kHz.

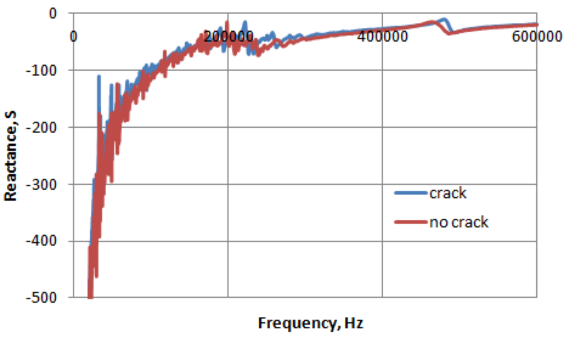
Pic.2-4 show an example of the primary outcome of EMI for transducer embedded to the sample with a crack. The magnitude of the EMI, the resistance and reactance of PZT are presented.




Pic.2. Crack opening influence to EMI magnitude at the tensile load 12 kN



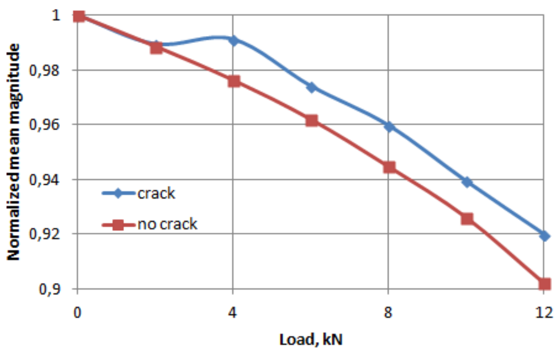

Pic.3. Crack opening influence to EMI resistance at the tensile load 12 kN



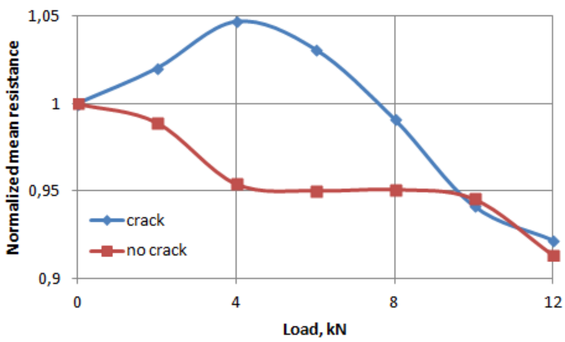

Pic.4. Crack opening influence to EMI reactance at the tensile load 12 kN

To get the clear assessment of the effect of the fatigue crack opening the simplest integral criterion was used: the mean value of the parameters of EMI in the frequency range of 20-40 kHz. Comparison of these parameters for samples with and without a crack in normalized form are shown in Pic. 5-7 depending on the static tensile load.

It can be seen the different effects of the load increasing to parameters of EMI of samples with and without a fatigue crack. The average magnitude and the imaginary part (reactance) of the EMI at the low load (crack is closed), similarly the same as for a sample without a crack. After reaching the load about 4 kN the constant shift between the curves of undamaged and damaged states occurs. The crack opening effect on the real part of the EMI (resistance) is more complicated. Up to a maximum load of crack opening the resistance increases the (in contrast of its reduction for the sample without crack). At further increasing of load the intensive redacting of resistance begins. Near the maximum load the resistance curves for damaged and undamaged samples are closed again.

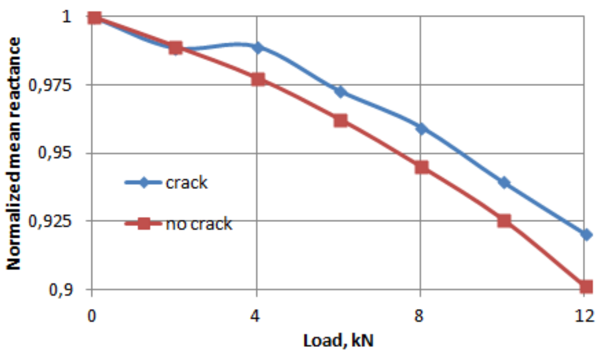



Pic.5. Crack opening influence to the EMI normalized mean magnitude




Pic.6. Crack opening influence to PZT normalized mean resistance

## Analysis and discussion



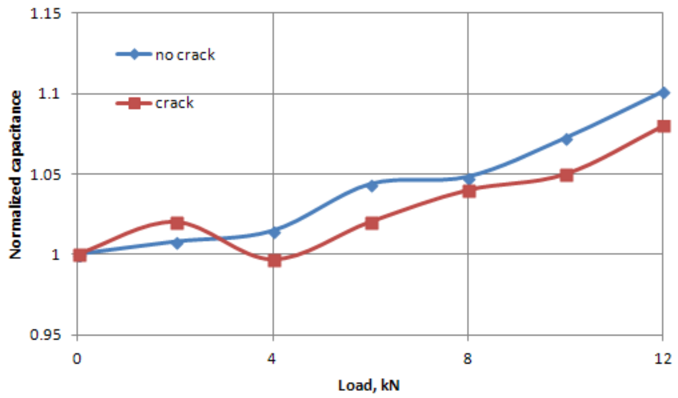

Pic. 7. Crack opening influence to PZT normalized mean reactance

First of all, the test results show the stable effect of a crack opening/closing to EMI of the system "sample – PZT". This effect is associated with two major sources:

1) Load effect to the relative permittivity of piezoelectric ceramics.

2) Elastic compliance of the sample increment at the crack opening

It is well known that the mechanical stress leads to a change in the relative permittivity of piezoceramics and others piezoelectric materials [27-33].



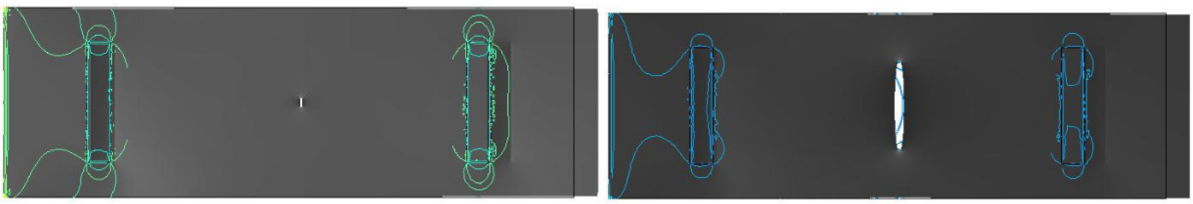

Pic. 8. The PZT normalized capacitance as a function of the tensile load

This parameter has a direct effect on the capacitance of the PZT, and this was observed in measurements of above described test. Pic.8 is represented the PZT capacitance (in a normalized form) as a function of the tensile load increasing for the sample without a crack, and at its presence.

Note that the capacitance measurement by the instrument C60 is not a priority. Therefore, measurement accuracy is relatively low, so that repeated measurements needed to obtain stable estimates.

It is seen that in both cases there is a tendency of capacitance growth by increasing the load. Moreover, full opening the crack causes a shift of the curve downward (for the sample with crack) which remains a further increase in load.

Natural to assume that the observed effect is due to a change in the stress-strain state of the PZT. At the closed crack and small tensile load the distribution of stress and strain in the sample and PZT is more similar to the stress-strain state of the intact sample. After the opening of crack the sample configuration changes which leads to a redistribution of stresses and strains. The finite element analysis of the samples with a different crack length at the maximum tensile load of 12 kN was conducted with purpose to determine the degree of influence of this cause (Pic. 9).



Pic.9. FEA of strain ( in direction of tensile load) of embedded PZT with small 4 mm crack (left) and 40 mm one (right)

Analysis shows that the mean strain (by volume) of PZT in the direction of tension for the sample with a crack is to 2.6% less of the same one of the sample intact. Such an estimate is in satisfactory agreement with the effect of crack to the PZT capacitance.
As can be seen from equation (1), the capacitance of PZT has a direct impact on the EMI, and this equation can be written in the following form:

$$Z[\omega, C(P)] = Z[\omega, C(0)]\frac{C(0)}{C(P)} \quad (2)$$

where $C(P)$ is the PZT capacitance at tensile force $P$, but $Z[\omega, C(P)]$ are the EMI under load $P$.

Assuming that the influence of permittivity affects only the PZT capacitance, then

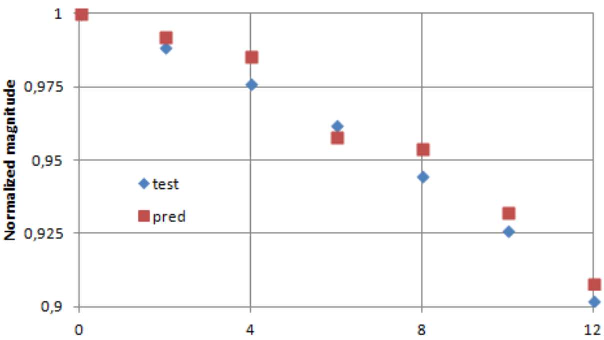
$$Z[\omega, C(P)] = \frac{Z[\omega, C(0)]}{\bar{C}(P)}$$

where $\bar{C}(P)$ is the PZT normalized capacitance.
Therefore

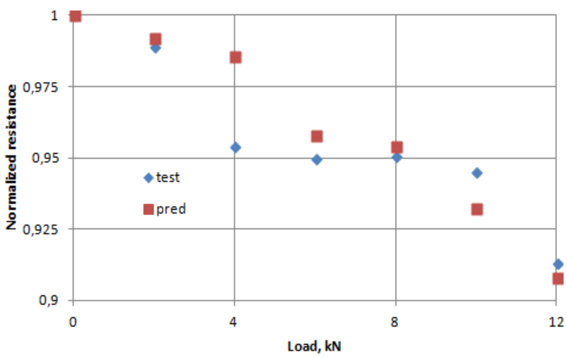
$$\frac{mag\{Z[\omega,C(P)]\}}{mag\{Z[\omega,C(0)]\}} = \frac{Re\{Z[\omega,C(P)]\}}{Re\{Z[\omega,C(0)]\}} = \frac{Im\{Z[\omega,C(P)]\}}{Im\{Z[\omega,C(0)]\}} = \frac{1}{\bar{C}(P)} \quad (3)$$

and normalized parameters of the PZT under tensile load can be predicted using only normalized capacitance as a function of load.

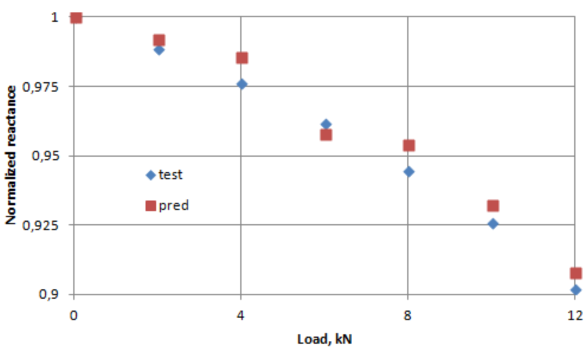
Below in Pic. 10-12 for undamaged sample there is presented a comparison of the predicted values of the magnitude of the EMI, resistance and reactance of PZT with the test data.




Pic.10. Comparison of predicted magnitude of EMI with test



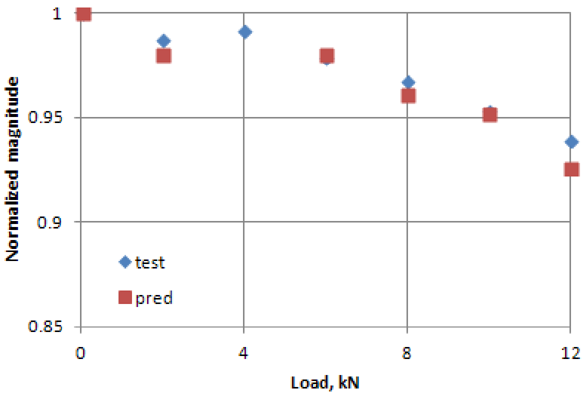

Pic.11. Comparison of predicted resistance of PZT with test



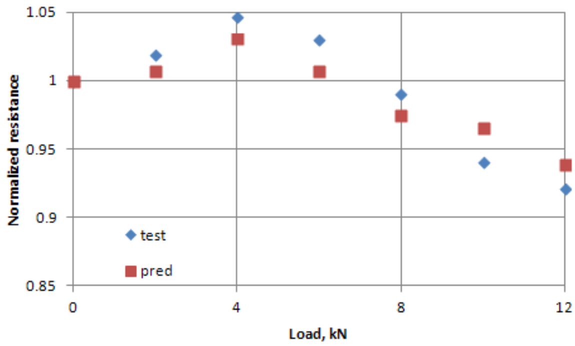

Pic.12. Comparison of predicted reactance of PZT with test

It can be seen that for the magnitude of EMI and the PZT reactance prediction results are close to the experiment. Predicted resistance is somewhat worse agreement with the test data. Therefore, for applications that do not require very high precision the EMI prediction using the capacitance change under load can be acceptable. Thus, we can conclude that for the intact sample the major impact of tensile load to the EMI is associated to the change of PZT capacitance under load. In this case, the effect of other factors is secondary.

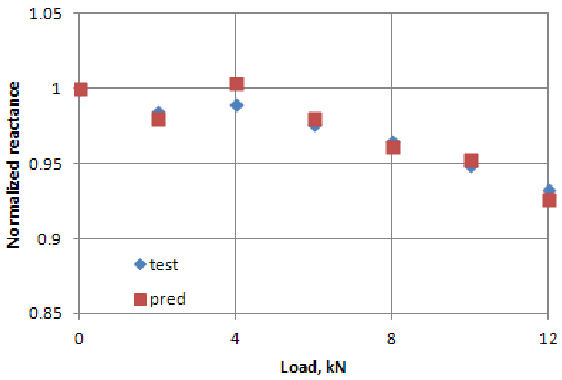
In the Pic. 13-15 for the sample with the 40 mm crack there is presented a comparison of the predicted values of the magnitude of the EMI, resistance and reactance of PZT with the test data.



Pic.13. Comparison of predicted magnitude of EMI with test data



Pic.14. Comparison of predicted resistance of PZT with test data



Pic.15. Comparison of predicted reactance of PZT with test data

Prediction the PZT magnitude and reactance performed using only the ‘ load- capacitance’ function. The PZT resistance also depends on the irreversible loss which varies at the presence of crack in comparison with an intact sample. To account for this fact in the PZT capacitance complex representation the loss factor was increased to 2% compared with the intact specimen (1%) and the resistance was estimated by the developed EMI model (1). As a result the technology of online structural health monitoring can be created. The key operations of it should be:

1) Static and modal dynamic analysis of intact structure with embedded PZT and this one with a fatigue crack;
2) Evaluation the change in capacitance of PZT due to the load for the damaged and undamaged components;
3) Definition of the function “the EMI parameter - the size of the crack”.

The developed model (1) of EMI of ’host structure – PZT’ [30, 31] allows to solve main problems of the SHM system designing and optimizing of its parameters.

## Conclusions

It is shown that using the effect of opening / closing of a fatigue crack under load the crack can be detected by the method of EMI. The special experiment shows that the opening / closing of a fatigue crack under load leads to changes in EMI of the embedded PZT. In this test, the effect was investigated in the frequency range of 20-40 kHz and is particularly significant to all component of the EMI especially to the resistance PZT. It is established that the effect of opening / closing mainly affects the capacitance of PZT that due the

change of piezoceramics relative permittivity under mechanical load,. Mechanism of the effect due to the change of the stress-strain state of PZT which is caused by the opening of a crack under load. The finite element analysis confirms this conclusion..
Change in the capacitance PZT almost uniquely determines the magnitude and reactance. More difficult is the change in resistance. The irreversible energy losses is an important factor of the resistance change of PZT.

In general it can be concluded that the result of the study is the base of some procedure of fatigue crack detecting by the EMI method. The developed model of EMI of 'host structure – PZT' [25,26] allows to solve main problems of the SHM system designing and optimizing of its parameters.

Finally note also that the specific system of SHM can be created using of the effect of changes in capacitance of PZT.

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