Some Applications of Electromechanical Impedance Technology for SHM

Vitalijs P. PAVELKO [1], Sergey KUZNETSOV [1], Ilmars OZOLINSH [1], Igor PAVELKO[2]

[1] Aeronautics Institute, Riga Technical University; Riga, Latvia
[1] Phone: +371 97089961, Fax: +371 97089990; e-mail: vitalijs.pavelko@rtu.lv , sergejs.kunecovs@rtu.lv, ilmars_o@inbox.lv
[2] Centre Composite ; Riga, Latvia; e-mail: igors.pavelko@composite.lv

Abstract
The paper focuses on the further development of the model of the electromechanical impedance (EMI) of the piezoceramics transducer (PZT) and its application for aircraft structural health monitoring (SHM). The opportunities of new model of any dimension (1D, 2D, 3D), and independence from host structure specific shape and constraints are discussed. Determination of the dynamic response of the system "host structure - PZT", which is crucial for the practical application supposes the use of modal analysis. The use of models for the free and constrained transducer is demonstrated. In all cases there was analyzed the influence of the dimension of the model (2D and 3D). The validity of the model is confirmed by experimental studies. Correlation between the fatigue crack length in a thin-walled Al plate and EMI of embedded PZT was simulated and compared with test result.

Keywords: electromechanical impedance, aircraft structural health monitoring, dynamic response, modal analysis

1. Introduction

In ultrasound non-destructive inspection the concept of electromechanical impedance (EMI) was used primary in [1-6]. Since this time the several authors used the EMI method for structural health monitoring. The impedance method was used efficiently for damage detecting in different kinds of structures. Many examples of application of EMI method can find in fundamental monographs [7,8]. 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 [9,10].

Different methods of SHM of the bolt-joints are applied and one of them is the electromechanical impedance (EMI) method [11-25]. Integrated structural health monitoring assessment system was illustrated in [11]. The Lamb wave propagation was combined with EMI technology of damage different structural damage detection including bolt-joint loosening. The system that includes the bolt-joint members equipped by piezoelectric transducer and a wireless EMI device for data acquisition and communication is presented in [12]. Some simple model of EMI of this system was proposed and performed experimental verification. Other kind of SHM system for bolted joint loosening based on variation of EMI was developed in [13].

For effective application of the EMI technology for SHM system the adequate prediction of the effect of monitored structure degradation to parameters on EMI is very important. Therefore a large number of models of EMI was developed. The 1D model of transducer is well in many application, especially if it is used in its eigenfrequency range that is defined by one of the dimensions (for example, rectangular form transducer with significant difference between length and width). Of course the 2D is more correct and less limited for application. These kinds of models were developed in number of works [18-25].

The effective drive point impedance of the host structure can also be defined on similar lines, by applying interaction force on the surface of the host structure the concept of effective mechanical impedance was developed and applied in [20,21]. The mechanical impedance of structure for 2D interaction with transducer in matrix form is presented in [22]. The 2D model was developed and used also in [23]. Interesting solutions are proposed in [24-25].

The version of 2D model was developed [26] using modal decomposition of displacements of transducer and the host structure. A separate modal analysis of PZT and the structural element is first step of application of this version. Next step involves the determination of interaction forces between a transducer and host structure due to the condition of compatibility. In general case, the integral equation can be numerically resolved using an corresponding system of linear algebraic equations. At third step the dynamic response of the PZT as well as the host structure can be obtained that finally defines EMI. The model previous versions were described earlier [18,19]. The new version of this model and some its applications were done in [27,28]. The model generalized on the three-dimensional case, and more effective and productive approach of this problem resolving was proposed. This paper mainly focuses to problem of model practical applications and its further improvement.

2. Brief description of general model of EMI

A piezoelectric transducer of small constant thickness h is continuously glued on the surface of host structural component. In-plane shape of PZT is defined by some closed line (Fig. 1). PZT is undergoing piezoelectric expansion induced by the thickness polarization electric field.

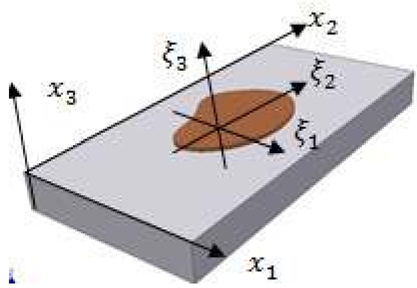

Figure 1. “Host structure-transducer” common geometrical model

The electric field is produced by the application of a harmonic voltage between the top and bottom surface electrodes. The resulting electric field is assumed uniform over the piezoelectric transducer. Because the voltage excitation is harmonic, the dynamic response of the system “PZT – host structure” is also harmonic, i.e., the displacement vector components are harmonic functions of time with coordinates-dependant complex amplitude.
In analysis it is convenient to use two reference systems. The global 3D system defines all displacements as the functions of vector $\boldsymbol{x}$. But local 2D reference system (ξ_1, ξ_2, ξ_3) is convenient at elastic analysis of transducer. The piezoceramics usually is transverse isotropic[8]. It is assumed the electrical field vector is perpendicular to plane of transducer (only the E_3 is non-zero component). Therefore in a plane (isotropy plane) of transducer the directions of axis (ξ_1, ξ_2) can be selected arbitrarily in accordance with the geometric features of the PZT shape.
Using standard procedure of analysis the specific form of EMI expression was obtained:

$$Z(\omega) = \frac{1}{i\omega C}\left\{1 + \frac{k_{31}^2 \int[(S_{e1}+S_{e2})+2\nu' S_{e3}]dW - k_{31}^2 \frac{d_{33}}{d_{31}} \int\left[-\nu'(S_{e1}+S_{e2}) - \frac{E'}{E}(1-\nu)S_{e3}\right]dW}{d_{31}E_3 A\left[(1-\nu) - 2\frac{E}{E'}\nu'^2\right]}\right\}^{-1} \quad ....(1)$$

where $k_{31}^2 = \frac{d_{31}^2}{\varepsilon_{33} s_{11}}$ is the electromechanical coupling coefficient, ε_{33} is the dielectric constant at zero stress, and d_{31} is in-plane and thickness wise induced-strain coefficients; C is the

capacitance of PZT; E_3 is the electrical field amplitude and ω is its cyclic frequency; E and E' are the elasticity modulus, and ν and υ' are the Poisson ratios of transverse isotropic material of PZT; S_{e1}, S_{e2}, S_{e3} are the principal strains of PZT induced by elastic deformation only.
In general the dynamic response of a structure and a PZT was expressed using dynamic elasticity and final EMI equation is as follow:

$$Z(\omega) = \frac{1}{i\omega C}\left[1 + \frac{k_{31}^2\omega^2}{\left((1-\nu)-2\frac{E}{E'}\nu'^2\right)A\delta}\Phi(\omega)\right]^{-1} \text{......................(2)}$$

where

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

where $\epsilon_{jk} = \frac{\partial U_{jk}}{\partial x_j}$, $(j = 1,2,3)$; M_k, ω_k are modal mass and frequency, U_k is a mode k vector.

Solution of EMI using modal decomposition can be obtained by two ways.
First of them supposes definition of dynamic response of a host structure and a transducer separately. At next step the interaction forces on contact surface between a host structure and a transducer should be defined and, using Eq.(19) the dynamic response can be computed. This mean was used for analysis of some dynamic systems including a bolt-joint in the some aerospace structural component[26].
The second mean supposes the direct simulation of dynamic response of the dynamic system 'host structure – transducer'. In this case, all sufficient data can be obtained as a results of computational simulation. This mean is used below.

3. Experimental study

3.1 Non-constrained piezoceramics transducer

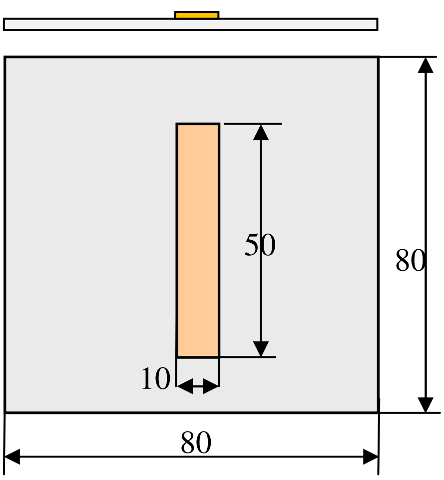

Figure 2. The scheme of a test sample

The PI Ceramic PIC 151 piezoceramics 0.5x10x50mm transducer was used in first test. The goal of test is the EMI measurement at non-constrained state of PZT and further comparison with simulation.
Basic properties of PIC 151 piezoceramics: 1) Permittivity 2400 (in the polarization direction) and 1980 (perpendicular to the polarity) ; 2) electromechanical coupling factors k_{31}=0.38, k_{33}=0.69; piezoelectric charge constants d_{31}=-210·10^{-12} (C/N), d_{33}==500·10^{-12} (C/N); 3) modulus of elasticity are E =6.67·10^{10}Pa, E' =5.26·10^{10}Pa, ν =0.34, ν' =0.29.
The EMI of the non-constrained PZT was measured during this test and used below for validation of developed model.

3.2 Experimental study of EMI of constrained transducer

This test was conducted to determine the adequacy of a reaction of the developed EMI model to any constrain that occurs when the PZT is embedded to a host structure. The simple configuration of ‘host structure – transducer’ is used.
The PI Ceramic PIC 151 piezoceramics transducer sized 0.5x10x50mm was glued in centre of an Al alloy 2024-T3 1x80x80 mm plate (Figure 2). PZT was bonded to the plate surface with the Epoxy Paste HYSOL EA 9309. The impedance of constrained PZT was measured by the Cypher instruments(c) C60 tool in frequency band 0-1MHz. Total samples number of single measurement set is equal 1024. Note that in the constrained state the electrical capacitance of PZT is smaller about 14% than its theoretical value. It should be noted that in a constrained state the electric capacitance of PZT approximately 14% less than the theoretical value (or measured value in non-constrained state). Therefore, the actual measured value of the capacitance is used in the further simulation.

3.3 EMI investigation during fatigue test

This test is focused to investigation of a fatigue crack effect to EMI of PZT.
Aluminium alloy 1x80x300mm plate was equipped with two PZT as shown in Figure 3. PZT parameters and technology to install them on the surface of the sample are the same as the previous tests. In the center of the sample a hole of 4 mm diameter was drilled for the initiation of fatigue crack. After installation in the grips of the testing machine Instron the length of the working part of the sample was 240 mm. Tests were conducted under tensile cyclic load at 10 Hz at cycle stress 50/150 MPa (minimum / maximum stresses). The main purpose of the test was to establish the correlation between the length of the fatigue crack and the parameters of the ultrasonic signals received by the transducer after transmitting of elastic wave through a crack (pitch –catch technique) or after reflection from its surface (pulse-echo technique). Parallel measurement of EMI both PZT in order to establish the effect of the crack was also conducted. For this purpose, the loading was periodically interrupted for measurement of EMI of transducers and accurate measurement of fatigue crack length. Main results are shown below in comparison with the corresponding simulation.

Figure 3. The test sample with two PZT

4. Simulation results and comparison with test

4.1 Non-constrained transducer

The simulation of non-constrained transducer EMI was performed. Its parameters are adopted by the relevant PZT used in the test. The modal analysis is the main part of the simulation and it was performed using COMSOL Multiphysics software in frequency range up to 3 MHz. More than the 7500 modes where found in this range. First of all the comparison of simulation with corresponded test data was done. The 2D version of EMI model was used, and results of comparison are presented in Figure 4 for EMI magnitude. This plot demonstrates the adequacy of the proposed model and its suitability for the prediction.

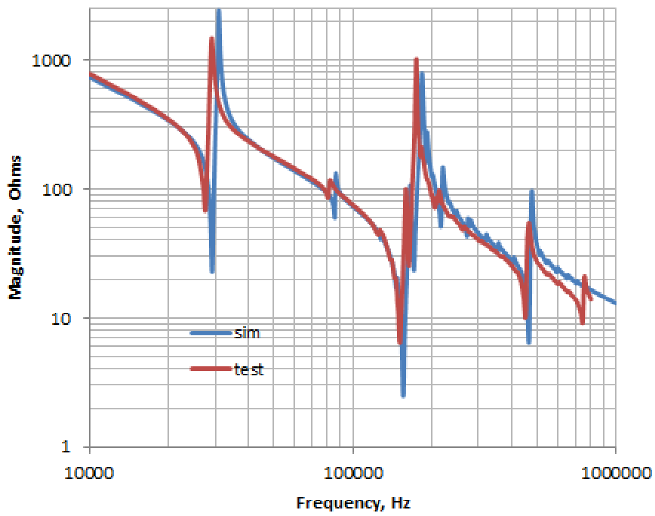

Figure 4. Comparison of the predicted EMI magnitude of non-constrained PZT (2D model) with test

The comparison of both 2D and 3D models is performed. Component of strain S_{e3} in Eq. (1) and (2) gives this ability. To account for the inelastic mechanical and electrical energy losses the loss coefficient is assumed to be equal 0.01. In Figures 5 the magnitude of EMI as the frequency functions are presented. Sufficient difference between two model for magnitude is observed at frequencies more than 1MHz. It can be seen that at low excitation frequencies, this strain is small. This explains the absence of any significant differences in the application of both models at low frequency range. However, at high frequencies, the inertia forces in the out-plane direction become capable of causing considerable deformation.

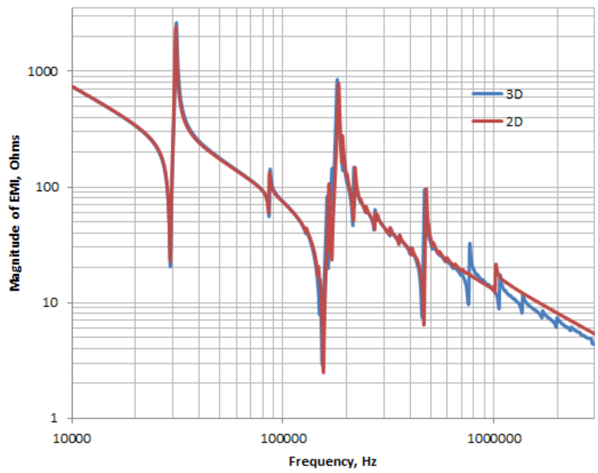

Figure 5. Comparison of the predicted EMI magnitude of non-constrained PZT using 3D and 2D models

4.2 Constrained PZT

The model reproduces the PZT glued on the Al 1x80x80 mm thin plate corresponding to the conditions of test 2 (Figure 2). In the simulation there is assumed that the surface of the contact of a plate and a transducer is continuous, and adhesive layer thickness is equal to zero. The host structure (a plate) is simulated with free edges.

First of all simulation data is compared with test. The plot of EMI magnitude as a function of frequency is presented in Figure 6. It is seen that the simulation curve is close to measured one. The biggest deviation of resonance frequency (from measured value 321 kHz) is equal to -13% . Resonance amplitudes mainly are also close.

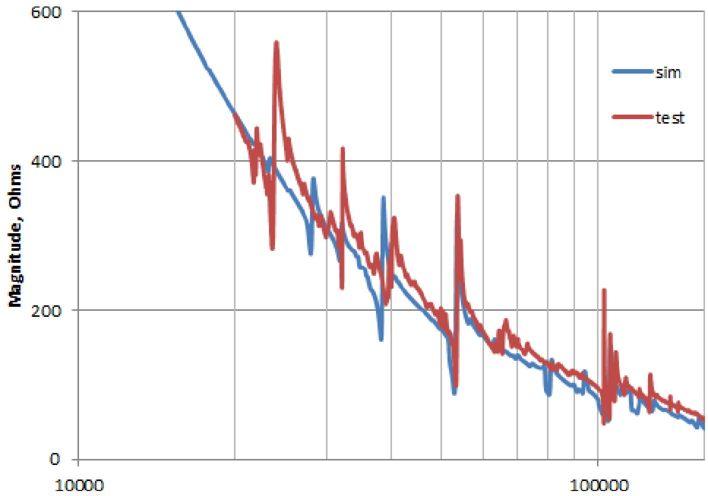

Figure 6. Comparison of simulation and test for EMI magnitude of constrained PZT

4.3 Effect of fatigue crack in a plate carrier for EMI

This study is concerned with evaluation of the effectiveness of developed model for the structural health monitoring or the non-destructive inspection of the structural component. Simulations were performed for the configuration 'host structure – PZT' with two PZT. The test specimen corresponds to the conditions of fatigue tests described in section 3.3 (Figure 3). Simulation and test results are compared in Figures 7-9.

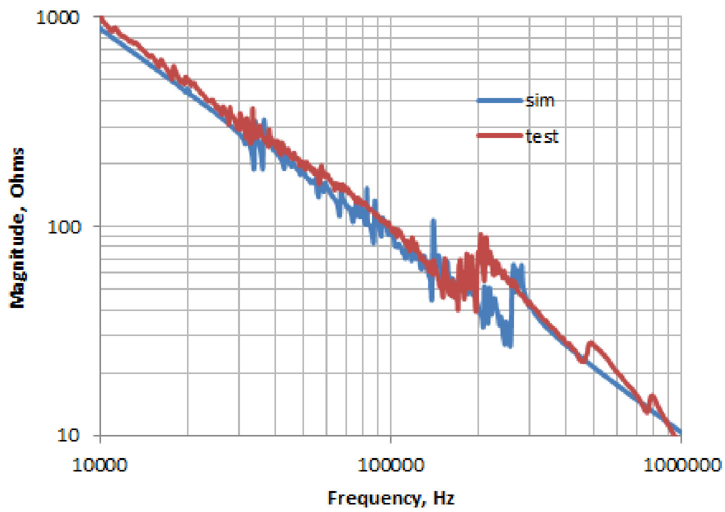

Figure 7. Comparison of the magnitude of EMI predicted by 2D model and measured during fatigue test

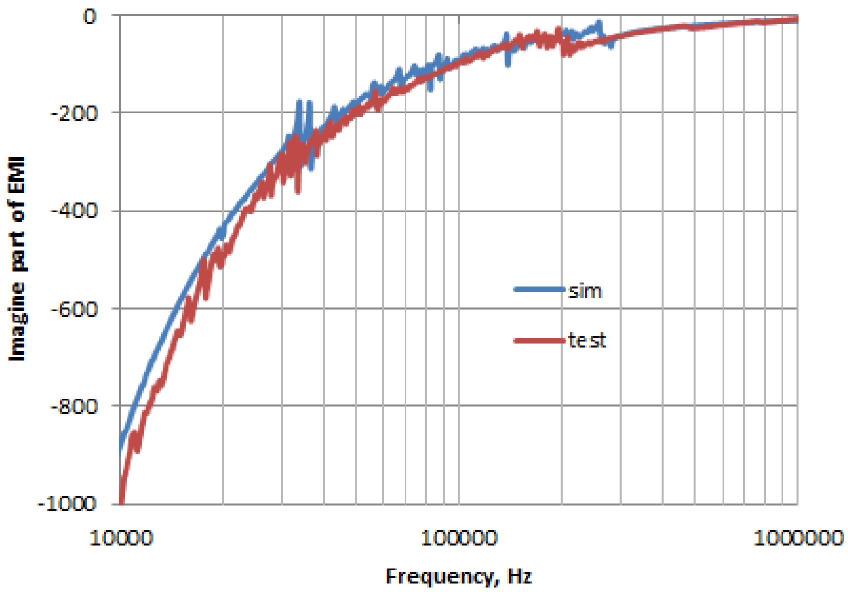

Figure 8. Comparison of the imaginary part of EMI predicted by 2D model and measured during fatigue test

It is seen that simulation and test corresponding curves are similar. The most significant resonance frequencies (predicted and measured) are close.
The root mean square deviation (RMSD) of real part of EMI was used for estimation of fatigue crack effect. It is

$$RMSD = \sqrt{\frac{\sum_{n=1}^{N}(ReZ_k - ReZ_{0k})^2}{\sum_{n=1}^{N}(ReZ_{0k})^2}}, \qquad (3)$$

where ReZ_k is the real part of EMI, N indicates the number of frequencies. The subscript '0' indicates the baseline of the EMI real part.
This effect of fatigue crack growth to EMI of the transducer is illustrated in Figure 15. The predicted RMSD of EMI is shown in first column of each set in Figure 15. Second and third columns indicate the result of measurement of EMI for two PZT.

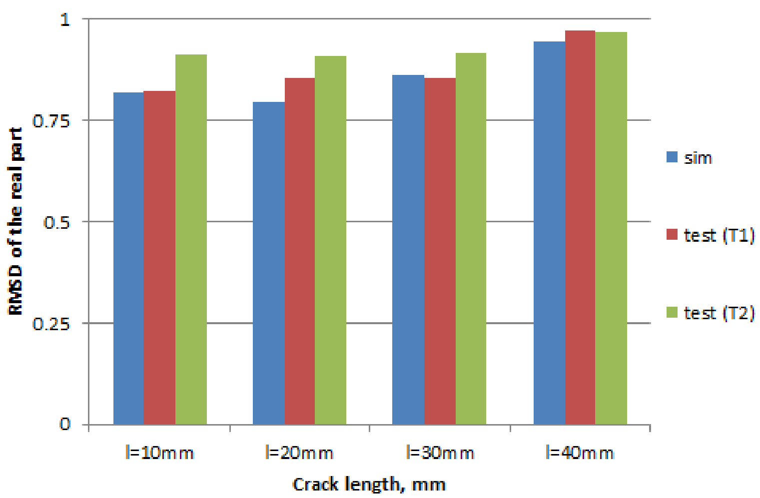

Figure 9. Crack growth effect to RMSD of EMI: simulation and measurement comparison

5. Discussion and conclusions

First of all, it should be noted that this research confirms the validity of the developed model of electromechanical impedance of a piezoelectric transducer based on modal decomposition of the dynamic response of the PZT as well as a host structural member. An important advantage of the model is a common algorithm: application of the model irrespective of the type and shape of the piezoelectric transducer, its dimension (1D, 2D, 3D) , the geometric and structural features of the host structural component. The main component of EMI prediction procedure is reduced to a modal analysis of the elastic system. Especially effective variant of the model application is considered here. It supposes the common modal analysis of the entire system "host structure +PZT". Modern computer tools make it possible to quickly perform using a standard procedure of modal analysis. As a result, the developed model allows to solve a large number of EMI predicting problems of non-constrained or constrained PZT with different boundary conditions and their partial loss as an effect of degradation.

Confirmed also a known fact that the method of EMI can be used as an effective and relatively simple solution of the structural health monitoring problem. Change of structural stiffness due the appearance of damage affects the impedance of PZT mounted on the monitored unit, and damage can be detected by changes in the parameters of EMI. It is shown that the effect of the fatigue cracks can be predicted in advance by using the proposed model . This has important implications for the designing of SHM systems.

However, there are certain problems associated with the use of the developed model. First of all, they are connected with this method using for large structures. In this case, there are purely technical problems with the implementation of modal analysis, especially at high frequencies. On the other hand, the effect of a damage appearance is usually local affecting the structure portion, whose dimensions are comparable with the size of the damage. In this situation, the entire structure simulation is impractical. In this regard the problem of the adequate simulation of structural damage effect to the dynamic response of the damaged area only is actual. In this respect the computational simulation of low-reflecting boundaries is perspective. This technique has been successfully applied to create a model for the monitoring of EMI of bolt-joint of helicopter [26].

The second difficulty is induced by the possible errors of numerical modal analysis especially at high frequencies. Obviously, the dimensions of the finite element of a model should be less than the length of the elastic waves generated by the harmonic excitation.

The results of calculations and measurements of electromechanical impedance of embedded PZT indicate that the responses of different nominally identical PZT on the same damage may significantly differ. In particular, it is clearly seen in Figure 9: two PZT symmetrically disposed about the crack have substantially different parameter RMSD of EMI real part. In the same time, the statistical variation of this parameter for each PZT is negligible. This problem should also be in the field of further research.

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