Electromechanical Impedance Technique and Scanning Vibrometry for Structure Characterization

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ABSTRACT

The operating principle of electromechanical impedance method is based on measurement and analysis of impedance – based quantities of piezoelectric transducers bonded on or embedded in investigated structure. The method assumes that any structural change (especially damage) should influence the impedance characteristics of the transducers. Electromechanical coupling between transducer and the host structure causes that mechanical resonances can be seen as peaks in impedance characteristics.

In this paper the impedance method was used to diagnose the structural state of isotropic beam. The piezoelectric elements were bonded to the surface of the host structure and supplied by alternating low voltage source. Different measurement cases were investigated using various configurations of power supply to piezoelectric transducers such as different or the same polarization applied to transducers bonded on the opposite sides of the beam. Piezoelectric transducers were supplied from the same source, so they also affected each other. Transducers used in experiment are a CeramTec SONOX P502 piezoelectric transducers. Measurements were conducted using Impedance Analyzer – HIOKI IM3570 for wide frequency range. Results showed that there was a significant difference in electric parameters of these two transducers related to changes in polarization of supplying voltage to them.

The electromechanical impedance method is widely used in high frequency range. It can be treated as modal analysis for high frequencies (up to MHz), because the impedance is directly related to frequency response function of the system. However

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the method is also influenced by electrical characteristic of piezoelectric transducers. In order to support these statements scanning laser vibrometry was used to learn about the relationship between the mode shapes of structure and resonant peaks in electromechanical response.

INTRODUCTION

The electromechanical impedance technique (EMIT) is focused on the spectral measurements of electric – based parameters of piezoelectric transducers bonded to investigated structure. Due to bonding, an activation of a piezoelectric element causes vibrations of a host structure. These oscillations make significant change in the electric permittivity of a sensor. One can draw conclusions about mechanical impedance of structure basing on the electric impedance of a sensor.

Modelling of impedance of piezoelectric sensor and host structure was first proposed by Liang in 1994 [1]. Park et al. proposed monitoring system of steam pipeline of 3 inches thickness using EMIT [2–4]. Change of mass of 0.002% was noticeable. Another idea was to monitor condition of high – temperature objects, where environment influences had to be met. Soh et al. presented the monitoring system of CR bridge using EMIT [5]. In 2001 Giurgiutiu proposed application of artificial neural networks for damage detection using EMIT [6]. In 2004 Giurgiutiu summarized state of art in damage detection and localisation using EMIT in beams and plates [7]. At the same time Park et al. also summarized the state of art in EMIT and pointed problems to be solved [8]. In 2006 Kim et al. proposed usage of two piezoelectric transducers in modified EMIT to investigate welded structures [9]. Modification proposed by Kim tells about actuating one sensor with alternating voltage and measuring the current flow through second transducer. Combination of these two quantities gives transfer impedance. In 2008 Yang et al. investigated influences of heavy environmental conditions on life rate on piezoelectric transducers using electric parameters as indicators [10]. Experiments have shown that piezoelectric parameters remain constant even after burying in soil or protecting by silicon. In last few years, usage of integrated electric circuits in EMIT, e. g. AD5933 – impedance analyzer, has been in the centre of interest of many scientists [11].

PRINCIPLES OF EMIT

From the electric approach to EMIT one can assume piezoelectric transducer as a real capacitor with a dissipation resistance (fig. 1). Impedance of such circuit is described by equation:

$$\underline{Z}(\omega) = R_s + \frac{R_p}{1+\omega^2 R_p{}^2 C^2} - j\frac{\omega R_p{}^2 C}{1+\omega^2 R_p{}^2 C^2} \tag{1}$$

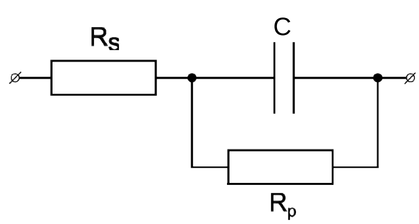

Figure 1. Equivalent circuit for a piezoelectric transducer.

where: ω – angular frequency [rad/s], R_s – equivalent serial resistance [Ω], R_p – equivalent parallel resistance [Ω], C – capacity of piezoelectric transducer [F], j – imaginary unit.

Impedance can be calculated as a ratio of the voltage between electrodes and the current across them. Both of these quantities are complex numbers, because of their alternating character. This is the principal function of many impedance analyzers. Basing on the voltage and the current, impedance analyzers can calculate most of other parameters, e. g. resistance, admittance, quality factor, phase angle. Due to electromechanical coupling in piezoelectric crystals, local strain of a host structure causes change in polarisation of dielectric material. This phenomena can strengthen or diminish the charge capacity of sensor. Impedance of a plane capacitor can be written as:

$$\underline{Z} = \frac{1}{j\omega\underline{C}} = \frac{d\varepsilon_r^{"}}{\omega\varepsilon_0\left(\varepsilon_r^{"2} + \varepsilon_r^{'2}\right)S} - j\frac{d\varepsilon_r^{'}}{\omega\varepsilon_0\left(\varepsilon_r^{"2} + \varepsilon_r^{'2}\right)S} \qquad (2)$$

where: $\underline{C}$ – complex capacitance [F], d – distance between electrodes [m], S – area of one electrode [m^2], ε_0 – permittivity of vacuum [F/m], $\varepsilon^{"}_r$ – relative permittivity corresponding to energy dissipation in material [-], $\varepsilon^{'}_r$ – relative permittivity of crystal [-]. It is the electric permittivity that couples mechanical strain and polarisation of piezoelectric, so it is also a complex function of angular frequency. If a resonant frequency of a structure is close to the frequency of applied voltage, the increase of resistance is observed.

It is important to mark out that mechanical resonance does not correspond to electrical resonance. Due to definition, electrical resonance takes place when reactance (the imaginary part of the impedance) vanishes. Mechanical resonance of a structure results in growth of a resistance and inflection of a reactance of a piezoelectric transducer.

EXPERIMENTAL SETUP

During the experiment HIOKI IM3570 Impedance Analyzer was used. This unit allows user to execute measurements in a large frequency range – from 4 Hz up to 5 MHz. Such high frequencies are useless unless temperature is not being measured during experiment and involved in signal processing. It has been revealed that for higher frequencies temperature influences are greater than changes in impedances caused by damage. Fig. 2 presents the schema of experiment during electromechanical investigation. Experimental setup was built using clamped – clamped beam (1000x20x2 mm), 2 pairs of piezoelectric sensors SONOX P502, vibrometry scanning head POLYTEC PSV – 400 3D and mentioned impedance analyzer. Laser vibrometry is nowadays popular contact–less laboratory method for measurements of structures, e.g. elastic wave propagation or vibrations. It basis on a Doppler effect and register the frequency shift between sent laser beam and reflected one. It allows to measure vibrations up to 24 MHz and velocity up to 20 m/s.

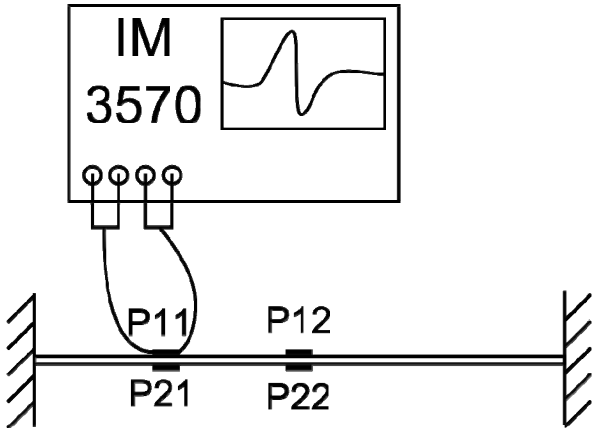

Figure 2. Experiment setup for impedance investigation.

Sensors were bonded on a quarter and on a half of length of a beam, as it is presented in fig. 2. They were excited using 5 Vrms for every frequency. The same beam was investigated using vibrometry scanning head to identify relation between mechanical resonance peaks and changes in electrical impedance. All calculations were conducted using MathWorks MATLAB.

EXPERIMENTAL RESULTS

Before bonding all four piezoelectric transducers were measured using impedance analyzer. Their capacitances were approx. 1.65 nF. After bonding, their ability to store charge decreased for 18% and new capacity is approx. 1.36 nF. Parallel connection of two bonded piezoelectric transducers results in capacity of 2.87 nF. These values are very important in elimination of a main hyperbolic trend that is present in the reactance. Mechanical resonance peaks are deviations from main trend and they are often almost invisible because of it. In the fig. 3 red line presents the calculated reactance using mentioned capacity. Green line presents measured reactance. In the fig. 4 the difference between these two quantities is presented.

As it is known from the physics, reactance can be easily calculated into resistance (and conversely) using Kramers – Kronig bidirectional relations:

$$\mathrm{Re}\left(\underline{Z}(\omega)\right) = \frac{2}{\pi}\int_0^\infty \frac{\omega' \,\mathrm{Im}\left(\underline{Z}(\omega')\right)}{\omega'^2 - \omega^2} d\omega' \tag{3}$$

$$\mathrm{Im}\left(\underline{Z}(\omega)\right) = -\frac{2}{\pi}\int_0^\infty \frac{\omega \,\mathrm{Re}\left(\underline{Z}(\omega')\right)}{\omega'^2 - \omega^2} d\omega' \tag{4}$$

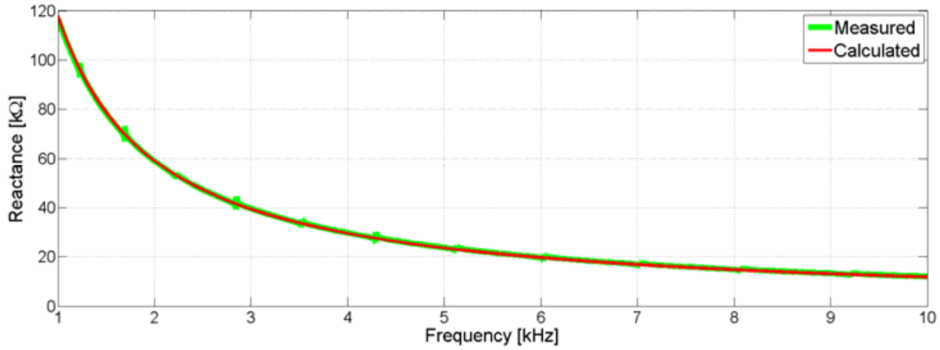

Figure 3. Measured (green) and calculated (red) reactance.

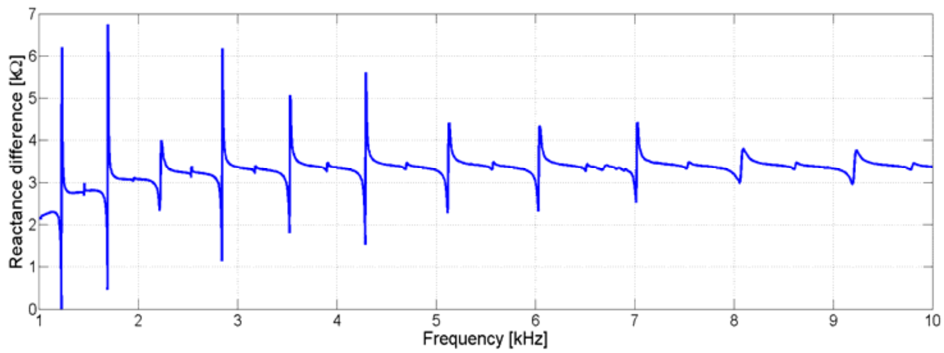

Figure 4. Difference between calculated and measured values of reactance.

It is easier to observe resonance peaks using resistance plot. Fig. 5. presents the resistance of sensor P12 (fig. 2) and frequency response function measured by laser vibrometer in the out of plane axis . The biggest peaks in both vibrometry scan and impedance analysis correspond to the even flexural mode shapes. Odd flexural mode shapes are almost invisible in the electric investigation, while in vibrometry scan they are barely seen. Mode shapes which nodes are at the same place as piezoelectric sensor, will not be visible on the impedance spectra of this sensor.

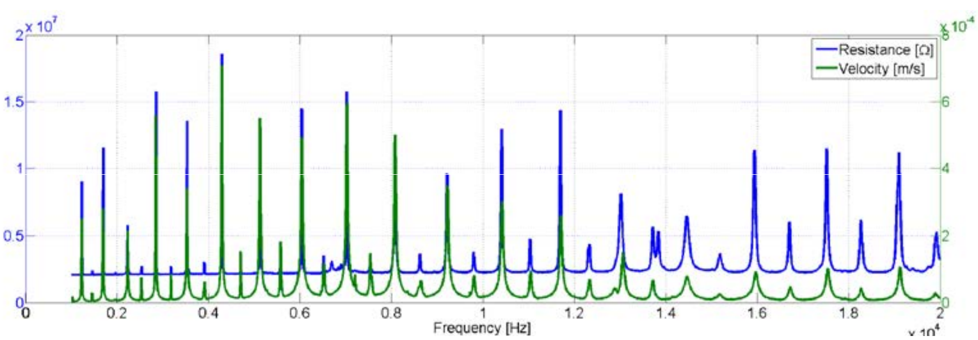

Figure 5. Comparison of mechanical and electrical spectra (sensor P12).

Flexural mode shapes in plane of a beam are present when multiple of half of a wavelength is equal to the width of a beam. In both electrical and mechanical investigation they can be seen as a disorder in a plot, but without 3D scan they cannot be distinguished between other peaks.

Interesting result can be obtained when two piezoelectric transducers are actuated at the same time. They can be in phase (both work on bending) or in antiphase (one will decrease the influence on a beam of another sensor). Fig. 6 presents the resistance of a transducer P12 in a comparison to a resistance of parallel connection of P12 and P22. Connected elements have a lower basic resistance (as it results from eq. 1). It can be seen that some resonances does not exist when piezoelectric elements are actuated in phase. It has been investigated using vibrometer and revealed that those resonances correspond mainly to torsional mode shapes. When both transducers are supplied by alternating voltage that makes them work in antiphase, peaks corresponding to flexural mode shapes vanishes (fig. 7). The remaining resonances correspond mainly to torsional mode shapes that were cut off in previous experiment.

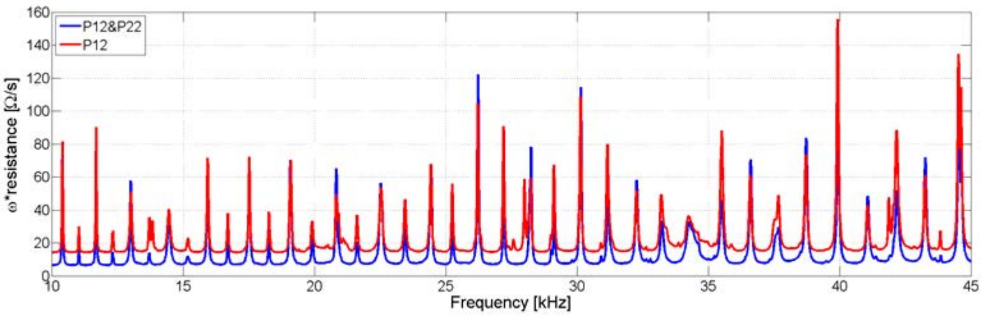

Figure. 6. Comparison of transducers connected in phase spectra and a simple sensor.

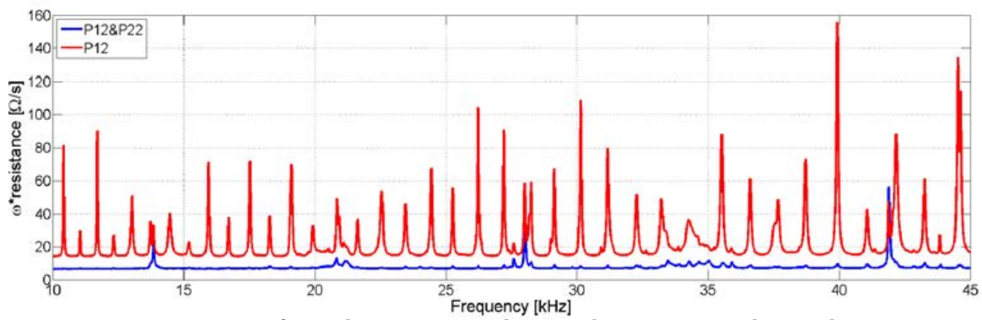

Figure 7. Comparison of transducers connected in antiphase spectra and a simple sensor.

CONCLUSIONS

Resonance identification of a structure is an important task in structural health monitoring techniques, e. g. damage detection basing on modal analysis. It has been shown that frequency response function for a beam can be easily measured using electrical quantities like resistance for a high frequencies. If two piezoelectric transducers are mechanically coupled (like pairs P11&P21 and P12&P22), it is important to notice the phase of voltage between them, because for no phase shift and shift of 180° their resonance spectra significantly varies. Basing on Kramers – Kronig equations it can be easily proved that reactance and impedance carry the same information.

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