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Delamination detection in CFRP panels using EMI method with temperature compensation

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ABSTRACT

In this paper result of detection and localization of artificially initiated delaminations in carbon fiber reinforced polymer (CFRP) samples were presented. Damage detection was based on electromechanical impedance method (EMI). This method utilizes electromechanical coupling of piezoelectric transducer with host structure. Due to this coupling mechanical resonances of structure can be seen in electrical impedance characteristic of a piezoelectric transducer. In the research real part of electrical impedance (resistance) was measured. Delamination in CFRP sample caused frequency shift of certain resonance frequencies visible in resistance characteristic. In this paper also changing temperature effects on EMI method were investigated. In order to remove this temperature induced effects compensation algorithm based on signal cross-correlation was utilized.

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1. Introduction

Nowadays carbon fiber reinforced polymers (CFRPs) are more and more utilized in many branches of industrial manufacturing. These materials are widely used in various aerospace structures like: passenger airplanes (e.g. Airbus A350 or Boeing 787), military aircrafts, and helicopters. Composite materials are also widely utilized in automotive industry. The main feature that makes CFRP so attractive in the manufacturing of structural parts is their strength to weight ratio. These materials are light and simultaneously their strength is very high. On the other hand these materials are very sensitive to impacts which are sources of delaminations between composite layers. A delamination very often is not visible during the conventional visual inspection. It can further grow till it reaches critical size that is dangerous for structural integrity. Therefore non-destructive testing (NDT) techniques need to be used in order to check structural state of composite elements. Application of conventional NDT techniques forces to exclude the structure from its normal exploitation what generates huge costs. In order to reduce the maintenance costs for composite aerospace structures approach called structural health monitoring (SHM) was proposed [1,2]. This is a technique that allows to perform continuous structural assessment of the structure. One of the very promising SHM techniques is electromechanical impedance method (EMI) [1]. This method utilizes measurements of electrical parameters of piezoelectric transducer bonded to host structure. Due to electromechanical coupling of transducer with the structure, mechanical resonances can be seen in electrical characteristics of piezoelectric transducers. Damage is a source of stiffness change and influences the resonant characteristic of structures. Research related to this method started with publication of papers by Liang [3,4], where the essence of electromechanical impedance method was presented. Liang developed one dimensional analytical model of piezoelectric transducer bonded to structure.

Generally EMI method is very sensitive to small damage and is very often utilized for SHM [5–8]. This method was utilized for such structures like beams [9], plates [10] and railroad tracks [11]. Authors of work [12] determined load influence on measurements for EMI method. In the paper [13] author utilized EMI method for detection of opening/closing fatigue crack in aluminum panel. Effect of opening/closing of crack influences the capacitance of piezoelectric transducer. This effect is related to change of relative permittivity of piezoelectric transducer under the load. EMI method was also used for assessment of bolted joints in pipes [9] and riveted aerospace structures in [14,15]. Many examples for application of EMI method for metallic structures can be also found in [16], where the author utilized EMI method for simple beams, complex metallic aerospace panels and gas turbine blades.

This method was also used with success for composite materials. Authors of the work [17] used EMI method for damage detection in composite stiffened panel. Authors utilized the RMSD damage index. They noticed that damage index increases with damage radius. However, the damage index values did not

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correlate with distance to damage. Authors of work [18] utilized combination of guided Lamb wave based method and EMI method for delamination detection in a composite wing mock-up specimen with stringers. Damage was modeled by placing piece of industrial putty. Authors reported large damping of the structure. In composite structures especially with large dimensions the range of EMI method is strongly reduced due to large damping. Authors of work [20] proposed solution that allows to enhance sensitivity of EMI method for damage detection in composite structures. In proposed approach resonant frequency range below 80 kHz was used for the damage detection. This approach allows to obtain large sensing area. Idea of proposed approach is to create resonant peaks in the part of frequency band where it was not present before. In practice this is simply realized by attaching a piezoelectric transducer to metallic element which have resonant frequencies in the lower range. Next this element with transducer is bonded to the structure. A novel approach for composite structures with complex geometry was proposed in [21]. This approach is based on piezoelectric transducer attached to a steel wire which is next attached to the composite structure. Proposed approach is suitable for damage detection and sensor debonding assessment. Interesting solution was presented in [22], where author utilized two piezoelectric transducers located concentrically. This approach is very suitable for large structures where utilization of one transducer allow to perform only local assessment. Authors of paper [23] utilized EMI method for assessment of adhesive bonds in CFRP samples. Different scenarios of weak bond were investigated in this research: chemical contamination, moisture, improper curing temperatures. Conductance spectra for very high frequencies, around 3.8 MHz were investigated in this research. This approach was based on thickness mode and it is a local approach.

Despite the advantages EMI method has also some drawbacks. The range of the method is limited in composite material due to strong damping. Moreover, this method is also very sensitive to ambient temperature change. Increasing temperature causes leftward shift of peaks in real part of electric impedance (resistance) characteristics [8,24]. This influence of temperature needs to be compensated for proper damage detection. Without temperature compensation false alarms can occur.

After literature review it can be clearly noticed that there is still not enough research done on damage detection in composite materials. Existing papers related to damage detection in composite material do not deal with problem of temperature influence compensation. The exception is the work [18]. Generally problem of temperature influence and its compensation is still not solved completely.

Presented research is a continuation of previous authors work related to delamination detection in small (100 mm × 100 mm) CFRP samples with utilization of EMI method [25]. In the present paper authors analyze much larger composite samples with different size of artificially made delaminations. Moreover authors investigate in details the influence of temperature and its compensation using signal-cross-correlation. This part of the paper was inspired by paper of Baptista et al. [8] where temperature compensation algorithm was proposed but it was not used for damage detection. This algorithm was based on frequency shift of temperature influenced spectra (horizontal shift) in order to achieve maximum value of cross-correlation between referential and temperature influenced spectra. Moreover, the algorithm was tested for delamination detection with temperature influence.

2. Composite samples

During the research three composite samples manufactured of CFRP pre-pregs (GG204P IMP503 42) were utilized. First sample was a small plate with dimensions 100 mm × 100 mm × 3.5 mm (Fig. 1a). The second one was larger plate with dimensions: 600 mm × 200 mm × 3.5 mm (Fig. 1b). The third was a plate with dimensions: 500 mm × 200 mm × 3.5 mm (Fig. 1c). The samples had 8 layers with [0/90/0/90]s stacking. All CFRP samples were instrumented with piezoelectric transducers. First and third sample was equipped with one piezoelectric transducer (Fig. 1a and c) whereas the second with three piezoelectric transducers (Fig. 1b). However, in the case of second sample only transducer marked as P2 was utilized in research presented in this paper. All piezoelectric transducers were disk-shaped with 10 mm diameter and 0.5 mm thickness. Transducers were manufactured using NCE51 piezoelectric material (manufactured by NOLIAC).

Measurements were performed using HIOKI IM3570 impedance analyzer. During research serial resistance Rs was measured with 10 Hz step. After measurements, the registered Rs spectra were interpolated in order to improve the frequency resolution. Final frequency resolution was equal to 1 Hz.

3. Electromechanical impedance method

EMI method is based on measurements of electrical parameters of piezoelectric transducer coupled with the investigated structure. Due to electromechanical coupling of piezoelectric transducer and the host structure, mechanical resonances of structure can be observed in electrical characteristics of piezoelectric transducer. According to Na and Lee [7] the coupled relationship between the electrical and mechanical impedance was first introduced by the one-dimensional equation proposed by Liang [27]:

$$Y(\omega) = i\omega a\left[\varepsilon^T(1 - i\delta) - \frac{Z_S(\omega)}{Z_A(\omega) + Z_S(\omega)} d_{3x}^2 Y^E\right] \tag{1}$$

The $Y(\omega)$ is the electrical admittance of the PZT element. $Z_A(\omega)$ and $Z_S(\omega)$ are the mechanical impedance of the PZT actuator and the host structure respectively. Any changes in these impedances can be detected by monitoring the electrical admittance. a, ε^T, δ, d_{3x}, Y^E are the transducer geometric constant, zero stress dielectric constant, dielectric loss tangent, piezoelectric coupling constant and complex Young's modulus of the transducer at the zero electric field respectively.

In this method electrical parameters like impedance, admittance, their real parts (respectively resistance and conductance) and their imaginary parts (reactance and susceptance) can be registered and analyzed.

According to literature, imaginary part of electrical parameters is used for monitoring of bonding layer between transducer and structure or diagnosis of the transducer itself [5], whereas real part of electrical parameters is utilized for monitoring of the structure. For example, in [16] reactance was utilized as a parameter that allows to detect transducer debonding, while the resistance was used for assessment of the structure. However, in the paper [27] resistance and susceptance were used to detect sensor faults.

In order to distinguish the damage state from the referential state of the structure, different damage indexes can be utilized. Most popular are the *root mean square deviation* (RMSD) and *cross correlation distance* (CCD) that can defined as follows [8]:

$$\mathrm{RMSD} = \sum_{i=1}^{n} \sqrt{\frac{(R(i)_D - \mathrm{Re}(i)_R)^2}{\mathrm{Re}(i)_R^2}}, \tag{2}$$

$$\mathrm{CCD} = 1 - \sum_{i=1}^{n} \frac{[R(i)_R - \overline{R}_R][\mathrm{Re}(i)_D - \overline{R}_D]}{\sigma_R \sigma_D}, \tag{3}$$

where $R(i)_R$ – i-th sample of the serial resistance of piezoelectric transducer for referential (undamaged) state, $\mathrm{Re}(i)_D$ – i-th sample

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