Damage detection in submerged composite materials using electromechanical impedance spectroscopy

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Abstract

In this paper authors present results of application of electromechanical impedance methods for damage detection in composite materials. In this research Glass Fiber Reinforced Polymer GFRP sample was investigated. Fiber reinforced composite materials are widely used in many branches of industry like aerospace, automotive, wind energy or maritime. These materials have many advantages that makes them so attractive from the point of view of its application. However, some features related to composite materials like for example large material damping could be a problem in the field of Structural Health Monitoring SHM. Large damping could reduce the range of SHM methods, it reduces the area around the sensors where damage could be detected. Motivation of research was to determine the influence of damping on the electromechanical impedance method based damage assessment. Authors investigate the influence of damping related to composite material and also damping coming from water immersion of composite structure. In this purpose composite sample was immersed into the water. Based on results authors analyzed the sensitivity of electromechanical impedance and its range in the problem of damage detection in composite materials especially water immersed.

1. Introduction

In the fields of non-destructive testing (NDT) and structural health monitoring (SHM) many different damage assessment methods are utilized. Most often utilized methods are based on: guided wave propagation (GW) and electromechanical impedance (EMI). Authors of this paper utilized latter method for simulated damage assessment in GFRP sample. In the literature EMI method was utilized for damage assessment of metallic parts – smart washer of bolts which are utilized for stabilisation of rocks [1]. Authors of paper [2] applied EMI method for detection of wall thinning in metallic parts. In paper [3] application of EMI method was utilized for assessment of metallic parts of rotating machinery. This method was also utilized for debonding detection in fibre reinforced polymer (FRP) concrete beam [4]. Authors of work [5] utilized EMI method and embedded sensors for health monitoring of concrete bridge. Authors of paper [6] utilized EMI method for delamination detection in carbon fibre reinforced polymer (CFRP) panel. Anomalies and changes in EMI spectra caused by the modifications of the adhesive bonds in CFRP samples were investigated by authors of paper [7]. These modifications included: prebond thermal treatment, prebond contamination with de-
icing fluid, and precuring of the adhesive. The EMI method has also been applied successfully for damage detection in a tubular carbon fiber composite structure [8] and a model of a grouted connection of an offshore structure [9]. Interesting application of EMI can be found in paper [10] where authors utilized this method for assessment of stability of dental implants.

Beside applications of EMI for damage assessment of different materials also different EMI based signal processing methods can be found in literature. In order to distinguish referential state from damaged state of structure different simple damage indices are utilized in EMI method. Most popular are two indices based on root mean square deviation (RMSD) [3], [4] and cross correlation (CC) [11]. Authors of [12] proposed a new approach based on analysis of measurements results for EMI in time-frequency domains. In the paper [13] authors proposed extreme learning machine (ELM) approach. Authors compared numerical results obtained from ANSYS with experimental results. Probabilistic neural networks was utilized for wall thickening detection based on EMI method in paper [2].

It is very important to utilized signal processing methods able to remove external influences on EMI measurements. In paper [11] authors investigated influence of changing temperature on EMI and possibility of its compensation. Authors of paper [6] proposed temperature compensation algorithm which improved results of damage detection. Authors of paper [3] proposed utilisation of data normalization procedure for compensation of changes in environmental and operating conditions of rotating machine (load due to unbalance and changes in rotating speeds, temperature). Proposed compensation technique is based on a hybrid optimization method. Moreover, a statistical model is utilized for determination of threshold based on the Statistical Process Control (SPC) method.

In the current paper EMI method is utilized for simulated damage detection in GFRP sample. Influences of large damping in composite and due to immersion of sample in the water are investigated here. This paper presents preliminary results of research related to development of EMI based SHM system for composite maritime structures.

2. Theoretical background

Electromechanical impedance method is based on measurements of electrical parameters (impedance, admittance or its real/imaginary parts) of piezoelectric transducer bonded on the structure. Due to electromechanical coupling of piezoelectric transducer and the structure, mechanical resonances of the structure with piezoelectric transducer could be seen in the electrical parameters of transducer measured which are measured in frequency domain. Any kind of structural changes have influence on changes in mechanical resonances of structure and as consequence they can be noticed as changes in electrical characteristic of piezoelectric transducer coupled with structure. According to Liang [14] the admittance of a 1D system consisting of a structure coupled with a piezoelectric transducer can be defined by:

$$Y(\omega) = j\omega \frac{w_{l}}{h} \left[ \frac{z_{A}(\omega)}{z_{A}(\omega) + z_{S}(\omega)} \frac{d_{33}^2 \tilde{Y}_{11}^e \tan(\kappa l)}{\kappa l} + \tilde{\varepsilon}_{33} \right], \quad (1)$$
where: $z_a(\omega)$, $z_s(\omega)$ - mechanical impedance of piezoelectric transducer and structure; 
$\omega$ - excitation frequency; $l, w, h$ - length, width and thickness of piezoelectric transducer respectively; $\kappa$ - is wavenumber; $d_{31}$ - is piezoelectric constant at zero stress; $\varepsilon_{33}'$ - is complex dielectric constant of piezoelectric material under zero stress; $\nu_{11}'$ - is complex modulus under zero stress.

3. Experimental setup

Experimental setup consisted of HIOKI IM3570 laboratory impedance analyser, personal computer for data acquisition and GFRP panel with bonded piezoelectric transducer. IM3570 laboratory impedance analyser allows to measure impedance in frequency range 5 Hz - 5 MHz. However, in results presented in this paper only frequency range 1 kHz – 100 kHz was utilized. Measurements were taken for the GFRP sample with dimensions: 500 mm x 100 mm x 3.5 mm. Piezoelectric transducer in the form of a circular disc with diameter 10 mm and thickness 0.5 mm made of Noliac NCE51 material was attached in the middle of the sample (Figure 1).

![GFRP sample boundary conditions](image)

Figure 1. GFRP sample boundary conditions: a) hanging sample (only part immersed in water), b) sample supported on two edges (one surface in contact with the water)

In this preliminary research damage was modelled by the magnets attached on both sides of sample. Electromechanical impedance measurements were taken for the dry sample and for the sample immersed in the water. Two type of water immersions were investigated: first where only one part of sample was immersed (Figure 1a) and second where one side of sample surface were in contact with the water (Figure 1b).

4. Experimental results

Dry conditions

At the first step electromechanical impedance measurements were taken for sample hanging in the manner presented in Figure 1a). There was no water immersion in this case. Only real part of impedance (resistance) was registered and analysed in this
research. Measurements were made for frequency range 1 kHz – 100 kHz and were conducted for referential state of the sample and two damage cases. In the damage cases additional mass in the form of two magnets attached on both sides of sample was used for the purpose of defect simulation. Two diameter of magnets were utilized: 5 mm and 10 mm. Results of measurements were presented in Figure 2.

![Figure 2](image.png)

**Figure 2. Resistance plots for referential state and for additional mass in the form of magnets, distance of additional mass from transducer: a) 100 mm, b) 200 mm**

These plots were made only for narrow frequency band 1.4 kHz – 5 kHz in order to make changes in the signals clearly visible. In the Figure 2a) resistance plots for referential state and states with magnets with diameters 5 mm and 10 mm located at distance 100 mm from piezoelectric transducer were presented. In this case magnets with both diameter are located at short distance from transducer. In the Figure 2a) changes of resonant frequencies (shift of resonant peaks) and amplitudes reduction of resonant peaks for damaged cases can be noticed. These changes are larger for magnet with diameter 10 mm than for magnet with diameter 5mm. In the Figure 2b) resistance plots for referential state and cases for magnets with two diameters located at larger distance – 200 mm from transducer were presented. In this case shifts of resonant peaks frequencies and amplitude reductions are clearly visible. Larger changes (frequency shift and amplitudes) can be seen for magnet with larger diameter. However, comparing these changes with results for distance 100 mm (Figure 2a) we see that there are smaller changes of impedance for larger distance. However damage cases could be still easily distinguished from referential one.

In order to characterise changes in the signals damage index was calculated. In order to calculate its value signals from two states of the structure need to be used. In this research RMSD damage index was utilized:
\[
\text{RMSD} = \sum_{i=1}^{n} \left( \frac{(R(i)_n - \text{Re}(i)_n)^2}{\text{Re}(i)_n} \right)
\]

where: \( R(i)_n \) – \( i \)-th frequency of serial resistance of piezoelectric transducer for referential (undamaged) state, \( \text{Re}(i)_n \) – \( i \)-th frequency of serial resistance of piezoelectric transducer for damaged state. Value of damage index close to zero means that structure is still in referential state. Growing damage causes increasing damage index value. It should be mentioned that damage index can not only indicate the existence of structural damage but also the changes in the signal due to varying operational conditions (temperature, loads). Varying temperature is always problematic for impedance measurement and need to be compensated what was already reported in papers [3],[6],[11]. In research presented here temperature was maintained at the same level (differences was in the range \( \pm 0.5^\circ\text{C} \)).

Results in the form of RMSD damage index calculated for additional mass in the form of magnets with diameter 5 mm and 10 mm were presented in the Figure 3a) and Figure 3b) respectively. In this case signals for frequency band 1 kHz – 100 kHz were utilized.

![Figure 3](image)

**Figure 3.** RMSD damage index values for dry conditions and additional mass (magnets) with diameter: a) 5 mm, b) 10 mm

In the Figure 3a) damage index values for referential state (two measurements at referential state) and damage states when smaller magnets were attached at distances: 100 mm, 150 mm and 200 mm are visible. Lowest value of damage index was achieved for referential state when much larger values of damage index were achieved for additional mass located at different distances from transducer. Value of damage index decreases with the increasing distance of simulated damage from the transducer. In the Figure 3b) similar results for larger magnets (diameter 10 mm) were obtained. In this case also damage index value for referential state is much lower than for damage states with additional mass located at different distances from transducer. Damage index value decreases also with the increasing distance of magnet from transducer but in this case these changes are not strictly correlated with distance. However in both cases presented in Figure 3a) and Figure 3b) damage state can be clearly distinguish from the referential state even for largest distance of additional mass from transducer (200 mm).
Water immersed conditions I

In next step simulated damage detection possibility was tested for sample immersed in the water. In this case GFRP specimen was hanging in the same manner like in previous case but part of the sample was immersed in the water (Figure 1a). The length of the part of sample immersed in water was equal to 170 mm. In these conditions measurements were conducted for referential state – specimen immersed in the water but without magnets and for damage states for water immersed sample with two magnets sizes (diameters: 5 mm and 10 mm) and for two distances of magnets from transducer 150 mm and 200 mm. Magnets were located in the water immersed part of sample.

Results in the form of RMSD damage index values for all investigated cases for data set #1 were presented in Figure 4a). Lowest value of damage index was achieved for referential state (two measurements for water immersed sample without magnets). Then larger values of damage index were achieved for larger magnets (10 mm) located at distances 150 mm and 200 mm.

![Figure 4. RMSD damage index values for wet conditions I and for different distances from transducer and magnet sizes: a) data set #1, b) data set #2](image)

Smallest values of RMSD index were achieved for smaller magnets (5 mm) at the same distances. Values of RMSD damage index decrease with the increasing distance of magnet from transducer for both sizes of magnets. The same behaviour was observed for data set #2 for which results were presented in Figure 4b).

Water immersed conditions II

The third step was related to verify possibility of simulated damage detection for the GFRP sample with one surface immersed in the water. In this case sample was supported on two edges like it was presented in Figure 1b). This time measurements were conducted for: referential sample not immersed in the water (dry), referential sample immersed in the water, sample immersed with small magnets (diameter 5 mm) and for the immersed sample with large magnets (diameter 10 mm). In both cases of magnets, distance from transducer was equal 200 mm. At the end measurements for the sample immersed in the water but with removed magnets (referential state) were repeated. Whole set of investigated cases is presented in Table 1.
Table 1. Investigated cases (r-referential state, d-damage state)

<table>
<thead>
<tr>
<th>Case no.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>wet (r) – dry (r)</td>
</tr>
<tr>
<td>2</td>
<td>wet (r) – wet (r)</td>
</tr>
<tr>
<td>3</td>
<td>wet (r) – magnet 5 mm (d)</td>
</tr>
<tr>
<td>4</td>
<td>wet (r) – magnet 10 mm (d)</td>
</tr>
<tr>
<td>5</td>
<td>wet (r) – wet (r)</td>
</tr>
</tbody>
</table>

Results in the form of RMSD damage index were presented in Figure 5. Results presented in Figure 5a) are based on data set #1. Largest value of damage index was achieved for comparison of referential state of sample immersed in the water and not immersed. Lowest value of RMSD index was achieved for comparison of two referential cases of sample immersed in the water. Then value of RMSD index increases for case with smaller and larger magnets respectively. At the end measurement for sample immersed in water but with removed magnets was repeated. RMSD index values of this case is not the same like for the case 2. This is caused by mounting/demounting sample in the stand (sample is lying on two supporting elements – see Figure 1b). Sample was removed from the stand in order to attached magnets and then back mounted in the stand what was a source of slight changes in the boundary conditions. In consequence it was also seen as slight changes of damage index. As it was mentioned before temperature was maintained at the same level during the measurement. It need to be underlined here that changes due to manipulations with the sample caused similar level of RMSD index changes like for smaller magnets (compare cases 3 and 5 in Figure 5a).

In the Figure 5b) RMSD damage index values for data set #2 were presented. Here the situation is similar to the previous one. However, RMSD index values of smaller magnet is similar to the referential state for sample immersed in the water (case 2). Manipulations of the sample in this case caused much smaller changes of RMSD index (see case 5). It could be concluded here that damage detection algorithm based on RMSD index was able to detect the larger magnet with diameter 10 mm. RMSD index sensitivity for smaller magnet is at the similar level like the sensitivity to slight boundary condition changes related to mounting/demounting of sample.
It also need to be mentioned here that first sample mounting manner (hanging like in Figure 1a) caused much smaller changes in the signals for the different manipulations (mounting, removing sample from the stand) than second manner (support on the edges like in Figure 1b). However, second manner is more realistic that first one. In real conditions such specimen as single element will be joined to the structure. Aim of this research was only to simulate more realistic boundary conditions.

Comparing results for sample in dry and immersed conditions it could be noticed that changes of RMSD index for conditions change are much larger than for simulated damage (Figure 5 – cases 1, 3, 4). In the Figure 6 resistance signals for dry referential and referential water immersed sample were compared. First of all, analysing resistance signal for dry sample it could be noticed that clear narrow resonant peaks are visible only up to frequency 30 kHz. For higher frequencies peaks are very wide and they amplitudes are strongly reduced. This is caused by large damping related to fibre reinforced polymer materials.

![Figure 6. Comparisons of resistance signal for dry and immersed referential sample](image)

Second, comparing resistance signal for dry and immersed sample large differences could be noticed. Water immersion caused additional damping (amplitude reduction, wider resonant peaks). Beside the fact of large damping of composite material and influence of water it is still possible to detect larger magnets located at distance 200 mm from transducer. However, as referential signal, one from immersed conditions need to be used.

4. Conclusions

In this research authors verified the possibility of simulated damage detection in the case of GFRP sample immersed in the water. Damage was simulated as additional mass (magnets) with diameter 5 mm and 10 mm. Two types of boundary conditions and two manner of water immersions were investigated. For the case where the only part of sample was immersed in the water it was possible to detect both magnets sizes when they were located at distance 200 mm from transducer. In the case where whole surface of the sample was immersed it was only possible to detect magnet with diameter 10 mm located at distance 200 mm from transducer. In the case of smaller magnet it was not possible to distinguished signal changes due to slight boundary condition changes (mounting/removing of the plate) from the damage case. Comparing results for sample in dry and immersed conditions it could be noticed that changes of RMSD index for conditions change are much larger than for simulated damage.
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