Assessment of piezoelectric sensor adhesive bonding

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Abstract. Piezoelectric transducers are widely utilized in Structural Health Monitoring (SHM). They are used both in guided wave-based and electromechanical impedance-based methods. Transducer debonding or unevenly distributed glue underneath the transducer reduce the performance and reliability of the SHM system. Therefore, quality assessment methods for glue layer need to be developed. In this paper, the authors present results obtained from two methods that allow the quality assessment of adhesive bonds of piezoelectric transducers.

The electromechanical impedance method is utilized to analyze transducer adhesive bonding. An improperly prepared bonding layer is a source for changes in the electromechanical impedance characteristics in comparison to a perfectly bonded transducer. In the resistance characteristics of the properly bonded transducer the resonance peaks of the structure were clearly visible. In the case when adhesive layer is not equally distributed under sensor, the amplitudes of structural resonance peaks are reduced. In the case of completely detached transducer, the structural resonance peaks disappear and only resonance peaks of the transducer itself are visible. These peaks (peaks of free transducer hanging on wires) are significantly larger than the resonance peaks of the investigated structure in the considered frequency interval.

The bonding layer shape is also analyzed using time-domain terahertz spectroscopy in reflection mode. This method allows to visualize the adhesive layer distribution based on C-scan analysis. C-scans of signals or envelope-detected signals can be used to estimate the area of proper adhesion between bonding agent and transducer and hence provides a more quantitative approach towards transducer inspection.
1. Introduction

Structural Health Monitoring (SHM) is a set of techniques that allow monitoring the mechanical condition of structures in real-time by utilization a permanent transducer network distributed over the structure. Two approaches can be distinguished: passive and active measurement methods. In a passive system, the sensor network (strain gages, fiber optic strain sensors, accelerometers) is utilized for “listening” of signals coming from evaluating damage. In active systems, the transducer network (piezoelectric transducers) is utilized for generation and sensing of signals. Very often in SHM systems, especially active, piezoelectric transducers are utilized. These transducers can generate and sense diagnostic signals based on inverse and simple piezoelectric effect. Based on registered signals diagnostic process is conducted. In such a piezoelectric based SHM system two very popular diagnostic methods are utilized which are based on elastic wave propagation phenomenon and electromechanical-impedance measurements. First method is based on the fact that damage in the structure is a source of changes in elastic wave propagation. In second method due to electromechanical coupling of piezoelectric transducer and structure all structural changes can be noticed in measurements of electrical impedance of transducers. This method is very analogous to conventional modal analysis (vibration based method). However, here much higher frequencies are utilized, very often up to few hundred kHz.

Transducer diagnostics in SHM is a very important topic. Degradation of sensors can lead to reduction of damage detection ability or can generate false diagnostic reports. In this topic two subtopics can be distinguished: first related to fault or degradation of sensor itself and second related to low performance or degradation of sensor bonding layer. This paper deals with the second problem – diagnostic of transducer bond quality assessment.

Many authors reported possibility of detection piezoelectric transducer debonding by utilization electromechanical impedance method. In [1] authors have analyzed changes in imaginary part of admittance (susceptance) for free and surface bonded transducers. Authors have observed decrease in the slope in the susceptance characteristics caused by the existence of bonding layer. In relation to the bonded transducer its debonding causes increase in the slope of the susceptance characteristics. This problem is related to changes in capacitance of the transducer after its bonding to the structure. Moreover, authors have observed that degradation of transducer performance (fracture in the sensor) causes downward shift of susceptance (both transducers are bonded). It allows distinguishing the problem of bonding performance from the transducer’s performance itself. In [2] authors have found that the bond layer properties can significantly modify the measured admittance and lead to incorrect identification of the frequencies peaks. They also conclude that there is no universal method or metric available to assess the quality of the bonding condition. In [3] the author has utilized the imaginary part of impedance (reactance) as a parameter allowing to detect transducer debonding, where real part of impedance (resistance) was utilized for assessment of the host’s structural state. The author concluded that in the case of debonding transducer’s free vibrations are observed and the structural resonances disappear. In [4] resistance and susceptance measurements were used to detect sensor faults. These measurements were focused on regions with resonant frequencies.

In this paper, the authors propose the combination of two methods: Time-domain Terahertz spectroscopy [5] and electromechanical impedance testing. The aim of the first method is to determine the distribution of the bonding layer between piezoelectric transducer and host structure. The second method was utilized for verification of results obtained by THz spectroscopy. This THz technique is utilized in nondestructive testing [6]. In [7] THz spectroscopy was utilized for damage detection in fiber reinforced composite parts of wind turbine. Defects were in the form of saw-cut delaminations. This technique was also utilized for heat induced damages in porous materials [8]. THz spectroscopy is also a very promising tool for moisture detection in materials [9].
2. Experimental set-up

Two experimental set-ups are used here. The first one is Terahertz spectrometer Teraview TPS Spectra 3000 which generate impulses in frequency range from 0.1 up to 3 THz which are sent repeatedly and interact with the investigated material. This non-contact measurement system allows to perform measurements in reflection and transmission modes but the results presented in this paper were based exclusively on measurements done for the scanning heads working in reflection mode. Reflection mode is more feasible for analyzing real structures where access to the structure is very often limited to only one side. The spectrometer is equipped with moving table that allows for XY scanning of large objects.

The second experimental set-up is electrical impedance analyzer HIOKI IM3570 connected to the piezoelectric transducer. This equipment was utilized for measurements of electrical characteristics of piezoelectric transducers bonded to the investigated sample.

Investigated sample was in the form of panel with dimensions 500 mm x 200 mm x 2 mm made out of glass fiber reinforced polymer (GFRP) with fiber layer orientation [0/90/0/0/90/0]. Composite sample was clamped on one edge during electromechanical impedance measurements.

This sample was equipped with three piezoelectric transducers (SONOX P5 discs with diameter 10 mm and thickness 0.5 mm), compare Figure 1. One transducer was perfectly bonded (marked as #1 in the Figure 1) whereas two of them were partially debonded (#2 and #3 in the Figure 1). Bonding agent was two part epoxy glue PRO WELD® QUICK Pro Seal which is suitable for real environmental condition and for temperatures up to 150 °C.

3. Results for Terahertz spectroscopy

In the case of THz spectroscopy the scanning heads were on the opposite side of the sample with respect to the side with bonded piezoelectric transducers. The aim of measurements was to determine bonding agent planar distribution between sample and transducers. It should be mentioned that in the case of GFRP sample, THz radiation penetrates through the thickness and next reflects from bonding agent and piezoelectric transducer. This approach is not suitable for carbon fibers reinforcement polymers (CFRP) because conducting fibers will reflect or absorb the incoming signal either immediately at the surface or within a few sample layers, depending on the polarization of the incoming waves [10]. Hence, the deep penetration of the electromagnetic-radiation into the material is currently not possible.

The analyzed sample with bonded transducers is presented in Figure 1. Results of THz spectroscopy in the form of C-scans were presented in Figure 2. In the Figure 2a) slices of a C-scan based on raw radio-frequency signals was presented, whereas in Figure 2b) envelope-detected signals were utilized. The signal processing was performed using envelope notion of time-domain signal used in C-scan. Analyzing results presented in the Figure 2a) and comparing it with bonding agent distribution presented in Figure 1 it is hard to determine this distribution from THz measurements. Additional signal processing applied to raw signals improved contrast in the new C-scan. Analyzing that result (Figure 2b) it is much easier to determine how the bonding agent is distributed. Moreover circular shape of transducer is much easier visible for perfectly bonded transducer (marked by circles in Figure 1).

In the Figure 3 glue layer distribution after post-processing of THz measurements is presented. The signal processing procedure was as follows: a) the non-equidistant measurement points from the continuous measurement were firstly interpolated to a regular grid; b) isosurfaces were calculated to extract regions of constant THz-waveform amplitudes. This technique is the straightforward extension of the planar slices approach shown in Figure 2 and allows description of oblique effects. This figure shows distribution of bonding agent between composite sample and piezoelectric transducers. This should be kept in mind that proposed approach could not be suitable for other bonding agents. Authors noticed problems with very popular cyanocrylate Super Glue bonding agent. However, results obtained for THz spectroscopy for PRO WELD bonding agent can be utilized in order to validate the electromechanical impedance method used for bond state assessment.
Figure 1. Photo of GFRP sample equipped with three piezoelectric transducers: #1 perfectly bonded, #2, #3 partially debonded.

Figure 2. Terahertz C-scan for: a) raw measurements, b) measurements after signal processing.

Figure 3. Glue layer distribution obtained from THz measurements after signal processing.

4. Results for electromechanical impedance method
In this section the results for electromechanical impedance method were presented. This method was utilized for quality assessment of bonding layer which is located between piezoelectric transducer and composite sample. The aim of this method was to validate results obtained for THz spectroscopy. Despite of the name of method (electromechanical impedance) very often instead of electrical impedance, such parameters like its real part (resistance) or imaginary part (reactance) are measured and analysed. Very often parameters of admittance (inversion of impedance): its real part (conductance) and imaginary part susceptance are utilized. Generally real part of electrical impedance/admittance of piezoelectric transducer coupled with the host structure is utilized for assessment of structural state of the structure. On the other hand imaginary parts of electrical impedance/admittance are related to the piezoelectric transducer bonding layer assessment are widely used in literature [1], [3].
Conducted research has shown that real part of impedance/admittance can also be utilized for performance assessment of piezoelectric transducer bonding layer. However, it is important to distinguish the resonances of piezoelectric transducer from the resonances of host structure.
In Figure 4–Figure 7 the plots of resistance, reactance conductance and susceptance for frequency ranges 1 kHz–1 MHz and 1–5 MHz were presented. Measured parameters were: resistance and reactance (real and imaginary parts of electrical impedance), and conductance and susceptance (real and imaginary parts of electrical admittance). Analysing plot of parameters related to electrical impedance measured for frequency range 1 kHz–1 MHz (Figure 4a and Figure 5a) group of resonances can be observed, where the one is dominating (around 230 kHz). Similar situation can be observed for frequency range 1–5 MHz, (Figure 4b and Figure 5b) where group of resonances exist but one peak (around 4.4 MHz) has largest value. Analysing parameters plots related to the electrical admittance for lower frequency band (Figure 6a and Figure 7a) and higher frequency band (Figure 6b and Figure 7b) similar behavior can be noticed, but frequencies of resonances are slightly different. For lower frequency range largest peak is located around frequency 190 kHz (Figure 6a and Figure 7a) and for higher frequency range around 3.9 MHz (Figure 6b and Figure 7b). Differences in peak frequencies related to components of impedance and admittance results from serial and parallel resonant frequencies of piezoelectric transducer. Generally peaks visible in Figure 4–Figure 7 are related to transducer resonant frequencies.

The situation changes when piezoelectric transducer is bonded to host structure. Due to mechanical coupling, peaks related to the resonant frequencies of host structure are observed in the measurements. Peaks related to resonant frequencies of piezoelectric transducers can be still visible when the transducer is improperly bonded or partially debonded. When the stiffness of the bonding layer is decreased, then the resonances of free piezoelectric transducer are more and more visible.

Next part of results is related to the transducers bonded to the GFRP sample. Three frequency ranges: 1–10 kHz (host structure resonances), 180–280 kHz (free transducer resonances – low frequency range), 3–5 MHz (free transducer resonances – high frequency range) were analysed. Moreover four transducer bonding cases were analysed: perfectly bonded, two cases of partially debonded, completely debonded (free).

Starting from frequency range 1–10 kHz it can be noticed that peaks related to the resonant frequencies of composite/host structure are clearly visible for resistance (Figure 8a) and conductance (Figure 9a) only for the case of perfectly bonded transducer (marked by #1 in the figures). In the case of imaginary parameters like reactance (Figure 10a) and susceptance (Figure 11a) instead of peaks a zero-crossing can be noticed. However they are not so clear for perfectly bonded transducer (#1) in comparison with real parameters like resistance and conductance. Analyzing all parameters for the cases with partially debonded transducers (#2 and #3), peaks have very small amplitudes and completely disappear for unbounded transducer (#4). Case #4 corresponds to the PZT #1. Its debonding causes characteristics upward shift is observed in susceptance curve (Figure 11a) like in [1].

Debonding causes also significant reduction of peak amplitudes in resistance (Figure 8a) and conductance (Figure 9a). In the next step, analysis was related to frequency region equal 180–280 kHz. Debonding of piezoelectric transducer causes increase of peak values (real components) and maximum/minimum value near zero-crossing (imaginary components) for all parameters (Figure 8b, Figure 9b, Figure 10b, Figure 11b). However, the location of these peak values (zero crossing for imaginary parts) are related to resonance of free piezoelectric transducer. They are located around frequency 230 kHz in resistance (Figure 8b, peak) and reactance (Figure 10b, zero crossing). For conductance and susceptance curves the peak and the zero-crossing are located around frequency 190 kHz (Figure 9b, Figure 11b, respectively). It is clearly visible that characteristic values (peak amplitude and maximum/minimum values near zero-crossing) of all parameters are lowest for perfectly bonded transducer (resonant frequencies of free transducer disappear). For partially debonded transducers values of all parameters are located between two mentioned cases. Moreover some frequency shifts of peaks and shape modifications of the curves are observed.
Figure 8. Electrical resistance for different piezoelectric transducer bonding states: a) 1–10 kHz, b) 180–280 kHz, c) 3–5 MHz; #1 – bonded, #2, #3 – partially debonded, #4 – free (PZT #1).

Figure 9. Electrical conductance for different piezoelectric transducer bonding states: a) 1–10 kHz, b) 180–280 kHz, c) 3–5 MHz; #1 – bonded, #2, #3 – partially debonded, #4 – free (PZT #1).

Figure 10. Electrical reactance for different piezoelectric transducer bonding states: a) 1–10 kHz, b) 180–280 kHz, c) 3–5 MHz; #1 – bonded, #2, #3 – partially debonded, #4 – free (PZT #1).

Figure 11. Electrical susceptance for different piezoelectric transducer bonding states: a) 1–10 kHz, b) 180–280 kHz, c) 3–5 MHz; #1 – bonded, #2, #3 – partially debonded, #4 – free (PZT #1).
The same situation can be noticed for analysis of all plots (Figure 8c, Figure 9c, Figure 10c and Figure 11c) for highest frequency range (3–5 MHz). Different frequencies for resonances in resistance/reactance (4–4.5 MHz) and conductance/susceptance (3.5–4 MHz). Largest amplitude of all parameters were achieved for unbonded transducers and lowest for perfectly bonded.

For partially debonded transducers (#2, #3) parameters have values located between the ones for two extreme states (#1 – perfectly bonded and #2 – free). Frequency shift for different bonding states (#1–#3) and free transducer (#4) are also observed for each parameter.

5. Conclusions

Results presented in the paper have proved that both proposed measurement methods can be utilized for quality assessment of bonding layer.

Terahertz spectroscopy allows imaging of bonding layer distribution for specified types of adhesive. The considered adhesive must produce high contrast in THz image scans. Additionally, this technique is limited rather to GFRP samples. It can be utilized also for CFRP however it should be taken into account that in this case polarized THz radiation can penetrate only through the single layer. This method can be used as non-destructive testing (NDT) of bonding layer.

Electromechanical impedance method was utilized in order to verify results obtained for THz spectroscopy. This verification was successful and shown that for performance of bonding layer real and imaginary components of electrical impedance/admittance can be utilized. However, frequencies of unbounded (free) piezoelectric have to be known. This method can be utilized as NDT technique as well as in continuous mode in SHM systems. The electromechanical method can be used for quality assessment of glue of any type. The resonant frequencies of free transducer possess higher amplitudes of the vibration than amplitudes of the structural peaks visible in electrical characteristics of the transducer. This feature is responsible for the success of transducer’s debonding detection by the use of electromechanical impedance in the frequency region where resonances of free transducer exist.

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