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ASSESSMENT METHODS FOR COMPOSITE AEROSPACE STRUCTURES

T. Wandowski[*], P. Malinowski[*], M. Radzienski[*], S. Opoka[*], W. Ostachowicz[*,†]

[*]Polish Academy of Sciences, Institute of Fluid–Flow Machinery,
14 Fiszera St., 80–231, Gdansk, Poland
tomaszw@imp.gda.pl, pmalinowski@imp.gda.pl, mradzienski@imp.gda.pl,
szop@imp.gda.pl, wieslaw@imp.gda.pl

[†]Warsaw University of Technology, Faculty of Automotive and Construction Machinery,
84 Narbutta St., 02–524 Warsaw, Poland

Key words: electromechanical impedance EMI, laser vibrometry, guided waves, terahertz spectroscopy, composite materials.

Summary: *In this paper result of detection and localization of artificially initiated delaminations in small carbon fibre reinforced polymer CFRP and glass fibre reinforced polymers GFRP samples were presented.*

The first method was 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 piezoelectric transducer. Instead of electrical impedance other parameters such as resistance, conductance, admittance or susceptance are very often utilized. 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.

The second method was a laser vibrometry. It is a noncontact technique that allows to measure vibration of structure excited by piezoelectric transducer. During research standing waves (vibration–based method) and propagating waves (guided waves–based method) were registered for CFRP sample. In the vibration–based method, the frequency shifts of certain resonance frequencies were analyzed. In guided waves-based technique, the interaction of elastic waves with delamination can be seen in the RMS energy map.

The third method is Terahertz spectroscopy. The device uses an electromagnetic radiation in the terahertz range (0.1–3 THz). The spectrometer is equipped with moving table that allows for XY scanning of large objects. During research the scanning heads working in reflection mode were utilized and the measurements were taken for GFRP sample with delamination. During research time signals as well as sets of signals creating B–scans and C–scans were analysed. The obtained results showed that the THz spectroscopy technique can detect and visualize delamination between the GFRP layers.

1 INTRODUCTION

Nowadays *carbon fiber reinforced polymers* CFRPs and *glass fiber reinforced polymers* GFRPs are more and more utilized in many industrial manufacturing branches. These materials are widely used in various aerospace structures (e.g.: passenger airplanes like Airbus A350 or Boeing 787, military aircrafts and helicopters, small planes and gliders). Composite materials are also utilized in automotive and maritime industry (car chassis, yacht, boats). Moreover these materials are widely used in renewable energy for wind turbine blades.

The main feature that makes CFRP and GFRP 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. Source of impact can be for example a fall of spanner utilized by airplane maintenance crew or bird strike into the fuselage skin. As a consequence of such impact delamination can initiate in composite structures. This delamination very often is not visible during the conventional visual inspection of the airplane composite structure. Such a internal delamination can further grow till it reaches critical size that is dangerous for structural integrity.

Therefore non destructive testing techniques NDT need to be used in order to check structural state of composite elements. Application of conventional NDT techniques is related to exclude of structure from its normal exploitation, moreover in many cases additional preparation of structure is needed. Moreover personnel that performing NDT inspection must be highly qualified. In aerospace such excluding of airplane from exploitation generates huge costs.

In order to reduce the maintenance costs for composite aerospace structures approach called structural health monitoring SHM was developed [1], [2]. This is a technique that performs continuous structural assessment of the structure. Instead of periodic NDT inspection, SHM system can continuously (in–real time) asses the structure even during its normal exploitation. Moreover highly qualified personnel is no longer needed.

Very promising SHM techniques are based on piezoelectric transducers. Such transducers are very light, thin and can be used as sensors and actuators due to direct and inverse piezoelectric effect. Piezoelectric sensors can be used to generate and receive elastic waves or can be utilized for electromechanical impedance measurements EMI, [1].

Due to many problems with such a SHM system certification for aerospace applications and many problems with development such a reliable system for real structures, nowadays NDT techniques are still used. Besides conventional damage like delaminations or fiber cracking composite materials in aerospace structures are exposed to thermal degradation (exhausting gases from jet engine, strike lightning), chemical degradation (Skydrol, Kerosene, deicing agents) or moisture uptake, [3]. Therefore novel extended NDT method (E–NDT) need to be developed.

In this paper results of application extended NDT and SHM techniques for detection of delamination in CFRP and GFRP samples are presented. Investigations were conducted for such a methods like: electromechanical impedance method, laser vibrometry and terahertz spectroscopy.

2 COMPOSITE SAMPLES

During the research two composite samples were used. First one was small plate with dimensions 100 mm × 100 mm × 3.5 mm, manufactured of carbon fiber reinforced polymer CFRP pre–pregs GG204P IMP503 42 (Figure 1a). The second one was also plate with dimensions: 100 mm × 100 mm × 3.3 mm made out of glass fiber reinforced polymer GFRP (12 plies with stacking [0/90/0/90/0/90]s, glass S fibers with Araldite LY1564 epoxy) **–** Figure ***1***b.

First sample was prepared in autoclave while the second one by infusion method. carbon pre–pregs are mainly utilized in aerospace structures (passenger airplanes, helicopters) while composite made out by infusion methods are utilized very often in yacht and boat industries. CFRP sample was instrumented with piezoelectric transducer (Figure 1a) and was tested using following methods: electromechanical impedance EMI and scanning laser vibrometry (vibration–based method and guided wave based method). Transducer was in the form of disc with diameter 10 mm and thickness 0.5 mm manufactured of NCE51 piezoelectric material (manufactured by NOLIAC).

Three structural states of CFRP sample were investigated: referential, with small delamination *Dam 1* and with large delamination *Dam 2* (extended size of *Dam 1*). Damage was initiated on the bottom edge of the sample (according to Figure 1a). Extent of the *Dam 2* delamination will be clearly visible for results of guided wave technique based on laser vibrometry.

GFRP sample was tested only by terahertz spectroscopy technique. This approach is not suitable for carbon CFRP sample 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, [4]. In GFRP sample two delaminations were initiated. Location and size will be discuss in the section with terahertz spectroscopy.

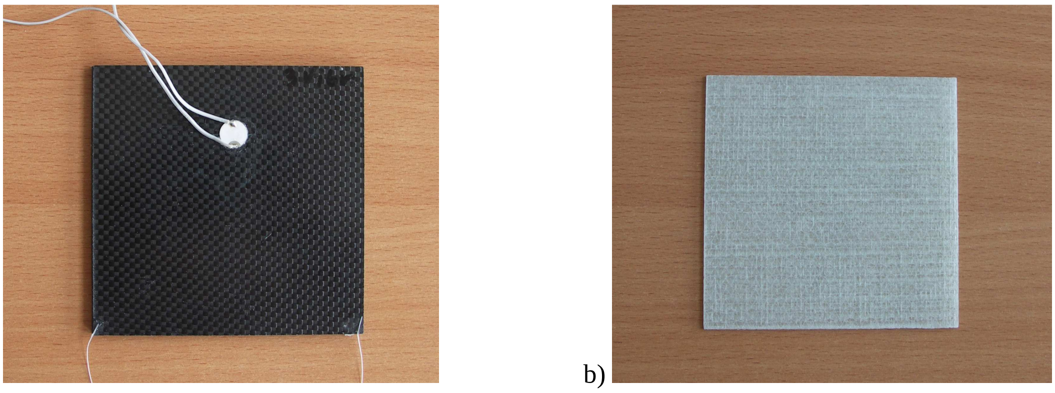
a)  b)

Figure 1: Composite samples investigated during research: a) CFRP instrumented with piezoelectric transducer, b) GFRP.

3 ELECTROMECHANICAL IMPEDANCE METHOD (EMI)

This method is based on measurements of electrical parameters of piezoelectric transducer attached to the investigated structure. These measurements are performed in frequency domain. Due to electromechanical coupling of piezoelectric transducer and the host structure, mechanical resonances of structure can be observed in electrical characteristics of piezoelectric transducer. In this method such a electrical parameters like impedance, admitance, its real parts (respectively resistance and conductance) and its imaginary parts (reactance and susceptance) can be registered and analyzed.

Imaginary part of electrical parameters is used for monitoring of bonding layer between transducer and structure or transducer itself, [5] when real part of electrical parameters is utilized for monitoring of the structure. For example, in [6] the imaginary part of impedance (reactance) was utilized as a parameter that allows to detect transducer debonding, while as real part of impedance (resistance) was used for assessment of the structure. However, in [7] resistance and susceptance measurements were used to detect sensor faults. It should be underlined that in this case measurements were focused on regions with resonant frequencies.

Generally this method is very sensitive to small damage and is very often utilized in structural health monitoring SHM [5], [8], [9], [10]. However this method is also very sensitive to ambient temperature change what is a main drawback of this method. Increasing temperature causes leftward shift of peaks in real part of electric impedance (resistance) characteristics of piezoelectric transducer attached to the structure [10], [11].

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 are defined as follows, [10]:

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

$$CCD = 1 - \sum_{i=1}^{n} \frac{\left[\mathrm{Re}(Z(i))_R - \overline{\mathrm{Re}}(Z)_R\right]\left[\mathrm{Re}(Z(i))_D - \overline{\mathrm{Re}}(Z)_D\right]}{\sigma_R \sigma_D}, \tag{2}$$

where: $\mathrm{Re}(Z(i))_R$ – *i*–th sample of real part of electrical impedance of piezoelectric transducer for referential (undamaged) state, $\mathrm{Re}(Z(i))_D$ – *i*–th sample of real part of electrical impedance of piezoelectric transducer for damaged state, $\overline{\mathrm{Re}}(Z)_R$, $\overline{\mathrm{Re}}(Z)_D$ – averaged values for referential and damaged state respectively and σ_R, σ_D – are the standard deviations for referential and damaged state. Value of damage index close to zero means that structure is still in referential state. Growing damage causes increasing damage index value.

In order to calculate these indexes signals from two states of the structure need to be used. It should be mentioned that these indexes can not only indicate the damage of the structure but also the change of the temperature of structural element.

In order to evaluate the state of the composite CFRP sample measurements at four states were taken. In the first (initial) state sample was intact, which means that there was no damage inside the sample. The ambient temperature was equal 22 ^{o}C in this case. In the second case the ambient temperature was equal to 24 ^{o}C and sample was still in the intact state. In the second and third case delamination with different extent was introduced to the sample.

In these last two cases ambient temperature was the same like in initial case – 22 ^{o}C. Parameter analyzed in this research was real part of electrical impedance (resistance) of piezoelectric transducer bonded to the CFRP sample. Location of piezoelectric transducer can be seen in Figure 1a.

In the Figure 2a characteristics of resistance for referential case in temperature 22 ^{o}C (*Ref*) and in temperature 24 ^{o}C (*Temp*) are compared. Small horizontal shift in frequency and vertical shift in values (for frequencies below 5 kHz) can be simply noticed. In the Figure 2b comparison of signal for referential sample state at 22 ^{o}C (*Ref*) is compared with case with introduced smaller delamination (*Dam 1*). Here frequency shift of few characteristic peaks (not all) can be noticed. Moreover change of its amplitudes are also visible. For the case of much larger delamination *Dam 2* (Figure 2c) this frequency shifts and amplitude changes are much larger.

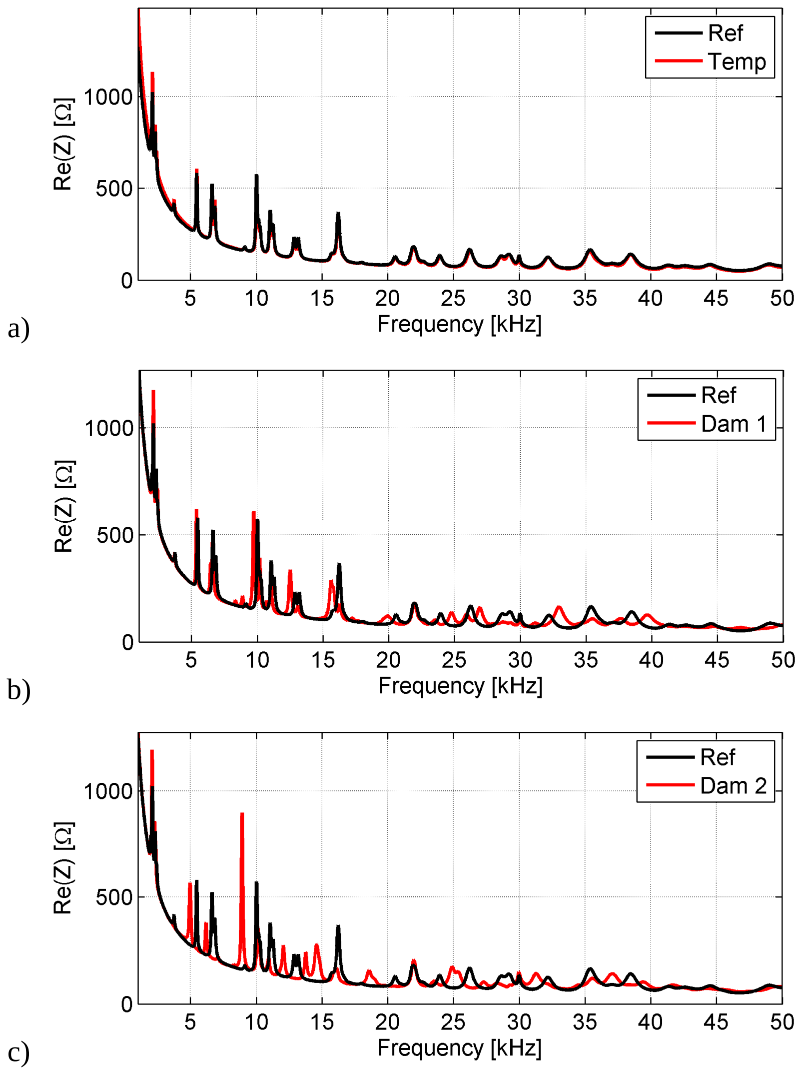
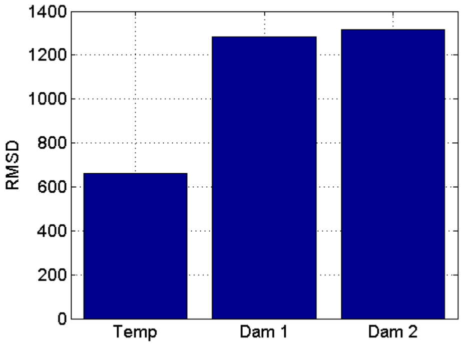


Figure 2: Resistance plots for comparison of referential CFRP sample state with other investiagted states: a) temperature change, b) damage–delamination 1, c) damage–delamination 2.

In next step values of proposed indexes (1) and (2) were computed for investigated cases. In the Figure 3 values of the both indexes for three states of structure were presented. In all cases first initial state (at temperature 22 ^{o}C) was utilized as referential one. Analysing the results for RMSD damage index (Figure 3a) it can be noticed that for temperature change value of index is relatively large in comparison to the first and second case with delamination.

It means that this RMSD index is very sensitive to changing temperature. RMSD index is generally sensitive to vertical and horizontal signal shift as well for small signal fluctuations. Source of such fluctuations can be related to measurements instability like mentioned temperature but also due to equipment sensitivity, measurement errors or electromagnetic interferences. Large RMSD index value for the case of changing temperature is mainly caused by vertical shift of resistance curve for frequencies bellow 5 kHz (Figure 2a). The RMSD index value for smaller delamination is larger than for the temperature influence however the size of this delamination is relatively large in comparison to whole sample area. Moreover temperature changed only a little (2 ^{o}C). In the case of smaller damage than investigated it can be hard to distinguish damage case from the temperature–influenced case. Sometimes temperature influence can be even larger than influence of the damage. This will cause false alarm of SHM system.

Analysing the results for CCD index presented in Figure 3b, it can be noticed that in this case, index value for temperature change achieves much smaller value than for the case of smaller and larger delamination. Moreover extent of delamination can be simply distinguished by comparing CCD index values. Small value of CCD index due to temperature is because this index is sensitive only to horizontal signal shift. CCD index is not sensitive to vertical shift of signals and small fluctuations (without horizontal shift). As it was mentioned in this particular research, temperature change is mostly seen as vertical shift of resistance characteristic and as very small horizontal shift. In this case temperature change was very small but for much higher temperature change, large horizontal shift of the resistance characteristics can be observed [10], [11]. Is such a cases this temperature dependent signal shift must be compensated.



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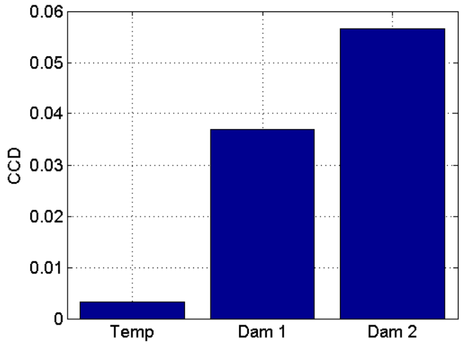


b)

Figure 3: Damage indexes for different sample states: a) RMSD, b) CCD.

EMI method allows only to detect the delamination but not to determine its shape or location. The main advantage of this method is the possibility of its application in structural health monitoring system. However sensitivity of this methods to changing temperature need to be taken into account and appropriate compensation method for this influence must be used in order to reduce the false alarm probability. Range of the method (distance from the transducer where damage can be still detected) strongly depends on the composite parts mostly due to its damping properties. This must be also considered during SHM system development.

4 LASER DOPPLER VIBROMETRY

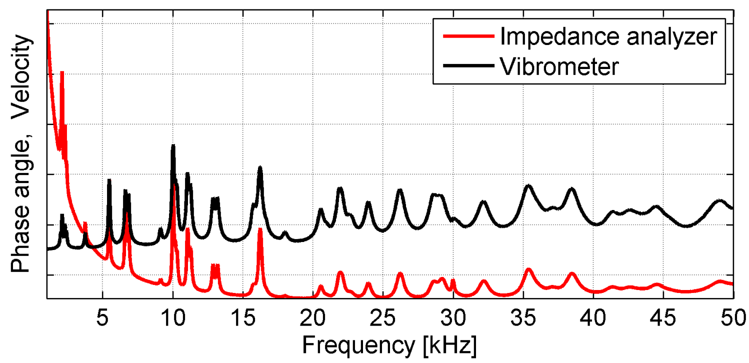
Laser Doppler Vibrometry LDV is noncontact measurement technique that allows to measure velocities or displacements of vibration in structural parts. This technique can be utilized for measurements of standing waves as well as guided wave propagating in the structure. This technique is very often called SLDV when Scanning Laser Doppler Vibrometer is utilized. In experimental research authors utilized Polytec 3D Scanning Laser Doppler Vibrometer PSV400 that is able to measure 3D components of vibrations velocity (out–of–plane and in–plane components). However during the research all measurements were performed only in 1D scanning mode which allow to measure only out–of–plane vibration velocity component. Measurements were related to standing waves as well as guided waves propagating in the CFRP sample. In both cases piezoelectric transducer was used for vibrations and guided waves excitation.

4.1 Vibration-based method

In the vibration–based method with using scanning laser vibrometry the structure is excited using for example piezoelectric transducer or electromechanical exciter. Next, laser vibrometer registers velocities (sometimes displacements or accelerations) of structural vibration of the sample. These measurements are performed for dense mesh of points that cover the sample surface. As result frequency response function can be created for chosen point or its average value for all measured points. Moreover mode shapes can be simply extracted and visualized. Frequency Response Function (FRF) presents distribution of the resonant frequencies of the sample. Such a analysis is very often called modal analysis.

During research for CFRP sample its vibration velocities were measured for excitation produced by piezoelectric transducer. Excitation signal was in the form of chirp signal. Averaged frequency response function was measured by laser vibrometer. Next this function was compared with electromechanical impedance measurements. In the case of the EMI method real part of electrical impedance and phase angle were taken into account for this comparison.

In the Figure 4a averaged frequency response function extracted from laser vibrometer measurements was compared with real part of electrical impedance (resistance) of piezoelectric transducer placed on CFRP sample. These measurements were performed for initial referential case (in both cases temperature was constant, equal 22 ^{o}C).



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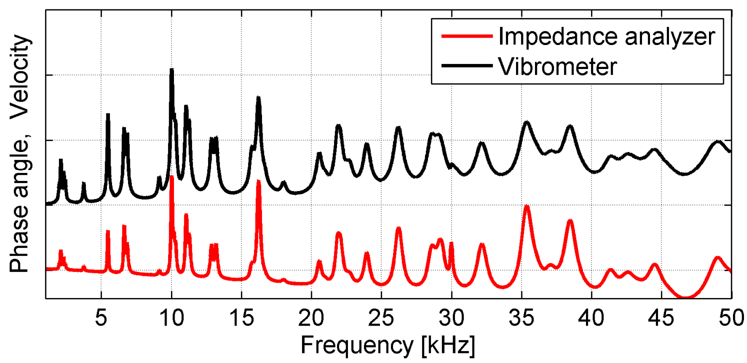
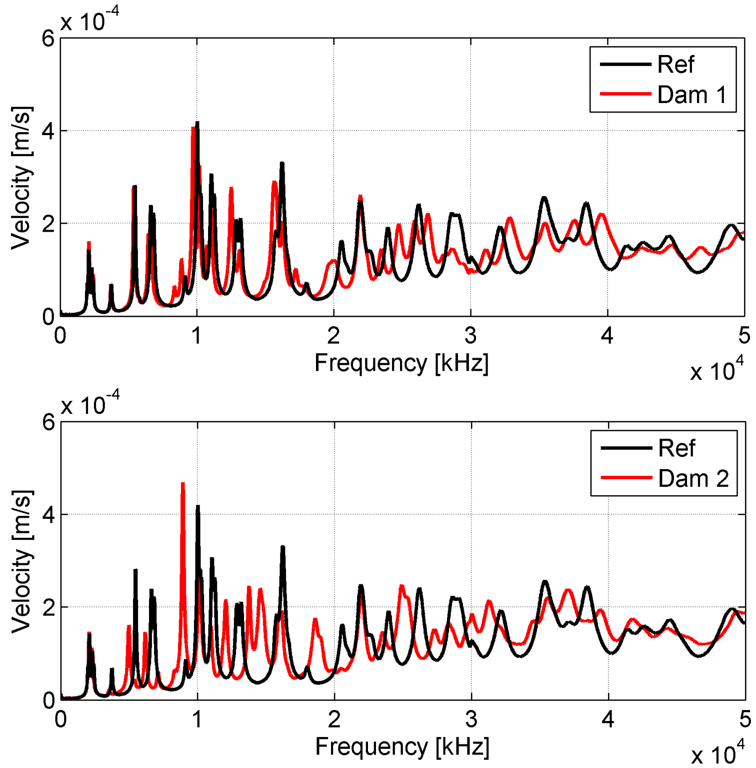


b)

Figure 4: Comparison of frequency response for impedance analyzer and laser vibrometer: a) resistance and vibration veloctiy, b) phase angle and vibration velocity.

It should be mentioned that both characteristics were scaled in such a manner that allows to compare them easily in one figure. Analysing results presented in Figure 4a it can be easily noticed that both characteristics are very similar, only small differences in the peak amplitudes can be noticed. The comparison of both characteristics is a little bit difficult due to noticeable trend of the resistance characteristic. For the better comparison phase angle for EMI method can be plotted against the frequency response function for velocities (for laser vibrometry). In this case (Figure 4b) analysis is much easier and similarity of both plots can be simply noticed. It should be mentioned that such a agreement of laser vibrometry and impedance analyzer not always occurs. In this research only out–of–plane velocities were measured. Piezoelectric transducer measures directly strains that are converted to charge/voltage. In order to achieve full agreement of piezoelectric sensor measurements and laser vibrometry measurements additionally in–plane velocities should be registered using vibrometer.

However, these comparisons have shown that electromechanical impedance method is very similar to the conventional modal analysis. However, in the EMI method very often much higher frequencies are analysed (especially for the metallic structures due to much lower damping). These frequencies can go up to hundreds of kilohertz, [6] or even up to megahertz, [12]. In the work [12] composite materials with high damping were investigated however, only local effect very close piezoelectric transducer was interrogated. In the CFRP sample used in the present research measurements, were performed till 50 kHz. However, narrow clear resonance peaks can be noticed only for frequency range lower than 20 kHz (Figure 2 and Figure 4). Large damping of composite material reduces the size of area where damage can be detected by piezoelectric sensor. This remark should be kept in mind that during SHM system development for composite structures.



a) b)

Figure 5: Comparison on frequency responses for different CFRP states: a) referential–delamination 1, b) referential–delamiantion 2.

In the Figure 5 frequency response functions extracted for different CFRP sample states by laser vibrometry are presented. In Figure 5a comparison of FRF for initial–referential state and for the state with smaller extent of delamination is presented. Natural frequency shift can be simply noticed in this Figure. In the Figure 5b FRFs for referential state and state with larger delamination are compared. Here the frequency shift is much larger however size of delamination is also much larger than in previous case.

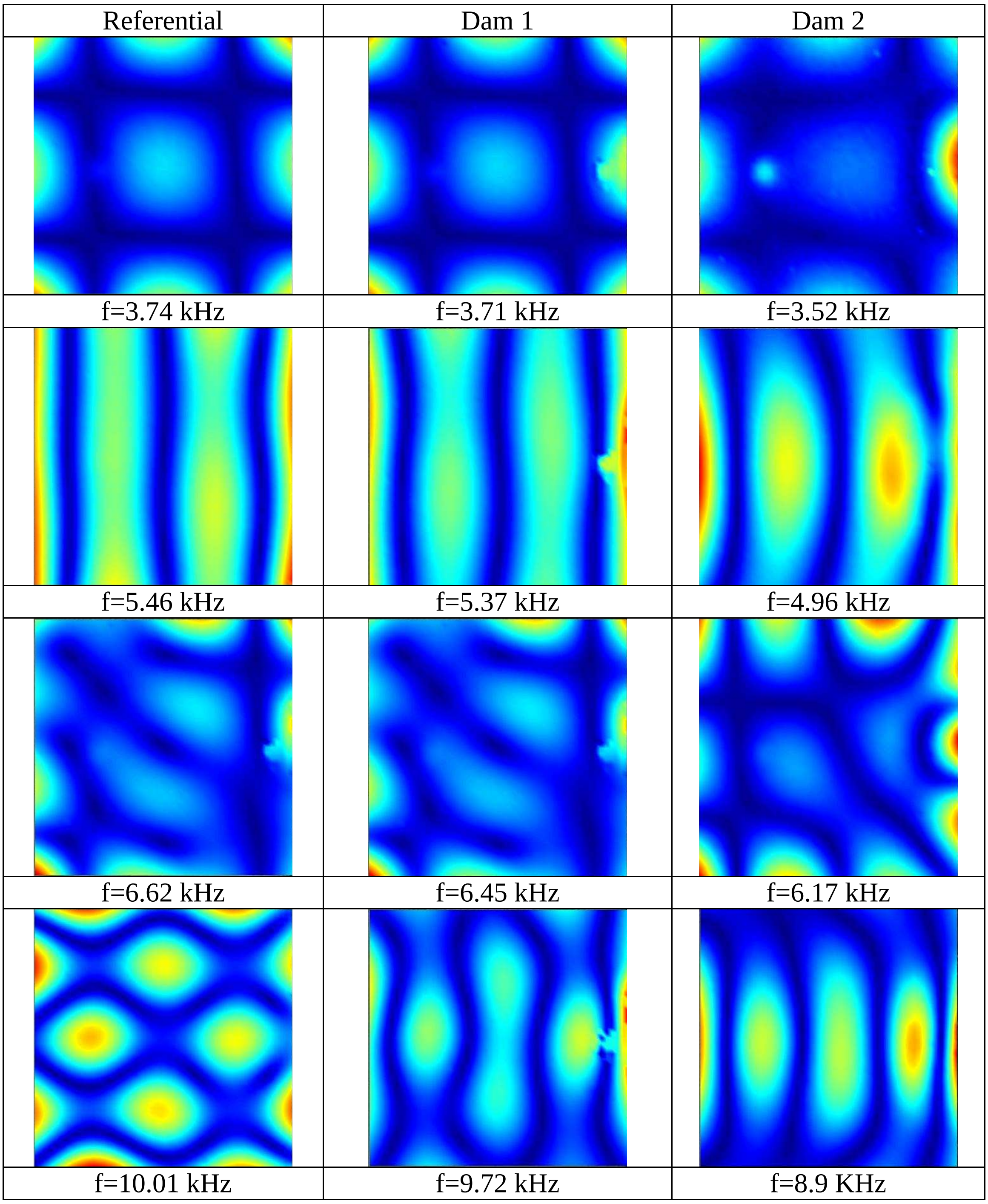


Figure 6: Comparisons of mode shapes for few choosen frequencies and different CFRP sample states.

In next step mode shapes for CFRP sample vibrations for three investigated states were extracted. In Figure 6 chosen mode shapes were presented for: referential state, *Dam 1* (small delamination) and *Dam 2* (large delamination). Location of the piezoelectric can be noticed for mode shape (*Dam 2*, f=3.52 kHz) on the left in the respect to the sample middle. Delamination is located near the edge on the right hand side. Introduction of delamination causes frequency shift of natural vibrations as well as mode shape change. These changes are very large for the larger size of delamination (*Dam 2*). All these mode shapes are related to frequency peaks visible in Figure 5.

In next step simple algorithm that creating RMS energy map for vibration velocity was used. Such a map indicates the region with concentration of energy related to structural vibration of composite sample. Such a energy concentration can be noticed mostly in the place where the wave excitation was applied, near the sample boundary and in the all places where different discontinuities are located (for example damage). RMS index for chosen scanning point *j* can be created based on the following formula:

$$RMS_j = \sqrt{\frac{1}{N}\sum_{k=1}^{N} S_{j,k}^2}\ , \tag{3}$$

where, $S_{j,k}$ – signal gathered in the point *j*, N –length of the signal. Computing RMS index values for full mesh of scanning points allows to create RMS energy map. Such a maps for the energy of vibration for the referential state, state with small delamination and with large delamination are presented respectively in Figure 7a–c. Here full frequency band of registered vibration was utilized. In all cases location of piezoelectric transducer can be simply noticed.

In Figure 7a some energy distribution in the place where smaller delamination is existing can be noticed. Approximated shape and size of delamination can be noticed. In the case of Figure 7c approximated shape and extent of delamination can be noticed.

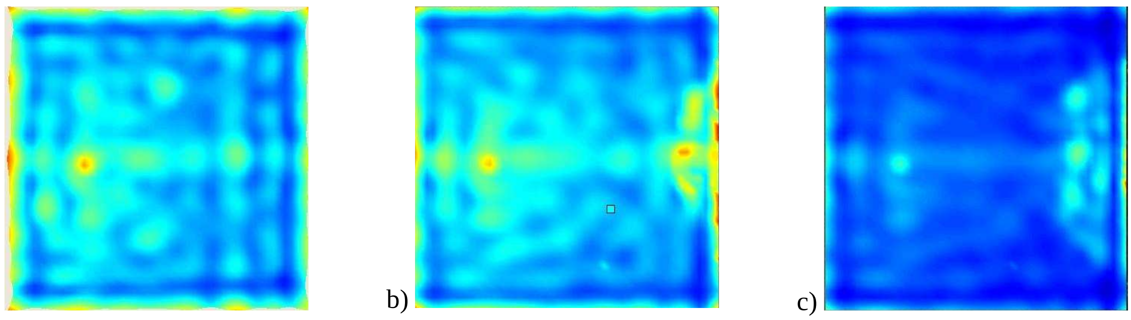

a) b) c)

Figure 7: RMS maps for different CFRP sample states: a) referential, b) smaller delamination – *Dam 1*, c) larger delamination – *Dam 2*.

4.2 Guided waves-based method

Scanning laser vibrometer measurements performed for surface of CFRP sample allowed also to visualize guided wave propagation. This measurement approach is called full wavefield approach. For this purpose dense mesh of measurement points was spanned over the sample surface.

Measurements were performed on the surface without piezoelectric transducer. In this case only the damage case was investigated, where delamination with larger size (*Dam 2*) was located in the sample. Excitation signal was in the form of tone burst with five cycles. Three values of signal carrier frequencies were investigated: 16.5 kHz, 100 kHz and 150 kHz.

It should be mentioned that guided wave–based method is more sensitive to much smaller damage that vibration based method due to utilization of higher frequencies. In guided wave–based method frequencies up to few hundreds of kilohertz are utilized while for the vibration–based method till tens of kilohertz. That means that for the excitation frequency equal 16.5 kHz sensitivity of method will be very poor due low frequency and large wavelength.

In next step of research all gathered signals have been processed using simple method based on RMS energy map calculated for propagating elastic waves. In the Figure 8 such a RMS energy maps calculated for different excitation frequency were presented. These maps are presented in the logarithmic scale (map amplitude). For the case of excitation frequency equal 16.5 kHz (Figure 8a) the space resolution and sensitivity is very low what was mentioned above. However some energy concentration around the sample edges and on the right side where the delamination is located can be simply noticed. In the case of frequency 100 kHz (Figure 8b) wave energy is concentrated mainly in the place where piezoelectric transducer is located and generates guided waves. However further energy concentration can be simply noticed in the delaminated region. Moreover shape of delamination can be here clearly distinguished. For the highest excitation frequency 150 kHz (Figure 8c) the image is very similar to previous one.

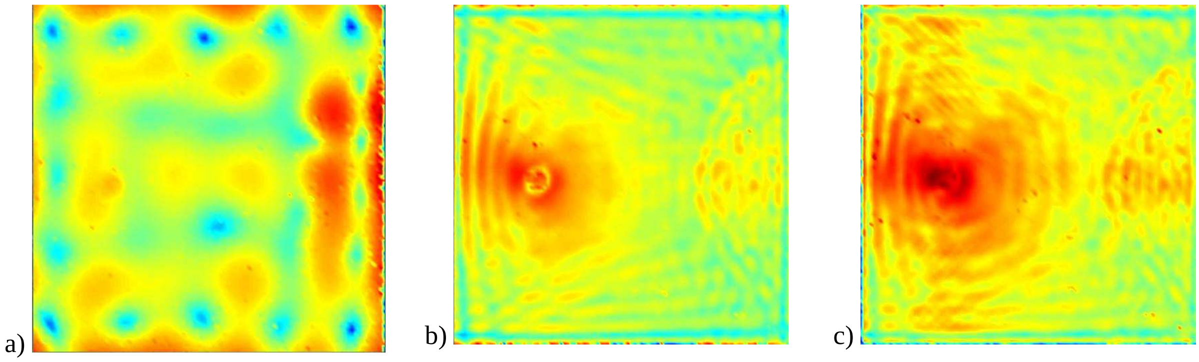


Figure 8: RMS energy maps for guided waves propagation for damage state 2, excitation frequency: a) 16.5 kHz, b) 100 kHz, c) 150 kHz.

Guided wave–based method can be simply utilized in SHM system when piezoelectric transducers are used for guided wave excitation and sensing. This is the main advantages of this method apart from its high sensitivity to very small damage in early stage of growth. However in the case of this method large damping related to reinforced composite material need to be taken into account.

This method allows to localize delamination and even to determine its shape. Laser vibrometry can be useful tool during development and prototyping of SHM system (actuator/sensor placement, analysis of guided waves in complex structures [13], [14]) or for non destructive testing purpose.

5 TERAHERTZ SPECTROSCOPY

Terahertz spectrometer Teraview TPS Spectra 3000 which generates impulses in frequency range from 0.1 up to 3 THz was used in these investigations. These impulses are sent repeatedly and interact with the investigated sample material. This equipment works in time domain and is called time domains spectroscopy TDS, [15]. 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 it is very often limited to only one side. The spectrometer is equipped with moving table that allows for XY scanning of large objects.

Investigated GFRP sample was presented in Figure 9. Two delaminations were initiated in this sample. Larger delamination located on the sample edge is clearly visible, the smaller one is located in the corner on the right and bottom part of sample. Aluminum strip causes strong reflection of THz radiation and is used for determination of sample orientation during the measurements.

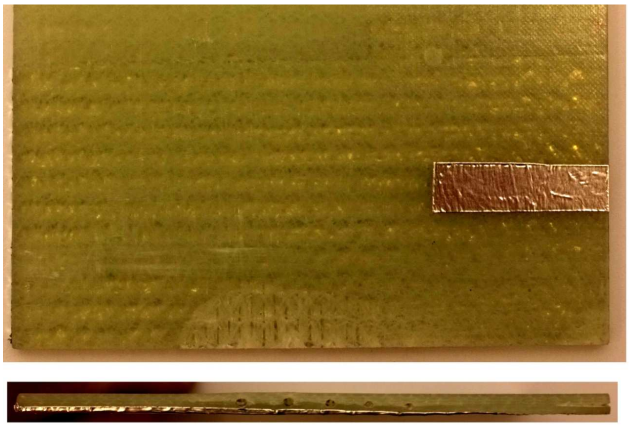
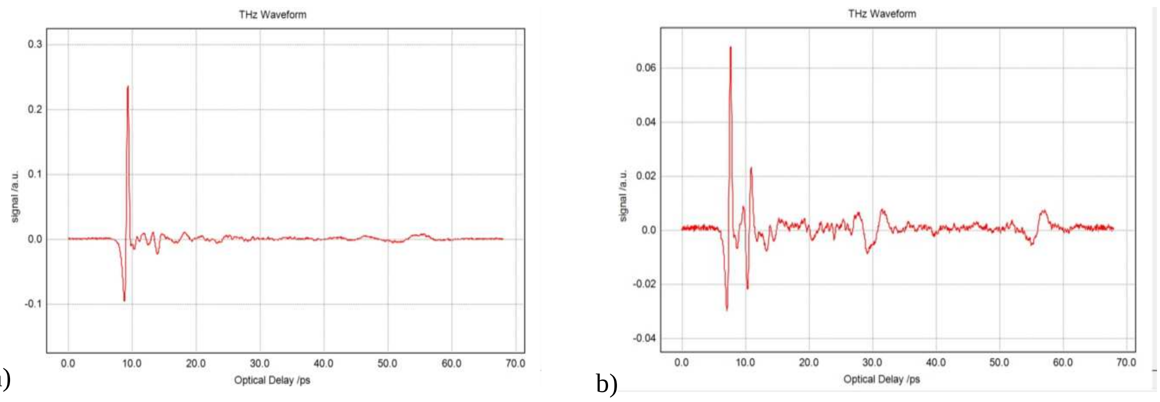


Figure 9: GFRP sample with delamiantion and aluminium strip.

In the Figure 10, THz signals taken from GFRP sample in referential region and region with delamination were presented. In the case of signal for referential region (Figure 10a) two reflections can be distinguished: with larger amplitude (at 10 ps) – related to top surface reflected THz waves and with smaller amplitude (at 50 ps) – related to reflection from bottom surface of the sample. In the case of delamination additional reflection can be noticed (at 30 ps).



a) b)

Figure 10: THz signal taken from: a) referential region (without delamination), b) region with delamination.

In the Figure 11, B–scans for the referential sample region and for the region with delamination were presented. In the case of the delaminated sample, damage can be clearly observed in the B–scan observing region between top and bottom surface (Figure 11b).

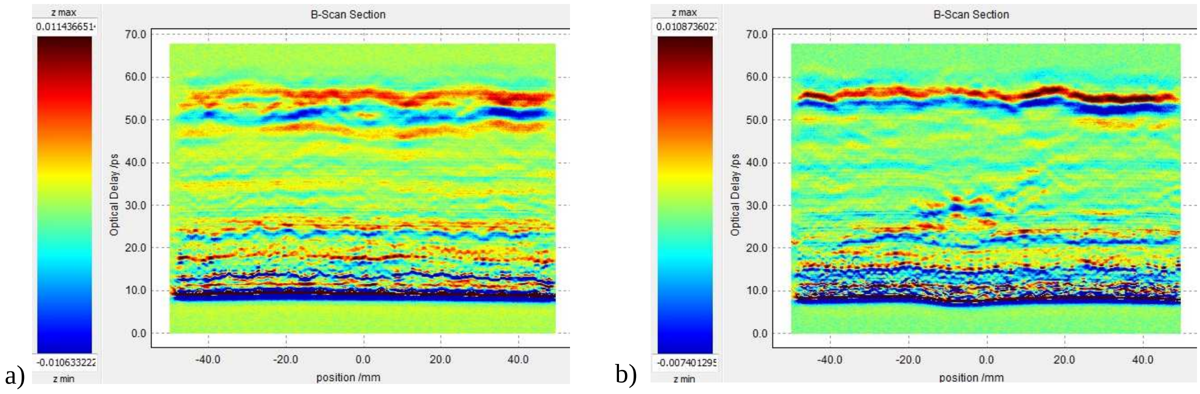


Figure 11: B–scan for GFRP sample: a) referential region, b) region with delamination (see position –20;0 and delay 25–35 ps).

In the last step C–scan was created for the sample with delaminations. Analysing this C–scan strong wave reflection can be noticed that is related to aluminum strip on the sample surface (on the right, in the middle of the sample edge). Both delaminations (more strictly surface waviness caused by delamination) are also visible on this C–scan: larger one (in the middle of the bottom edge) and smaller one (bottom corner on the right side). During creation of C–scan plot *"Max Peak Size"* feature was used.

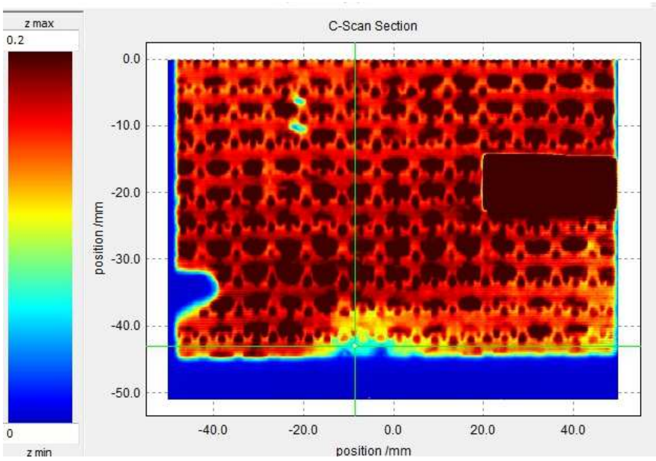


Figure 12: C–scan for GFRP sample with delaminations.

Results prove that this NDT teqchnique is approporiate for delamination detection in GFRP composites. This method can determine the shape of the delamination as well as its location in respect to the thickness (only in reflection mode).

As it was mentioned earlier this method can not be used for CFRP. Limitation of this method is also thickness of the sample. Thick composite material will damp the THz radiation and penetration depth can be limited. Moreover length of signal in this equipment is also limited which also determines maximum allowable thickness of investigated sample.

6 CONCLUSIONS

In this paper result of detection and localization of artificially initiated delaminations in small CFRP and GFRP samples were presented. During research electromechanical impedance EMI method, laser vibrometry (vibration–based and guided wave–based method) and terahertz spectroscopy were investigated.

EMI method is very sensitive to small damage but results are also influenced by changing ambient temperature. These temperature changes need to be compensated in order to eliminate false damage detection. This method utilizes piezoelectric transducers that can be permanently installed on interrogated structure and it is possible to perform real–time structural monitoring (SHM). Range of the method (distance from the transducer where damage can be still detected) depends on damping properties of composite materials as a consequence of thickness, stack lay–up or geometrical complexity.

Laser vibrometry technique can be used for vibration–based damage detection. This is similar to the conventional modal analysis where changes in natural frequencies and mode shapes are investigated. It is also possible to detect damage based on analysis of distribution of vibration energy (RMS energy map). Method is also similar to EMI method however in the first one much higher frequencies can be utilized (depending on damping). However laser vibrometry is NDT technique that can be used for laboratory measurements or real structures measurements. Moreover this method can be also utilized for optimization of sensor placement for EMI method (for lower frequencies).

Laser vibrometry can be also utilized for guide–based damage localization method. By observing of guided wave energy distribution (RMS energy map for guided waves) it is possible to detect and localize damage. This method can be used similarly like EMI method for higher frequencies up to hundreds of kilohertz. It offers high sensitivity to small damage due to small wavelength for high frequencies. Laser vibrometry can be used for optimization of sensor placement and guided wave propagation analysis during SHM systems development which is based on the piezoelectric transducer and guided waves method.

The last one is Terahertz spectroscopy method. This is extended NDT method that can be used for delamination detection. This method is appropriate for GFRP and other materials that are not electrically conducting. Method can determine the location of delamination in GFRP sample.

Further research will be related to determination the range of EMI method in much larger CFRP and GFRP samples.

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