Highlights and challenges in nondestructive evaluation for metallic and composite structures

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ABSTRACT

The paper presents methods and techniques oriented towards structural health monitoring (SHM) and (ENDT) for both metallic and composite structures. Particularly the paper is dedicated to elastic waves propagation phenomenon, scanning laser vibrometry, electromechanical impedance and terahertz spectroscopy. Selected numerical modelling aspects of the phenomena related to the mentioned methods are addressed.

Moreover it covers the main disciplines which are related to above mentioned techniques as piezoelectric sensors and transducers, and signal processing. The signal processing approach is crucial allowing extracting damage related features from the gathered signals.

Investigated damage is in the form of mechanical failures as cracks, delaminations, debonding, voids. Also methods dedicated to thermal degradation, moisture and chemical contamination are shown. Presented methods are also suitable for performance of bonded joints assessment. Problem of external factor (temperature, load) on investigated methods is also discussed in this paper. The characteristic of each method is summarized by a critical look.

Promising combination of selected techniques should lead to an innovative approach to ensure safety operation of structures. All problems have been dealt with a hybrid experimental – numerical approach.

Keywords: extended non–destructive testing, structural health monitoring, damage detection and evaluation

1. INTRODUCTION

Contemporary aerospace structures are made with various materials. Aluminum alloy, GLARE, CFRP, GFRP are widely used and the up–to–date NDT techniques should handle with the wide range of these materials. Moreover, not only typical damage as cracks and delamination [1], [2] should be considered but also it is important to assess, for example, the surface quality, the performance of structural bonds or moisture content. The adhesive bonding is present at the manufacturing process as well as in service in the form of composite repair patches used for repairs. Previous research proved that fluid absorption influences the mechanical performance of composites [3], [4] so the a NDT for detecting the presence of a fluid would be crucial for ensuring the integrity of the structure. The performance of adhesive bonds depends on the physico – chemical properties of the adhered surfaces. In [5] the effect of pre–bond release agent and moisture absorption on mode–I fracture toughness of CFRP bonded joints was qualitatively and quantitatively studied. It was shown that the release agent contamination may lead to about 60% drop of critical crack energy release rate (GIC). Improperly chosen curing temperature of the adhesive leads also to changes even up 95% reduction of GIC for temperature lower by one third, [6]. This indicates that the effective NDT methods should have a broad spectrum of usage and it is not to be expected that only one method would be suitable for all these tasks, therefore new techniques are sought and investigated.

Nowadays metallic and composite structures need to be assessed using conventional NDT, extended NDT (ENDT) or SHM techniques in order to maximize the safety of the structure exploitation. Still very popular methods are ultrasound testing (UT) method or X–ray based methods. However many other methods have been developed and still are being improved. An example is the method based on guided wave propagation. This technique can be used in SHM as solution where the guided waves are excited and registered using piezoelectric transducers (point–wise method). However, this

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technique can be also exploited as NDT approach where guided waves are still excited by piezoelectric transducers but signal measurements are realized using scanning laser vibrometry. It is noncontact measurement technique that allow to perform full wave–field measurements. This allow to visualize guided wave propagation process in an animation. Moreover detailed analysis of frequency–wavelength domain can be conducted in this approach [7], [8], [9].

Next method suitable for assessment of metallic as well as composite structures is the electromechanical impedance method (EMI). This method can be used in the SHM for damage detection and for sensor self diagnostics. More details can be found for example in [10]. This method will be wider presented and discussed in this paper. Interesting method suitable for ENDT is terahertz spectroscopy. This method is similar to the X–ray technique but electromagnetic radiation utilized here is in the terahertz range and does not cause ionization. Method can be utilized for assessment of composite structures consisting of electrically non–conducting materials (e.g. glass fiber based composites).

In the case of application of SHM and ENDT techniques influence of external factor need to be taken into account. Transducers utilized in SHM (piezoelectric, fibre optic and other) need to be bonded to the structure using a bonding agent suitable for application for operational condition in which the structure is exploited. Influence of changing temperatures, UV radiation, moisture, aggressive agents need to be taken into account during selection of bonding agent, bonding procedure or transducer isolation.

Moreover external factors have influence on measurement results for such methods like guided wave propagation or EMI. Both methods are very sensitive to temperature changes [11], [12]. In the case of guided wave based method, the velocity of guided wave propagation depends on material properties that on the other hand depends on temperature. As consequence velocity of guided wave propagation varies with temperature. This feature need to be taken into account in SHM. Signal processing algorithm for compensation of temperature influence need to be utilized. Changing temperature cause also changes in the measurements characteristics taken for the EMI method. Due to temperature change horizontal shift of frequency peaks is observed [13], [14]. This feature also need to be compensated.

EMI method is also influenced by changing the load of investigated structure [14], [15]. These all mentioned external influences need to be considered during the utilization of ENDT or SHM techniques.

This paper is divided into two major sections. Firstly, the methods and examples for inspection of metallic structures are presented. Secondly, the methods and examples for inspection of composite structures are described. The paper ends with concluding section.

2. INSPECTION OF METALLIC STRUCTURES

Nowadays in many branches of industry engineers use more and more composite materials. However, many metallic structures are still developed and continuously exploited. Therefore it is need to develop nondestructive testing/inspection (NDT/NDI) techniques for metallic structures. Guided wave propagation method is a very attractive technique that can be utilized in either SHM or NDT. The aim of this method is to detect the changes of guided wave propagation caused by initiated damage. Guided waves propagating in structure interact with any discontinuities located in the structure. These interactions can be observed as wave reflection, scattering, diffraction or mode conversion. Many research papers presenting application of this method for detection and localization of simulated (notch, cut, hole) or real damage (crack) can be found in [10]. In these studies the phenomenon of wave reflection and transmission through the damaged region was used. Beside this phenomenon mode conversion can be observed due to interaction of elastic wave with discontinuities or damage. In this section we show some results of mode conversion for damage detection purposes. In Figure 1 chosen frame from animation of guided wave propagation in aluminum panel was presented. This animation was created based on experimental measurements with utilization of Scanning Laser Doppler Vibrometer (SLDV). Measurements were preformed with the use of one scanning head (1–D mode measurements). This means that only displacement components along the laser beam were measured. Panel had dimensions 1000 mm × 1000 mm × 1 mm and was equipped with piezoelectric transducer placed at the middle. In this case NOLIAC NCE51 disc with 10 mm diameter and 0.5 mm thickness was utilized. In Figure 1 guided wave propagation on only one quarter of the panel was visualized. Excitation can be noticed in the right bottom corner. Frequency of excitation was equal 100 kHz (5 cycles, toneburst). Two fundamental guided wave modes are clearly visible: symmetric S_0 and antisymmetric A_0. Two modes can be distinguished through different wave lengths (A_0 mode has shorter wave length than S_0). In this plate five throughout holes with diameters 2, 3, 3.5, 4 and 5 mm were drilled. Moreover notch with length 3 mm was made on the back side of the plate (not measured by SLDV). In the result presented in Figure 1 propagation of S_0 (fastest one) and A0 mode can be clearly noticed. Moreover mode conversion S_0/A_0 as result of interaction with holes and notch can be observed. This conversion can be seen as propagation of A_0 mode starting from place where mentioned holes and notch are located.

Mode A_0 from the transducer at that time instant has not reach these location yet. Guided wave mode conversion can be noticed for all diameters of drilled holes. This example shows that presented method can be utilized for detection of cracks or corrosion located on the not accessible surface of the panel.

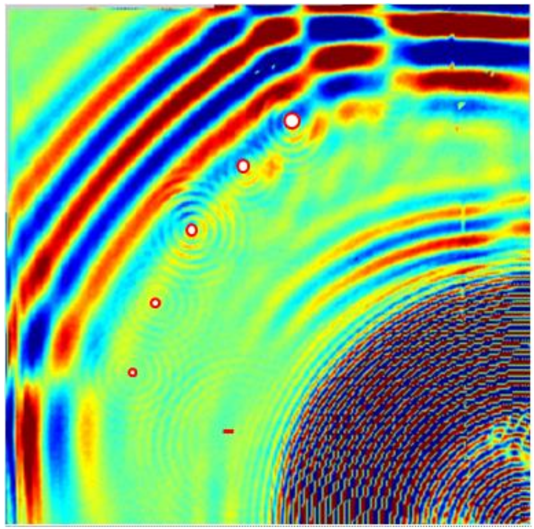


Figure 1. Guided wave mode conversion S_0/A_0 due to interaction of wave with 3 mm–long notch and drilled holes with diameters: 2, 3, 3.5, 4 and 5 mm.

Next example shows application of mode conversion phenomenon due to interaction of guided wave with two stiffeners joined to the aluminum panel using bolted joints. In this case five bolted joints with different tension forces due to applied different torques were investigated. The size of stiffeners located on the top panel surface can be seen in Figure 2. Second stiffener located on the other side is shorter and ends between third and fourth bolted joints (counting from the top–left panel corner). Tension forces in bolts are reduced from the top–left to the bottom–right. In this case frequency was also equal 100 kHz and the same form of excitation signal was utilized. Chosen frame from animation of guided wave propagation in this panel was shown in Figure 2. In this case propagation of both fundamental A_0 and S_0 mode can be observed similarly to the previously presented example. Moreover guided wave mode conversion S_0/A_0 can be observed as result of interaction of mode S_0 with bolted joints. Different intensity of mode conversion (seen as amplitude of mode A_0 generated due to this conversion in the locations of bolted joints) can be noticed. This is strictly related to different tension force in bolted joints. Moreover in the location where the maximum torque was applied to the bolted joint (first on the top–left) it can be noticed that the shape of wave front of A_0 mode generated by conversion is related to the stiffener geometry. Moreover, guide wave propagates in the stiffener starting from this bolted joint. It should be also emphasized that for the first three bolted joints counting from the top–left panel corner there is symmetry (stiffener on both panel sided) but mode conversion still occurs. According to the literature mode conversion does not occur for symmetrical boundary conditions, [1]. However, this symmetry in this case could be not ideal. Presented example proves that the methodology could be exploited for the assessment of the bolted joints.

In the next step situation was slightly more complicated. In this case only one shorter stiffener was joined using one bolted joint located on the top–left (Figure 3). The bolt on the right side of stiffener was removed. Farther to the right one drilled hole was located and two bolted joints with similar tension forces (similar torque applied). These two bolts "join" only top and bottom panel surface. Excitation signal form and frequency were the same like in the previously presented examples.

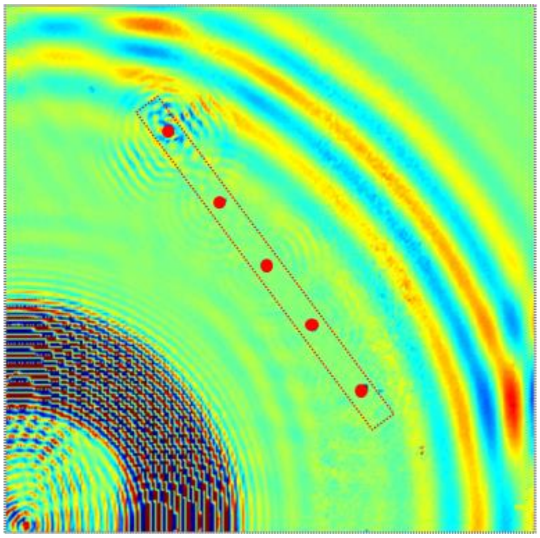


Figure 2. Mode conversion due to interaction of S_0 mode with bolted joints with different tension forces in the bolts

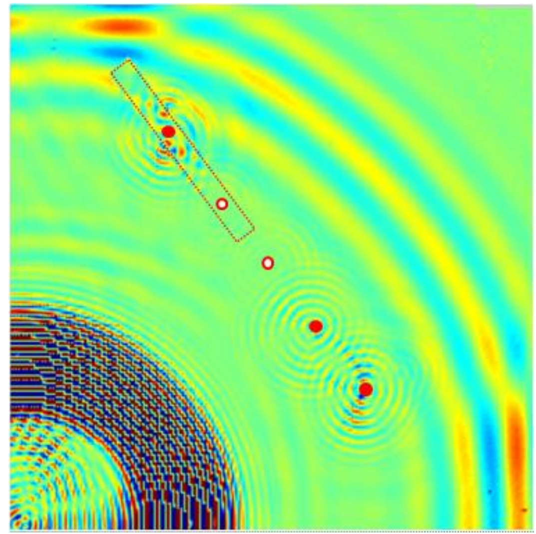


Figure 3. Mode conversion due to interaction of S_0 mode with bolted joints and drilled holes; drilled hole – marked by circle, bolted joint – marked by filled circle.

Chosen frame from the animation for this case was shown in Figure 3. Strong mode conversion can be observed at the location where bolted joint connects the stiffener to the panel (top–left). Very low amplitude of converted S_0/A_0 mode can be noticed in locations of removed two bolts. Strong amplitude of A_0 as result of conversion of S_0 mode can be observed in the location where two bolted joints are located (bottom–right). This strong and similar value amplitudes are caused by large and comparable tension forces in both bolts.

3. INSPECTION OF COMPOSITE STRUCTURES

In the topic of composite assessment a separate branch of research should be underlined. This branch is devoted to the assessment of adhesive bonds quality. It gains huge importance as the riveting of aircraft CFRP panels is still used. Resigning from the rivets and leaving only adhesive bond would help to reduce the mass of an aircraft. In this part the EMI method is considered as NDT (Non–destructive testing) method for adhesive bonds assessment. The EMI method uses a piezoelectric sensor that excites and senses the response from the host structure. In order to extract structure condition–related features various frequency bands of EMI are analyzed. These bands depend on the inspected structure and the used piezoelectric sensor. A comparison of damage sensitivity of high and low frequency bandwidth was presented in [17]. The authors underline the good sensitivity of the EMI method based on analysis of the bandwidth near the high frequency thickness vibration mode of the piezoelectric sensors. In the reported investigations a piezoelectric disc thickness resonance is around 4 MHz. This resonance is visible in the admittance ($|Y|$) and conductance (G) as a strong peak. The susceptance (B) has a zero–crossing at this point. The relation between these three quantities is as follows:

$$Y = G + iB \tag{1}$$

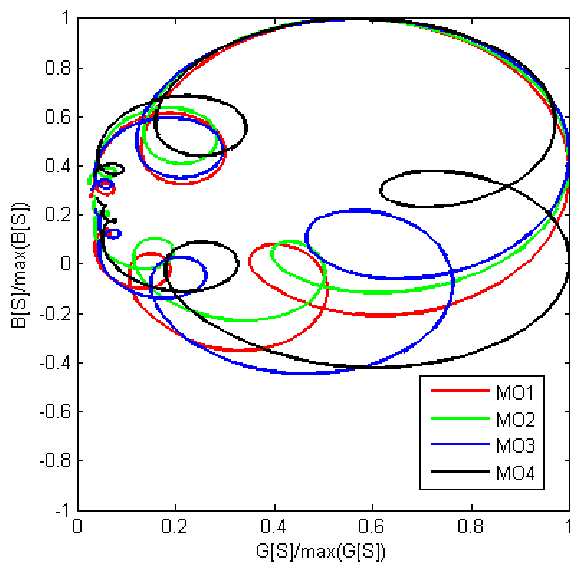


Figure 4. Admittance curves for bonded samples with moisture contamination.

The analysis of the electromechanical impedance was conducted in the vicinity of the 4 MHz thickness resonance: 3–5 MHz bandwidth. CFRP samples with adhesive bonds were considered. The sample is comprised of a 1.5 mm–thick and 2.6 mm–thick plates joint with a film adhesive. The planar dimensions of the samples were 100 mm × 50 mm. The sensors were bonded at the middle of each sample face. The goal of this research is the search of a relation between the adhesive bond condition and the EMI response. For this purpose samples with pre–bond contamination were investigated. One of the adherend samples was contaminated with moisture before adhesive bonding. Four cases were investigated each with different level of moisture obtained by keeping the samples in environmental chamber with controlled humidity. The level of contamination was expressed by mass increase related to amount of moisture intake (Table 1). The ascending numbering of the samples MO1–MO4 corresponds to the ascending contamination level.

Table 1. Considered adhesive bond cases with moisture contamination

Symbol	Prebond mass increase due to moisture
MO1	0.45 %
MO2	0.80 %
MO3	1.13 %
MO4	1.25 %

The admittance characteristic for the MO samples are presented in Figure 4 on a complex plane. The horizontal axis (Real) represents conductance (G), while the vertical axis (Imaginary) represents the susceptance (B). Both quantities were normalised to their respective maximum values in order to facilitate the comparison. In order to quantitatively assess the adhesive bonds the Frechet distance was calculated between the curves. The promising results of using this distance to assessment of adhesive bonds contaminated with release agent were presented in [18]. The Frechet distance is the minimum distance required to connect two points constrained on two separate paths, as the points travel without backtracking along their respective curves from one endpoint to the other. The definition is symmetric with respect to the two curves.

The analysis of the curves presented in Figure 4 is conducted here. The values of the Frechet distance were calculated for MO1–MO4 samples in relation to the sample with the lowest contamination level (MO1). The F values inform about the dissimilarity of the curves. The results were plotted in color scale in Figure 5. The distance between the same curves is zero. One can notice that there are differences among the tested cases. The MO2–MO4 samples have F value higher than zero. The increase of F value correlates with the increase in contamination level. The results indicate that the admittance curves become more and more different as the bondline contamination level increase.

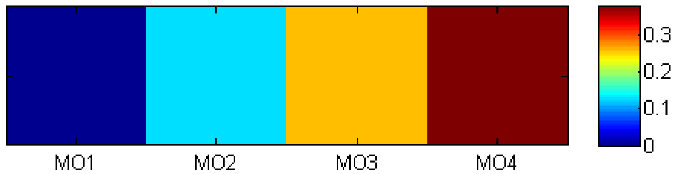


Figure 5. Results (Frechet distance) of comparison of admittance characteristics for the bonded samples with moisture contamination.

The necessity of ensuring safe bondline determine to seek for efficient means of surface prebond inspections. One of the promising methods is the laser induced fluorescence (LIF). It is a spectroscopic method that can be applied for large surface material analysis using surface scanning technique. In the reported research LIF spectra were recorded using laboratory system equipped with laser excitation sources: DPSS cw Nd:YAG 532 nm, 0.2 – 2 W output power (Spectra Physics) and pulsed Nd:YAG 532 nm, 6 ns pulse diration (Briliant B, Quantel). The 532 nm excitation was chosen following previous research reported in [19]. Excitation at this wavelength showed maximal sensitivity to surface state condition. Fluorescence detection system was based on 0.3 m Czerny–Turner type monochromator (SR–303i, Andor) and spectroscopic ICCD camera (DH–740 Istar, Andor). In the detection path excitation laser radiation was blocked by a band pass filter (OG550, Shott). The investigation was focused on thermal degradation of sample surface. The mechanical tests presented in [20] showed that prebond thermal degradation weakens adhesive bond of CFRP. Sensitivity to temperature of exposition was reported in [19], so here the influence of duration of heat source exposure was investigated. Thermal processing of samples was carried out by means of heat gun giving a stream of hot air 5 mm in diameter and temperature set at 450˚C The research was conducted on woven CFRP 3 mm–thick samples with 4 layers. Four times of exposure were tested 5, 10, 20 and 30 s. For each time of exposition the response was measured in 10 random points at the sample surface. The response is very non–uniform. The intensity varies from point to point. The intensity value was calculated as an integral over the wavelength range 550–800 nm. Significant changes in the intensity occur for 20 s heating and longer (Figure 6). Increasing the exposure by 10 s (up to 30 s) results in intensity value increase by an order of magnitude.

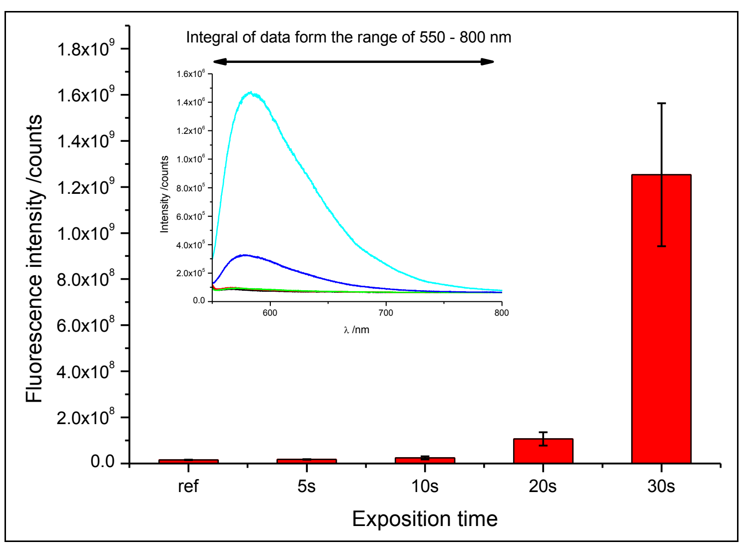


Figure 6. Fluorescence intensity for 4 times of exposition to heat source in relation to reference case (untreated sample).

Composite structures can also be assessed using guided wave propagation method. Comparing phenomenon of guided wave propagation in metallic (isotropic) and composite (orthotropic) structures important difference can be noticed analysing the shape of the wave front. In the metallic structures velocity of guided wave propagation is the same for all direction of propagation. As consequence shape of wave front is circular in this case. In the case of composite structures velocity of guided wave propagation strictly depends on directivity of reinforcing layer distribution. This phenomenon can manifests as noncircular shape of wave front. Comparison of wave front shape for metallic and composite panel can be seen in Figure 7a and Figure 7b respectively. These frames were chosen from animation of guided wave propagation created based on measurements taken by SLDV.

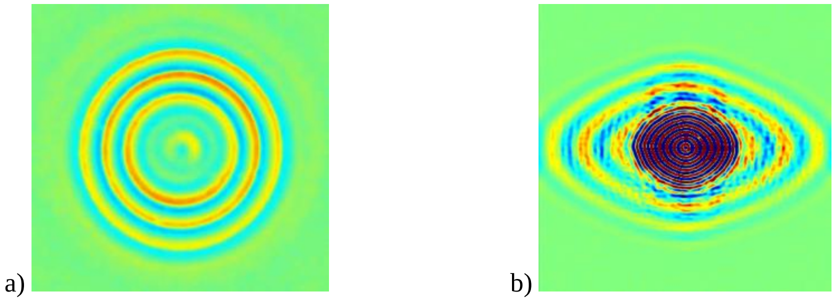


Figure 7. Frames from animation of guided wave propagation in: a) aluminium panel, b) CFRP panel $[0/0/0/0]_S$ – experimental results based on scanning laser vibrometry.

Phenomenon of guided wave propagation can be effectively simulated using Spectral Element Method (SEM). More information about this method can be found in [21]. In this section results of simulation of guided wave propagation in composite panel with dimensions 1000 mm × 1000 mm × 1.5 mm, with elliptical delamination (16 mm × 8 mm) based on SEM methods were presented. In the simulation composite panel with three carbon fibre reinforced layers with orientation [0/90/0] was utilized. Delamination was located between first and second layer counting from the top surface. SEM model also includes piezoelectric transducer which is located in the middle of the panel, on the top surface. Excitation frequency was equal 100 kHz (5 cycles of sine modulated by Hanning window). In the Figure 8 chosen frames from animation of guided wave propagation in CFRP panel created by numerical simulations were presented. This animation was based on out of plane displacements (transverse). Analysing these frames propagation of symmetric and antisymmetric mode can be noticed (symmetric mode has very small amplitude). Moreover non–circular wave front of symmetric and antisymmetric mode due to orthotropic material properties can be observed. Wave front of symmetric mode is much more susceptible to orthotropic properties and as consequence its shape differ much more from circular shape. Analysing presented results damage induced antisymmetric mode reflection can be clearly seen.

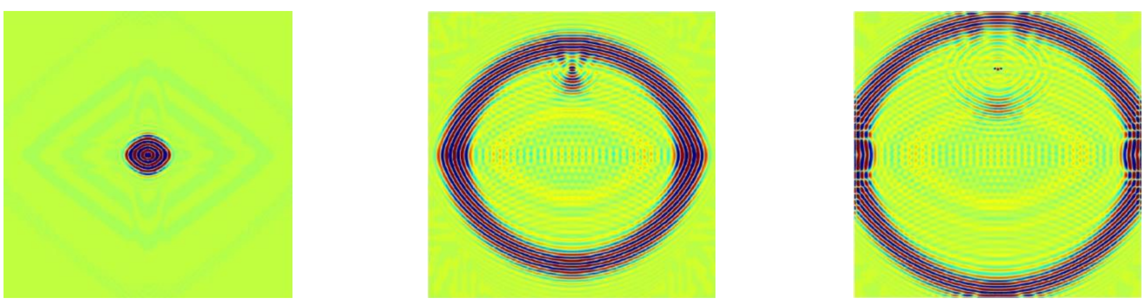


Figure 8. Chosen frames from animation of guided wave propagation in CFRP panel – numerical results from SEM method.

SEM method can be used for simulation interaction of both symmetric and antisymmetric modes with damage in the form of delamination. Moreover, this method can be utilized for investigation of guided wave mode conversion phenomenon. Guided wave mode conversion occurs as a result of interaction of particular wave mode with discontinuities located in the structure. In order to prove the effectiveness of SEM method for modeling of mode conversion phenomenon this method was used for simulations of guided wave propagation in CFRP panel with rectangular delamination located non–symmetrically in relation to panel thickness. Three carrier excitation frequencies were analysed, namely 50 kHz, 100 kHz and 150 kHz. Results are shown in Figure 9. Propagation of the symmetric S_0 and antisymmetric A_0 guided wave modes can be observed in all investigated cases. Moreover mode conversion phenomena due to interaction of S_0 mode with delamination can be also observed in all cases. As a result of mode conversion new mode S_0/A_0 is generated in the location of delamination. It seems that the size of delamination can be estimated by image analysis for the chosen frequencies. However, for excitation frequency 150 kHz wavefield contains more Lamb wave modes which increase complexity of wave pattern. It also causes that reflection of A_0 and A_1 modes from boundaries of delamination are weaker.

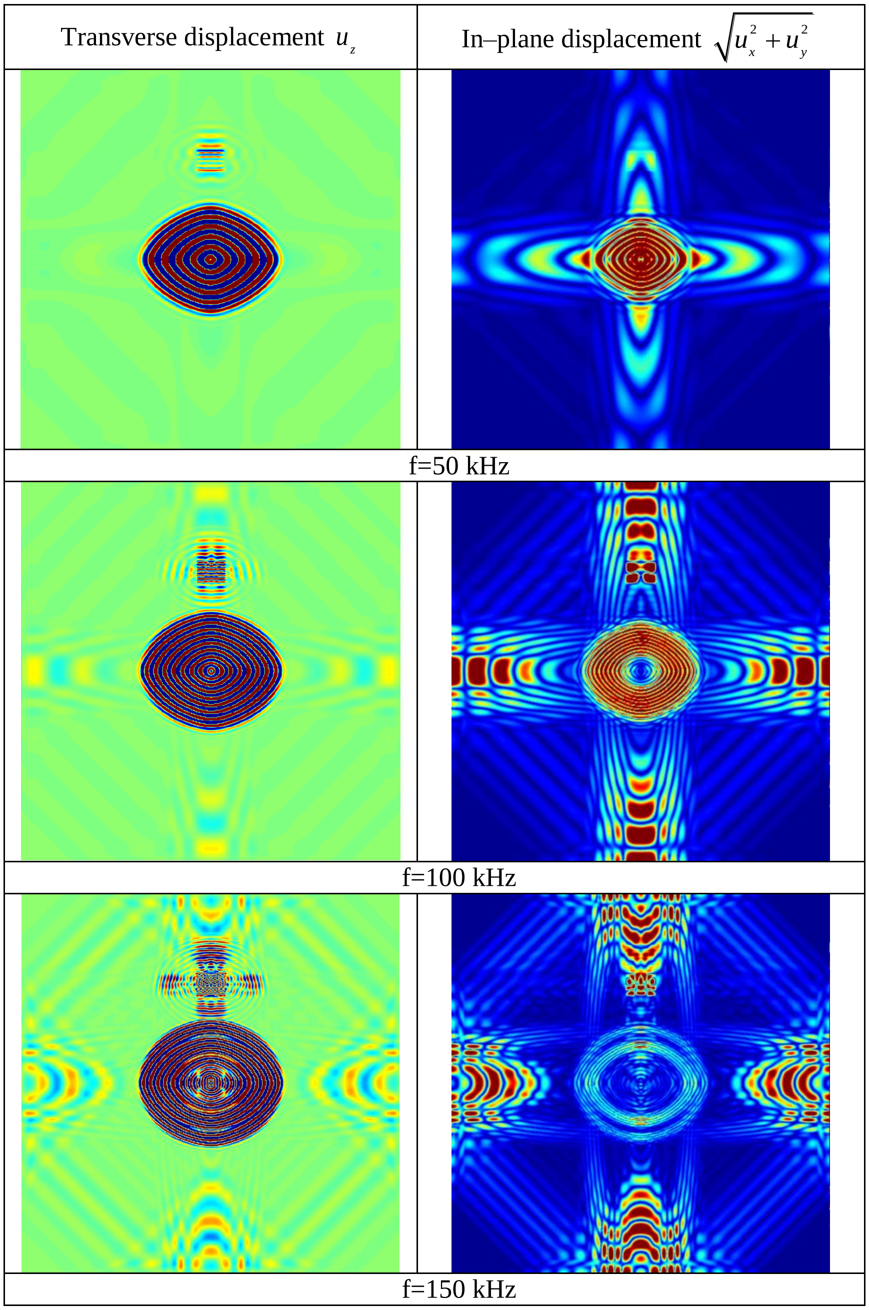
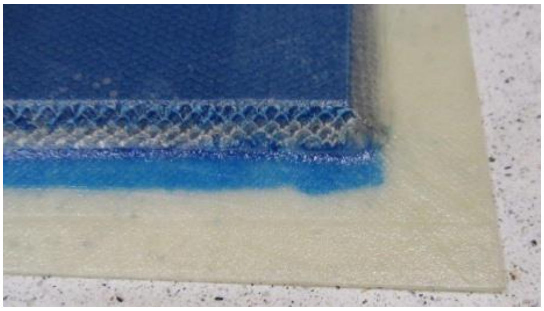


Figure 9. Interaction of guided wave with rectangular delamination of the size 40×30 mm for excitation carrier frequency: 50 kHz, 100 kHz and 150 kHz.

Presented results have shown that SEM method can be useful numeric tool for simulation of guided wave propagation in the composite structures with delaminations.
In the case of inspection of composite structures based on guided wave propagation method SLDV is used. This method allow to perform full wave–field measurements. Based on these measurements animation of guided wave propagation in investigated structures can be created. Frames from such animations were already presented in Figure 7. These results

were related to simple aluminum and CFRP panels. However scanning laser vibrometry is very useful experiment tool that can be utilized for measurements of guided wave propagation in much more complex structures. In the Figure 10a panel manufactured of glass fiber reinforced polymer GFRP with internal aluminum based honeycomb structure is presented. In this panel Teflon insert was introduced in order to simulate delamination (Figure 10b). This Teflon insert was located between honeycomb filament and GFRP skin.

a) 

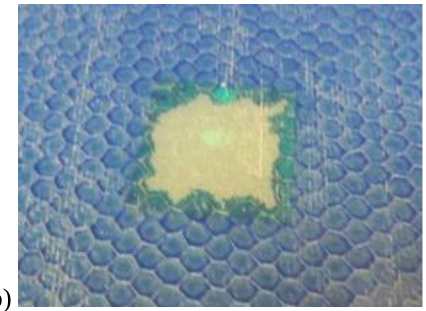
b) 

Figure 10. GFRP panel with aluminum based honeycomb filler: a) panel with visible internal structure, b) Teflon insert for delamination simulation.

This panel was equipped with piezoelectric transducer utilized for excitation of guided wave propagation. Piezoelectric transducer was placed on the same side where the Teflon insert was located. Guided wave propagation measurements were taken for dense mesh of measurement points for laser vibrometer. In the Figure 11 example result in the form of RMS energy map for excitation frequency 50 kHz was presented. Such RMS energy map for guided waves indicates the regions with concentration of energy related to interaction of waves with any kind of discontinuities in the investigated structure. RMS index for chosen scanning point j can be created based on the following formula:

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

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. Energy concentration can be noticed in the Figure 11 mostly in the place where the wave excitation was applied (PZT) and in the location of simulated delamination (D).

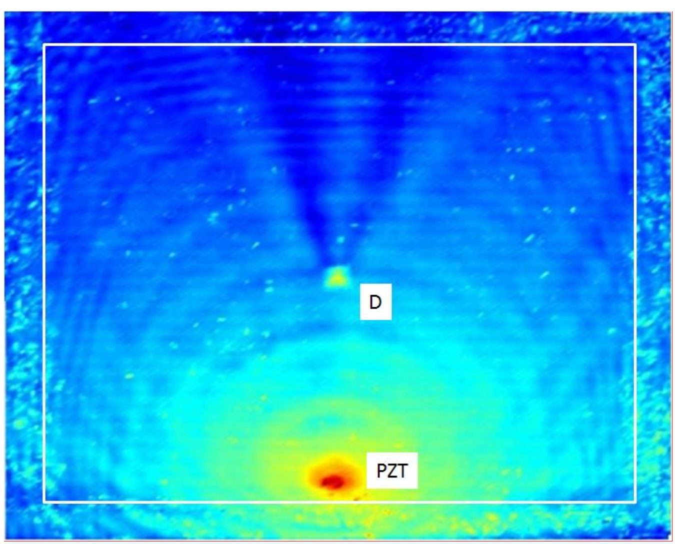


Figure 11. RMS energy map for guided wave propagation in GFRP honeycomb panel with simulated delamination.

This method can be also used for assessment of even more complex structures like the CFRP panel with Ω–shape stiffeners presented in the Figure 12. This is example of real composite aerospace structure. In this case measurements of guided wave propagation were also based on scanning laser vibrometry. Two cases were investigated: damage–free panel and panel with three Teflon inserts and one additional mass (industrial putty) simulating delamination and icing (Figure 12). Panel was instrumented with piezoelectric transducer which location can be seen in Figure 12. In this case frequency of excitation was also equal 50 kHz (five cycles of tone–burst).

Figure 12. CFRP panel with stiffeners (example of real aerospace structure).

Based on laser vibrometry measurements for both investigated cases RMS energy maps were created. In the Figure 13a RMS energy maps for damage–free panel was presented. Analysing this result, strong energy concentration around excitation point (piezoelectric transducer) can be seen. Moreover, due to wave interaction with stiffeners, energy concentration can be noticed at locations that are strictly related to stiffeners. It needs to be underlined that measurements were taken on the second (flat) surface without visible stiffeners. Internal structure of panel (stiffeners on the backside) are clearly visible. In the next step measurements taken for panel with simulated damage were analysed. In this case also RMS map was created. This map was presented in Figure 13b. Analysing RMS map location of one delamination (denoted as D) and place where additional mass in the form of industrial putty was located (denoted as M) can be clearly noticed. The locations of the rest two simulated delaminations (locations visible in Figure 12) were not indicated. In the case of detected delamination its diameter was equal 30 mm while as the diameters of the not detected delaminations were equal 10 mm and 20 mm.

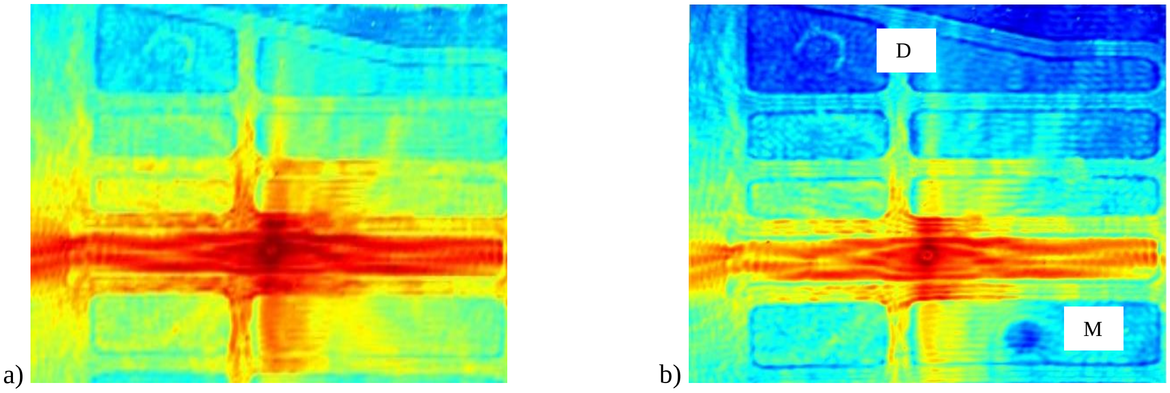
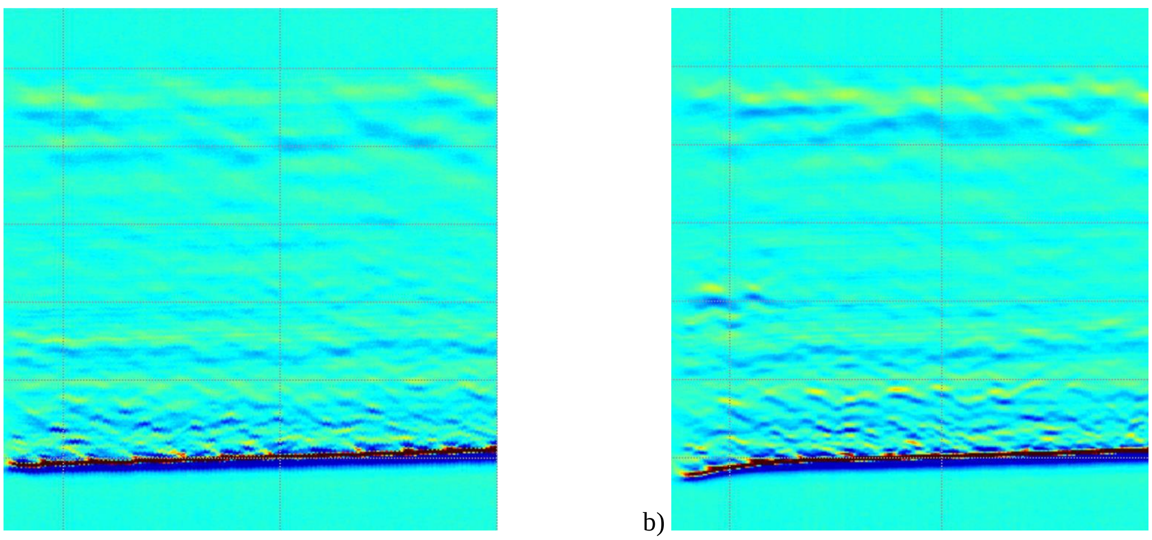


Figure 13. RMS energy map for CFRP stiffened aerospace panel: a) damage–free panel, b) panel with delamination (D) and additional mass (M); excitation frequency f=50 kHz.

Presented results shows that guided wave propagation method combined with SLDV is a very useful experimental tool. It allow to analyse of guided wave propagation phenomenon in complex structures.

Composite structures that are manufactured of electrically not conducting materials like glass fiber based GFRP can be also assessed using terahertz spectroscopy method. The THz spectrometer Teraview TPS Spectra 3000 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 the research the scanning heads were working in the reflection mode. However this equipment allow to conduct transmission measurements as well. THz spectroscopy technique in the time domain (TDS) seems to be very suitable method for detection of internal defect like delamination in composite materials [22], [23]. According to the paper [24] delaminations and moisture contamination can be visualized using TDS THz spectroscpy but the success of the technique depends on depth, matrix material, and size of the defect. Using the delay between reflections at the surface and the reflection from the defect itself the location of the defect can be identified. This can be done if a defect has not too deep location in the sample.

During the research measurements were taken for GFRP sample consisting of 12 layers with total thickness 3.5 mm. The obtained results also showed that the THz spectroscopy technique can detect and visualize delamination between the GFRP layers. Results of THz measurements in the form of B–scans for the GFRP sample with referential state (damage free) and sample with delamination were presented in the Figure 14. Analysing result for the case of B–scan for damage free sample reflection of THz radiation from top sample side (bottom side in Figure 14a) and backside (upper size in Figure 14a) can be clearly distinguished. Reflection from the top sample side is much stronger than reflection from backside. Moreover, layered structure of composite sample is also clearly visible due to reflection of THz radiation from glass fiber reinforcing layers. In the case of the sample with delamination (Figure 14b) two characteristic features can be noticed. The first one is the curvature of top sample side due to internal delamination. Second feature is additional strong reflection of THz reflection from delamination visible in B–scan.



a) b)

Figure 14. THz B–scan for the GFRP sample: a) damage free, b) with delamination.

4. CONCLUSIONS

In this paper selected extended nondestructive testing ENDT and SHM techniques have been presented. Presented methods have been exploited in the purpose of assessment process of metallic and composite structures. In the paper results of assessment for simple panels as well as real complex composite structures used in aerospace have been presented.

In the paper also results for EMI method have been presented. The method has been utilized for detection of moisture contamination in CFRP samples.

Attention has been focused particularly on phenomenon of guided wave propagation and its application for structural assessment. Especially the phenomenon of elastic wave mode conversion due to interaction with different discontinuities has been investigated and discussed. In the frame of guided wave propagation topic numerical as well as experimental results were presented. Numerical results have been obtained using spectral element method (SEM). Experimental results have been obtained by utilization of scanning laser vibrometry.

Additionally, the results for delamination detection in GFRP sample using THz spectroscopy have been presented.

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REFERENCES

[1] Su, Z. and Ye, L., [Identification of damage using Lamb waves], Springer–Verlag, Berlin Heidelberg (2009).

[2] Wandowski, T., Malinowski, P., Kudela, P. and Ostachowicz, W., "Guided wave–based detection of delamination and matrix cracking in composite laminates" Proceedings of the Institution of Mechanical Engineers Part C–Journal of Mechanical Engineering Science 225, 123–131 (2011).

[3] Sala, G., "Composite degradation due to fluid absorption" Composites: Part B 31, 357–373 (2000).

[4] Pantelakis, Sp. G., Katsiropoulos, Ch. V., Tserpes, K.I. and Felgeyrolles, Th., "Effect of water absorption on strength of the aeronautical composite material Fiberdux HTA/6376" Key Engineering Materials 417, 457–460 (2010).

[5] Markatos, D.N., Tserpes, K.I., Rau, E. and Pantelakis, S., "Degradation of mode I fracture toughness of CFRP bonded joints due to release agent and moisture pre bond contamination" The Journal of Adhesion 90(2), 156 – 173 (2014).

[6] Markatos, D.N., Tserpes, K.I., Rau, E., Markus, S., Ehrhart, B. and Pantelakis, Sp., "The effects of manufacturing–induced and in–service related bonding quality reduction on the mode–I fracture toughness of composite bonded joints for aeronautical use" Composites Part B: Engineering 45 (1), 556–564 (2013).

[7] Ruzzene, M., "Frequency–wavenumber domain filtering for improved damage visualization" Smart Material and Structures 16(6), (2007).

[8] Carrara, M. and Ruzzene, M., "Frequency–wavenumber design of spiral macro fiber composite directional actuators" SPIE Smart Structures and Materials, 94350M–12 (2015).

[9] Kudela, P., Radzienski, M. and Ostachowicz, W., "Identification of cracks in thin–walled structures by means of wavenumber filtering" Mechanical Systems and Signal Processing 50-51, 456–466 (2015).

[10] Giurgiutiu, V., [Structural Health Monitoring with piezoelectric wafer active sensors], Elsevier (2008).

[11] Croxford, J., Moll, J., Wilcox, P.D. and Michaels, J.E., "Efficient temperature compensation strategies for guided wave structural health monitoring" Ultrasonics 50 (4), 517–528 (2010).

[12] Grisso, B.L. and Inman, D.J., "Temperature corrected sensor diagnostics for impedance–based SHM" Journal of Sound and Vibration 329, 2323–2336 (2010).

[13] Baptista, F.G., Budoya, D.E., Almeida, V.A. and Ulson, J.A., "An experimental study on the effect of temperature on piezoelectric sensors for impedance–based Structural Health Monitoring" Sensors 14, 1208–1227 (2014).

[14] Lim, H.J., Kim, M.K., Sohn, H. and Park, C.Y., "Impedance based damage detection under varying temperature and loading conditions" NDT&E International 44, 740–750 (2011).

[15] Annamdas, V.G.M., Yang, Y. and Soh, C.K., "Influence of loading on the electromechanical admittance of piezoceramic transducers" Smart Materials and Structures 16, (2007).

[16] Benmeddour, F., Grondel, S., Assaad, J. and Moulin, E., "Experimental study of the A_0 and S_0 Lamb waves interaction with symmetrical notches" Ultrasonics 49(2), 202–205 (2009).

[17] Park, S., Yun, C.–B., Roh, Y. et al., "Health monitoring of steel structures using impedance of thickness modes at PZT patches" Journal of Smart Structures and Systems, 1(4), 339–353 (2005).

[18] Malinowski, P., Wandowski, T. and Ostachowicz W., "Study on Adhesive Bonds Influence on EMI Signatures" Proceeding of 10th International Workshop on Structural Health Monitoring 1, 213-220 (2015).

[19] Malinowski, PH, Sawczak, M., Wandowski, T., Ostachowicz, WM and Cenian, A., "Characterisation of CFRP surface contamination by laser induced fluorescence" Proc. of SPIE 9064, 90640E (2014).

[20] Markatos, D.N, Tserpes, K.I., Rau, E., Markus, S., Ehrhart, B. and Pantelakis, Sp., "The effects of manufacturing–induced and in–service related bonding quality reduction on the mode–I fracture toughness of composite bonded joints for aeronautical use" Composites Part B: Engineering 45, 556–564 (2013).

[21] Ostachowicz, W. et al, "Spectral Finite Element Method, in Guided Waves in Structures for SHM: The Time–Domain Spectral Element Method", John Wiley & Sons Ltd, Chichester, UK (2012).

[22] Kuei–Hsu, D., Lee, K.–S., Park, J.W., Woo, Y.–D. and Im, K.–H., "NDE Inspection of Terahertz Waves in Wind Turbine Composites" International Journal of Precision Engineering And Manufacturing 13(7), 1183–1189 (2012).

[23] Im, K.–H. Kuei–Hsu, D., Chiou, C.–P. et al., "Terahertz Wave Approach and Application on FRP Composites" Advances in Materials Science and Engineering, (2013).

[24] Ospald, F., Zouaghi, W., Beigang, R., et al, "Aeronautics composite material inspection with a terahertz time–domain spectroscopy system" Optical Engineering 000153(3), 031208 (2013).