

IMPLEMENTATION OF GUIDED WAVE BASED DAMAGE LOCALIZATION ALGORITHM IN ANDROID OS

Tomasz WANDOWSKI¹, Pawel MALINOWSKI¹, Wieslaw OSTACHOWICZ^{1,2},
Grzegorz BOROWIK³, Tadeusz LUBA³, Karol KOWALSKI³, Pawel PECIO³

¹ Institute of Fluid–Flow Machinery of Polish Academy of Sciences,
Fiszera 14 St., 80–952, Gdansk, Poland

² Warsaw University of Technology, Faculty of Automotive and Construction Machinery,
Narbutta 84 St., 02-524, Warsaw, Poland

³ Warsaw University of Technology, Faculty of Electronics and Information Technology,
Nowowiejska 15/19 St., 00-665, Warsaw, Poland
email: tomaszw@imp.gda.pl

Abstract. The paper presents an implementation of damage localization algorithm based on guided wave propagation method. Developed application is designed for Android based devices, including phones and tablets, and allows user for inexpensive mobile visualization of damage localization. Guided waves are generated and sensed using network of piezoelectric transducers. Initiated damage is a source of changes in structural elements. Due to utilization of high frequency guided wave signals this method shows high sensitivity to damage localization and is very attractive for Structural Health Monitoring. Damage localization algorithm is based on pulse-echo approach and is written in Java and Groovy languages. A calculation time for mobile device takes a few seconds only which allows fast analysis of monitored structure state. In current approach, signals gathered from the structure are located in the server and they are subsequently downloaded for processing to mobile device. As a result, a colour damage map is created which presents wave reflections from discontinuities.

Introduction

Structural Health Monitoring (SHM) is a technique for continuous damage assessment of structures. SHM systems are passive when listening to damage induced signals, and active when exciting and sensing diagnostic signals [1]. Different method of damage assessment can be utilized in SHM. Nowadays, however, very promising is technique based on guided wave propagation phenomenon. This method utilizes a fact that initiated damage is potential source of change of stiffness of structural element. The change of stiffness is subsequently source of changes in elastic wave propagation (wave reflection, amplitude reduction, mode conversion). This feature can be utilized in damage detection and damage localization. The method is very effective, i.e., a very small damage just after an initiation can be detected by this method. This sensitivity is caused by utilization of high frequency elastic waves. Very often guided waves are excited and sensed by utilization of piezoelectric transducers. Due to simple and inverse piezoelectric effect the piezoelectric transducer can excite and sense elastic waves in the structure. Such piezoelectric



transducers are grouped into arrays of different topologies in order to perform the process of damage localization. This approach is called point-wise method. Measurements of propagating waves are taken by the transducers in the few location in the structure.

However, in literature many research papers can be found which are related to full-wavefield method. This method is based on noncontact measurement techniques that utilizes Scanning Laser Doppler Vibrometry SLDV. In this approach guided wave signals are sensed in very dense mesh of measurement points spanned over the whole investigated are of structure. In the case of regular mesh of points, spatial density is strictly related to length of propagating waves. This techniques allow to visualize propagation of guided waves in the structure, what is very helpful for analysis of this phenomenon in complex structures. On the other hand, it allow to better understanding of interaction of guided waves with the substructure of the complex structure (combination of different materials, thickness change, stiffeners, riveted/bolted joints, bonded joints, honeycomb fill). Moreover, this approach allow to perform wavenumber filtering by utilization of 2D/3D Fourier transform. Thanks to it selected forward and back propagating modes of guided waves can be filtered [2],[3]. Such approach is very helpful in analysis of interaction of particular guided wave mode with discontinuities. Due to utilization of noncontact technique, laser vibrometry is rather non-destructive testing technique (NDT) than SHM. However, interesting approach in the form of hybrid NDT-SHM technique based on piezoelectric transducer for elastic wave excitation and laser vibrometer for guided wave sensing was proposed [4].

Returning to conventional SHM based on point-wise method, which is utilized in this paper, very important part of this system, beside the transducer array, is signal processing algorithm. The aim of signal processing is feature extraction from gathered signals. Main purpose of this task is damage detection and localization. Signal processing module can be integrated together with signal generation/acquisition system as well as with results presentation system in the embedded system. Example of such embedded system consisting of microcontroller-based electronic system for guided wave generation/sensing with signal processing and wireless transmission modules can be found in [5]. Microcontroller based approach was also presented in [6]. The aim of the system was excitation and sensing of Lamb waves and further signal processing together with network communication. In [7] combined solution based on microcontroller and Field Programmable Gate Array (FPGA) was presented. System performs signal processing and data transmission tasks. FPGA combined with System on a Programmable Chip (SOPC) were utilized for signal processing in [8]. Apart from signal processing, this system presents also results in the form of damage map. In the paper [9] SOPC system with reconfigurable ultrasonic testing system (RUTS) were presented. In work [10] embedded phased array system: Phased Array Monitoring for Enhanced Life Assessment (PAMELA III) was presented. Aim of system is signal generation and acquisition, signal processing and result presentation in the form of SHM map. Nowadays due to common accessibility to mobile devices (phones, tablets) equipped with very powerful multi core CPU, signal processing tasks and presentation of results can be realized based on these devices. In [11] distributed SHM system based on smart devices was presented. This system consists of network of smart devices equipped with onboard accelerometers. System performs measurements of micro vibration of civil structures. In the paper [12], mobile wireless platform based on smartphone was presented. This platform is developed in the purpose of damage detection based on nonlinear acoustic. Nonlinear vibro-acoustic wave modulation were utilized for damage detection purpose.

The aim of our research was continuation of previous research related to development of piezoelectric transducer arrays for SHM, development of damage localization algorithms and its implementation in embedded system based on FPGA/SOPC system [8], [13]. In the

current approach damage localisation algorithm was implemented in Android based application for mobile devices.

1. Experimental set-up

The main part of experimental set-up is electronic equipment for guided wave excitation and sensing. Guided waves were excited and sensed by utilization of Noliac piezoelectric transducers. Excitation signal was in the form five cycles tone burst. It should mentioned that utilized transducers and frequency range causes that mostly fundamental antisymmetric mode A_0 was noticed in signals. Amplitude of fundamental symmetric mode S_0 was negligibly small. Piezoelectric transducers was arranged in circular array (8 transducers) with one additional transducer in the middle of the array. Each transducer was utilized as actuator and next as a sensor. As result all combinations of excitation and sensing were utilized (81 signals in total).

2. Damage localization algorithm

The aim of the algorithm is to present damage location results in the form of colour damage map. Colour scale reflects the intensity of wave reflection in the structure. These reflections are caused by all discontinuities (boundary and damage). Damage map is created based on dense mesh of points spanned over investigated surface of the sample. Next for each point damage index is calculated. In this purposed, in the first step, total distance from the actuator to the chosen point and from this point, back to the sensor is calculated. In the next step time duration of wave propagation through this distance is calculated based on the known velocity of utilized fundamental guided wave mode (symmetric or antisymmetric). Later rectangular time window is utilized in order to extract the part of the signal gathered by sensor starting from calculated time duration. Length of window is related to time duration of excitation signal. For extracted part of signal fast Fourier transform FFT is calculated and amplitude of carrier frequency component is picked as damage index. This value is next connected with the coordinates of point chosen for analysis. Large value of damage index indicated source of wave reflection. Repeating of this procedure for all points from mesh, damage map can be created. More information about this algorithm can be found in [13], [14].

3. Experimental results

Experimental verifications were performed in the case of panel made out of aluminium alloy 5754 with dimensions 1000 mm x 1000 mm x 1 mm. In the middle of the panel circular array consisting of nine piezoelectric transducers was located. During experimental research, four diameters of circular array were investigated. Transducers were attached to the specimen by utilizing wax for accelerometers mounting. Damage localisation algorithm was coded in MATLAB[®] environment for the purpose of its verification.

In the first step circular arrays with diameters: 20 mm, 60 mm and 80 mm were analyzed. In this case damage was simulated by additional mass equal 2 g (total specimen mass was approx. 2700 g). Additional mass was in the form of two magnets on both sides of specimen. It should be mentioned that this is not realistic type of “damage”. Additional mass can be only related to ice covering aerospace structures or wind turbine blades. However, it is very useful type of wave reflector, utilized during the experiments – it can be simply move around the structure. In this case excitation frequency was equal 220 kHz

(five cycles). Damage localisation is based on the antisymmetric mode (its velocity of propagation is utilized), amplitude of symmetric mode was negligibly small. Damage maps in logarithmic scale created for analysed case are presented in Fig. 1. Analysing these results, strong wave reflection intensively around: transducer array (in the middle) and around the panel edges as well as near panel corners can be seen. Damage maps indicate also lower wave reflection intensity in the location of additional mass (indicated by circle).

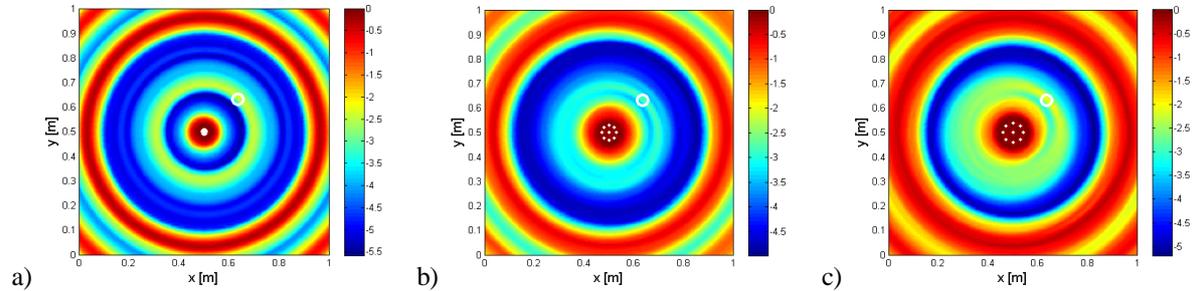


Fig. 1. Logarithmic scale damage maps for additional mass and circular array with diameter: (a) 20 mm, (b) 60 mm, (c) 80 mm.

In order to analyse only the results of damage location, wave reflections between transducers and from the panel edges were rejected from analysis. It was performed by limitation of time range in signals taken for analysis. Results for this case were presented in Fig. 2. In this case linear scale was utilized and values of damage map were normalized to unity. Now, damage maps indicated only damage location. It can be seen that with increasing diameter of transducer array directivity of damage map also increases. For small diameter of array only distance do damage can be extracted.

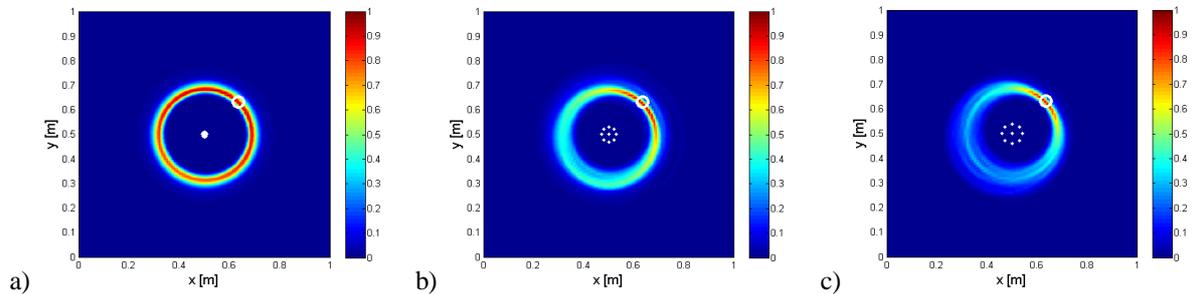


Fig. 2. Linear scale damage maps for additional mass and circular array diameter: a) 20 mm, b) 60 mm, c) 80 mm.

In the next step damage was simulated in more realistic manner by 10 mm long notch (0.5 mm deep) and through thickness drilled hole with diameter 2.5 mm. In this case circular transducer array with diameter 40 mm was utilized. Results in the form of damage maps in logarithmic and linear scales were presented respectively in Fig. 3a) and Fig. 3b).

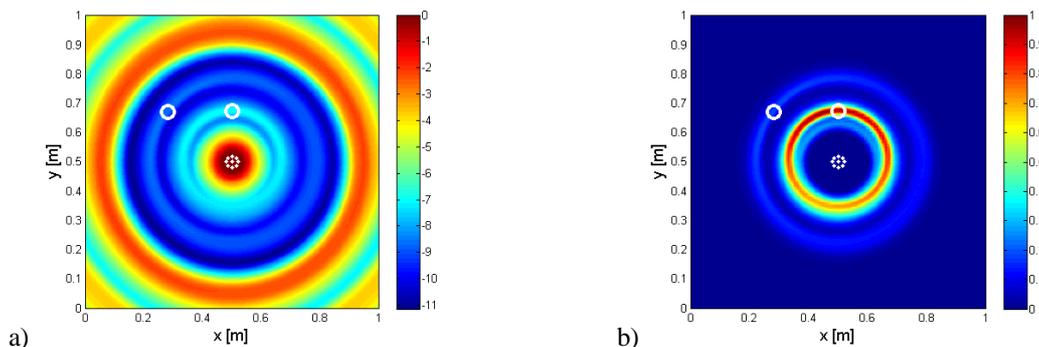


Fig. 3. Damage maps for notch and drilled hole: a) logarithmic scale, b) linear scale; transducer array diameter – 40 mm.

It should be mentioned that in the case of linear scale of damage map, wave reflection between transducers and reflections from panel edges need to be discarded from analysis. In these maps damage in the form of drilled hole is located closer to transducers array, where as notch is located farther and on the left. Analyzing indications of damage map in logarithmic scale (Fig. 3a), two areas with large wave reflection intensities related to both discontinuities can be simply noticed. In the case of damage map with linear scale (Fig. 3b), directivity of damage indication is much better visible. Investigated cases proved that damage localization algorithm works correctly.

4. Implementation of damage localisation algorithm in Android OS

Presented damage localisation algorithm developed initially in MATLAB[®] was in the next step coded in Java and Groovy languages for the purpose of its implementation on mobile platforms with Android operating system. Nowadays mobile devices like smartphones and tablets are in common usage. These devices are equipped with very powerful multi core CPU with additional devices like accelerometers, gyroscopes, WIFI and GPS systems. Powerful CPU allow to perform tasks related to signal processing and graphical presentation of results. Due to WIFI they have easy access to the internet. This was motivation for us for development of damage localisation application for such devices. In the current approach developed application downloads signals from the server. These signals are taken from our device for elastic wave generation and sensing and are uploaded on the web server. Developed application allow to set the processing parameters (velocity of wave propagation, time range of signals). Next it reads file with coordinates of transducers in the array and next, file with gathered signals. Further steps are related to signal processing and presentation of damage map. Prototype of application launched in Android Studio was presented in Fig. 4. It should be mentioned that damage map presented in this case is in linear scale with limited time range of signals. This was case of two discontinuities (notch and drilled hole as in fig. 3). Due to linear scale of damage map only reflections between transducers and from the panel boundaries are visible normally. In order to show damage influence, logarithmic scale or linear scale with limited time range of signals need to be utilized.

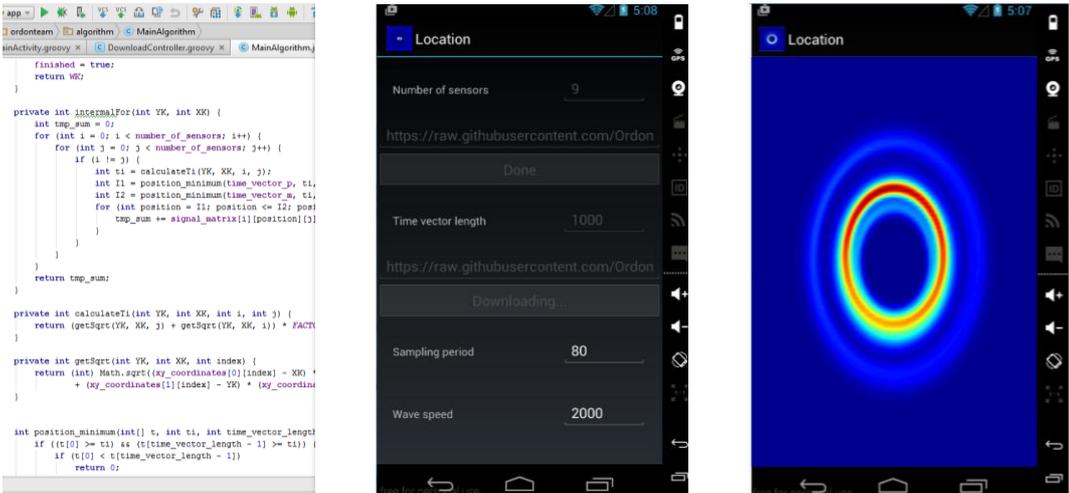


Fig. 4. Prototype of software launched on Android Studio: in the left - code of algorithm, in the middle part related for input parameters, in the right damage map.

Total time of its calculation takes few seconds for mesh of points 100 x 100 and was slightly longer for the case of calculation in PC with MATLAB[®].

5. Damage localization in composite panel

Experimental results presented in previous sections of this paper were related to very simple structure in the form of metallic panel with isotropic properties. Nowadays, structures utilized in aerospace are mostly based on composite materials with glass and carbon reinforcing fibres (GFRP and CFRP). These structures are characterised by orthotropic properties. It means that from the point of view of guided waves, its velocity of propagation varies with the direction of propagation. Wave front does not look like circle anymore like for metallic structures (Fig. 5a) but will be rather elliptical (Fig. 5b) or rhombus (Fig. 5c). It depends on reinforcing fibre layers orientation. In the Fig. 5 chosen frames taken from animations of guided wave propagation in metallic and composite materials are presented. These results are based on measurements performed by scanning laser Doppler vibrometer in our laboratory.

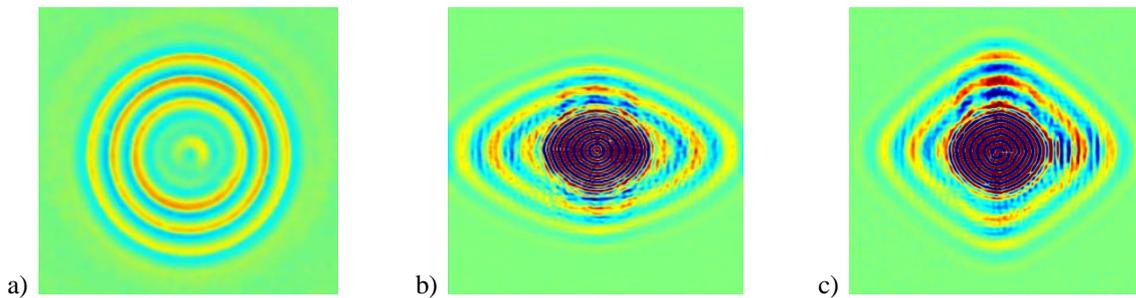


Fig. 5. Frames from animation of guided wave propagation in: a) aluminium panel, b) CFRP panel [0/0/0/0]_s, c) GFRP panel [0/90/0/90]_s.

It can be noticed that in composite structures wave front shape strictly depends on directivity of reinforcing layer distribution. It was needed to modify previously developed damage localisation algorithm for correct work for composite structures. In this purpose angular characteristic of velocity of wave propagation need to be input to the algorithm. When the distance from actuator to arbitrary point of mesh is extracted also angle of line connecting actuation point and arbitrary point (wave propagates along this path) need to be calculated. Next during calculation of time of wave propagation between actuator and chosen point, velocity of propagation for calculated angle is used. The same approach is utilized for propagation from this chosen point of mesh, back to the sensor. Thanks to it algorithm takes account change of velocity of wave propagation with angle of propagation. This algorithm was implemented only in MATLAB[®] and aim of this task was preliminary testing of it. In the verification process signals from numerical simulation of wave propagation based on Spectral Element Method (SEM) were utilized. More information about this method can be found in [15]. SEM method was utilized for modelling of wave propagation in composite panel with dimensions 1000 mm x 1000 mm x 1.5 mm, with simulated elliptical delamination (16 mm x 8 mm). In the simulation three carbon fibre reinforced layers with orientation [0/90/0] were assumed. Delamination was located between first and second layer counting from the top surface. Model also includes piezoelectric transducer which is located in the middle of the panel, on the top surface. Signals in the form of displacements were taken from simulated circular array with diameter 100 mm. Excitation frequency was equal 100 kHz (5 cycles of sine modulated by Hanning window). In the Fig. 6 results of simulation in the form of choose frames, taken from animation of guided wave propagation in CFRP panel are presented. Analysing these frames three things can be noticed. First – propagation of symmetric and antisymmetric mode can be noticed (symmetric mode has very small amplitude). Second thing – non circular wave front of symmetric and antisymmetric mode due to orthotropic material properties can be observed.

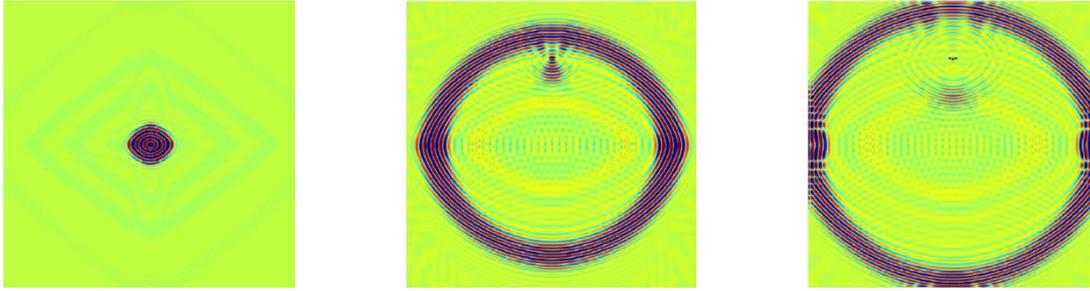


Fig. 6. Chosen frames from animation of guided wave propagation in CFRP panel – numerical results from SEM method.

Moreover its shape looks like ellipse instead of rhombus due to non symmetric reinforcing $[0/90/0]$ lay-up. Wave front in the form of rhombus can be clearly noticed in Fig. 5c) for symmetric lay-up $[0/90/0/90]_s$. Moreover, wave front of symmetric mode is much more susceptible to orthotropic properties and as consequence its shape differ much more from circular shape. Third – damage induced antisymmetric mode reflection can be seen.

In the next step developed damage localisation algorithm for composite materials was tested based on signals taken from simulations based on SEM. In the Fig. 7 results in the form of damage maps with logarithmic and linear scale were presented. In this case velocity of propagation of antisymmetric mode was utilized in the algorithm. Symmetric mode had negligibly small amplitude. In the case of logarithmic scale (Fig. 7a) strong wave reflection from panel boundary can be seen, however damage location can be still noticed (indicated by circle). Much better results of localisation of delamination were obtained in the case of linear scale (Fig. 7b), if, additionally, time duration of signals taken for analysis was limited. It was done in order to discard wave reflection from boundaries.

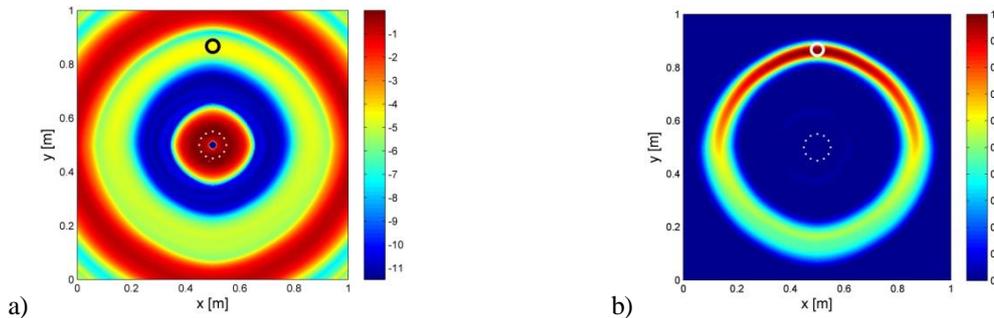


Fig. 7. Damage localisation map for CFRP panel with elliptical delamination based: a) logarithmic scale, b) linear scale with limited time length of signals.

6. Summary

This paper presents results of implementation of damage localization algorithm in the Android application for mobile devices. Implemented version of the algorithm is dedicated to metallic structures (isotropic material properties). The preliminary result presented coming from developed damage localization algorithm for composite structures (orthotropic material properties). For the presented in this paper research, the algorithm was implement in MATLAB[®] and experimentally verified based on signals from model developed by Spectral Element Method.

Next steps of our research will be focused on validation and verification of the algorithm based on experimental signals for composite structures. After positive results of tests we plan to develop an algorithm for mobile devices.

Acknowledgments

This research was supported by the project entitled: Non-invasive Methods for Assessment of Physicochemical and Mechanical Degradation (PBS1/B6/8/2012) granted by National Centre for Research and Development in Poland.

The authors would like to also thank for financial support provided by National Science Centre of Poland granted by agreement number UMO-2014/13/D/ST8/03167.

The authors also would like to thank Dr Pawel Kudela (IFFM PAS) for numerical simulation of guided wave propagation in composite panel with delamination.

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