DETECTION AND LOCALIZATION OF LOW-VELOCITY IMPACT DAMAGES OF COMPOSITE STRUCTURES BASED ON WAVELET ANALYSIS OF MODAL SHAPES

A. Katunin[a*]

[a]*Institute of Fundamentals of Machinery Design, Silesian University of Technology*
18A Konarskiego Street, 44-100 Gliwice, Poland
**andrzej.katunin@polsl.pl*

Keywords: non-destructive testing, wavelet analysis, impact damages, composite structures.

Abstract
The proposed method is based on non-destructive and non-contact measurements of displacements of modal shapes and then processing the acquired signals using spatial wavelet transform. The experimental studies were carried out on the laminated composite plates with artificially inputted impact damages with various energies of impacts and different geometric properties of impactors. The application of different impactors allows for simulation of different types of stress distributions (tension, shear or both stress components) and consequently different types of damages. The modal shapes acquired experimentally were analyzed using wavelet-based algorithm, which allow to extract diagnostic information about the damage presence and location. The results of the damage detection studies prove the effectiveness of the proposed method and a possibility of its practical application.

1. Introduction

Non-destructive testing (NDT) of composite structures is often differing from that of metallic structures mainly due to their heterogeneity, anisotropy and the damaging mechanisms. During their operation the different types of damages may occur, e.g. interphase cracks and delaminations. The serious danger cause internal damages, which could propagate and may induce catastrophic consequences, and which could not be visible on the surface of a structure. One of the types of damages in composite structures, which often have internal extension of cracks and delamination are the low-velocity impact damages. These damages occur in many structural elements in aircraft and aerospace vehicles, where such structural damages may occur during operation. The characteristic mechanisms of damaging of composites during impacts cause both surface cracks and internal damages such as delaminations. Often these damages are not visible on the surface of a structure, however their internal structure may contain numerous cracks and delaminations in a wide area with respect to the contact surface of an impact.

A typical low-velocity impact damaging of composite structures occurs in aircraft vehicles, e.g. by lofting of stones and other foreign objects from the runways and roads by the vehicle's tires or wind flows [1,2] or caused by the hail [3]. During the lofting of stones the most vulnerable part of the aircraft vehicles is a fuselage often made of composite materials. There are two areas of increased frequency of incidents: bottom area of the fuselage just behind the front chassis and lateral areas on the fuselage behind the back chassis [4]. The actually applied strategy of the fault tolerant design in the aircraft industry [5] requires information about structural health of particular elements of the vehicles, therefore the development of appropriate diagnostic and monitoring systems is necessary for this purpose.

The applied methods of damage evaluation should allow for detection of all types of damages occurred in the composite structures during their operation. Many of the NDT methods are limited to the laboratory conditions, because of the usage of the special equipment or due to the special types of excitation. One of the NDT methods, which were successfully applied for the damage assessment, is the modal analysis [6]. This type of analysis has several advantages with respect to other methods: when the operational modal analysis is carried out there is no necessity to unmount the tested element from the machine; moreover the measurements could be carried out in the field conditions. However, the modal analysis allows for detection the changes of natural frequencies of vibration and gives mere information about damage presence and no information about its location. Following this, it is necessary to apply adequate signal processing techniques in order to extract important diagnostic information from the measurement data.

The promising signal processing technique, which was intensively developed in the last decade [7-10], is the wavelet analysis of modal shapes. Due to the great sensitivity of the wavelet analysis to any non-monotonicities and sudden changes of analyzed signals, it could detect and localize even the smallest changes in the modal shapes. In the case of application of wavelet analysis as a diagnostic tool several important factors should be considered. As it was reported in the earlier studies [9,10] the accuracy of detection and localization of damages in composite structures is strongly dependent on the type of wavelet transform, selected wavelets and their parameters, the influence of measurement noise and boundary effect, etc. All of these problems were discussed in the review paper [11]. Considering the previous results [10] it was shown that the discrete wavelet transform (DWT) is the most appropriate for the damage assessment problems due to its great accuracy with simultaneous low time-consuming computational algorithm. In the previous studies DWT was used together with 2D B-spline wavelets, which are separable, i.e. constructed from the combinations of 1D scaling and wavelet functions. As a result one obtains a scaling function and three wavelet functions: horizontal, vertical and diagonal. These wavelets have preferred directions (vertical and horizontal) and the diagonal wavelet function does not have a straightforward interpretation [12]. Such preferred directions not always coincide with the shape of the identified damage, thus the direction-invariant wavelets seems to be more suitable for the analysis.

The properties of direction invariance could be fulfilled by the non-separable wavelets. The wavelets of such a type were developed by Van Der Ville et al. [12-14] and called quincunx wavelets due to their lattice configuration. The subsampling scheme of these wavelets allows for finer scale progression than the dyadic scheme used in classical DWT. The decomposition with use of quincunx-based scheme results in a single set of approximation coefficients and a single set of detail coefficients, regardless the DWT, where three directional sets of detail coefficients were obtained after the single-level decomposition. The existence of only one set of detail coefficients simplifies the analysis of damage identification.

The presented study deals with the detection and localization of low-velocity impact damages in the composite square plates. The damages were artificially inputted into the structure by various impactors with immersed stones, which allow simulating the real stone-impact damages occurred in the aircraft structures. The specimens prepared in such way were then scanned by laser Doppler vibrometer (LDV) in order to acquire modal shapes of vibration of them. From the obtained frequency response functions (FRF) the modal shapes were acquired and analyzed using wavelet transform with quincunx wavelets. Selected results were presented, compared with the ultrasound scans (C-scans) and discussed.

2. Experimental studies

The tests were performed on the 10-layered epoxy laminated plates reinforced with E-glass cloth with the weight of 200 g/m^2 with dimensions of 300×300 mm and a thickness of 2 mm, which were manufactured and supplied by Izo-Erg S.A., Gliwice. At the first stage of experiments the plates were artificially damaged on the own designed test rig using four types of impactors with immersed granite stones (see [15] for details). The difference between the impactors is that the stones were oriented in different way: vertex-oriented, edge-oriented, rough surface-oriented and flat surface-oriented, which allows to simulate different types of damages. A test rig and used impactors were presented in Figs.1a and 1b, respectively. The specimens were impacted using the described impactors with various energy amounts in the range of 5÷40 J with a step of 5 J. As a result, 20 specimens were selected for the further analysis considering that not every combination of an impactor shape and impact energy amount resulted in visible changes of a given specimen.

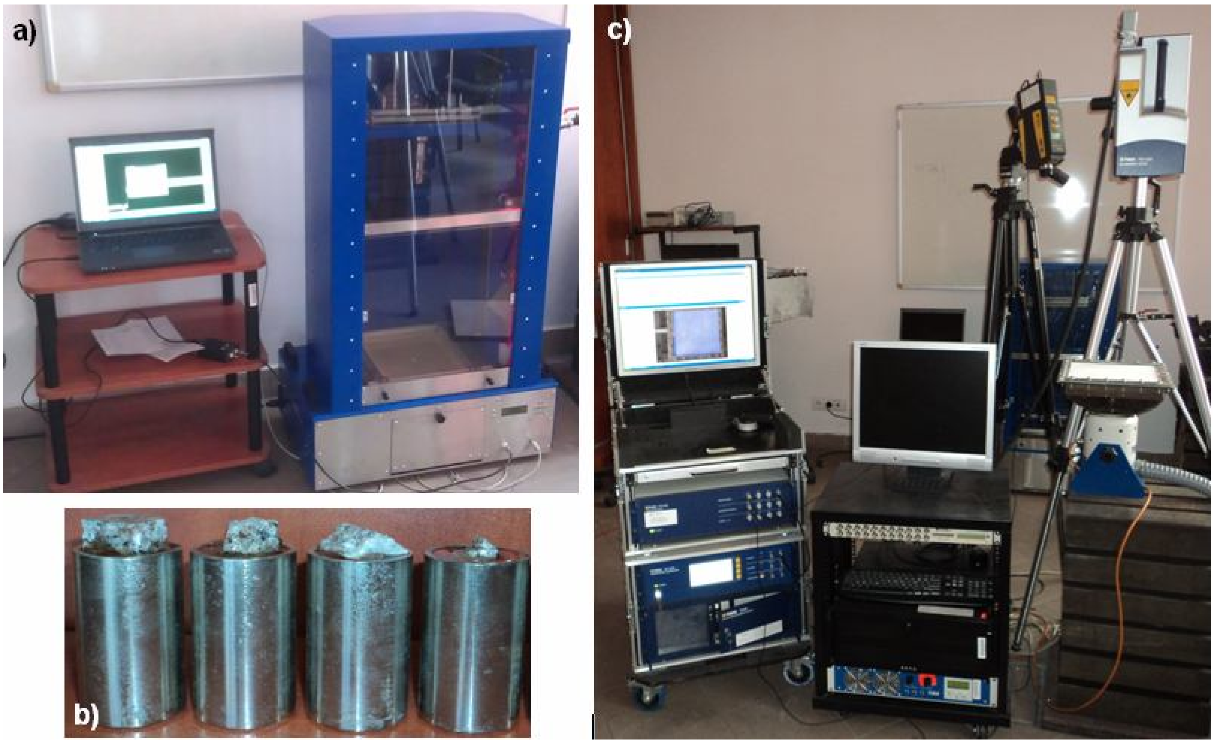

Figure 1. Testing rigs and setups: a) impact testing rig, b) considered impactors, c) modal testing setup.

During the next stage of an analysis the modal testing of the selected specimens was performed. The tests were carried out using scanning LDV for the measurements of FRFs of a specimen and a point LDV for the reference signal. The specimens were clamped in the steel frame along the edges and mounted on the electrodynamic shaker, which was excited the specimen to vibrations by the pseudo-random noise signal. Considering that the frame partially covered a specimen the measurement area was limited to 250×250 mm. On this surface the net of 64×64 equidistant measurement points was defined. The frequency bandwidth was defined in the range of 0÷3200 Hz with the a resolution of 1 Hz and the sampling frequency of 8192 Hz. Five averaging cycles of the FRFs were defined. After the modal analysis the modal shapes were selected for further analysis from the obtained FRFs. A testing setup was presented in Fig.1c. Considering a fact that the detectibility of the damages is strongly depended on the magnitude of velocity of displacements the modal shapes were selected using the following rule: if the magnitude of velocity of displacements of a given modal shape with respect to the magnitude of displacements of the first modal shape was equaled or higher than 5%, then the given modal shape was considered in the further analysis. The collected modal data were converted into Matlab® environment for performing the wavelet analysis.

At the last stage the collected data were analyzed using wavelet-based algorithm with application of quincunx wavelets. The application of this transform has numerous advantages, i.e. a single set of details coefficients and avoiding the boundary effect, which occurs when the separable wavelets are used [9]. This transform proposed in [14] is based on McClellan transform (known also as diamond transform) and sampling on the quincunx lattice. The chosen set of scaling and wavelet functions was based on the isotropic polyharmonic B-splines [12] – the wavelets with emphasized isotropy, which converge to the Gaussian ones during the increase of their order, similarly as the integer B-spline wavelets [9]. Such wavelets could improve the sensitivity of the method due to more accurate features detection and ensure rotation invariance. Only the second-level detail coefficients after decomposition were selected due to the better localization of a damage and lower noise influence. For each case the selected modal shapes (according the above-presented rule) the wavelet transform was performed separately and the resulted second-level detail coefficients were added up within the analyzed case in order to increase the detection and localization ability. Then, using the single-parameter minimization procedure, the order of quincunx wavelet was selected. The applied quincunx wavelet has an order of 1.8272. The selection of such a value could be explained by the small support with high-magnitude values and their quick decay from the origin of the wavelet.

3. Results and discussion

The processing procedure of modal shapes was performed for all of the selected cases. For clarity of description of results the symbols A, B, C and D were assigned to the considered impactors according to their order as it was presented in Fig.1b. In the cases A with all energy amounts considered in the analysis none of the damages have been observed, which was conducted both by the proposed method and by the reference method (ultrasound C-scans). For the cases B the damages were detected for the range of impact energy amounts of 20÷40 J, for the cases C the damages were detected for the range of 25÷40 J, while for the cases D the damages were detected for the range of 10÷40 J. The selected results were presented in Fig.2, where in the first column contains the images of damages obtained using transmitted light imaging (see [16] for details), the second column consists results of analysis using the presented method and the third column consists the C-scans of the investigated cases. Note that the resulted images, obtained using proposed algorithm (second row), have the dimensions of 250×250 mm.

The comparative study shows that the damage detection capability of the proposed method with respect to ultrasound measurements seems to be similar. The great influence of the damage detectibility has the geometry of the stone, which contacted with a composite structure during the impact. The main advantage of the application of quincunx wavelets of optimally selected fractional order for the damage identification is the increasing the sensitivity of the method with simultaneous decreasing of the computational time.

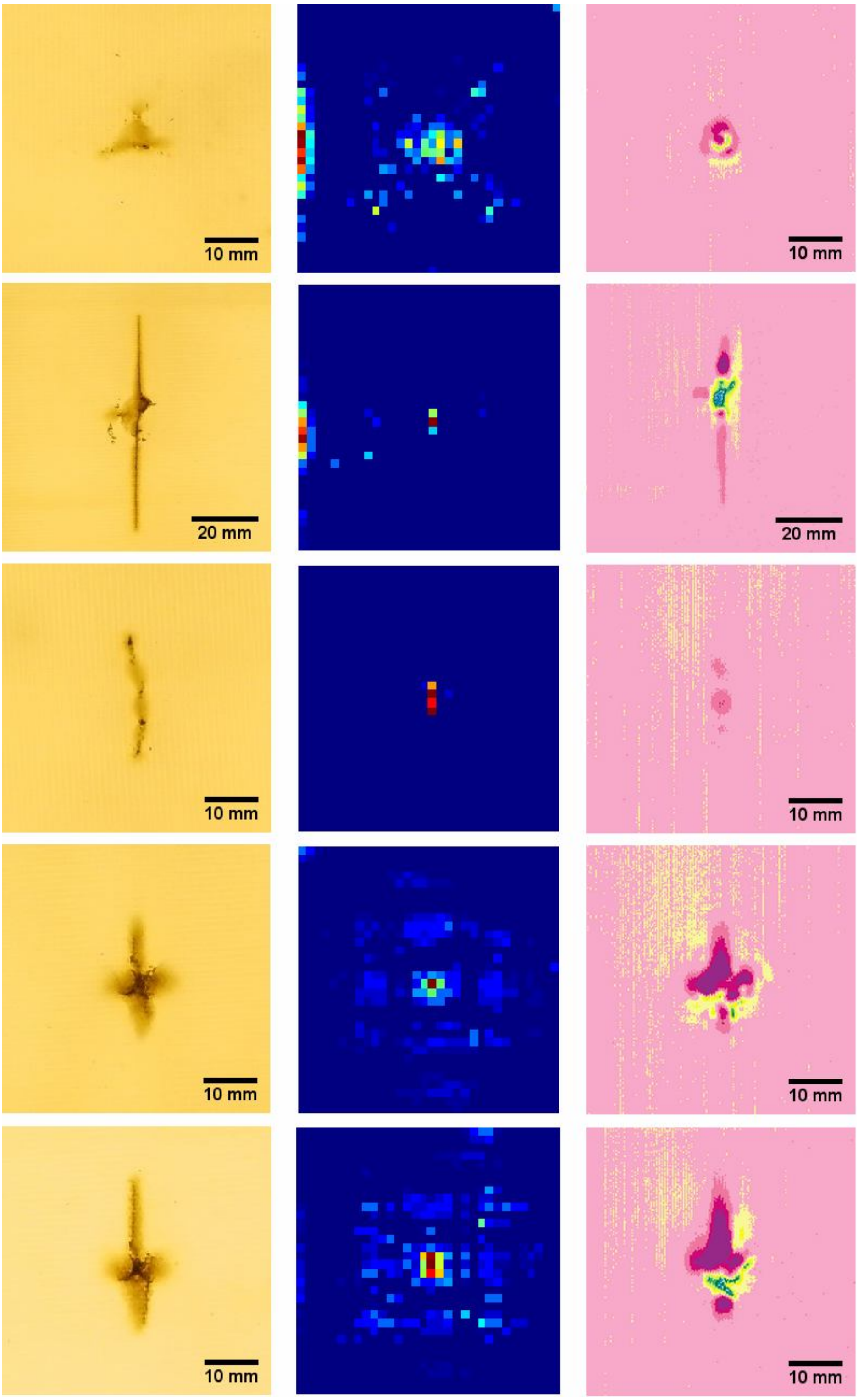

Figure 2. Results and comparison of selected damaged plates using various methods: first row – case B-25J, second row – case B-40J, third row – case C-30J, fourth row – case D-20J, fifth row – case D-35J.

The results of the damage detection studies prove the effectiveness of the proposed method and a possibility of its practical application.

Acknowledgements

The research project was financed by the National Science Centre (Poland) granted according the decision no. DEC-2011/03/N/ST8/06205.

References

[1] S. N. Nguyen, E. S. Greenhalgh, R. Olsson, L. Ianucci and P. T. Curtis. Modeling the lofting of runway debris by aircraft tires. *Journal of Aircraft*, 45(5):1701-1714, 2008.
[2] S. N. Nguyen, E. S. Greenhalgh, R. Olsson, L. Iannucci and P. T. Curtis. Parametric analysis of runway stone lofting mechanisms. *International Journal of Impact Engineering*, 37(5): 502-514, 2010.
[3] P. Starke and F. Mayer. Hail impact simulation on CFC covers of a transport aircraft. In *8th European LS-DYNA Users Conference*, Strasbourg, 2011.
[4] D. N. Beatty, F. Readdy, J. J. Gearhart and R. Duchatellier. The study of foreign object damage caused by aircraft operations on unconventional and bomb-damaged airfield surfaces. VA, US: BDM Corp Mclean, Report no. ADA117587, 1981.
[5] P. Goupil. Oscillatory failure case detection in the A380 electrical flight control system by analytical redundancy. *Control Engineering Practice*, 18(9):1110-1119, 2010.
[6] A. P. Herman, A. C. Orifici and A. P. Mouritz. Vibration modal analysis of defects in composite T-stiffened panels. *Composite Structures*, 104:34-42, 2013.
[7] C.-C. Chang and L.-W. Chen. Damage detection of a rectangular plate by spatial wavelet based approach. *Applied Acoustics*, 65(8):819-832, 2004.
[8] M. Rucka and K. Wilde. Application of continuous wavelet transform in vibration based damage detection method for beams and plates. *Journal of Sound and Vibration*, 297(3-5): 536-550, 2006.
[9] A. Katunin. Damage identification in composite plates using two-dimensional B-spline wavelets. *Mechanical Systems and Signal Processing*, 25(8):3153-3167, 2011.
[10] A. Katunin and F. Holewik. Crack identification in composite elements with non-linear geometry using spatial wavelet transform. *Archives of Civil and Mechanical Engineering*, 13(3):287-296, 2013.
[11] A. Katunin. Modal-based non-destructive damage assessment in composite structures using wavelet analysis: A review. *International Journal of Composite Materials* 3(6B):1-9, 2013.
[12] D. Van De Ville, T. Blu and M. Unser. Isotropic polyharmonic B-splines: scaling functions and wavelets. *IEEE Transactions on Image Processing*, 14(11):1798-1813, 2005.
[13] D. Van De Ville, T. Blu, B. Forster and M. Unser. Isotropic-polyharmonic B-splines and wavelets. In *International Conference on Image Processing ICIP '04*, Singapore, 2004.
[14] M. Feilner, D. Van De Ville and M. Unser. An orthogonal family of quincunx wavelets with continuously adjustable order. *IEEE Transactions on Image Processing*, 14(4):499-510, 2005.
[15] A. Katunin and M. Sznura. Experimental test rig for the controlled impact tests of composite plates (in Polish). *Aparatura Badawcza i Dydaktyczna*, 18(4):297-302, 2013.
[16] A. Katunin and M. Zuba. Influence of the impactor geometry on the damage character in composite structures. *Modelling in Engineering*, 18(4):33-39, 2013.