Angelika WRONKOWICZ, Andrzej KATUNIN
Silesian University of Technology, Institute of Fundamentals of Machinery Design

DAMAGE EVALUATION IN COMPOSITE STRUCTURES BASED ON IMAGE PROCESSING OF ULTRASONIC C-SCANS

Summary. The article presents a method of reconstruction of planar ultrasonic maps into a three-dimensional form based on levels of attenuation of ultrasonic waves through a tested composite structure. A developed algorithm is based on image processing techniques, which allows enhancing ability of interpretation of damage extent at particular depths of a tested structure.

Keywords: ultrasonic testing, structural diagnostics; composite structures; impact damage; 3D reconstruction; image processing

OCENA USZKODZENIA STRUKTUR KOMPOZYTOWYCH W OPARCIU O PRZETWARZANIE OBRAZÓW ULTRADŹWIĘKOWYCH

Streszczenie. Artykuł przedstawia metodę rekonstrukcji płaskich map ultradźwiękowych do postaci trójwymiarowej na podstawie poziomów tłumienia fal ultradźwiękowych przez badaną strukturę kompozytową. Opracowany algorytm został oparty na technikach przetwarzania obrazu, które pozwalają na wspomaganie interpretacji rozległości uszkodzeń na poszczególnych poziomach głębokości w badanej strukturze.

Słowa kluczowe: badania ultradźwiękowe, diagnostyka strukturalna, struktury kompozytowe, uszkodzenia udarowe, rekonstrukcja 3D, przetwarzanie obrazów

1 The publication is nanced from the statutory funds of the Faculty of Mechanical Engineering of the Silesian University of Technology. The authors wish to acknowledge a possibility of using the equipment for ultrasonic testing at the Institut für Leichtbau und Kunststofftechnik (ILK), TU Dresden.
1. Introduction

Ultrasonic testing (UT) is a widely applied non-destructive testing (NDT) method of diagnostics of elements made of composite materials. UT consists in transmission of ultrasonic waves (high frequency sound energy) into a tested structure and observation of the received echo. The propagation of ultrasonic waves occurs uniformly in homogeneous medium (e.g. oil, water, solid lubricant, or in modern devices – air), whereas if they come across any discontinuity, a portion of sound energy is reflected back from the defected surface. Usually, a structure is tested through its cross-section under the location of a probe, using longitudinal waves. Ultrasonic devices record two fundamental parameters of received energy: the relative amount (amplitude), and where it occurs in time with respect to a zero point (ToF – Time-of-Flight). Among different types of visualization of UT results, C-Scan ultrasonic imaging is the most commonly used during such inspections. It enables obtaining a 2D image, where each pixel carries the information about the maximum value of signal amplitude acquired at the corresponding point of a surface. The ToF C-Scan represents ToF of the signal component with the highest amplitude. It usually corresponds to damage located the closest to the surface of the inspected structure. Since composite structures are used, among others, for construction of many responsible elements in automotive, aircraft and aerospace industry, their periodical inspections are of a great importance. Such diagnostics should be performed both at the manufacturing stage of such elements (quality control), since there can occur defects caused by improper processes or materials used, as well as during their operation, where atmospheric conditions, mechanical and thermal impacts or overloads may have a negative impact on a structure.

The most common damage types, typical for composite structures, are disbonds (lack of adhesive), delamination (separation of a composite layers), porosity and foreign object inclusions. The most harmful factors threatening composites are impacts, since they cause serious consequences, often invisible on a surface of a structure – thus they are called Barely Visible Impact Damage (BVID). This fact makes it dangerous since even a low-velocity impact may cause vast internal damage, such as propagating delamination and a complex net of matrix cracking, which results in a significant loss in stiffness. BVID occurs quite often in the aircraft industry, e.g. during ground maintenance (the so-called tool drop) or stone lofting during runway of an airplane.

Besides poor detectability of BVID by a naked eye, such the type of damage has complex geometry resulted from the specificity of layered composites in the light of damage mechanics. During impact loading a typical conical shaped damage in the thickness direction occurs in composite structures (see e.g. [1]). This takes place due to the mechanical
anisotropy of laminated composites which, in consequence, results in bending and shear stresses near the area of impact. This is the reason of occurrence of extensive delaminated areas, matrix cracks or fibre pull-out. During ultrasonic scanning impact damage sites are usually distinguished with complex shapes and many grades of colours (attenuation levels), which often causes problems in interpretation of such sites, and concluding about damage presence.

Taking into consideration the above discussed complex nature of BVID, certain image processing techniques should be applied in damage evaluation procedure for proper interpretation of C-Scan images. Numerous approaches of image processing applied for UT have been reported in the literature. Corneloup et al. proposed an algorithm based on image segmentation by thresholding using coocurrence matrix analysis [2]. Another image segmentation approach was presented by Ouadfel and Meshoul [3], which was concerned with a hybrid algorithm of multilevel thresholding and optimization methods. In the paper of Bozzi et al. [4] a 2D wavelet transform and feature extraction process was employed in order to detect porosity defects in materials. Li et al. suggested an approach based on fuzzy logic, aimed at delamination detection in carbon fiber-reinforced polymeric panels [5]. Another algorithm employing artificial intelligence and various image processing approaches can be found in the paper of Kumar et al. [6]. In some papers, commercial software was used for ultrasonic image processing, e.g. in [7]. A 3D visualization of ultrasonic images for the purposes of NDT of composite materials was considered in the paper of Dragan [8]. However, most of the above-listed researches present only 2D visualization of C-Scan images. Such results do not bring complete information about extent of damage at particular depths of a structure (e.g. in layered structures – delamination between particular layers). An approach based on multilevel thresholding and morphological processing with 3D visualization was introduced in [9].

The aim of this paper was to evaluate internal architectures of damage and its spatial extent in composite structures. The second goal is to present the developed 3D reconstruction and visualisation approach of a damaged region for the purpose of proper interpretation, i.e. determining a type and parameters of damage based on its 3D shape. The approach presented in this paper is based on reconstruction of a 2D ultrasonic map to a 3D matrix by distribution of individual pixel values into the individual layers and adding up the areas of successive layers in a manner consistent to mechanics of damaging in layered polymeric composites. Then, additional operations were elaborated for effective 3D visualization of the obtained 3D matrix. The method, owing to its simplicity, is universal and can be used for supporting structural diagnostics of layered polymeric composites. The obtained 3D shape of damage can be used as an input to prepare a finite element (FE) model with taking an existing damage
into consideration. Such a model can be used for prognostics of a life cycle of a structure and evaluation of its residual life, which, in the light of the aircraft industry, is a solution that may reduce costs of inspection by eliminating numerous experimental tests.

2. Materials and testing procedures

The tested specimens were manufactured in the form of glass-fibre reinforced epoxy laminated sheets supplied by Izo-Erg S.A. (Gliwice, Poland). The detailed description of manufacturing process as well as main properties of the resulting material can be found e.g. in [10]. From the supplied sheets of a thickness of 2.5 mm, plates of spatial dimensions of 300×300 mm were cut. The defects were introduced artificially using the own-designed drop weight impact testing machine (see details in [10]) with various impactors and impact energy values in order to achieve a variety of cases of impact damage. Besides the traditional metallic impactors the ones with immersed granite stones were used during the artificial damaging procedure. This allows simulating damage caused by stone lofting from runways or hail storms in the case of aircraft composite structures. Each specimen was impacted in its geometrical centre.

Afterwards, the specimens were subjected to ultrasonic inspections on the area of 120×120 mm, centring damage in the centre of the scanning area. The tests were performed using the air-coupled ultrasonic transducers system HFUS 2400 AirTech manufactured by the Ingenieurbüro Dr. Hiliger and dedicated for testing of composite materials [11], which was provided by the Institut für Leichtbau und Kunststofftechnik (ILK), TU Dresden. The focusing distance between the 250 kHz emitter AirTech 4412 and the receiver AirTech 4422 probes was set to 50 mm following the recommendations provided in [11]. The range of attenuation was defined as from -31 dB to 0 dB with 16 levels between. The wave running time was set to 250 μs.

From the variety of impact damage types four cases were selected and simulated with use of: hemispherical impactor R17 with impact energy of 40 J (Fig. 1a), hemispherical impactor R5 with impact energy of 30 J (Fig. 1b), conical impactor with impact energy of 40 J (Fig. 1c), and impactor with an immersed stone with rough impact surface and impact energy of 40 J (Fig. 1d). The colours visible in Fig. 1 denote attenuation, and the scale bar shown in Fig. 1a is the same for all presented cases. The labels of the axes in Fig. 1 denote coordinates in mm, where the Scan axis refers to consecutive points of scanning (columns), while the Index refers to rows. The choice of cases was motivated by presenting different characters of damage propagation in the structure.
3. Algorithm of damage evaluation and 3D reconstruction

The algorithm of damage evaluation and 3D reconstruction of the obtained C-Scan ultrasonograms was implemented in Matlab®. The subsequent steps with motivation of their use are as follows. Firstly, a C-Scan ultrasonogram was loaded into the workspace as an RGB image. In order to obtain a matrix with values of attenuation levels, corresponding to these given in each case from Fig. 1 (in dB), a decision rule was introduced by which RGB values of pixels of image were converted to the equivalent values of attenuation levels. Afterwards, a 3D reconstruction of the obtained 2D matrix was performed by assigning pixels of values of each attenuation level to particular layers of the 3D matrix in order to be consistent with the increase of attenuation. In other words, pixels seen as different colours in Fig. 1 were decomposed into 16 successive layers of a 3D matrix. Since regions of higher attenuation of transmitted ultrasonic waves are partially covered by regions of lower attenuation values, only
their fragments (usually outer edges) are seen in a C-Scan. For proper 3D visualization of damage, these missing areas should be filled up. For this purpose, the damage mechanics of layered composite structures were taken into consideration, namely the appearance of a typical conical shaped damage in the thickness direction. This fact allowed for introduction of the next step of the algorithm, i.e. the iterative adding of successive layers of a 3D matrix, which is in accordance with the conically growing expanse of damage. These procedures enable evaluation of damage at particular layers of the structure as well as simple calculation of its extension by measuring properties of regions of each layer. This step should be preceded by image thresholding in order to remove pixels representing undamaged regions and perform calculations on a binary image. The limitation of this method is that values of attenuation representing undamaged regions should be indicated by a user of the algorithm. Nevertheless, selection of undamaged areas should not be done automatically since interpretation of ultrasonic scans is required to be performed by a certified expert in this area. As it was highlighted before, interpretation of C-Scans is difficult and sometimes there occurs an uncertainty about identifying of these areas. One can observe in Fig. 1 that the attenuation levels of $-6 \text{ dB}$ (seen as light pink) and $-8 \text{ dB}$ (light yellow) indicate undamaged regions. There are, however, some fragments of these regions that may be also a part of damage (e.g. the areola-like region around the yellow boundaries visible in Fig. 1c). In order to ensure the continuity of damage in the 3D visualization, at layers corresponding to values indicated as undamaged regions the pixels were introduced with the same location as the adjacent damaged layers. Finally, additional visualization effects were added, such as different colors for each of a layer, for better readability of a resulting image.

4. Selected results

The previously described C-Scan evaluation and reconstruction algorithm was applied for the selected C-Scans presented in Fig. 1. The results of reconstruction are presented in Fig. 2, in the same order.

One can observe that the typical conical shaped sites were properly extracted and reconstructed. The conical shape of damage (visible in every considered case) resulted mainly from shear stresses occurred in particular layers during impact loading. This causes occurrence of matrix shear cracks which successively enlarged the damage extent in the direction of impact loading. In several cases the matrix cracks in the bottom layers of the tested structures occurred (violet colour in the reconstructed C-Scans in Fig. 2). Such
the cracks resulted from bending stresses of this layer, which redistributes along the directions of reinforcement (see Fig. 1d and Fig. 2d).

![Figures](image.png)

**Fig. 2.** Results of 3D reconstruction of the considered C-Scans
**Rys. 2.** Wyniki rekonalizacji 3D rozpatrzonych skanów typu C

Such the 3D representations of damage sites significantly improve cognition of internal damage architecture as well as they can be used for evaluation of damage extent at particular depths. Taking into account the mentioned concept of the authors, the resulting 3D matrix could be used as an input to prepare a FE model for the purpose of prognostics of a life cycle of a structure.

The consecutive layers with damage for the exemplary case, presented in Fig. 2c, are presented in Fig. 3 as binary images. Such the results can be easily further processed and the damage extent can be calculated individually for each layer, e.g. based on the surface area of the non-zero pixels or extraction of their contours. Description of approaches to calculation of damage extent based on ultrasonic images can be found in the studies [9,12].
5. Conclusions

The presented approach of 3D reconstruction of ultrasonic C-Scans has two main advantages. The reconstructed image of damage can be used for supporting damage evaluation procedure of tested structures and gives a possibility of precise determination of damage extent at particular depths. Such reconstruction can significantly simplify inspections and further analysis of the experimental data. The other advantage of using reconstructed C-Scans is a possibility of consideration of identified and reconstructed damage sites in FE models, which allows modelling of various scenarios including complex loading, fatigue, etc. This creates a possibility of structural prognostics which can be very profitable in the case of expensive elements, e.g. applied in the aircraft and aerospace industries. This approach coincides well with actually used philosophy (in the aircraft industry) of the fault tolerant control. Reconstruction of damage and numerical analyses may be used to enable prognosis of residual life of an element, and plan its schedule of repairs.

BIBLIOGRAPHY


Omówienie

Z uwagi na szerokie zastosowanie kompozytów polimerowych w przemyśle motoryzacyjnym, lotniczym i kosmicznym, w ciągu ostatnich dziesięcioleci znacznie rozwinięły się metody badań nieniszczących. Jednymi z najczęściej stosowanych technik są badania ultradźwiękowe z obrazowaniem w trybie C (C-Scan), które pozwala na uzyskanie informacji diagnostycznej w postaci dwuwymiarowych map, w których kolory oznaczają wielkość tłumienia ultradźwięków przepuszczanych przez badane struktury. Sposób ten jest bardzo skuteczny w zakresie wykrywania i lokalizacji różnych typów uszkodzeń.
w strukturach kompozytowych, jednakże istnieje zasadniczy problem z interpretacją uzyskanych map, zwłaszcza interpretacją zmiany kształtu uszkodzenia w przekroju poprzecznym struktury. Proponowane podejście w tym artykule jest oparte na rekonstrukcji płaskich map ultradźwiękowych (Rys. 2) do postaci trójwymiarowej (Rys. 3) na podstawie poziomów tłumienia fal ultradźwiękowych. Takie rozwiązanie pozwala na właściwą interpretację rozległości uszkodzenia, np. ocenę stopnia uszkodzenia na poszczególnych głębokościach struktury, jak również jego wizualizację 3D. Proponowane rozwiązanie może być przeznaczone do celów prognozowania uszkodzenia, w przypadku zastosowania zrekonstruowanych map jako wejścia do symulacji numerycznych prognozowania wytrzymałości resztkowej oraz propagacji uszkodzeń w strukturach kompozytowych.

Addresses

Angelika WRONKOWICZ:
Silesian University of Technology, Institute of Fundamentals of Machinery Design, Konarskiego 18A Str., 44-100 Gliwice, Poland, angelika.wronkowicz@polsl.pl.

Andrzej KATUNIN:
Silesian University of Technology, Institute of Fundamentals of Machinery Design, Konarskiego 18A Str., 44-100 Gliwice, Poland, andrzej.katunin@polsl.pl.