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COMPOSITES THEORY AND PRACTICE

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NUMERICAL APPROACH FOR ULTRASONIC IMAGINING OF DEFECTS IN COMPOSITES

The article presents the approach for damage characterization in composite aerospace structures for the ultrasonic non destructive evaluation technique. The damages which affect the structural integrity of such components are the following: disbonds, delaminations, foreign object inclusions and many others. Different NDE techniques are used for the characterization of composite structures. There are numerous limitations and advantages of each technique. One of the most suitable techniques for that purpose is the ultrasonic one. The most important issue in that method is proper selection of inspection parameters and the next issue is signal processing. The approach to signal processing may contain analysis in the frequency and time domain of one and two dimensional signals. Moreover for the size of the damage evaluation, the amplitude (signal value) is used very often. In the article, the 2D signal value evaluation approach is presented. The article will highlight the problems and advantages of signal processing and will show new possibilities of 3D composite characterization (e.g. ply stacking sequence).

Keywords: composites, low energy impacts, signal processing

WYKORZYSTANIE ŚRODOWISKA OBLICZEŃ NUMERYCZNYCH DO OCENY ULTRADŹWIĘKOWEJ DIAGNOSTYKI OBRAZOWEJ W KOMPOZYTACH

Przedstawiono podejście do badań kompozytowych konstrukcji lotniczych z wykorzystaniem metody ultradźwiękowej. Uszkodzeniami wpływającymi na integralność konstrukcji są: odklejenia, rozwarstwienia, wtrącenia ciał obcych i inne. Do badań kompozytowych konstrukcji lotniczych stosuje się szereg metod badań nieniszczących. Każda z metod charakteryzuje się zarówno pewnymi możliwościami, jak i ograniczeniami. Jedną z metod dedykowanych do diagnostyki laminatów jest metoda ultradźwiękowa. Jednakże metoda ta wymaga dostosowania szeregu odpowiednich parametrów do badania. Kolejnym istotnym zagadnieniem jest analiza sygnałów. Taka analiza może przebiegać zarówno w dziedzinie czasu, jak i częstotliwości. Do analizy wykorzystuje się bardzo często amplitudę rejestrowanego sygnału. W artykule przedstawiono podejście do oceny wyników badań z wykorzystaniem analizy ultradźwiękowych sygnałów 2D. Ponadto artykuł przedstawia problematykę i zalety nowego podejścia do oceny konstrukcji kompozytowych z wykorzystaniem zobrazowania 3D (np. możliwość wyznaczania orientacji kolejnych warstw).

Słowa kluczowe: laminaty FML, badania nieniszczące, uszkodzenia w kompozytach

INTRODUCTION

There is a need to interpret, identify and quantify composite structure damage on existing ageing aircraft because of the possibility of failure occurrence. In the present paper, the authors propose an expert numerical system geared towards the quantification of composite material damage in the form of damage description, a system that will make use of the existing infrastructure and inspection methodologies, but will also be able to accommodate new sources of data. Classic NDT method results should be employed, and any past records should as well as be examined to obtain knowledge about damage mechanisms and the condition of the inspected structure. It can be seen that typical results of NDI such as e.g. thermography, ultrasonic C-SCAN and B-SCAN, but also eddy currents measurements and so on, are the easiest to handle, analyze and process in the form of 2D maps or more simply put - images. Therefore, such a form is selected as a basis for the predictive network. The image processing approach is suitable because composite damage and especially delamination may be posed as a 2D multilayer problem. The computer graphic visualization of NDT data allows the extraction of useful information to form large data sets and visual data analysis. Appropriate image processing will feed the system with current, even if partial, information about the current state of the structure, which will be supplemented by classifier-based filtering and reasoning algorithms. Any information gathered or synthesized that characterizes the current state will be a basis for finite element numerical simulation, which will be used to predict the growth of delamination, and enable a more precise quantification of the remaining useful life in an automatized manner. Because of significant experience in the method at the ITWL, as well as because of the relative ease of inspection in real-life structures, the ultrasonic C-scan method will be the main reference method considered for the system as it is the technique which provides sufficient characterization of delamination damage in composites in a reasonable time frame.

The typical failures which affect the structural integrity and residual strength of composites include: disbonds, delaminations, foreign object inclusions and damage called **BVID** - ***B****arely* ***V****isible* ***I****mpact* ***D****amage* [1, 2].

The characterization of such failure modes is not easy when using single NDT techniques [3, 4]. In order to perform a complete damage description, multimode **N**on **D**estructive **E**valuation (**NDE**) of composites should be implemented. A list of candidate techniques may include ultrasonics, Mechanical Impedance Analysis (MIA), shearography, thermography, X-ray radiography and some others [5].

DAMAGE DETECTION IN COMPOSITES WITH USE OF IMAGE COLLECTING AND ULTRASONIC TECHNIQUE

There is a number of failure modes which may occur in composites [5-7]. Among them we have: delaminations, disbonds, foreign object inclusions, impact damages causing ***BVID (B****arely* ***V****isible* ***I****mpact* ***D****amage*), resin rich and poor areas, wrinkling fibers, matrix and fiber cracks, voids and porosity etc [5]. Depending on the manufacturing process as well as maintenance procedures, different faults and failure modes may occur in composites. The application of appropriate NDE (Non Destructive Evaluation) must be taken into the consideration. In this article mainly application of the ultrasonic technique was considered [8].

For these techniques automated data acquisition has been used. Generally, acoustic waves propagation in solid media may be expressed as [9, 10]:

$$(\lambda+\mu)u_{j,ji}+\mu u_{j,jj}+\rho f_i=\rho\ddot{u} \tag{1}$$

Here λ and μ are the Lame constants, ρ is the medium density, and $\boldsymbol{u}$ is the displacement.

In the case of isotropic media, Eq. (1) allows us to obtain solutions for different coordinate directions. Anisotropic composites represent a more difficult case because their acoustic properties depend on fiber directions. The velocity of the elastic waves in a composite which are described in Equation (1) for compressional waves (considered) in the article may be described as:

$$c_l=\left(\frac{\lambda+2\mu}{\rho}\right)^{\frac{1}{2}} \tag{2}$$

Based on the measurement of the time of flight of an ultrasonic wave in the material and using the value of the velocity determined for the composite, the damage location may be obtained. One of the solutions for the reflected wave is the equation of wave motion in solid media. The equation may be expressed as follows:

$$u_x^{\ R}=A_R e^{-i(kx-\omega t)} \tag{3}$$

where: A_r - amplitude of wave reflected in the media, $k=\omega/c_1^{(2)}$ - wave number.

For the pulse echo technique, the amplitude of the reflected wave is collected for structural echogenic assessment (damage type determination).

In automated data acquisition systems, the data are presented as a two dimensional scan of the signal value related to the position of the scanner over the test sample. That visualization (scan) has been called C-scan. One of the advantages of such data presentation is the possibility of comprehensive data assessment (especially large surfaces) by the person who is doing the inspection. Another approach for data assessment is the application of image processing techniques for damage evaluation and comparison.

A digital image is a two-dimensional discrete signal. It means that for processing purposes, such signals can be presented as a brightness function of two independent variables (an array) of an *MxN* size. As an example, the data from a monochrome digital image of an *n* bits resolution per pixel may be presented as [11]:

$$f(x,y)=\begin{pmatrix} f(0,0) & f(0,1) & \cdots & f(0,N-1) \\ f(1,0) & f(1,1) & \cdots & f(1,N-1) \\ \vdots & \vdots & \ddots & \vdots \\ f(M-1,0) & f(M-1,1) & \cdots & f(M-1,N-1) \end{pmatrix} \tag{4}$$

where: $f(x,y)\in C$; $0\le f(x,y)\le L-1$ and $L=2^n$.

For such image presentation, each pixel of the digital data corresponds to an array element. As an example, the images used for analysis presented further in the article were grey scale values (where n = 8 therefore L = 256).

DATA PROCESSING

For damage processing purposes, operations on the **R**egion **o**f **I**nterest (**RoI**) were performed. RoI may be defined as the locations of damages on the inspection image. Depending on the number of damages located on the scan image, automated extraction of the RoIs (based on indication of damage locations) for the subarrays has been performed. Moreover, detailed RoI analysis based on array operations of the selected area is possible. Sub-arrays are created in accordance to the following procedure:

$$A[x_i, y_i];$$
$$RoI[m,n] = C[M - x_i, N - y_i]; \tag{5}$$

where: C [M,N] - scan image, $A[x_i,y_i]$ - array with damages coordinates, RoI [m,n] - subarray of C[M,N] array which include RoI with *i-rows* and *j*-columns and where:

$$i = M\text{-}x_i, j = N\text{-}y_i$$

The next step is to determinate the damage edges, which is done with the use of the amplitude and direction gradient [11]:

$$|\nabla f(x,y)| = \sqrt{\left(\partial_x f(x,y)\right)^2 + \left(\partial_y f(x,y)\right)^2} \tag{6}$$

$$\nabla f(x,y) = ArcTan\left(\frac{\partial_y f(x,y)}{\partial_x f(x,y)}\right) \tag{7}$$

The local extremes of Equation (7) define the damage edges. Determination of the value of those edges is possible with the use of the following equation:

$$\Delta f(x,y) = \partial_{xx} f(x,y) + \partial_{yy} f(x,y) \tag{8}$$

Based on the information related to the edges location it is necessary to determine the mean values of the brightness (amplitude) on the area related to the damage (inside the edge) and around the damage. The following equation enables such activity:

$$\mu[x,y] = \frac{1}{N^2}\sum_{i=0}^{M}\sum_{j=0}^{M} f[x+i, y+j] \tag{9}$$

where: x and y - are the coordinates of the single element (pixel) brightness value in a selected area.

For the purpose of determining the size, the use of the **S**ignal to **N**oise **R**atio (**SNR**) is presented

$$SNR\,[dB] = 10\log_{10}\frac{f(x,y)\_S}{f(x,y)\_B} \tag{10}$$

where: $f(x,y)$_S – mean value of signal in damage area (signal value) $f(x,y)\_B$ – mean value of signal outside damage area (noise value).

Based on the SNR indication, the damage size may be determined. For that purpose the threshold function may be used. The threshold filtering algorithm has been presented below:

$$RoI[x,y] * f_T(SNR) = qRoI[x,y]$$
$$f_T(x,y) = \begin{cases} 1 \;\Rightarrow\; RoI[x,y] \in T \\ 0 \;\Rightarrow\; RoI[x,y] \notin T \end{cases} \tag{11}$$

As the result of filtration, the binary array (0,1) has been created. That array includes the number of pixels which fulfill the requirements of the SNR criteria. Consecutive calculations will determine the size of the damage taking into consideration the pixel size and image resolution of the acquisition system. Consecutive processing is just purely an IT problem associated with the data processing acquisition system.

EXAMPLES OF DATA PROCESSING

The first example of the image processing capabilities is the determination of the damage edges in the Fibre Metal Laminate - FML (called **GLARE**). In such a laminate, artificial damages called foreign object inclusion were implemented. Image processing and the use of the procedure for the edge of the damage is presented. In Figure 1 the results of the image processing for the purpose of edge detection is presented. The results of ultrasonic inspection of the FML are presented. The damages visible on the image are foreign object inclusions embedded between the layers of the laminate. Such collected data was processed in the Mathematica software with the use of Image processing. The result of image processing according to equations (5)-(10) is the damage contour. For such results, further processing may be applied to determine:

- damage shape
- damage size
- damage profile (e.g. 3D profiling for FEM model)

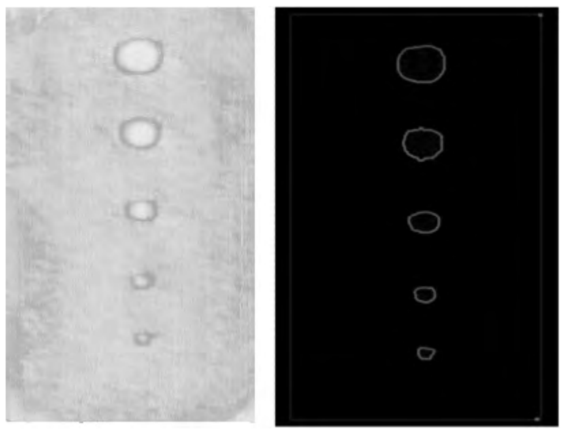

Fig. 1. Results of edge detection (right) of ultrasonic ToF C-scan

Rys. 1. Wynik wyznaczenia krawędzi (po prawej) uszkodzeń z badania ultradźwiękowego w zobrazowaniu trybu C

One of the interesting damage analysis cases is the impact damage characterization. The impact damage affects the structural integrity as multiple damages (delaminations) are located at different depths. Such damage is named Barely Visible Impact Damage. Depending on the structure (unidirectional, matrix fabric, as well as material), the shape of the impactor, the impact energy, the shape and the size of the damage is different.

Figure 2 presents multiple delaminations located at different depths in an epoxy carbon fibre reinforced laminate. The delaminations are the results of impact damage for a unidirectional laminate. Four main regions located at different depths of different shapes and sizes are visible. Figure 2 also presents the RoI processing algorithm, edge detection and 3D profile which shows that these delaminations are separated and located at different depths.

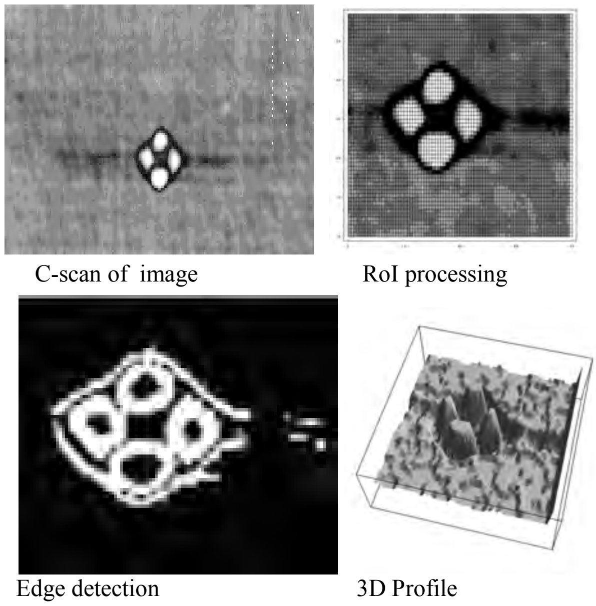

Fig. 2. Results of signal processing for BVID detected in ultrasonic ToF C-scan

Rys. 2. Wynik przetwarzania sygnału dla uszkodzenia typu BVID dla badania ultradźwiękowego w zobrazowaniu tryb C

The abovementioned damages in composites such as foreign object inclusions or delaminations are failure modes which may be quite easily detected with the use of ultrasonic waves (location perpendicular) to the sound path. However, damages such as BVID and delaminations are not possible to determine with the use of X-Ray. That leads to another issue such as the characterization of in-plane damages such as:

- resin rich areas
- resin starved areas
- fiber cracks
- fiber misalignment
- fiber rich areas and fiber poor areas

Considering the abovementioned problems with respect to ultrasonic testing, one of the key issues for composite characterization may be e.g. ply stacking sequence determination for a unidirectional composite with the use of ultrasonic testing technology. Such an issue is possible due to the image processing of consecutive ply C-scans with the use of automated data collection.

For that purpose selection of the proper scan parameters such as:

- inspection frequency
- signal to noise ratio
- gate selection
- image resolution selection

is required.

Figure 3 presents the results of the ply to ply inspection with the use of ultrasonic and data image collecting. In the first column, the C-scan results of the single ply are presented. Image processing was then applied to such data. For the purpose of the ply (unidirectional fiber) orientation, the use of spectral functions were selected such as the 2 D Fourier Transform. The plies have got a –45, +45 orientation so there are visible differences in the main directions in the ply stacking image processed with the use of the 2 D Fourier Transform as well as the intensity in the power spectra. There are promising results for the fabricated specimens data analysis, however, there are still a few important issues which are associated with the C-scan preparation as well as the necessity of the unwanted spectral components filtration.

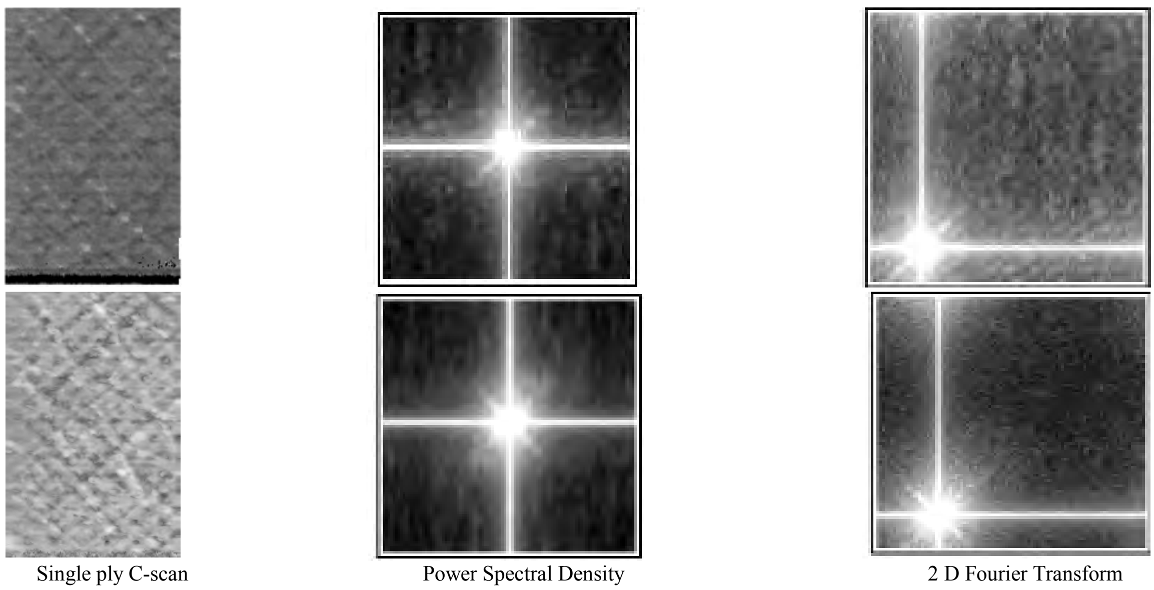

Fig. 3. Results of ply stacking determination with use of image processing

Rys. 3. Wynik wyznaczenia kierunków ułożenia warstw dla kompozytu z wykorzystaniem przetwarzania obrazów

Further steps in in-plane damage detection such as ply stacking sequence visualization as well as detection e.g. resin rich, resin poor areas are in progress.

SUMMARY

The article presents an approach to the composite damage characterization in aerospace structures for the ultrasonic non destructive evaluation technique. Different NDE characterization techniques are used for the characterization of such damages. There are numerous limitations and advantages of each technique. The most important is conscious selection and use of multimode inspection when necessary. The next issue is signal processing. The approach for signal processing may contain analysis in the frequency and time domain of one and two dimensional signals. Moreover for the size of the damage evaluation, very often the amplitude (signal value) is used. In the article, the 2D signal value evaluation approach was presented. Depending on the application: quality control, maintenance, after incidence check, etc., different demands of the inspection may be required.

The approach presented in the article contains a software elaborated approach for ultrasonic signal processing which may be used for service life inspections. The advantages of such an approach are connected with fast, reliable data assessment. Moreover, the data comparison from previous inspections and all the necessary calculations connected with size damage monitoring may be done automatically. The output data from the calculations are the image of the defect in the structure. The data contains 3 dimensional information which enables damage characterization which may be presented in the graphical mode.

The graphical results of the calculations may be transferred to numerical tools which enable structural durability calculations such as Finite Element Modeling. Such an approach especially for composite structures opens the new way for structural design qualification as well as health monitoring. Another step in the damage detection of a composite is elaboration of the approach for in-plane damage detection in composites as well as determination of the ply stacking sequence.

Such an approach is one of the activities of interest for future research projects which will be conducted in the author's laboratory.

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