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COMPOSITES THEORY AND PRACTICE

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DAMAGE SIZE MONITORING OF COMPOSITE AIRCRAFT STRUCTURES BASED ON ULTRASONIC TESTING AND IMAGE PROCESSING

According to damage tolerance philosophy, a composite component with a flaw is allowed to be operated if it is included in a maintenance program that will ensure damage detection before it reduces the residual strength of the structure below an acceptable limit. One of the damage tolerance approaches includes damage extent identification and monitoring of its growth. In view of the progressive behaviour of damage in composite structures, they should be periodically inspected to monitor damage progression. This article presents an approach to damage size monitoring of composite aircraft structures by means of ultrasonic testing with the C-scan mode and a developed algorithm based on image processing techniques. To test the algorithm, pairs of results of ultrasonic testing of composite elements of aircraft, carried out at time intervals, were used. The analysis of such results is difficult due to the complexity of the obtained C-scans, which is caused by the variable thickness of the aircraft skin and the presence of other elements in the tested structure (e.g. rivets and reinforcements). The proposed method enables the extraction of damage contours, preceded by indication of regions of interest by an expert, and calculation of an increase in the damage surface area, based on two input C-scans, as well as comparison of their contours.

Keywords: damage size monitoring, composite structures, ultrasonic testing, image processing

MONITOROWANIE ROZMIARU USZKODZENIA W LOTNICZYCH STRUKTURACH KOMPOZYTOWYCH OPARTE NA BADANIACH ULTRADŹWIĘKOWYCH I PRZETWARZANIU OBRAZU

Zgodnie z filozofią tolerancji uszkodzeń, element kompozytowy z wadą jest dopuszczony do eksploatacji, jeżeli jest włączony w program obsługi serwisowej, który zapewni wykrycie uszkodzenia zanim zredukuje ono resztkową wytrzymałość struktury poniżej dopuszczalnego limitu. Jedno z podejść tolerancji uszkodzeń obejmuje identyfikację rozmiaru uszkodzenia i monitorowanie jego wzrostu. W świetle postępowego zachowania uszkodzeń w strukturach kompozytowych, powinny one być okresowo kontrolowane w celu monitorowania postępu uszkodzenia. W artykule przedstawiono podejście do monitorowania rozmiaru uszkodzeń w kompozytowych strukturach lotniczych za pomocą badań ultradźwiękowych z obrazowaniem w trybie C oraz opracowanego algorytmu opartego na technikach przetwarzania obrazu. Do testowania algorytmu wykorzystane zostały serie wyników badań ultradźwiękowych kompozytowych elementów konstrukcji lotniczych, przeprowadzonych w określonych odstępach czasu. Analiza takich wyników jest trudna ze względu na złożoność otrzymywanych zobrazowań w trybie C, co jest spowodowane zmienną grubością poszycia samolotów oraz obecnością innych elementów w badanej strukturze (np. nitów i wzmocnienia). Zaproponowana metoda umożliwia ekstrakcję konturów uszkodzenia, poprzedzoną wskazaniem obszaru zainteresowania przez eksperta, oraz obliczenie wzrostu powierzchni uszkodzenia, na podstawie dwóch wejściowych zobrazowań w trybie C, a także porównanie tych konturów.

Słowa kluczowe: monitorowanie rozmiaru uszkodzenia, struktury kompozytowe, badania ultradźwiękowe, przetwarzanie obrazu

INTRODUCTION

Composite structures, owing to their numerous advantages, are widely used in the aircraft industry nowadays. However, these structures are subjected to many factors that may cause defects, both during the manufacturing process and throughout the service life of a composite component. Porosity (presence of voids), foreign object inclusion, delamination, incorrect fibre volume distribution, defective bonding, fibre or ply misalignment, and ply cracking are among the most common defect types of composite structures formed during their production. From among the in-service defects, delamination, bond failure, cracking, moisture ingress, fibre buckling or fracture and failure of the interface between the matrix and fibres can be distinguished. In general, in-service defects of composite structures may result from impacts, static overloads, fatigue, overheating, hydrothermal effects, lightning strikes or creep [1]. In the case of the aircraft elements, foreign object impacts are the source of the most concern. Low energy impacts (e.g. runway debris, hailstorms) or small dropped objects (e.g. maintenance tools) may cause remarkable internal damage in the form of matrix cracks, fibre breakage and propagating delamination with simultaneous, very limited visible marks on the impacted surface [2]. Such impact damage, regarding its detectability is classified as so-called barely visible impact damage (BVID).

Since the damage of a composite element of an airplane (e.g. fuselages, wings, stabilizers) may lead to catastrophic consequences, certain diagnostic procedures are required be implemented. In accordance with commonly respected damage tolerance philosophy, flaws are permitted to exist in a structure of a component being in operation if certain requirements are met [3]. A structure is considered to be damage tolerant if it does not weaken the structural integrity. Thus, a maintenance program has to be implemented that ensures detection of a defect or damage before it reduces the residual strength of the structure below an acceptable limit. One of the damage tolerance approaches includes damage extent identification and monitoring of its growth. Such a procedure is of great importance since the damage occurring in layered composites is a complex phenomenon and propagates progressively. According to Giurgiutiu [4], a general scenario may look as follows: micro-cracks develop in the matrix due to cyclic loading. Continuing cyclic loading causes growth of the micro-cracks so they become macroscopic cracks. Then the cracks in the matrix spread through the ply in which they initiated. Other micro-cracks develop in the plies on either side of the initial ply as a result of stress concentrations. The stress concentrations between the plies cause the development of local delaminations. Finally, when delaminations have formed, damage increases rapidly up to total failure. In view of this progressive damage behaviour, composite structures should be periodically inspected to monitor damage progression [4].

The most commonly applied non-destructive testing (NDT) method for composite structures is ultrasonic testing (UT) with the C-scan presentation mode. The reason for favouring ultrasonic inspection is its high sensitivity to the defect types commonly found in composite structures [1]. In general, UT consists in observing the propagation of ultrasonic waves in the tested structure. Ultrasonic waves propagate uniformly in homogeneous medium (e.g. oil, water, solid lubricant), whereas when they encounter a discontinuity, a portion of sound energy is reflected back from the flaw surface. C-scan ultrasonic imaging enables obtaining a 2D image of the amplitude of the sound reflecting from the tested surface and the Time-of-Flight (ToF) of this signal, by which the depth of the surface can be determined.

For the purpose of damage size monitoring, an expert performs an analysis of the obtained C-scans and calculates the extent of damage using software dedicated to UT. In practice, the damage size is usually estimated based on manually selected areas on the C-scans. This, however, may bring unrepeatable results since some manual settings can be selected differently, which makes such an analysis difficult. One of the examples is presented in the paper by Meola et al. [5], where the overall delamination extension of carbon fibre reinforced composites was estimated by calculating the average diameter by selecting the region of interest (ROI) in a rectangle.

It should be noted that analysis and interpretation of ultrasonic scans is required to be performed by a certified expert in this area. Such a person should be very well acquainted with the specificity of UT, damage processes of composite structures, as well as the internal design of the structure with the location of embedded elements, bolt connections, etc. For the purpose of aiding the procedure of damage size assessment, it is necessary to apply image processing methods to the obtained C-scans. Various approaches have been reported in the literature to-date. An example is the methodology of damage sizing based on ultrasonic data segmentation by data clustering [6], or segmentation based on statistical mean and standard deviation [7]. Other examples of calculating the size of defects in composite structures with irregular contours can be found in [8], where Oculus software was used, and in [9], where the defects were analysed by means of ULTRAWIN software. The preliminary approaches to damage size assessment of the authors of this paper have been published, e.g. Dragan methodology [10] based on edge detection and Signal to Noise Ratio or the algorithm of Wronkowicz et al. [11] based on multilevel Otsu thresholding and morphological processing.

The aim of this study is to develop a universal, semi-automatic approach for aiding the damage size calculation procedure based on ultrasonic C-scans and image processing methods. In the next sections, the testing methodology of composite aircraft panels is described as well as the proposed algorithm with exemplary results and conclusions are presented.

TESTING METHODOLOGY

In the research presented in this article, composite parts used in military aircraft were tested. As an exemplary structure, part of a CFRP KMU-4e: ELUR-0.1p and ENFB based on epoxy resin was chosen. The laminates were manufactured by stacking layers in the sequence 0,90,–45,+45. The thickness of the inspected specimen was equal to 4 mm. A demonstrative fragment of an exemplary tested element is presented in Figure 1. For ultrasonic inspection, an automated MAUS® device by the Boeing company was used. The system enables ultrasonic data (ToF and amplitude peak location) capture based on selected signal gates. The inspection results can be visualized in the form of C-scan mapping representing a chosen signal feature, e.g. the amplitude or ToF of a peak, with respect to the position of the ultrasonic probe. On this basis, damage

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can be identified and characterized. The signal amplifier enables data generation within the frequency of 1÷20 MHz with a single sensor as well as the Phased Array technique. For the purpose of the inspection, a 5 MHz single transducer was used. Practically, the selected frequency is a trade-off between sensitivity and structure attenuation which is relatively high for epoxy composite structures. For C-scan mapping, there is a possibility of selecting a single step (X-Y) resolution for enhancing image resolution or fast inspection purposes. The MAUS® system enables obtaining an image resolution from 0.01″ up to 0.1″.

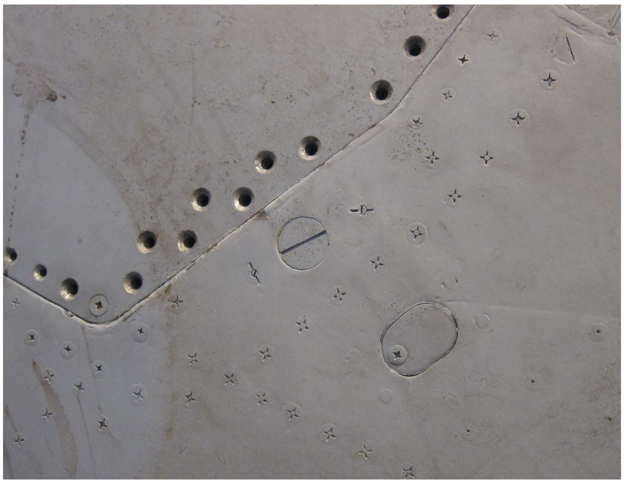

Fig. 1. Part of composite aircraft panel

Rys. 1. Fragment kompozytowego elementu samolotu

The pixel resolutions of the exemplary pairs of acquired C-scans (ToF maps) were diverse, depending on selection of the scanning area during UT (from about 120×120 to 280×570 pixels, where 1 pixel is equivalent to 0.05 mm). To test the image processing algorithm described in the next section, the authors used several pairs of results of UT carried out approximately at two different inspection intervals of aircraft operation.

IMAGE PROCESSING ALGORITHM

The generic scheme of the proposed algorithm, implemented in Matlab® with the use of the Image Processing Toolbox, is presented in Figure 2. The algorithm is divided into two main stages: damage extraction and calculation (which is performed separately on both input C-scans) and damage growth calculation and comparison (where the results of the first stage are analysed together). The consecutive steps are as follows.

Firstly, a pair of C-scan maps in the form of 8-bit matrices is loaded into the workspace (see example depicted in Fig. 3). Then both of them, treated further as images, are individually subjected to the following operations (notice that the demonstrative results of these steps are shown based on the processing of one of the input images, namely Figure 3a).

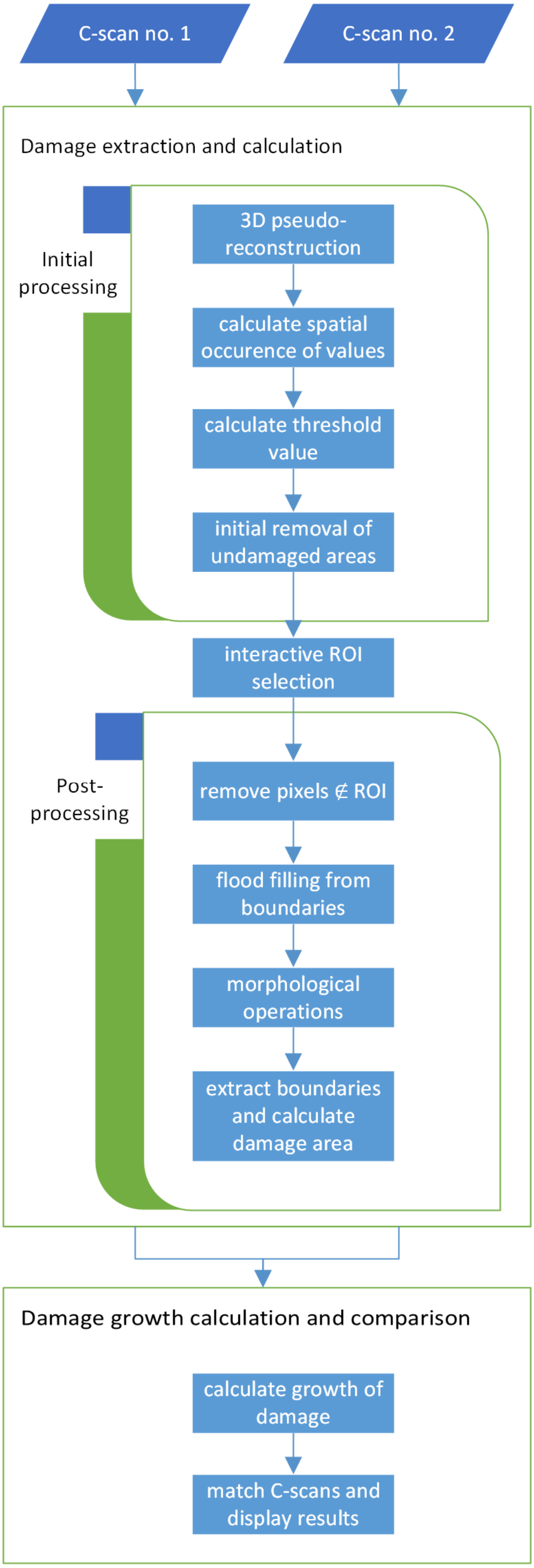

Fig. 2. Overall image processing algorithm

Rys. 2. Ogólny algorytm przetwarzania obrazów

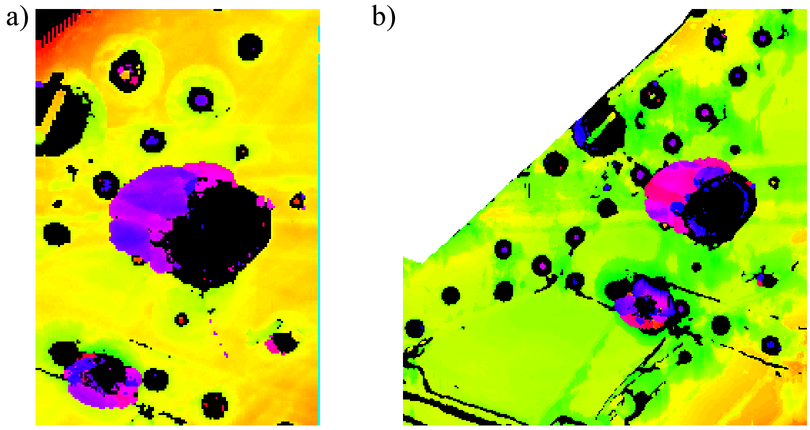

Fig. 3. Exemplary C-scans after UT performed in interval of two years

Rys. 3. Przykładowe zobrazowania w trybie C po badaniach ultradźwiękowych przeprowadzonych w odstępie dwóch lat

Firstly, for the purpose of initial estimation of a threshold for image segmentation, the following steps are performed. The image is 3D pseudo-reconstructed, i.e. the values of the 2D image are distributed to a 3D matrix, where each unique value lies on a level (layer) corresponding to this value (Fig. 4a). Then, the spatial occurrence of each value is calculated and plotted (Fig. 4b), which indicates how many times each value exists over the length and width, averaged, of each layer. The highest peak (global maximum) in Figure 4b indicates the values most widely distributed in the C-scan, thus it was assumed that it is expected to represent the proper (undamaged) regions of the structure (in Fig. 4a these are the areas with a cyan colour). If this assumption turns out to be incorrect in a particular case, an expert can correct the threshold value manually using the sliders and preview window of the results in the interface prepared for this algorithm.

The pixels with a value equal to and approximately 255 (seen as navy blue ones in Fig. 4a and black ones in Fig. 3a) are not taken into consideration since they present attenuation in the adhesive layer and areas of the structure after disassembly of the elements (flaps and rivets visible in Fig. 1). The rest of the values are the other attenuation levels of the tested structure that may indicate the presence of a defect or damage, other elements embedded in the structure (e.g. unremoved rivets) or noise. These can be the areas of, among others, red, orange and yellow colours observable in Figure 4a. Since proper interpretation of C-scans is the task of a certified expert, the algorithm was intended to be semi-automatic. The analysis of C-scans cannot be performed without an expert since full automation of the algorithm may result in errors, which is unacceptable in the case of NDT in the aerospace industry. Namely, the initial removal of undamaged areas, based on the described plot, is performed automatically, then an expert indicates a ROI by drawing a polygon around the identified damage location and finally, additional post-processing is performed automatically again.

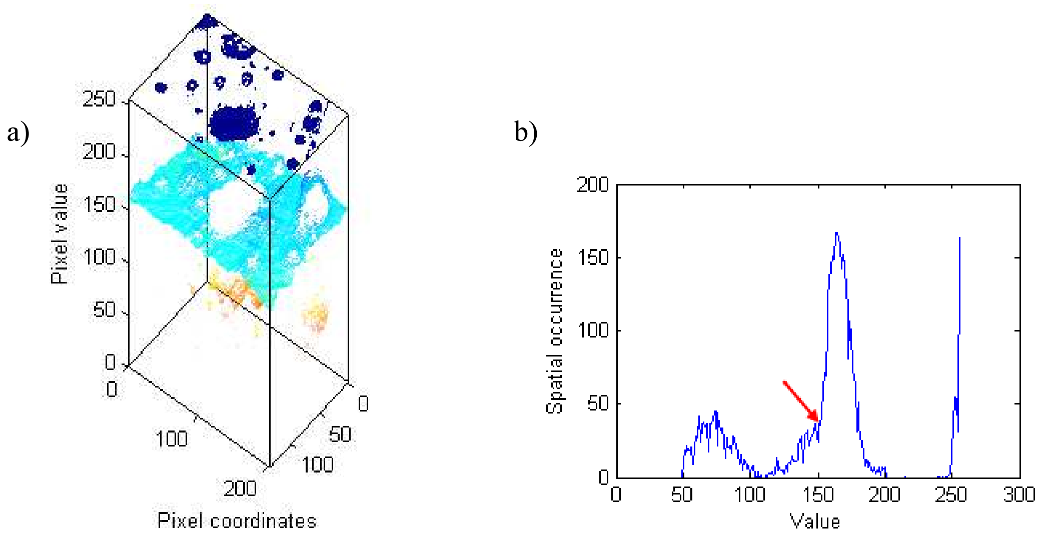

Fig. 4. 3D pseudo-reconstruction of C-scan presented in Figure 3a: a) 3D representation of values, b) plot of spatial occurrence of values

Rys. 4. Pseudorekonstrukcja 3D zobrazowania w trybie C przedstawionego na rysunku 3a: a) reprezentacja 3D wartości, b) wykres przestrzennego występowania wartości

For this purpose, the image is subjected to the initial removal of pixels representing the undamaged areas in such a way that the pixels of image I, whose values are higher than the calculated threshold T value, become zeros and those lower or equal - remain unchanged. Such an operation can be expressed by:

$$J(i,j)=\begin{cases} 0 & for \quad I(i,j)>T, \\ I(i,j) & for \quad I(i,j)\le T. \end{cases} \tag{1}$$

Threshold T is selected automatically by detecting peaks in a plot (Fig. 4b) and then, by the developed loop algorithm, aimed at finding a point where the occurrence value stops drastically descending on the left side of the highest peak (such a desirable point is the local minimum indicated by the red arrow in Figure 4b).

The next step is interactive and relies on selecting a region of interest (ROI) by the user (an expert) by means of indicating the points of a polygon around this region (Fig. 5a). Then, the pixels outside the selected ROI are removed (assigned to zeros).

Additional operations are performed in order to clean the potential remaining pixels. Firstly, the fuzzy recursive flood fill with the 8 directions algorithm is executed for each pixel belonging to the ROI contour. This operation aims at removing possible remaining areas being in contact with the ROI contour by filling with zeros areas with similar values to the source pixel (within a given threshold, e.g. ±3). This enables removal of only areas intersected by a contour around ROI, while not interfering in ROI itself, since filling (cleaning) is stopped when encountering areas with a different colour.

Moreover, additional steps were added to ensure the cleaning of small regions that could possibly remain after flood filling. For this purpose, the resulting image is temporarily binarized in order to perform morphological area opening. This operation enables the removal of all the connected components that have fewer than the specified number of pixels from a binary image. The resulting image after this step is presented in Figure 5b. Finally, the boundaries of the resulting object (nonzero pixels) are extracted and its surface area is calculated. For the purpose of visually verifying if the damage extent was extracted properly, the boundaries around the detected region are displayed on the input C-scan. The resulting images are presented in Figure 6a and b, respectively, for the exemplary pair of C-scans (extracted contours are in magenta).

The second stage of the algorithm includes calculating the difference between the damage areas of both C-scans and superimposing both input C-scans with the detected contours onto one figure (Fig. 6c) based on the location of the centroids of these contours.

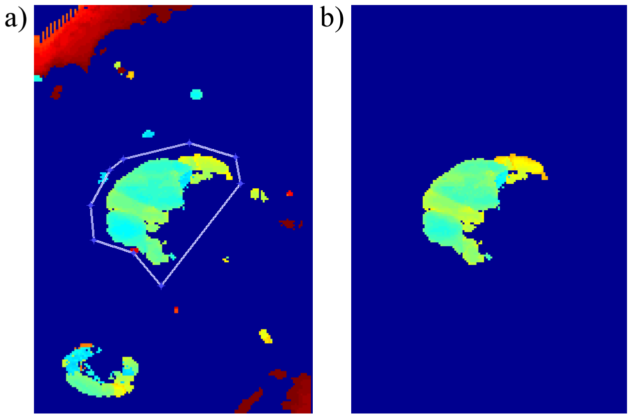

Fig. 5. Chosen image processing steps: a) selection of ROI, b) image before contour extraction

Rys. 5. Wybrane kroki przetwarzania obrazu: a) wybór ROI, b) obraz przed ekstrakcją konturu

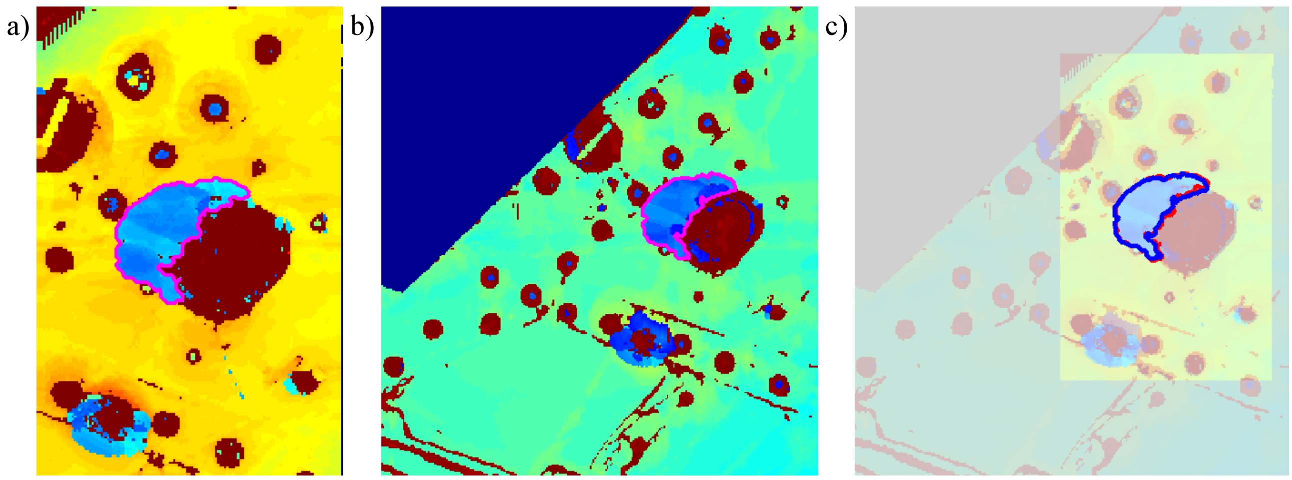

Fig. 6. Contours of selected damage: a) on 1st C-scan, b) on 2nd C-scan, c) superimposed contours

Rys. 6. Kontury zaznaczonego uszkodzenia: a) na 1 zobrazowaniu w trybie C, b) na 2 zobrazowaniu w trybie C, c) nałożone kontury

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RESULTS AND DISCUSSION

The algorithm described above was tested and implemented on several pairs of C-scans described above and the exemplary results are depicted in Figure 7. Visual analysis of the results reveals that in all the cases the contours of the delaminations were detected properly. In the presented cases, the damage growth was calculated as follows: 0.4, 11.1, 2.05 mm^2 for the cases presented in Figure 7a, 7b and 7c, respectively, and -0.75 mm^2 for the demonstrative case presented in Figure 6. Obviously, damage growth cannot be negative, thus the last of the mentioned results follows from either a measurement error, which must be taken into consideration during each NDT, or inaccuracy during image processing. One should be aware that the other results may also reveal certain measurement uncertainty, which is dependent on many factors, among others - the amount of couplant during UT or the presence of noise. Nevertheless, the obtained results show that image processing is very helpful in damage extent assessment and the developed algorithm may facilitate the diagnostic inference procedure. However, it should be recalled that final interpretation of the results and the decision about a potential repair should be made by an expert based on his experience.

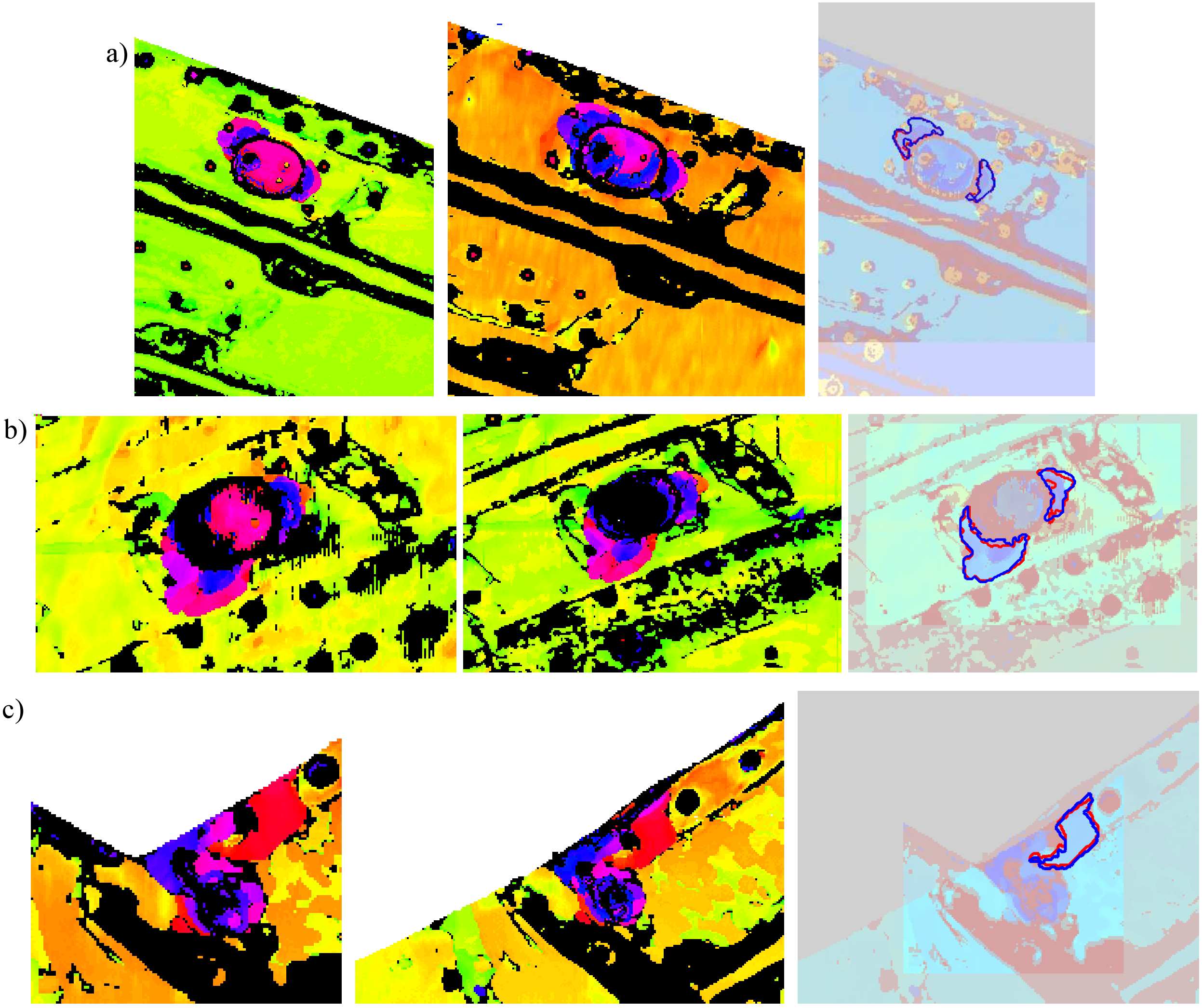

Fig. 7. Exemplary pairs of original C-scans and results of their damage extraction and comparison

Rys. 7. Przykładowe pary oryginalnych zobrazowań w trybie C oraz wyniki ekstrakcji uszkodzeń i ich porównania

CONCLUSIONS

The results presented in this paper are part of the ongoing research aimed at developing a comprehensive system of analysing data obtained by UT of composite structures. In this paper, an approach to damage size monitoring of composite structures based on UT with the C-scan mode and an algorithm based on image processing was presented. This algorithm was tested on several examples of pairs of C-scans obtained approximately at two different inspection intervals of aircraft operation. The analysis of such elements is difficult due to the complexity of the obtained C-scans caused by their variable thicknesses and the presence of other elements (flaps, rivets and reinforcements). The results show that the proposed method may be helpful in damage growth assessment and facilitate the diagnostic inference procedure. However, taking

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into consideration the risk of measurement error occurrence it should be noted that final interpretation of the results should be made by an expert based on his experience.

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