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A NOVEL AUTOMATIC DEFECT DETECTION METHOD FOR THE ULTRASONIC INSPECTION OF AIRCRAFT COMPOSITE PARTS

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ABSTRACT

A novel analysis method is proposed for the automatic detection of defects in aerospace composite structures. The method is based on an algorithm capable of automatically extracting relevant indications from a collection of pulse-echo signals. The algorithm is adaptive and considers the peculiarities and geometric features of each part. It consists of four main steps: 1) detection of relevant echoes in each A-scan; 2) reconstruction of a back wall by means of a spline fitting algorithm; 3) generation of reference envelopes using a statistical approach; 4) subtraction of the reference envelopes from the measured signals. The performance of the method is evaluated on a set of CFRP test specimens containing various artificial defects and is compared to a commercial software (ULTIS by Testia). The results show that the new method leads to better detection performance, especially for defects located close to the bottom surface.

Keywords: Ultrasonics, composites, automated analysis.

1. INTRODUCTION

Composite materials are extensively used in the design of modern aircrafts primary structures. Their high mechanical performance combined with low density allows for significant weight savings. Structural components in carbon fiber reinforced polymers (CFRP) must be 100% inspected to detect potential manufacturing flaws such as delamination, porosities or inclusions. Ultrasonic testing (UT) is the preferred method to perform the inspection of monolithic CFRP structural parts.

In the aerospace industry, UT scanning operations used in production are nowadays widely automated. The inspection of large composite structures with a scanning resolution of 1-2 mm generates tremendous amount of data. However, the data analysis is generally performed by human operators. This critical analysis is time-consuming, costly, requires highly trained personnel and may create bottlenecks in the manufacturing process. Automated analysis of ultrasonic data allows for major time savings while improving reliability.

Several methods implemented in commercial UT software perform the automatic detection of defects for a variety of inspection conditions [1]. However, these methods have limitations that could become critical for some applications: lack of adaptability to uncontrolled thickness variations, poor detection near part surfaces or in complex geometric features (co-cured stringers, ply drop-offs). To overcome some of these limitations, a new automatic analysis method is proposed.

2. METHODS

The method presented in this paper is capable of automatically extracting relevant indications from a collection of pulse-echo signals arranged in a rectangular grid called the A-scan matrix. The algorithm is designed to be adaptive and to consider the peculiarities and geometric features of each part. It consists of four main steps: 1) The first and last *relevant echoes* are automatically detected in each A-scan. 2) A matrix of back wall positions is computed based on the last relevant echoes. A reconstructed back wall is then obtained by smoothing positions of the last echoes using cubic splines. 3) Reference envelopes are computed for front and back wall echoes using a statistical approach. Different envelopes are calculated for the different regions of the part to account for the local signal characteristics caused by geometric and lay-up configurations. 4) Calculated reference envelopes are subtracted from the measured A-scans and a C-scan of remaining indications is finally computed.

2.1 Identification of front and back wall echoes

The method to identify front and back wall echoes is highly dependent on the data reduction technique used during the acquisition. The following procedure is suitable for A-scans processed using the ALOK method [2] and may require substantial modifications if a different data reduction technique

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is used. In each A-scan, an *echo* is defined as a sequence of peaks with successive time of flight values separated by at most half a signal period. The time of flight of the maximum amplitude peak in an echo is hereinafter referred to as the time of flight of the echo. The front wall echo is defined as the echo with the smallest time of flight. The other echoes can correspond to defects, the back wall or their respective repetitions. A back wall echo usually has a higher amplitude than all preceding echoes (except for the front wall echo) and should not occur at a time that is a multiple of the preceding echoes (otherwise it is a repetition). Using these criteria, a *last relevant echo* is identified in each A-scan. The *last relevant echo* might correspond to a defect rather than the actual back wall. Indeed, some defects can reflect enough energy to make the back wall echo too faint to be identified correctly. This is the reason why the smoothing procedure described in the next section is necessary.

2.2 Reconstruction of the back wall

Each A-scan in the A-scan matrix has an (x, y) position and a time of flight of its *last relevant echo*, t. These triplets (x, y, t) form a three-dimensional point cloud approximating the position of the part back wall. If an A-scan contains a defect, the time of flight of the *last relevant echo* might be different from the actual position of the back wall. Smoothing the approximate back wall will eliminate defects and noise while maintaining an accurate representation of the real back wall. The smoothing algorithm is based on two assumptions: 1) a defect area must be smaller than typical areas of thickness variations or surface deformations; 2) thickness variations due to geometric features or surface deformations must be progressive.

Univariate cubic splines are used for smoothing the approximate back wall [3]. Even though bivariate splines could be used directly, they pose a computational problem on large surfaces since the memory requirements for computing bivariate splines with millions of data points is often prohibitive. A smoothing spline is computed at each fixed x_i and each fixed y_j. These splines define a grid over the A-scan matrix. Since the back wall curvature should be relatively smooth, the derivative of the splines should vary slowly and neighboring splines should have similar values. Using sliding window statistics, points identified as outliers are removed from the approximate back wall and new splines are computed with the remaining points. After a few iterations (usually three to six), incorrect *last relevant echoes* are removed while maintaining a good fit even on regions where thickness varies (ply drop-offs, for instance). The final reconstructed back wall is obtained by averaging the two splines crossing at each position of the A-scan matrix and interpolating missing values using a simple bivariate linear interpolation.

2.3 Reference envelopes

Reference envelopes are constructed for both the front and back walls based on the echoes identified in the first step. For the back wall envelope, all *last relevant echoes* are superimposed (i.e. time-shifted in such a way that their maximum amplitude occurs at the same time of flight). The reference envelope amplitude for a given peak is the p^{th} percentile of all amplitude values superimposed at this time of flight. Choosing a high p (usually above 99) leads to an envelope that outlines the signals corresponding to the actual back wall while avoiding echoes caused by internal discontinuities. A second reference envelope is constructed in the same way for the front wall echo. A set of specific reference envelopes is defined for each region depending on its lay-up configuration (for instance, ply drop-offs or flat regions, presence of outer layers, etc.).

2.4 Echo subtraction and final filtering

For each A-scan position, the front reference envelope is shifted over the front wall echo to maximize cross-correlation between the two signals. The back reference envelope is shifted to the reconstructed back wall position. To compensate for noise and small discrepancies in the reconstructed back wall, the back reference echo can be further shifted by a small amount (less than half a period) to maximize cross-correlation. A new A-scan is obtained by subtracting the shifted reference envelopes from the original A-scan. A low amplitude thresholding is then applied to the resulting signal to suppress all non-significant peaks. At this stage, remaining peaks should correspond to indications.

3. RESULTS AND DISCUSSION

A set of 5 test specimens were used to assess detection performance of the developed method. The specimens are monolithic unidirectional CFRP panels with different thickness steps ranging from 1.70 to 5.68 mm. Various outer layers are used to consider the effect of different surface finishes commonly met in aerospace (see *Table 1* for details).

A total of 773 artificial defects were inserted in the test specimens. The defects are circular with diameters ranging from Ø3.2 mm to Ø12.7 mm. Multiple defect materials are used: Teflon tape inserts simulating delamination and diverse foreign object debris (FOD) usually found in a context of production: peel ply, bagging and release films. Defects are inserted in the flat regions of the panels as well as in the ply drop-off areas. They are distributed throughout the specimens' depth, from 1st to last carbon ply.

Test specimen characteristics	
Thickness steps	1.70 / 2.27 / 2.84 / 3.98 / 5.11 / 5.68 mm
Outer layers	Carbon ply / Glass ply / Copper mesh
Geometric features	Flat region / Ply Drop-off regions
Artificial defects characteristics	
Diameters	3.2 / 3.8 / 5.1 / 6.4 / 8.9 / 9.5 / 9.7 / 12.7 mm
Materials	Teflon / Peel ply / Bagging / Release film
Depth	From 1st/2nd to penultimate/last carbon plies

TABLE 1: TEST SPECIMEN AND ARTIFICIAL DEFECTS CHARACTERISTICS

The specimens were inspected using an industrial automated ultrasonic system. The inspection was performed by a 5 MHz, 40 elements phased-array probe in contact with the parts by means of a water box. A-scans were collected using the pulse-echo technique. The probe position was also recorded during the scan operation allowing for the generation of C-scans.

The data collected for each specimen was then analyzed by two automated process: the new method proposed in the present paper and a commercial software (ULTIS by Testia). The method implemented in ULTIS uses the back wall echo filter (BWEF) tool, which allows extracting indications from a time of flight C-scan using the local thickness variations. This tool partitions the C-scan image by grouping pixels with similar depths (using a threshold on standard deviation or local gradient) and then removes large partitions with greater depth than neighboring partitions. The aim is to suppress all echoes corresponding to the back wall [1]. Another method based on the subtraction of a static reference C-scan is also available in ULTIS but gave poor results for our specimens and was not further considered.

The BWEF parameters were optimized on actual complex aircraft parts in production to maximize defect detection while minimizing false calls. The same criterion on the maximum number of false calls was used for both the proposed method and the BWEF tool to ensure that detection performances between the two approaches are comparable. Time of flight C-scans of remaining indications were generated using either the BWEF tool or the current algorithm. Detection criteria (minimum defect length, width and surfaces) were applied to each C-scan and a hit and miss table was produced for each method. A probability of detection (POD) approach based on the likelihood ratio method [4] was used to compute $a_{90/95}$ values. Detection percentages (number of "hits" divided by total number of defects) were also calculated for three depth categories: *near* (between 1st and 2nd carbon ply), *inner* (from 2nd to penultimate carbon ply) and *far side* defects (between penultimate and last carbon ply). Two subsets of data were then analyzed to study the influence of an additional layer (glass or peel ply) on the bottom surface. Results are presented in *Table 2*.

Specimen region	Number of defects	Detection percentage					
		ULTIS - BWEF			New method		
		Near	Inner	Far	Near	Inner	Far
All	773	**70%** ($a_{90/95}$ = 13.4 mm)			**79%** ($a_{90/95}$ = 8.3 mm)		
		85%	77%	**49%**	82%	84%	**70%**
Additional layer on bottom surface	427	81%	81%	**73%**	79%	89%	**70%**
No additional layer on bottom surface	346	92%	73%	**26%**	86%	76%	**69%**

TABLE 2: DETECTION RESULTS BWEF vs NEW METHOD

The proposed method leads to a better overall performance than the BWEF tool for the samples studied: a larger proportion of defects is detected (79% vs 70%) and the resulting $a_{90/95}$ is significantly smaller (8.3 mm vs 13.4 mm). The detailed analysis show that while detection percentages are quite similar for *near* surface or *inner* defects, they are significantly higher for defects located close to the back wall surface (*far side* defects). The analysis of subsets shows that this effect is only observed when no additional layer is present on the bottom surface. In this case, *far side* defects echoes are very close to the back wall and it is thus more challenging to isolate the defects with the BWEF tool.

The generation of C-scan images confirms that the new method leads to more accurate representation of defects (see *Figure 1*).

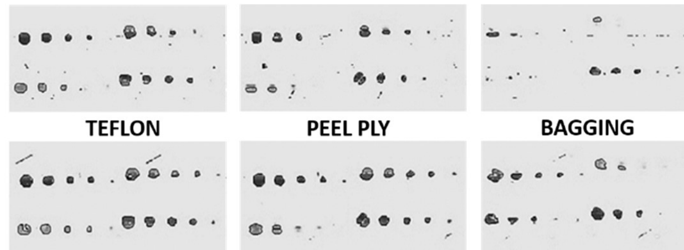

FIGURE 1: C-SCANS IN PLY DROP-OFF REGION: BWEF TOOL (top) vs. NEW METHOD (bottom).

The spline-based method seems to be more adapted to local thickness variations than the BWEF tool which uses a constant local gradient threshold to filter the back wall echo. Moreover, the subtraction of adaptive reference envelopes from each A-scan takes into account local signal peculiarities, e.g. widening of wall echoes due to outer layers with different acoustic impedances or ply drop-offs. This allows for the detection of low amplitudes echoes (small defects or weak acoustic reflectors) that would require very low detection thresholds in a method using static gates and would thus generate numerous false calls.

4. CONCLUSION

The novel defect detection method reconstructs the part back wall using spline smoothing and removes echoes corresponding to front and back wall by subtracting computed reference envelopes. A comparison of its performance against a commercial software showed that while maintaining a comparable performance near the front wall or inside the specimens, the new method is more effective for the detection of defects close to the back wall surface.

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