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Integration of reverse engineering and ultrasonic non-contact testing procedures for quality assessment of CFRP aeronautical components

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Abstract

Nowadays, the quality assurance of aeronautical components is a very crucial issue. Diverse defects can be generated during composite material components manufacturing such as voids, delamination, cracks, etc. The identification of these defects requires the use of different types of inspection methods. In this paper, two diverse non-contact inspection techniques, i.e. a laser-based reverse engineering method and an ultrasonic testing procedure, are integrated to provide a complete quality assessment of carbon fibre reinforced polymer components for applications in the aeronautical field. A custom made software code was developed in order to create a user interface allowing for the visualization and analysis of the reverse engineering and ultrasonic information for the detection of geometrical and internal flaws of the component under inspection.

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Keywords: Non-contact testing; Ultrasonic non-destructive inspection; Laser-based reverse engineering; Composite materials; Quality control

1. Introduction

One of the major advancements of the aircraft industry is the introduction of composite materials, in particular of carbon fibre reinforced polymer (CFRP) materials, for the construction of light weight aircrafts leading to a reduction of utilization costs and the increase of structure effectiveness [1].

Due to the non-homogeneous and anisotropic properties of composites materials, a large number of defects (e.g. delamination, cracks, voids, fibres fractures, etc.) can occur during composites manufacturing [2]. The damage development and propagation in composite components could eventually lead to the failure of the entire aircraft.

In this context, non-destructive inspection (NDI) techniques play a fundamental role for the detection of defects during both the manufacturing phase and the service life [3].

Currently, many types of NDI methods are available in the industrial field for flaw detection and analysis, but each method is used in separate laboratories that do not communicate with each other. Each NDI laboratory provides its NDI results on the inspected component without taking into account the other NDI inspections of the part [4-8].

The integration of different NDI results in a unique user interface can significantly improve the quality control of a component allowing for a complete evaluation of the possible defects [9-10].

In this paper, two NDI procedures, a laser-based reverse engineering (RE) scanning method and an ultrasonic (UT) non-destructive inspection technique, are considered for the quality assessment of a CFRP aeronautical component.

The RE method was employed using a laser scanner system in order to acquire the external geometry, whereas the UT NDI procedure was utilized to detect the internal material structure of the CFRP aeronautical component.

The acquired RE and UT data are subjected to a pre-processing phase in order to obtain data that are readable for the implementation of a new user interface.

A new custom made software code was developed in LabVIEW© environment to realize the integration between the

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improved RE and the UT data in a single user interface. In the implemented interface, the user can interactively visualize and manipulate the 3D model generated by the RE laser-based method and at the same time inspect the internal material structure of the CFRP component retrieving the corresponding UT information. Moreover, it is possible to inspect in more details a presumable defect by directly selecting the corresponding area on the integrated model.

2. The aeronautical component

The component considered for the inspection with the two non-contact testing techniques is a carbon fibre reinforced polymer panel utilized in the aeronautical field consisting of three sub-components (Fig. 1):

- the skin, that is the base panel with nominal dimensions equal to 304.8 x 914.4 mm
- two stringers with 5.7 x 914.8 mm nominal dimension.

Both the skin and the stringers are composed of CFRP prepreg plies made of CYCOM 977-2 epoxy matrix and Toray T300 carbon fibres. In particular, the skin is a laminate composed by 17 plies with the following symmetrical stacking sequence $[+45/90/0_2/-45_2/+45/0]_s$ whereas the stringers are constituted by laminates made of 11 plies symmetrically disposed with the following fibres orientation $[+45/90/0/-45/0]_s$. On the top and bottom surfaces of each laminate, a thin fibreglass ply is applied for corrosion protection.

3. Non-contact testing systems

A reverse engineering system based on the use of a laser scanner and an ultrasonic non-destructive inspection technique were utilized for the detection of the external geometry and the internal material structure of the CFRP component, respectively.

RE procedures based on laser scanner are commonly employed in the manufacturing sector for the acquisition of the geometrical features of a component in order to obtain a 3D digital model usable, e.g. for measurement and geometrical inspection, product repair, remanufacturing, etc. [11-14].

The functioning of a laser-based RE system is generally based on the triangulation method: a laser stripe is projected onto a surface and the reflected beam is detected by a camera obtaining a point cloud of the external surfaces of the scanned object [11]. The main advantages of this technique consist of the high acquisition velocity and part integrity assurance (there is no contact between the inspection probe and the part, thus assuring its integrity) [15, 16].

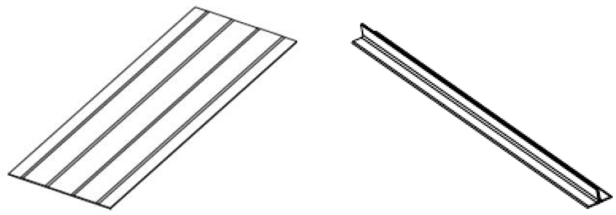
On the other hand, ultrasonic non-destructive inspection is the most utilized procedure in the industrial area for the quality control of components capable of detecting surface, subsurface and internal defects [17, 18]. This technique is based on the measurement of the variations of the reflected and/or transmitted UT energy generated by a piezoelectric transducer [19, 20]. Based on the information carried out by the UT signal, diverse types of flaws (e.g. crack location, flaw size, fibre orientation, etc.) could be achieved. The UT NDIs are capable to easily and rapidly inspect the part considering only one surface and detect defects in a fast and effective manner [21, 22]. Moreover, the UT NDI can be applied for the metrological characterization (e.g. thickness estimation) of a component.

3.1. Laser-based RE system

The laser-based RE scanning system considered in this paper is the VI 9i laser scanner by Konica Minolta (Fig. 2). It offers different measurement ranges and performances (accuracy and precision) for three different interchangeable lenses (tele, middle and wide) for the two selectable scan depth distance as summarised in Table 1.

In order to acquire the entire geometry of the aeronautical CFRP component, the sample was positioned in two diverse positions: front and back side. The laser was placed at a scan distance equal to 600 mm and a telephoto lens was utilized for the point cloud acquisition due to its high precision and accuracy levels.

The surfaces of the CFRP aeronautical component were acquired by performing 46 scans obtaining a highly dense point cloud with over 12 million points.

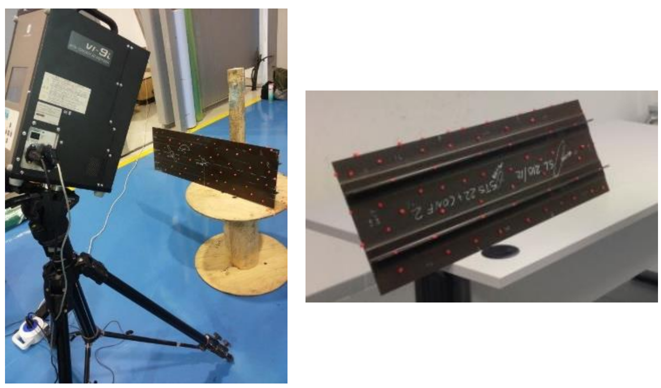


(a) (b)

Fig.1. Geometrical model of the aeronautical CFRP component: (a) the skin and (b) the stringer.

Table 1. The Konica Minolta laser scanner characteristics.

	Distance (mm)	Tele (mm)	Middle (mm)	Wide (mm)
Measurement range	600	111x83x40	198×148×64	359×269×108
	1000	185×139×110	329×247×176	598×449×284
Precision	600	±0.008	±0.016	±0.032
	1000	±0.024	±0.048	±0.096
Accuracy	600	±0.05	±0.10	±0.20
	1000	±0.10	±0.20	±0.40



(a) (b)

Fig. 2. Laser-based RE system: (a) front and (b) back side position of the CFRP aeronautical component.

3.2. UT NDI system

The UT NDI system (Fig. 3) utilized for the acquisition of the internal material structure of the aeronautical CFRP component is developed at the Fraunhofer Joint Laboratory of Excellence on Advanced Production Technology, Naples, Italy [20 - 22] and consists of:

- Oscillator/detector for the UT probe excitation and the detection of the UT returning signals
- Transmitter/receiver UT immersion probe
- Digital oscilloscope connected to the oscillator/detector and to PC
- 6-axis robotic arm for the UT probe displacement
- PC utilized for the UT waveform acquisition and processing as well as the UT probe displacement control

A pulse-echo UT technique was utilized for the detection of the entire UT waveform (full volume – FV) in the propagation direction (z-direction) during x-y scanning of the part surface [21]. The FV UT scan was executed in water using an immersion UT probe with a frequency of 5 MHz and a diameter of 4 mm covering an area of 100 mm x 300 mm with a scan step equal to 1 mm. The UT data, obtained after the UT scanning procedure, were stored in a volumetric file.

4. Pre-processing of the RE and UT data

The acquired RE point cloud and UT data were subjected to a pre-processing phase in order to obtain data suitable for the new software code development.

4.1. RE data pre-processing

As the output of the RE scanning process corresponds to multiple point clouds, the first step of the pre-processing phase is a point set registration corresponding to the alignment of the diverse acquired point clouds. Markers (red points in Figure 2) were applied on the aeronautical CFRP component in order to easily align the obtained multiple scans. After this step, a single point cloud containing the x, y and z information of the part surface was achieved.

This point cloud was then improved by using diverse tools: deletion of the unnecessary points, point cloud filtering, noise and overlap reduction aimed to reduce the high volume of the obtained RE data.

The resulting pre-processed point cloud was used to generate the STL file with a number of triangles over 2 million. Generally, an STL file approximates a point cloud with triangles defined by a perpendicular direction and three points representing the vertices of the triangle in the 3D coordinate system, obtaining the so-called "polygon mesh/polygonal model/mesh".

The obtained polygonal model of the CFRP component was subjected to a repairing and optimization phase including smoothing of the triangles, holes and gaps filling for the reconstruction of the incomplete triangles, and polygon triangle reduction (Fig. 4).

4.2. UT data pre-processing

The volumetric UT file obtained during the UT scan procedure is constituted by the whole set of full digitized UT waveforms for each material interrogation point.

For the UT data file pre-processing, a custom made software (RoboTest© v.2.0, developed in LabVIEW© environment) was utilized [23]. This software is capable to provide single or multiple UT images of the internal structure of the CFRP component under examination. The pre-processing phase starts with the selection of the typical UT waveform represented with a diagram where the x axis corresponds to the time of flight expressed in seconds whereas the y axis corresponds to UT signal in Volt/div (Fig. 5).

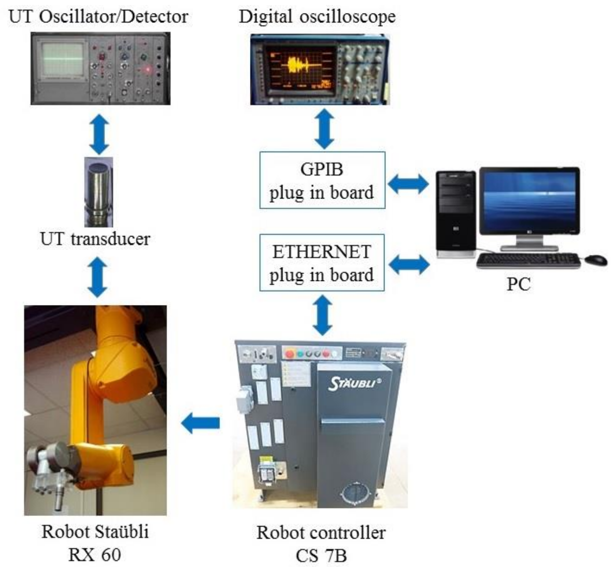
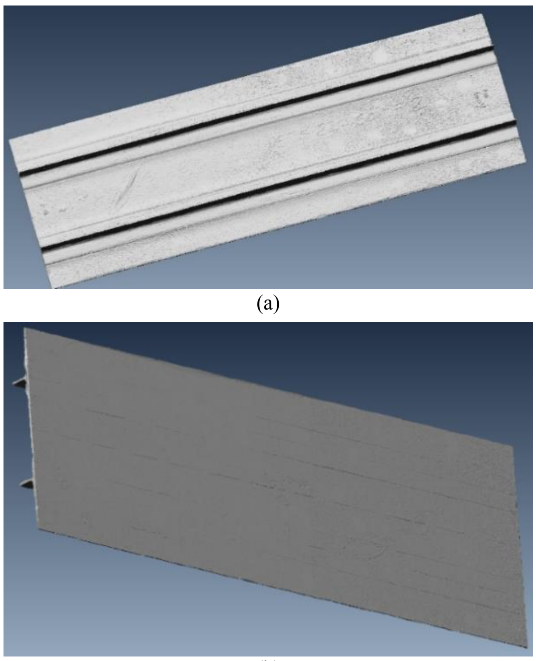


Fig. 3. UT non-destructive inspection system [20].



(a)

(b)

Fig. 4. STL of the aeronautical CFRP component: view of (a) the stringers and (b) the skin.

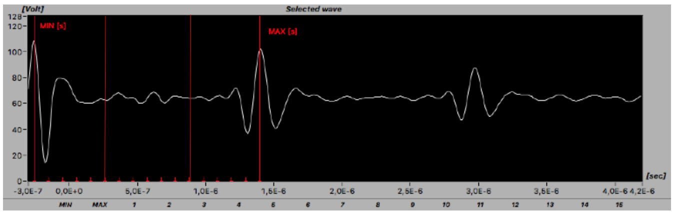
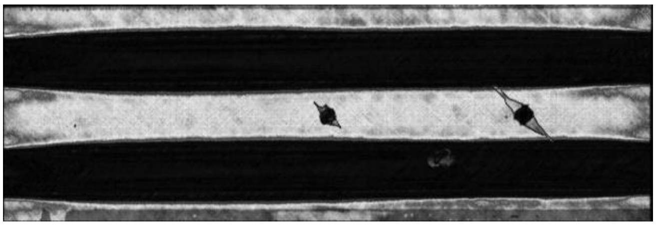
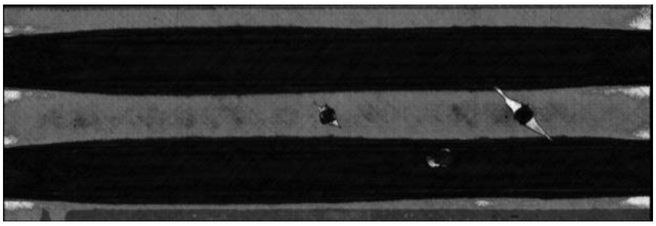


Fig. 5. Typical UT waveform of the aeronautical CFRP component.



(a)



(b)

(c)

Fig. 6. Three UT images of the material structure of the CFRP aeronautical component. Each UT image relates to 1/3 of the component nominal thickness.

By using a time gate subdivision (red lines), it is possible to divide the UT signal in a desired number (from 1 to 16) of equal sub-gates that will be utilized for the UT images generation. The time axis represents the UT propagation in the thickness direction of the CFRP component: in this way, each sub-gate width describes the internal material structure of the corresponding thickness portion of the CFRP component. In Figure 5, three equal subdivisions of the UT signal are chosen and the corresponding UT images are shown in Figure 6 where each UT image (a, b, c) corresponds to 1/3 of sample thickness.

5. Integration of the UT and RE data

The integration between the UT and RE data was realized through a new custom made software code development (Fig. 7) added to the previous described software "RoboTest©". Diverse steps are required for the software code implementation and are summarized below:

1. STL file (obtained from the RE scanning procedure) origin modification
2. STL 3D model import
3. Selection of the RE scanned point on the imported STL 3D model and relative UT waveform reclaim from the UT data file
4. UT image generation of the internal structure of the CFRP component
5. Projecting and wrapping of the generated UT image on the STL 3D model
6. Procedure iteration with the repetition of the steps 2, 3, 4 and 5.

5.1. STL file origin modification

In order to integrate the results obtained with the two diverse non-contact testing systems, the RE and UT data need to have the same origin in a unique 3D coordinate system. For this reason, the origin of the STL file was translated and fixed into a corner of the CFRP aeronautical component and the x and y axis were aligned to its two main borders following the same alignment of the UT scan procedure. Therefore, a correspondence between the coordinates of the STL file and the coordinates of the UT scan points was established.

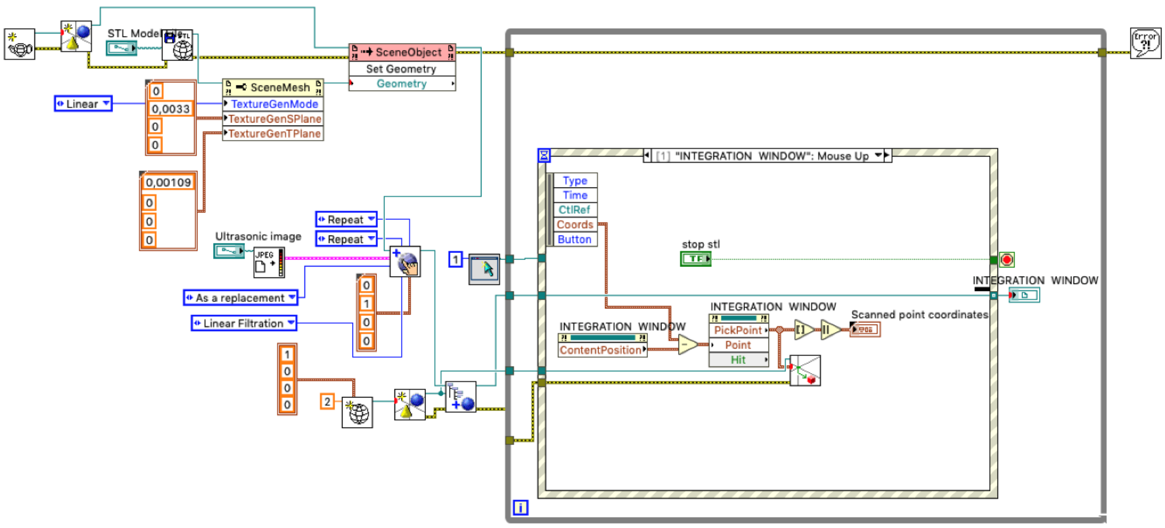


Fig. 7. STL 3D model import.

5.2. STL import

The first task performed by the new software code is to import the STL file. A pop-up window opens asking the path where the STL file is stored and in few seconds the 3D model is shown in the appropriate window (Fig. 8). In this window, an operator can visualize and manipulate the 3D model using the interactive user interface.

5.3. RE point selection and UT waveform reclaim

By using a red marker, a user can choose and select a point on the imported STL model and, considering its x and y coordinates, retrieve the corresponding UT complete waveform that will be plotted on a two-axis graph (Fig. 8).

5.4. UT image generation

As explained in sub-section 4.2, UT images can be generated by a user selection of the time gates on the chosen UT waveform.

Each pixel of the generated UT image has a grey tone value proportional to the peak amplitude of the corresponding UT waveform in that interrogation point. The overall grey tone scale ranges from 0 (black) to 255 (white), which are the minimum and maximum limits of peak amplitude observed in the set time-gate over all the scan points (Fig. 9) [21-22].

5.5. Integration of the RE and UT results

The integration of the RE and UT data is realized by projecting and wrapping the generated UT image on the STL model by matching the x and y coordinates of the scanned point with the relative pixel of the UT image. Therefore, an integrated 3D model is created containing both the 3D geometrical representation (provided by the STL file) and the UT information (Fig. 10).

5.6. Iteration of the integration procedure

The explained procedure can be reiterated selecting a new scan point on the STL model integrated with the previous projected UT image (Fig. 10). This represents a huge advantage for the user who can choose the new point directly by visualizing the UT scan that allows to effectively highlight possible component defects.

6. Conclusions

A new custom made software code was implemented for the realization of a user interface operating for the complete quality assessment of a CFRP aeronautical component.

Two diverse non-contact testing techniques, a laser-based reverse engineering scanning method and an ultrasonic non-destructive inspection technique, were considered for the detection of the external geometry and the internal material structure of the CFRP component, respectively.

The RE technique was based on the use of a laser scanner employed for the acquisition of the geometrical features with the aim to obtain the 3D digital model of the CFRP component.

The applied UT NDI procedure is based on a pulse-echo UT scanning technique in water through the use of an immersion UT probe. The UT data were utilized to inspect the internal structure of the CFRP component by visualizing the UT images provided by the software.

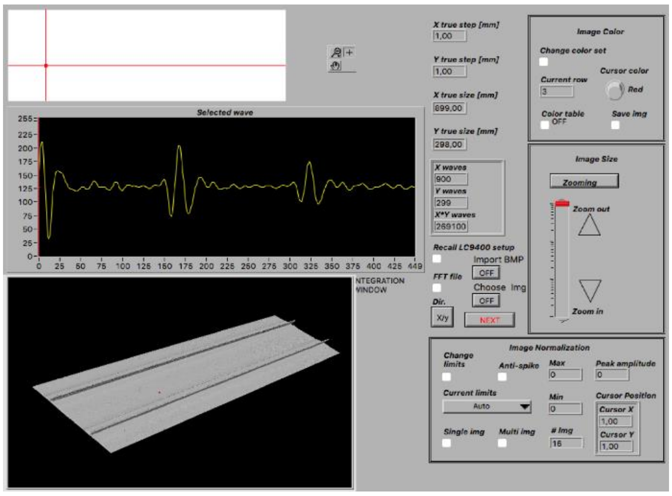


Fig. 8. STL 3D model visualization.

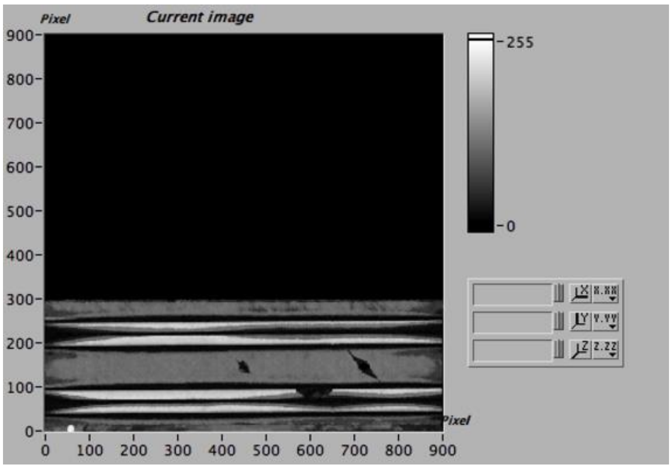


Fig. 9. UT image generation.

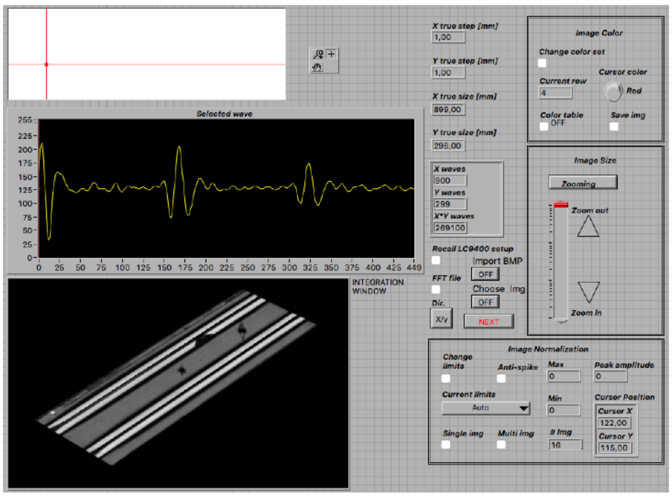


Fig. 10. RE and UT integration interface.

The results of the RE and UT procedures were pre-processed and then exploited to implement a new user interface containing the information of both non-contact testing methods.

In the new interface, a user can interactively handle the 3D digital model, choose a point on it and retrieve the corresponding UT waveform. The UT information was used to generate UT images describing the internal structure of the CFRP component.

The developed software code represents a remarkable tool for the inspection of a part because two diverse non-contact inspection techniques were considered simultaneously, allowing the detection of defects and their position in the component thickness.

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