On-line pulse echo ultrasonic inspection methodology for aeronautical composite structures during Full Scale and Flight Tests programs

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Abstract. Composite design of aeronautical structures is today mandatorily supported by test evidences through Structural Tests programs and service experience. These test programs consisting of subjecting the structure to static, fatigue and damage tolerance conditions (including the environmental effect) have to demonstrate the strength evidence under all critical load cases and associated failure modes in agreement with airworthiness regulations. These test programs also include a detail inspection plan to detect and monitor any structural damage whenever produced. Conventional Pulse echo ultrasonic inspection (PE UT) is nowadays the most reliable composite inspection technique and widely used for these inspection programs. This paper deals with the development of an effective inspection process based on ultrasonic inspection to be applied into Structural Test Programs and aiming to retain the unquestionable advantages of classical PE UT such as sensitivity, reliability or robustness but also adding new potential features to the technology, for example the capability for an immediate detection of the damage, the possibility to associate the damage detection/progression with corresponding load values, or also the option to perform a permanent inspection of hidden or very difficult accessible areas. A summary of the basic functional & implementation requirements, examples of the integration procedures in Manufacturing and FAL, and inspection results constitutes the content of this paper.

Introduction

Design of aeronautical composite structures is today mandatorily supported by on ground full scale structural tests and flight test programs. These complex test programs prepared in agreement with airworthiness regulations have to demonstrate the structural integrity under all critical load cases and environmental effects, and include in their schedule a detailed nondestructive inspection (NDI) plan to detect and monitor any structural damage whenever is produced. The longitudinal ultrasonic waves by pulse echo technique (UTPE) is actually nowadays the most reliable NDI technique for composites and that is why it is widely used inside these inspection programs.
In this paper is presented the work done for the adaption of this conventional and robust NDI technique – pulse echo- to online inspection structural test scenarios wherein new requirements related to the solid integration and environmental resistances will be necessary to add. The online inspection of the structures without the need to stop the tests aim to contribute to further potential features for the technology as for example the capability of the immediate detection of the damage, the possibility to associate the damage detection/ progression with corresponding load values, or also the option to perform a permanent inspection of hidden or very difficult accessible areas.

Fig. 1. Example of certification structural tests in composite structures.

Main requirements of the application

The search and identification of the requirements constitutes an essential part of this development. Similar to any structural health monitoring technologies aiming to inspect structural parts, the identification of the specific requirements would require from the particular and precise analysis case by case. This paragraph gathers the general requirements for nondestructive inspection method based on longitudinal ultrasound working online in this application, in order to select and prepare the most important feasibility tests for the different solutions. It is proposed to group the requirements into five different families:

- Performance requirements. They are similar to conventional NDI in composites structures and comprise requirements such as sensitivity, resolution, capability to characterize and assess the defects (type, size, position, etc.) and under a certain and minimum defined probability of detection and confidence level (90/95).
- Integration requirements. They refer in general to the compatibility of the solution proposed and its integration process with all the steps in the life of structural and flight tests. Example of some requirements to match inside this group are referring to simplicity of the installation process (manufacturing phase or FAL), un-intrusiveness or low-mass of transducers, connections and cables.
- Engineering requirements. Inside this group, there are requirements such as the capability of the technology to access to the inspection of difficult accessible areas,
hidden artificial or impact damage, the challenge to provide the inspection data synchronized with the level of the load or the need to repair the technology in case of damage.

- **Operational requirements.** This family includes the robustness of the technology in structural or flight test operation (environmental conditions such as loads, temperature change, vibrations, etc.), the preparation of right procedures to be used for maintenance operators to visualize and retrieve online inspection data, the self-diagnostic capability for sensors and UT interrogator or the compatibility of the technology with other systems.

- **Commercialization requirements.** They are related to the low-cost of the technology (material, installation procedure, acquisition unit) or the availability/maturity of the technology in the market to be applied in the scenario proposed under minimum or negligible modifications.

**Proposed solution**

Based on the previous requirements and especially because of the need of using a mature inspection concept, the proposed solution consists of the integration onto the structures of effective but also inexpensive piezoelectric transducers.

Classically a piezoelectric NDT transducer is composed of three main components:

- The piezo ceramic resonator which is usually a piezo ceramic of the “soft” type resonating at the center of the desired transducer frequency band.
- The acoustic impedance matching section, with normally only one matching layer and used for increasing the transducer efficiency and frequency bandwidth.
- The backing, used to improve the transducer bandwidth by absorbing the resonator back emission.

The design and construction of these transducers is a standard with some differences among the different manufacturers as for materials to use, electric matching networks, shape and dimensions.

The proposed solution requires a special selection and configuration for these three elements and always compatible with the processes and parts to be inspected. As in this application the ultrasound transducers are working permanently onto the structure it is of vital importance to ensure a solid bonding among them, with low mass, and the joint as a whole has to resist all elongations, compressions or strong vibrations that will take place in the structure. The coupling also has a key effect on the inspection result and need to be effective and uniform when structures are in rest and also when subjected to all mechanical solicitations such as tension, bending, buckling, torsion or thermal expansions. The low transducer mass and size reduction will be accomplished by eliminating the transducer case and connector and, in some cases even the backing section. The case and connector will not affect the transducer performances but the backing is critic concerning the bandwidth and so the temporal length of the pulse-echo signals. Hence the backing will be only removed when accepted by performance conditions. Another key design point is the electric connection of the two transducer faces. Dealers have different ways to make the connections. The solution adopted for this application consists of the use of the expander copper foil normally cured with composite layer for lightning protection issues as acoustic matching layer. Doing so, the matching layer will perform two tasks, firstly the acoustic impedance matching between the piezo ceramic and the tested composite structure, and secondly the connection of the piezo ceramic front face to ground. Finally with regard to
the transducer aperture and frequency, these are customized design parameters that will be chosen depending on the inspection requirements. In principle the adopted solution is feasible to work at any frequency and with classical apertures and shapes.

Next figure shows the scheme of the design proposed.

![Diagram of the design proposed](image)

**Fig. 2.** Design proposed.

**Simulation**

Previous to any implementation trial, the transducer concept was simulated with KLM model. The parameters of the materials used in the model are shown in next table.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density (g/m³)</th>
<th>Velocity (m/s)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP</td>
<td>2000</td>
<td>2900</td>
<td>6</td>
</tr>
<tr>
<td>Expanded copper foil</td>
<td>5000</td>
<td>1800</td>
<td>λ/4</td>
</tr>
<tr>
<td>Piezo ceramic PZT 5A</td>
<td>7700</td>
<td>4300</td>
<td>λ/2</td>
</tr>
</tbody>
</table>

**Table 1.** Parameters of the materials used in the model.

After simulation, first manufacturing trials were done and the experimental signal was compared with model results. The graphs below show cross correlation between the calculated and the experimental back wall echo for two frequencies 5 MHz and 2.25 MHz.

![Graphs showing correlation](image)

**Figure 3.** Correlation between model and experimental results.
Application procedures

The simple design proposed opens different possibilities for the implementation of the transducers to the structures. Two approaches have been used to this end, both requiring the previous selection of the right copper mesh in function of the inspection frequency used. The first one consists of integrating the piezo ceramics during the composite manufacturing process and locating them on the monitoring areas. This process would enable not only the location of the transducers on pre-preg material but also the preparation of a compatible cable network and connectors to interrogate the different transducers.

![Figure 4. Application procedure in composite manufacturing process.](image)

The second procedure consists of the previous preparation of the set piezo-copper mesh by polymer infiltration and then the bonding of the joint to the structure to be inspected. This solution is adequate for structures already manufactured but need of the right adhesive solution to match with elastic joint requirement and proper ultrasonic couplant.

![Figure 5. Application procedure by surface bonded.](image)

Experimental trials

Experimental trials comprise the two application procedures, for manufacturing and bonded surface.

a) The trials in manufacturing consisted in the production of two composite laminates with intermediate layer of adhesive. In the first panel 5 MHz transducers were
implemented and the second panel 2.25 Hz. The acoustic impedance matching was adapted for each case. The next pictures show the dimension of the panels, the position of the transducers on the panel and example of the signal of two transducer 2.25 MHz and 5 MHz, after manufacturing. The proper signal in 100% of the transducers embedded on the surface demonstrated the robustness of the method.

b) Bonding application trials were carried out firstly on test coupons (tension and compression) and secondly on a structural test panel that will be tested under shear static and fatigue load conditions in the short future. The trials on the coupons were used to demonstrate the consistency of the back wall echo signal for two frequencies, 5 and 2.25 MHz, and also to evaluate the resistance and elasticity of the transducer-material joint. Further to the panel, the transducers were installed in different positions close to impacts and artificial defects with the purpose to detect and follow the growth of this damage during test phase. The next pictures display the test coupon working in fatigue conditions and shear structural test with the position of the different transducers.
Summary and future work

Ultrasonic pulse echo on composite structural tests is feasible to be permanently implemented in test structures for online inspection. This technology that is today considered as the most adequate for the inspection of composites can result very convenient also when applied directly on the structures for the monitoring of hot spot composite areas such as stringer run out, impact damage or artificial defects specially if they are located in non-accessible areas. Two integration procedures were proposed and successfully tested in the lab. Both of them use expanded copper foil as acoustic impedance matching what actually is especially convenient for manufacturing.

As for the work to do for the next future it is important to mention the complete demonstration of the durability of the transducers during the complete life of an structural test including immersion cases, the design of new trials in production wherein not only the transducers but also the cable networks and connectors are embedded in the parts and the extension of the concept to other type of transducers such as flexible piezo composites, the incorporation of delays or phase array technology.

References