Non Contact Ultrasonic Techniques for Composite Material Diagnostics in Aeronautics Applications

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Abstract. The aim of this paper is to check the potential of "one side" non contact ultrasonic techniques with respect to the transmission configuration, in order to improve the accessibility of the inspection, e.g. on installed components, without decreasing its resolution and accuracy.
To this purpose the following ultrasonic transducer configurations have been considered: transmission, pitch&catch and delta. They have been applied to composite materials for aeronautics applications, in order to identify defects and flaws.
Carbon Fiber Reinforced Polymer (CFRP) panel and honeycomb specimens for aeronautic applications have been studied.
Two different ultrasonic systems are analysed in this paper, based on electro-capacitive and piezoelectric probes respectively. A scanning frame has been realized in order to place the various types of transducers in the different configurations with a fine adjustments of their position and orientation.
Delta configuration has been here investigated for the first time (to the author's knowledge) using non contact probes.
Potentials and performance of the studied techniques have been evaluated in terms of Signal to Noise Ratio (SNR) and defect identification capabilities. Furthermore, an experimental parametric study has been performed in order to define the optimal set-up of the measurement chain, in particular concerning the probe positions.
Moreover this work leads to discuss about limits and breakthroughs of non contact ultrasonic techniques and their effective implementation for industrial applications.

Introduction

Composite materials are widely utilized in several engineering fields because of their low weight and high structural performances [1]. For these reasons they are applied for aeronautics purposes.

From this point of view, the necessity of diagnostics and defect identification is enhancing for the urgent requests of integrity and quality assessment.

In this horizon, non contact ultrasonic techniques [2,3,4] have an important challenge with respect to the traditional contact techniques and the competitive non contact ones, such as X rays etc.. Their critical points are well known and they are mainly connected to the signal energy loss at any encountered air/material interface, due to the gap between the acoustic impedances, and the significant attenuation in air of the ultrasonic signal, specially in the high frequency range.

These factors significantly decrease the Signal to Noise Ratio (SNR) with consequent increase of measurement uncertainty.

In this paper the results measured on composite panels for aeronautics applications are going to be presented. The aim of this paper is to check the potential of “one side” non contact ultrasonic techniques with respect to the transmission configuration, in order to improve the accessibility of the inspection without decreasing its resolution and accuracy.

However, measurement performances and accuracy have to be carefully evaluated, because of important signal energy losses and reduced SNR generated by the absence of contact between probes and object.

Therefore the following ultrasonic transducer configurations have been considered: transmission, pitch&catch and delta.

1. Description of the investigated non contact ultrasonic configurations.

1.1 Transmission configuration

The transmission technique is a widely used one [5] as it is the most reliable, having intrinsically higher spatial resolution and SNR. It provides information about the travel times with the sample thickness and its echoes. Moreover it offers an integral of the sample response across its thickness, so that the decrease of the acquired signal amplitude reveals the presence of a discontinuity within the sample itself (see Figure 1).

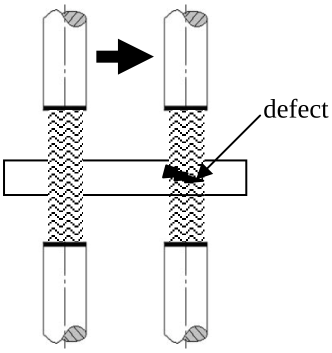

Figure 1. Inspection through transmission configuration for non contact ultrasonic technique.

This classical configuration has been reported in this work in order to compare it with the “one side” non contact ultrasonic techniques, which intrinsically have a lower resolution, but their important advantage is the possibility to have one side access to the sample which is crucial for applicability on complex geometry and installed components.

1.2 Pitch&Catch configuration

The Pitch&Catch technique is an application of ultrasonic testing where the ultrasonic beam follows a somewhat complex path (i.e. the beam is reflected one or more times before reaching the receiver). The two broad categories of Pitch&Catch techniques are *direct* and *indirect* methods. For *direct* Pitch&Catch, the receiver is placed where the reflected beam is expected if there are no defects. The presence of a defect is found if the signal is not detected, where it is expected, or if the signal strength is reduced. Conversely, for the *indirect* Pitch&Catch technique, the receiver is placed where the reflected beam is expected if a defect exists. Figures 2 and 3 illustrate the application of the *direct* and *indirect* Pitch&Catch techniques, respectively.

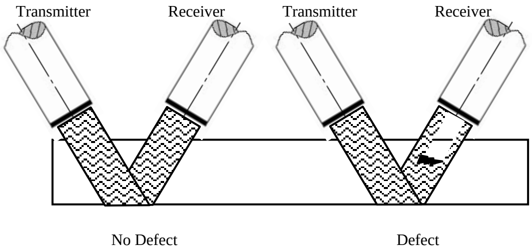

Figure 2 – Scheme of *direct* Pitch&Catch technique (signal amplitude is attenuated).

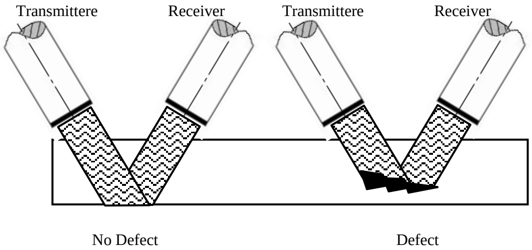

Figure 3 – Scheme of *indirect* Pitch&Catch technique (time of flight is reduced and the signal amplitude can be enhanced).

Typically, the *direct* Pitch&Catch technique is less prone to error caused by defect orientation and other defect characteristics. On the other hand, according to literature [6], the *indirect* Pitch&Catch technique is generally faster, but may miss some defects because of defect orientation.

1.3 Delta configuration

The Delta technique is a testing technique which utilizes the scatter or edge waves produced by the presence of a flaw. This technique was conceived for the water immersion inspection [7], but in this research work, it has been exploited for the first time with air-coupled transducers. In this technique, as shown in Figure 4, the transmitter transducer is placed in transmission configuration, but the receiver is placed obliquely on the same side of the emitter, in order to let it acquire the scattered waves generated by the defect.

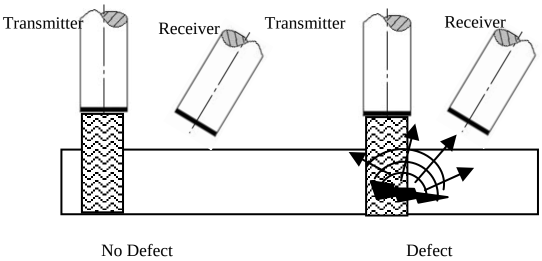

Figure 4. Scheme of the proposed Delta configuration.

2. The experimental setup.

The developed workbench is constituted by three parts:

- The ultrasound generation and acquisition system;
- The scanning frame with the sliding transducers holders moving in X and Y axis by stepper motors;

- The control unit governs and synchronizes the acquisition of the ultrasound signals with the movement of the scanning frame; furthermore it provides the output data, e.g. the maps of the monitored parameters.

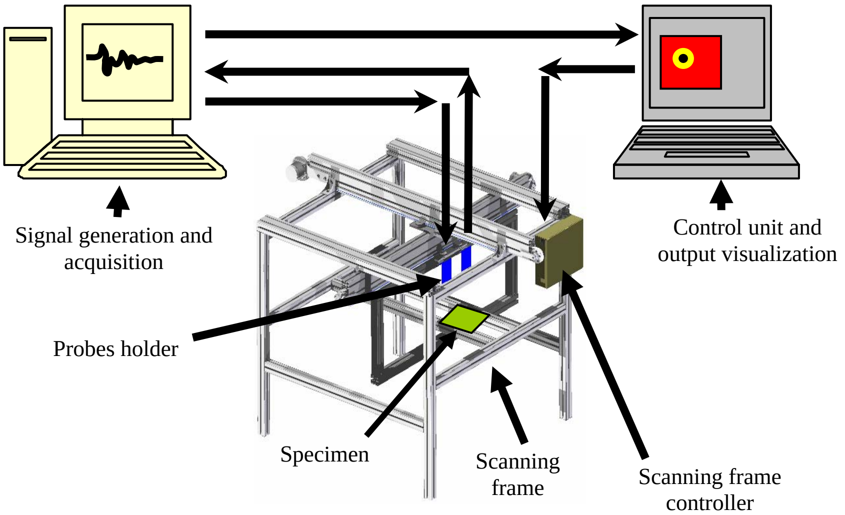

Figure 5. Sketch of the test bench main components.

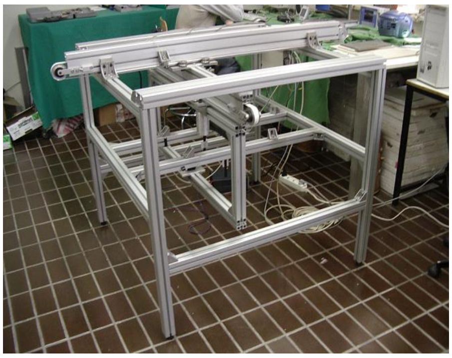

Figure 6. Scanning frame.

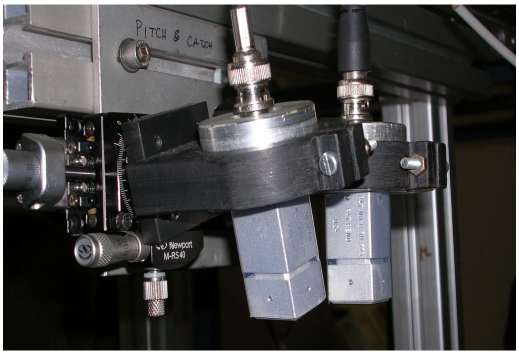

Figure 7. Transducers holder.

Two different ultrasonic systems have been tested in different configurations. The characteristics are reported in Table 1 [8,9].

Table 1. Characteristics of the tested ultrasonic systems.

	Electro-capacitive transducers	**Piezoelectric transducers**
– **Shape of the active area**	– Round	– Square
– **Dimension of active area**	– ϕ = 22 mm	– Square side 12 mm
– **Type of emitted ultrasonic signal**	– Burst	– Chirp
– **Max excitation voltage**	– 275V pk-pk	– 300V pk-pk
– **Characteristics of the emitted ultrasonic signal**	– Frequency 200 kHz; – Duration 12 µs	– Central frequency 422 kHz; – Bandwidth 175kHz; – Duration 100 µs
– **Acquisition board characteristics**	– Resolution 10 bit; Sampling Frequency 100MHz	– Resolution 12 bit; Sampling Frequency 20MHz
– **Tested specimen**	– Honeycomb	– CFRP panel

One is based on piezoelectric transducers and works at relatively high frequency (422 kHz), while the other one uses electro-capacitive probes at 200 kHz.

Because of the different frequency and characteristics, the piezoelectric probes have been used to analyse a thin CFRP sample, while the electro-capacitive probes, having a lower frequency and having improved sensitivity in the receiver, have been applied on a thicker honeycomb panel (see Par.3).

The acquired ultrasonic signal is post-processed using cross-correlation algorithms, considering a reference signal or the cross-talk. The integrated responses [9], the amplitudes and the times of flight [10] have been measured over Cartesian grids. These scalar quantities are then represented as 2-D maps of the specimens for the defect identification.

The resolution of the obtained map depends not only on the probes, but also on the spatial resolution of the scanning frame which, in this case, is of 1 mm for each translational directions.

3. Specimens

The composite material specimens have been chosen among those of interest for the aeronautics applications.

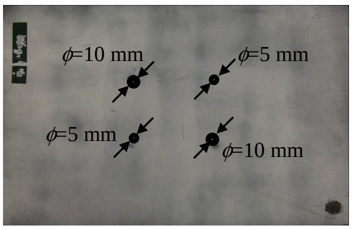

Figure 8. CFRP sample, with the defects localization.

A carbon fiber reinforced polymer (CFRP) sample has been studied with the piezoelectric probes. This sample has the following dimension 200 mm x 300 mm x 3 mm, with four circular Teflon inclusions inserted with different diameter dimensions (10 mm and 5 mm) in the central layer of the stratified medium (Figure 8).

Moreover an honeycomb panel, having the dimension of 200 mm x 300 mm x 18 mm has been inspected (Figure 9 and Figure 10). In this case the panel has two circular defects of about 12 mm diameter placed within the upper skin.

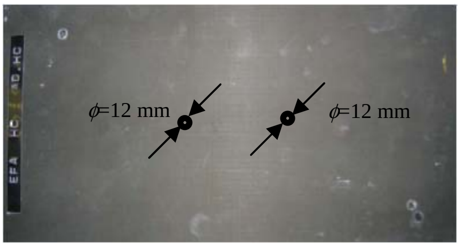

Figure 9. Honeycomb sample, with the defects localization .

Figure 10. Side view of the honeycomb sample.

4. Analysis of results

The transducer setup parameters: distance between emitter and receiver *b*, relative distance between transducers and sample *h*, relative angles between the transducer receiver and the normal to the specimen θ (Figure 12 and Figure 14), have been parametrically analyzed in order to evaluate the optimal configuration. To this aim the following δ parameter has been introduced in this study:

$$\delta = \overline{IR}_{no-defect} - \overline{IR}_{defect} \qquad (1)$$

where:

- $\overline{IR}_{no-defect}$: average integrated response on a non defect area [dB];
- $\overline{IR}_{defect}$: average integrated response on a defective area [dB];
- Integrated Response: integral area under the cross-correlation curve, inversely proportional to the signal attenuation.

δ is therefore proportional to the capability of the system to correctly identify and locate the defect: in practice this parameter expressed in dB, highlights the defect visualization capability of the measurement procedure. δ has been evaluated varying in a parametric way the investigated configurations, in such a way as to determine the optimal setup in correspondence to higher δ absolute values. Repeated measurements showed a repeatability in δ measurement of about 1 dB.

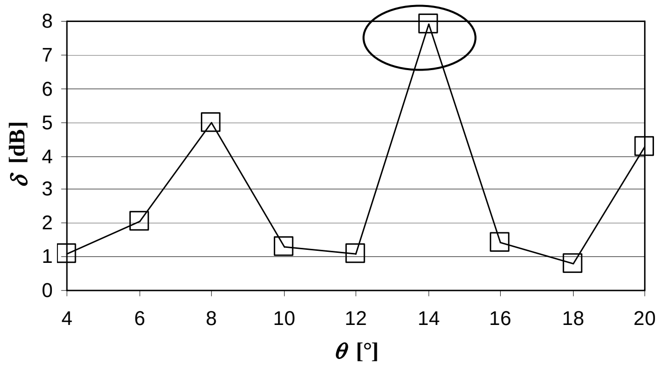

Figure 11. Parametric study in function of relative angle between the probe in direct Pitch&Catch and the normal to the inspected plane; b =60mm, h= 90 mm.

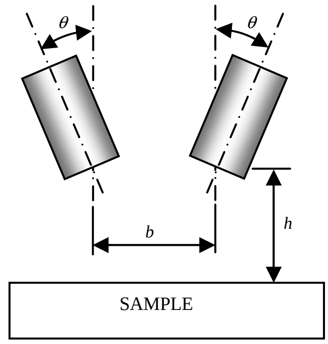

Figure 12. Direct Pitch&Catch transducers setup parameters

As an example, in Figure 11, it is possible to note that δ has a maximum value at an angle between the emitter and the normal with the CFRP specimen surface at 14° in direct Pitch&Catch. The same value results to be the optimal one for the Delta configuration applied at the same specimen (Figure 13).

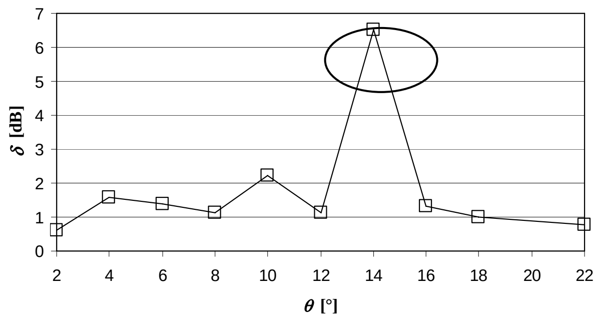

Figure 13. Parametric study in function of relative angle between the transducers in Delta configuration; b=60 mm, h=90 mm.

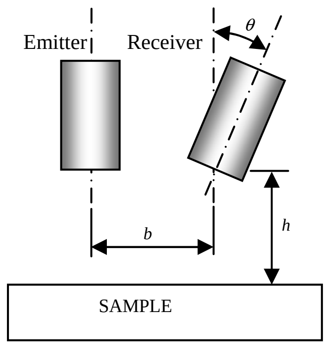

Figure 14. Delta transducer setup parameters.

For synthesis not all the parametric curves are shown as a matrix of more than 70 tests was performed for each configuration to statistically cover the possible combinations. Only the final optimal values of the transducer setup parameters are summarized in the following table (see Table 2) for the inspection of the CFRP panel using the piezoelectric probes, together with the achieved measurement parameters.

Table 2. Optimal transducer setup for Pitch&Catch and Delta technique applied on the CFRP panel.

	Pitch&Catch technique	**Delta technique**	**Transmission technique**
– **Relative angle between the transducer and the normal to the specimen** $\boldsymbol{\theta}$	– 14°	– 14°	– 0°
– **Distance between the transducers and the specimen** ***h***	– 90 mm	– 90 mm	– 50 mm
– **Relative distance between the transducer** ***b***	– 50 mm	– 65 mm	– -
– **SNR on the single acquisition**	– 15 dB	– 9 dB	– 19 dB
– $\boldsymbol{\delta}$	– 7 dB	– 6 dB	– 18 dB
– $\boldsymbol{\delta}$ **repeatability**	– 1 dB	– 1 dB	– 0,5 dB

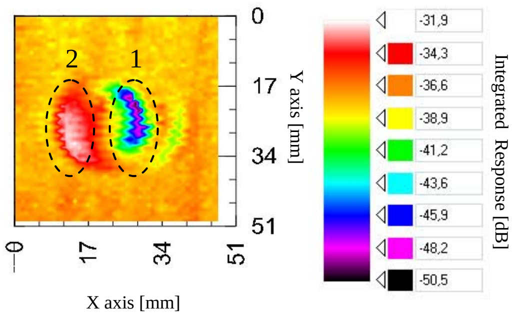

Figure 15. Detail of the acquisition with Pitch&Catch technique on the CFRP panel; the map reports the Integrated Response (δ= 7 dB).

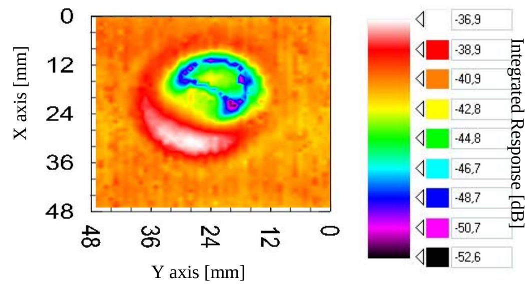

Figure 16. Detail of the acquisition with Delta Technique on the CFRP panel; the map reports the Integrated Response (δ= 6 dB).

Then the comparison between the Delta and Pitch&Catch techniques have been realized considering a defect of 10 mm of diameter.

As it is possible to note from the detail of the maps, shown in Figures 15 and 16 and which report the integrated response, the Delta technique provides an enhanced visualization of the defect edges with respect to the Pitch&Catch one. This is probably due to the fact that the Delta technique is more sensitive to border effects on the defect edges caused by localized scattering phenomena. However this also induces a visualization of defect with a dimension larger than the real one (more than the double in this case).

On the other hand, the results in Pitch&Catch could be influenced by the relative position between the probes and the defect. It could happen that the configuration shifts from *direct* (see Figure 2, signal amplitude attenuated) to *indirect* (see Figure 3, signal amplitude enhanced), while the scan is performed over the defect. As a consequence the defect is visualized by an area with reduced IR (area 1 of Figure 15) combined with an area with amplified IR (area 2 of Figure 15). Similar phenomena can be partly observed also in Delta configuration. However, these observations should be further investigated.

If the results are compared with the transmission analysis, it is possible to note that here the defect is even better described, thanks to the strong attenuation due to the defect presence (see Figure 17). In this case the SNR in the signal increases to 19 dB and δ reaches values of 18 dB. The transmission configuration can be thus confirmed as a reference for defect detection, but with limited in-field applicability due to the required accessibility on both sides. In this case also border effects generate a measured defect dimension larger than the real one (about 1,5 times).

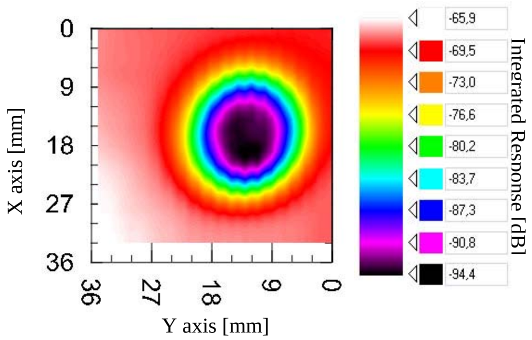

Figure 17. Detail of the transmission inspection on CFRP panel (δ= 18 dB).

With the honeycomb sample, which has higher thickness, the one side inspection with piezoelectric transducers has been more difficult as they work at higher frequency. The electro-capacitive transducers have allowed a more accurate inspection. In this case the SNR was about 27 dB, but δ decreased to 3 dB. The Pitch&Catch investigation results are reported in the following Figure 18. Also in this case the optimization study was performed. The final setup is described in Table 3.

Table 3. Optimal electro-capacitive transducer setup for Pitch&Catch applied on the honeycomb panel.

Pitch&Catch technique			
– **Relative angle between the transducer and the normal to the specimen θ**	– 15°	– **SNR on the single signal**	– 27 dB
– **Distance between the transducers and the specimen *h***	– 180 mm	– δ	– 3 dB
– **Relative distance between the transducer *b***	– 110 mm	– δ **repeatability**	– 0,6 dB

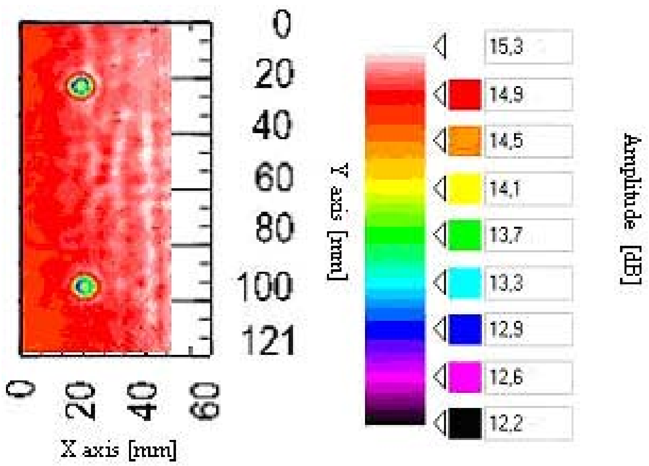

Figure 18. Attenuation map measured on the honeycomb panel using electro-capacitive probes in Pitch&Catch (δ= 3 dB).

5. Conclusions

In this work one-side inspection techniques by non-contact ultrasonic probes have been successfully applied on composite panels using both electro-capacitive and piezoelectric probes. In particular higher frequency piezo-electric probes have been used to investigate a 3 mm thin CFRP sample, while the electro-capacitive probes have been applied on a thicker (18 mm) honeycomb panel. The achieved SNR is in average higher than 9÷10 dB. This seems to be very promising for the composite material inspections, increasing the accessibility also towards analysis of complex geometry in real installations. In particular, Pitch&Catch and Delta configurations have been tested and compared with the traditional transmission configuration, which can be considered as a reference.

The transducer setup has been optimized through an experimental parametric study. This was mainly aimed at the determination of the optimal probes position. The optimisation has been performed in terms of defect detection capability.

The optimisation of the measurement chain is an important step also to reduce the number of averages to be performed for each point, thanks to the improved SNR, thus also allowing to enhance the scanning speed.

6. Acknowledgements

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