Narrowband Ultrasonic Spectroscopy for Inspecting Multilayered Aerospace Structures

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Abstract. A novel narrowband ultrasonic spectroscopy (NBUS) technique which utilizes specially designed resonance transducers with carefully selected narrow frequency bands is presented. The NBUS is based on sensing electrical impedance of the piezoelectric transducer in the vicinity of its resonance. The paper is focused on optimizing the NBUS setup consisting of a piezoelectric transducer coupled to a multi-layered structure. Variations of the electrical impedance of a piezoelectric transducer caused by variations of parameters of the inspected structure are estimated using an equivalent circuit model.
Selected simulation results obtained using the KLM equivalent circuit model, which takes into account mechanical loads on both surfaces of its piezoelectric element are presented. Variations of transducer's electrical impedance resulting from variable acoustical coupling to a multilayered structure are presented in function of frequency. Experimental results obtained from an aluminium sandwich structure and a carbon fibre composite panel are presented.
Contrary to common opinions, the presented results show that NBUS inspection of multilayered structures can be efficiently performed using transducers with much lower centre frequencies than those required in pulse-echo inspection of the same structures.

1. Introduction

Recently, an increased demand for effective NDE tools for layered structures in the modern aircrafts has been observed with the increased use of carbon fibre reinforced panels (CFRP) and bonded structures (e.g. Glare). NDE of multilayered aerospace structures can be performed using ultrasonic spectroscopy, which in contrast to the conventional on pulse echo inspection makes use of the information in the frequency domain. Ultrasonic resonance spectroscopy (URS) utilizes information in the frequency domain obtained due to the constructive and destructive interference of elastic waves. In a broadband resonance test an ultrasonic tone-burst with sweeping frequency is applied to an ultrasonic transducer and a resonance spectrum of the inspected structure is acquired, [1]. The acquired spectrum contains information about the properties of materials used for the structure and flaws that may be present in it. Generally, two setups are used in resonance test, the global test for smaller parts and the local test for larger structures.
The global test provides synthetic information about the entire inspected part and therefore it can be applied to relatively small parts where vibrations can be excited in the whole inspected volume.
The local test is more suitable for the aerospace structures, where the local structure condition is of interest, and only a selected part of the inspected structure is excited.
A fundamental limitation on resonance inspection is its sensitivity to factors that are unessential for the test, such as, variations in dimensions or material properties that may

° This work was supported by two projects funded by the European Community, INCA (Contract No: G4RD-CT2001-00507) and NANOSCAN (Contract No: G4ST-CT2002-50288).

mask the effect of smaller defects. This problem can be solved either by modelling or, when modelling is unfeasible, by employing sophisticated self-learning algorithms for tuning parameters of an intelligent defect classifier. In the case of multilayered aerospace structures modelling seems to be the most suitable option.
The purpose of the present paper is to enlighten the potential and the limitations of the URS techniques, especially, narrowband ultrasonic spectroscopy (NBUS) applied to aerospace structures. The material presented here is a result of our research aimed at the development of URS capable of coping with new applications and the increased demands.
We start from explaining NBUS principles for multi-layered structures and presenting a model enabling simulation of the tested structure and transducer. In the second part of the paper we present some experimental results.

2. The principle of NBUS

There exist commercially available instruments (bond testers) that operate on the principle of mechanical resonance in a multi-layered structure. A piezoelectric transducer, excited by a swept frequency sine wave is coupled to the surface of the inspected structure in the setup shown in Fig. 1. In most applications the instrument acquires the transducer's frequency spectrum in the range of some tens of kHz to several hundreds of kHz. Since a piezoelectric transducer is an electro-mechanical device its electrical impedance depends on the mechanical load, i.e., the acoustical impedance of the inspected material. An equivalent circuit can be used to illustrate the transducer operation, as shown in Fig. 1.

The inspected structure coupled to the NBUS transducer acts as a mechanical load for the transducer and results in a change of its resonance characteristics. The transducer transforms the load variations at its mechanical side to the electrical impedance at its primary (electrical) side as illustrated by the equivalent circuit in Fig. 1. Generally, resonance frequency of a loaded transducer will be shifted and its resonance peak will be widened. Thus, a change in acoustical impedance of the inspected structure will be reflected as a respective change of the transducer's electrical impedance.

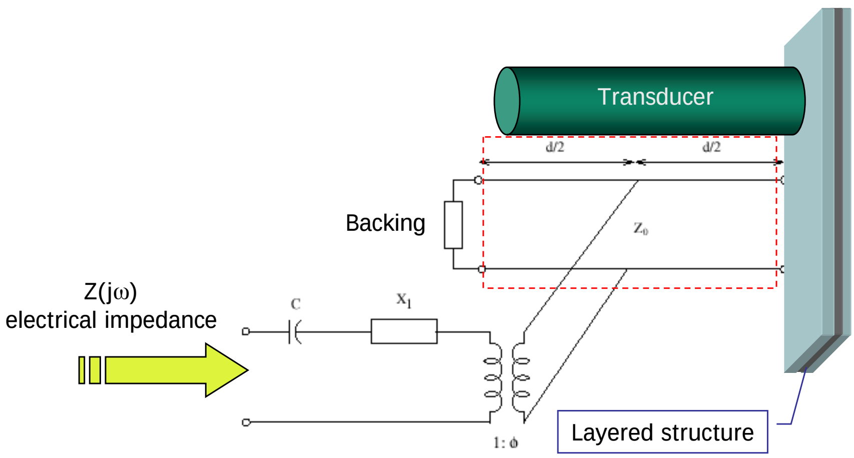

Figure 1. Principle of the narrow band resonance inspection of a layered structure.

Acoustic impedance of a layered structure takes the form of a complex valued function of frequency characterized by a number of resonance peaks corresponding to resonances in different layers [3], [4]. Generally, a resonance in a large layered structure occurs when the wave fronts travelling back and forth between two boundaries due to the discontinuities in acoustic impedances at the boundaries form a standing wave. For multi-layered structures, a number of resonance modes can be observed depending on their geometry and condition. A characteristic resonance pattern, an ultrasonic signature, obtained for each particular defect-free structure and given transducer can be used as a reference in the resonance test.

In the NBUS inspection of a structure, its surface is scanned with a resonant transducer and its frequency response is monitored in a narrow frequency band. Disbond detection is performed by an operator observing simple features of the acquired spectra, such as, shift in the resonance frequency or a phasor corresponding to transducer's electrical impedance for a pre-selected frequency in the vicinity of resonance. The first solution is applied in *Bond Tester™* from Fokker [5] while the second alternative is used in *BondMaster™* from *Staveley* [6]. In both cases that the operator has to perform a spectrum classification task based on primitive features extracted by the instrument. Below, we present theory and experiments illustrating this principle.

3. Theory

3.1. Modelling loaded piezoelectric transducer

Electrical impedance of a piezoelectric transducer can be calculated using the KLM model shown in Fig. 2, which takes into account mechanical loads on both surfaces of the piezoelectric element (for details concerning the KLM model see [7]). From Fig. 2 it can be seen that the KLM model includes a transmission line representing its mechanical side and a transformer converting the mechanical side to the electrical side.

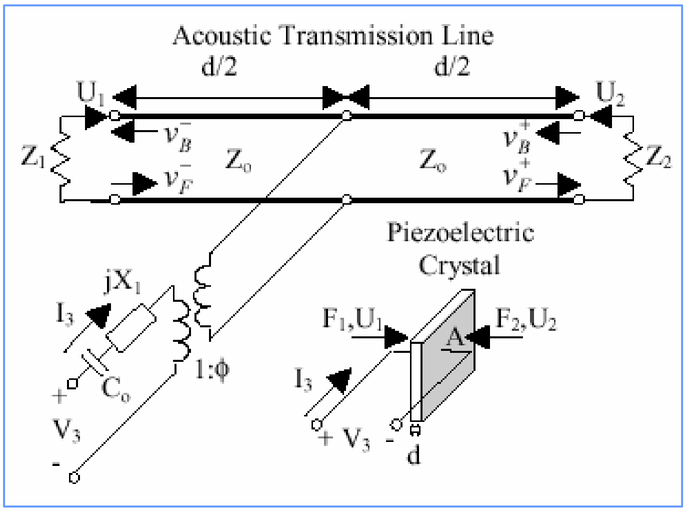

Figure 2. The KLM model of a piezoelectric transducer in thickness mode.

Input impedance of the transducer is a series coupling of the transducer capacitance C_0, the reactance X_1 and the impedance transformed from the secondary side

$$Z_{KLM} = \frac{1}{j\omega C_0} + jX_1 + \frac{Z_a}{\phi^2} \tag{1}$$

where Z_a denotes the acoustic impedance seen from the middle of the piezoelectric element, and $1:\phi$ is the transformer's gear ratio.

Close to the resonance frequency the impedance transformed to the electrical side will be $Z_a \cong \frac{Z_0^2}{Z_b + Z_m}$ and the transducer's impedance can be expressed as

$$Z_{KLM} \cong \frac{1}{j\omega C_0} + \frac{4h_{33}^2}{\omega^2}\frac{1}{\overline{Z}_{bm} + \Delta Z_m}; \qquad Z_b + Z_m = Z_b + \overline{Z}_m + \Delta Z_m = \overline{Z}_{bm} + \Delta Z_m \quad (2)$$

where Z_b, Z_m are acoustical impedances of backing and tested material, respectively, $\overline{Z}_{bm} + \Delta Z_m$ denotes variations of the acoustical load of the transducer due to the variations in the inspected material, and h_{33} is the piezoelectric constant for the piezoelectric element. Assume that the transducer designed for material inspection is included into a linearised bridge together with another identical dummy transducer. The active transducer is loaded with the impedance of the tested material $Z_m = \overline{Z}_m + \Delta Z_m$ while a reference piece with impedance $\overline{Z}_m$ makes up the dummy's load. Then the unbalance signal measured at the bridge output will be

$$U_x = k \cdot \Delta Z_{KLM} = k\frac{4h_{33}^2}{\omega^2}\left(\frac{1}{\overline{Z}_{bm}} - \frac{1}{\overline{Z}_{bm} + \Delta Z_m}\right) = k\frac{4h_{33}^2}{\omega^2}\left(\frac{\Delta Z_m}{\overline{Z}_{bm}(\overline{Z}_{bm} + \Delta Z_m)}\right) \quad (3)$$

where k is the bridge's gain.

Assuming that $\Delta Z_m << Z_m$ we get an approximate expression for the bridge unbalance signal in a narrow frequency band close to the transducer's resonance

$$U_x(\omega \cong \omega_0) \cong k\frac{4h_{33}^2}{\omega^2}\frac{\Delta Z_m}{\overline{Z}_{bm}^2}$$

(4)

Eq. (4) illustrates the principle of narrowband spectroscopy where a piezoelectric transducer excited with its resonance frequency is used for transforming the acoustic impedance of an inspected structure to electric impedance that can be directly measured using a vector voltmeter.

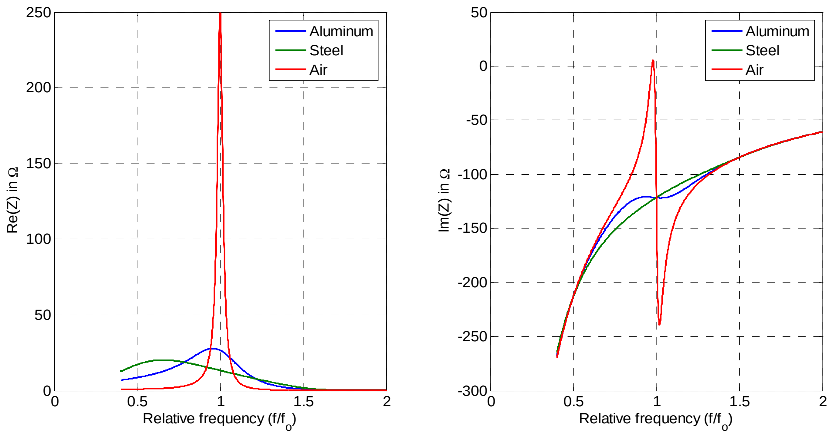

Figure 3. Impedance of an example 1 MHz transducer close to its f_0 in the air (red), after loading it with aluminum (blue) and steel (green).

Although Eq. 4 is accurate only for the resonance frequency the principle presented above is also valid for other frequencies (more details can be found in [8]). This is illustrated by Fig. 3 where the impedance plot of an example 1MHz transducer in air can be compared with those of the same transducer loaded with aluminium and steel, respectively. It should be noted that the impedance plots were simulated using KLM model for an idealized transducer made of Pz27[1] (neither backing nor wear plate were included in the model). For the real transducer the impedance plot in air would be much more similar to that of the loaded transducer. Fig. 3 illustrates problems encountered when using resonance frequency shift as a significant feature for the inspection (for instance in *Fokker Bond Tester*), the resonance of a loaded transducer is in general difficult to detect, especially, that in practical situations the impedance plot may be far from smooth.

Contrary to resonance frequency, electrical impedance can be reliably measured for any frequency and since it is a complex valued variable it yields two parameters that can be used in the similar manner as in eddy current technique.

3.2. Sensitivity issues

One of the major disadvantages of NBUS in practical applications is its sensitivity to coupling. Sensitivity to variations in coupling between the transducer and the inspected material is an important issue that has to be taken into account when choosing NBUS transducers and their working frequency. A well designed NBUS transducer has to be characterized by a high sensitivity to defect, and at the same time by the low sensitivity to acoustic coupling. Therefore, maximizing sensitivity to defects should be performed taking into account robustness of the NBUS test, that is, the relative insensitivity to the variations of couplant thickness.

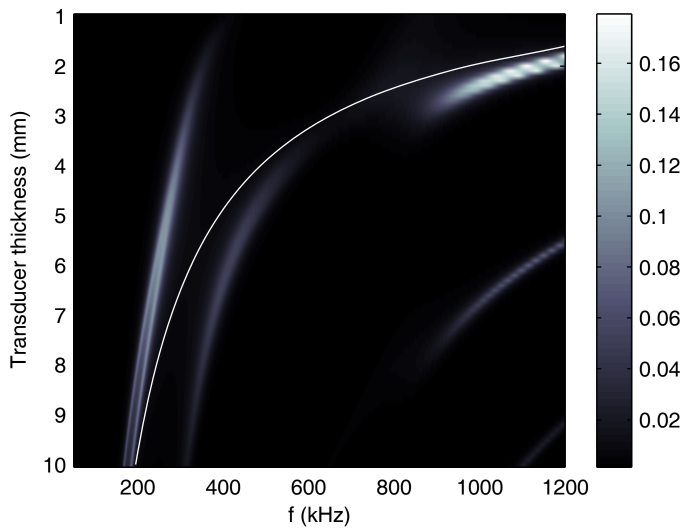

Figure 4. Relative admittance change of a +1μm thickness change in the water coupling layer (the nominal coupling hickness is 30μm). White solid line indicates resonance frequency of the free oscillating transducer in air.

The sensitivity issue is illustrated in Fig. 4 showing the relative admittance change of Pz27 transducers corresponding to a small change in the water couplant thickness. The relative

[1] Pz27 is a piezoelectric material from Ferroperm Piezoceramics A/S in Denmark

admittance change, coded in grey scale in Fig. 4, is plotted as function of transducer thickness and working frequency. The plot was obtained from the simulation performed using the KLM model for a Pz27 transducers placed on an aluminium sandwich structure.

Two bright lines well pronounced at the left hand side of Fig. 4 represent two fundamental resonances in the structure consisting of a transducer coupled to the aluminium structure: the half-wave resonance occurring at the lowest frequencies, and the full-wave resonance at the higher frequencies.

4. Experimental results

4.1 Inspection of sandwich structure

The above principle is illustrated by the results obtained for a specimen of sandwich structure, simulating wing skin structure with artificial disbonds between the aluminium plates.

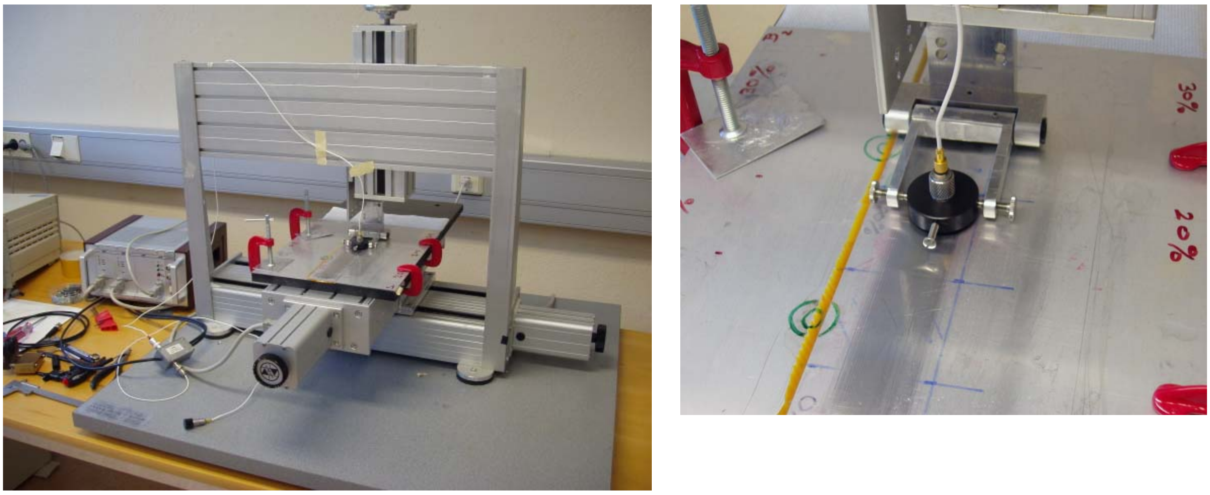

Figure 5. The scanning system used in experiments (left), and a detail of transducer suspension (right).

A sample of the wing skin structure was inspected using a setup shown in Fig. 5 consisting of a transducer operating at frequencies in the range of 1 MHz mounted in a *XY*-scanner and a computerized impedance measuring instrument. The transducer had a diameter of 0.5” and was fed with a single frequency sine wave with amplitude approx. 10 $V_{p\text{-}p}$. The transducer’s complex impedance was measured in discrete *XY*-points and stored in a PC. A small volume of water applied on the inspected surface was used to obtain contact between the transducer and the inspected structure. A complex valued C-scan obtained in this way was displayed directly at the PC’s screen.

The sample had a number of artificial disbonds in both adhesive layers (see Fig. 6a). A small area indicated in Fig. 6a was inspected and the resulting C-scan is shown in Fig. 6b. From Fig. 6b it can be seen that both disbonds were not only reliably detected but also correctly classified.

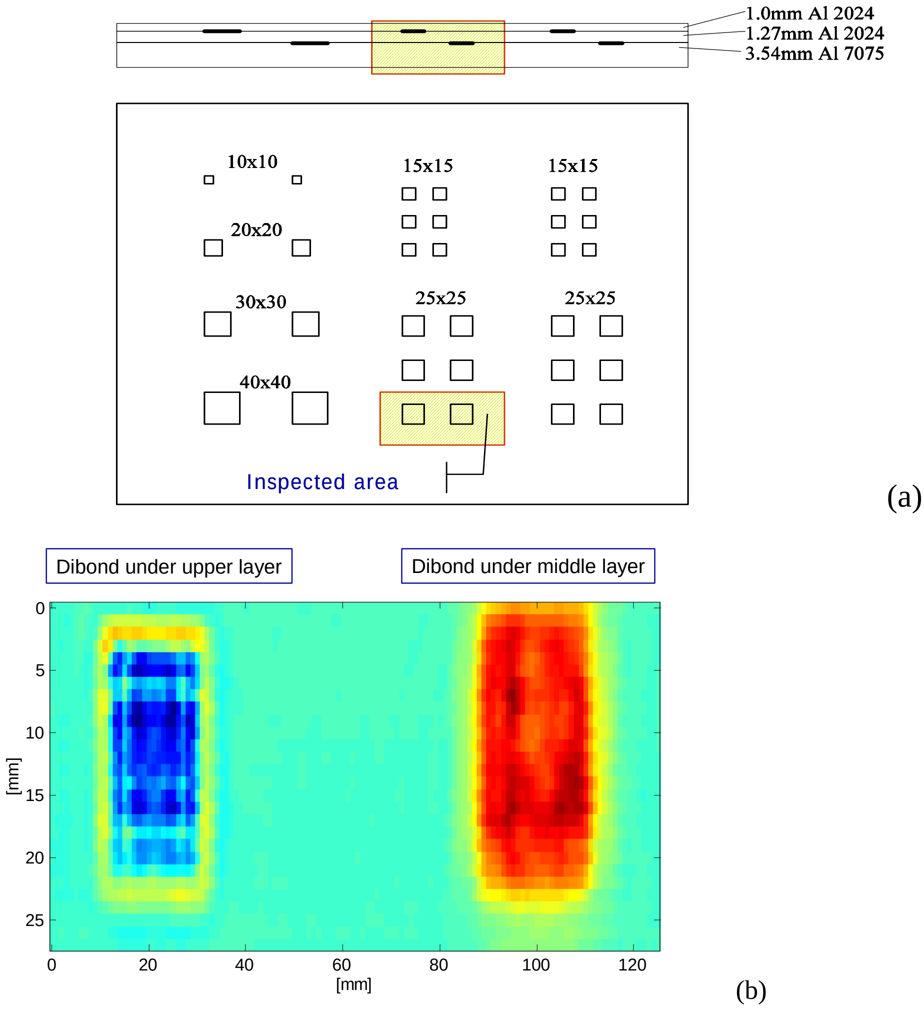

Figure 6. Results of NBUS inspection of the specimen Wing Skin with artificial disbonds. Specimen structure (top) and the NBUS scan of the indicated area with two disbonds (bottom).

4.2 Inspection of CFRP specimens

Mechanized inspection of CFRP samples was performed in the setup shown in Fig. 5 also using the 1 MHz transducer and water coupling. A step-wise CFRP specimen NNC-LP-02 with variable thickness and artificial defects simulating disbonds was inspected. In each step 6 artificial defects were manufactured to simulate the disbonds as shown in Fig. 7. The defects manufactured at each thickness step hade two sizes, 6 x 6 mm (left column) and 4 x 4 mm (right columns in Fig. 7). The defects in each column were located at different depths, in the lower row in Fig. 7 are the defects located at the depth of two plies from the top surface, in the upper row are the defects located two plies from the bottom surface, and the middle row represents defects in the middle of the step thickness.

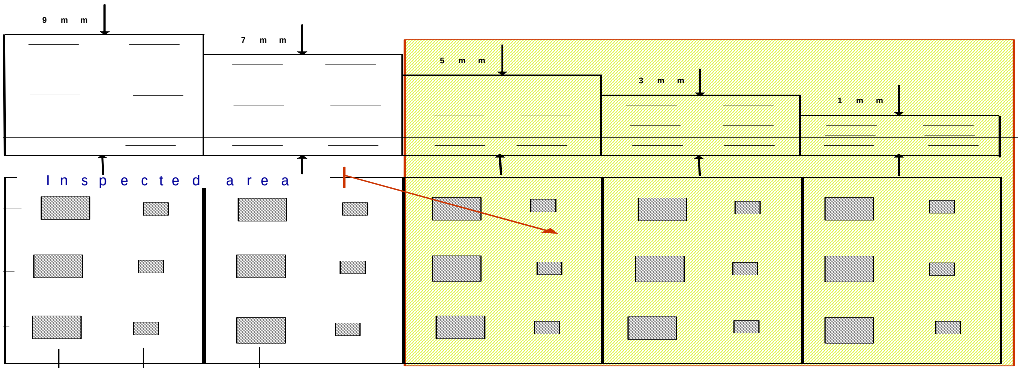

Figure 7. Structure of the NNC-LP-02 specimen

The NBUS results are shown in Fig. 8 together with the conventional ultrasonic C-scan obtained from the transmission inspection that serves as a reference. It is evident that the presented method is capable of detecting almost all defects in the inspected specimen; the most difficult seems to be detecting shallow defects in the thick section of 5mm.

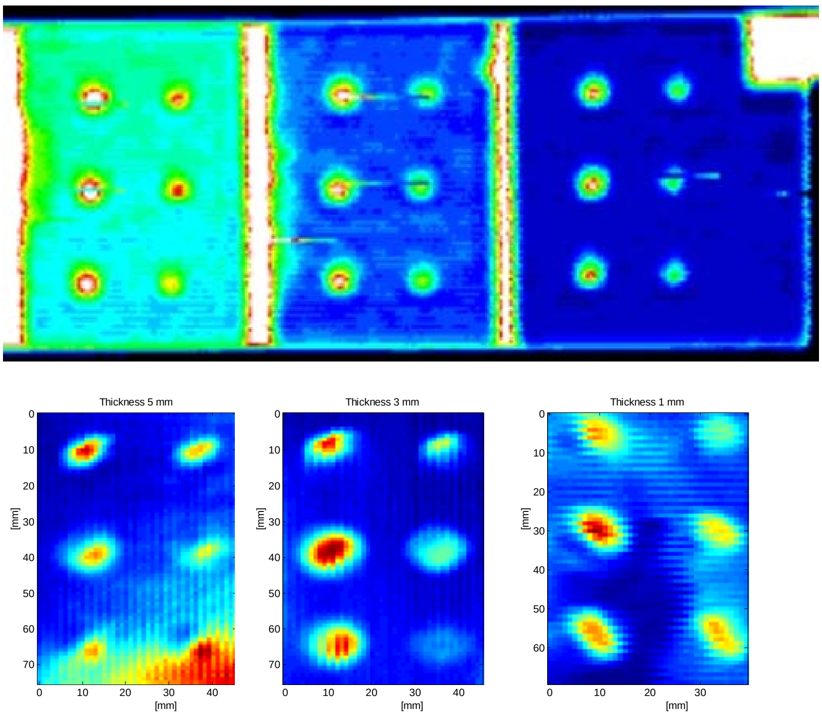

Figure 8. Inspection results obtained for the step-wise specimen of CFRP. Ordinary ultrasonic C-scan obtained in through transmission (upper panel) and C-scans obtained using the NBUS from one side (lower panels).

5. Concluding Remarks

Narrowband ultrasonic spectroscopy (NBUS) appears to be a very promising method for non-destructive inspection of multi-layered aerospace structures if properly designed transducers are provided. The method is based on sensing electrical impedance of a piezoelectric transducer in the vicinity of its resonance frequency. A simple theoretical model was presented, which explains the principle of a piezoelectric transducer transforming the acoustical impedance at its mechanical side to the electric impedance at its input.

An NBUS test of layered structure performed using a narrowband transducer requires proper choice of the transducer design and its resonance frequency. Today, this choice is performed ad hoc, based on operator's experience and some recommendations from the instrument manufacturer. The theoretical model of the multi-layered structure including the piezoelectric transducer presented in the paper makes this choice much easier and enables optimization of the transducer performance. The model enables optimizing sensitivity of the NBUS transducer to defects as well as accounting for the effects of natural variations in acoustic coupling.

Mechanized tests performed on selected specimens yielded very promising results – NBUS was capable of detecting artificial disbonds both in aluminium sandwich structures and in CFRP of different thicknesses.

NBUS can also be performed using broadband transducers sensing a large number of structure resonances. Naturally, the sensitivity obtained for the broadband transducer is much lower than that for a weakly damped one.

It is worth noting that the transducers with a resonance frequency considerably lower than that of the structure's fundamental modes can be successfully used for the NBUS.

6. References

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