Principles and Applications of Air-Coupled Ultrasonics

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(Based on work by Grandia *et al,* QMI)

Presented at the British Institute of Non Destructive Testing Seminar "Developments in Ultrasonic Transducers", 19 November 1997.

Introduction

Ultrasonic Flaw detection methods have been used for many years to locate flaws and discontinuities in manufactured parts. High frequency sound is reflected from the interface between materials of different acoustic impedance. The greater the mismatch the greater the reflection. Thus with suitable transducers, instrumentation and techniques, defects such as porosity, inclusions, cracks and disbonds can be readily detected.

Ultrasonic inspections are typically carried out in one of two ways:

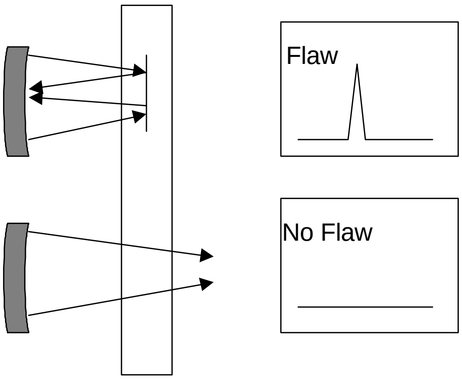

Figure 1: Pulse-echo inspection configuration

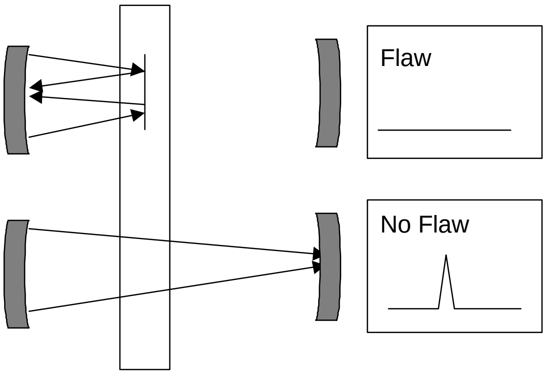

Figure 2: Through-transmission inspection configuration

The *pulse-echo* technique (Figure 1) using a single transducer: a flaw is indicated by the presence of a reflected signal. A variation of this technique uses separate transmit and receive transducers positioned close together (or constructed as a single assembly).

The *through-transmission* technique (Figure 2) uses separate transmit and receive transducers on opposite sides of the material under test. A flaw is indicated by the absence of a transmitted signal. This technique is particularly suitable for detecting disbonds in multi-layer or complex structures where the reflected signal might be difficult to analyze. It gives very good sensitivity but is limited by the need to access both sides of the material under test, and to coordinate the movement of two transducers. Most applications of the system under discussion use the through transmission approach.

The role of couplants

Almost all current ultrasonic inspection methods require the use of a couplant between the transducer and the material to be inspected. Typical couplants include water, glycerin, and a variety of oil or water based pastes. The couplant is essential for the sensitivity of the inspection in two ways.

The attenuation of the ultrasonic energy with distance is much greater in a gas than in a liquid. Over the frequency range up to 1 MHz the attenuation in air can be as much as 100 dB/m. However at reasonable distances of a few centimeters this is still only a few dB - not too great a loss.

More important is the effect noted above, that the amount of energy transmitted at an interface depends on the difference in acoustic impedance. More precisely this is defined by the equation:

$$\mathbf{T = 2.\sqrt{Z_1 Z_2}/(Z_1+Z_2)}$$

Where Z_1 and Z_2 are the acoustic impedances of the materials, these are usually expressed in Mrayls (= 10^6 kg.m^{-2}.s^{-1})

Thus at a single interface between steel (impedance ≈ 46 Mrayls) and water (impedance ≈ 1.5 Mrayls) 35% of the signal is transmitted, between steel and air (impedance ≈ 0.0004 Mrayls) it is only 0.6%

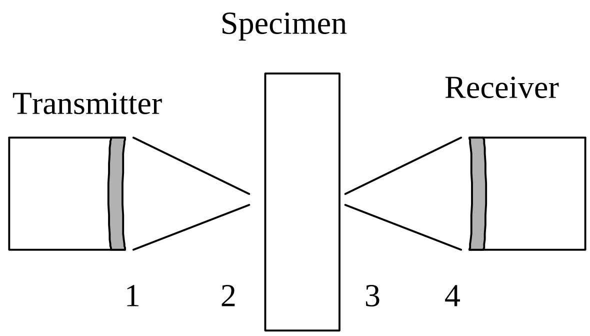

Figure 3: Acoustic interfaces

For a complete test system we have a minimum of four interfaces: From the transmitting probe material (typically a ceramic, having an acoustic impedance of maybe 35 Mrayls) to the couplant, to the test material, to the couplant, to the receiving probe. Thus using air as a couplant rather than water will give a total increased path loss of around 160dB or only 1/120,000,000th the energy transmission.

Advantages gained from eliminating couplants

If the decrease in sensitivity is so great why would we want to use an air coupled test at all? There are a number of situations where this would be very desirable:

In some situations there may be a requirement to avoid contamination which would affect later use of the product, typical examples include aerospace materials, particularly those which will be sealed by later processing, such as part-finished honeycomb structure. Other materials such as foam, wood or paper based products may be damaged by contact with water, or be incapable of withstanding the application of heat to dry them afterwards.

Water ingress may reduce the detectability of defects such as delaminations. When filled with air these may act as a complete block to the ultrasonic signal, but if filled with water they may pass most of the energy, and be easily missed. A common effect here is that the first inspection gives an indication, the water then seeps in, and attempting to confirm the presence of a defect shows it to have disappeared!

So called *dry-coupled* transducers (Soft-tipped or Roller probes) work well in some applications; they normally use a layer of synthetic rubber (acoustic impedance similar to that of water) to provide acceptable coupling between the probe and test piece. A common disadvantage is that to work reliably they require significant pressure to be applied, which may render the technique unsuitable for testing delicate materials. In some cases the pressure applied may mask critical defects such as detached skins on composite materials.

How can we overcome these problems?

A Number of approaches can be tried, and, as would be expected, a satisfactory solution requires us to use all the tricks available:

1. Obtain maximum acoustic output from the transmitter

2. Attempt to minimize losses throughout the system

3. Maximize the sensitivity of the receiver

4. Process the signal so as to maximize signal to noise

Transducer design

Transmitter Output is maximized by using a resonant transducer. A specially designed, un-damped ceramic disk is driven by a 500 Volt 15 cycle tone-burst. Using a resonant system for both transmitter and receiver can give a typical increase in sensitivity of nearly 100 times (40dB) compared to a conventional damped transducer.

The efficiency of transmitting sound from the ceramic to the air can be significantly improved by using an intermediate acoustic matching layer, typically a light polymer material.

As we have seen the transmission from a typical ceramic to air is around 0.7%

By using an intermediate layer having an impedance around 1 Mrayl the overall transmission at each interface is greatly improved, so even allowing for the two interfaces the overall transmission efficiency is approximately doubled i.e. an improvement of some 12 dB in total.

A basic transducer design is shown in figure 4. The transducer itself is constructed within a stainless steel casing similar to a conventional Ultrasonic probe (Figure 5).

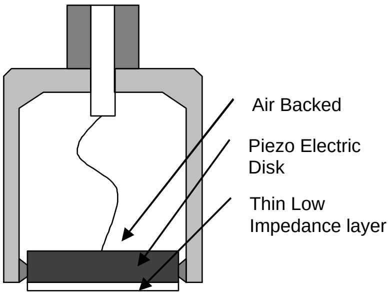

Figure 4 : Air-coupled probe design features

Figure 5: QMI AS400C Air-coupled probe

A further improvement in efficiency can be obtained by using an acoustic lens to focus the sound energy. By concentrating the sound beam to a focal spot a millimeter or so across we can obtain improvements in both sensitivity and resolution.

A number of design methods can be used to achieve focusing. A curved ceramic plate can be used (Figure 6) or external focusing 'optics' can be added. (Figure 7). An alternative approach is to manufacture a composite probe (Figure 8); Composite probes, effectively consisting of an array of very small probes, are useful for many applications, but in this case their low mechanical 'Q' limits resonance and appears to outweigh their other advantages.

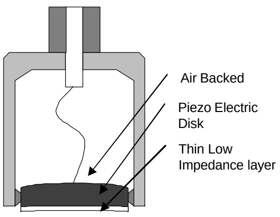

Figure 6: Focused air-coupled transducer using a curved piezo-electric element

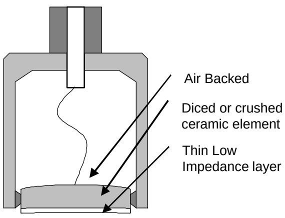

Figure 7: Focused air-coupled transducer using a curved piezo-composite element

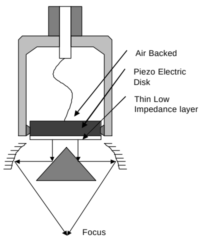

Figure 8: Focused air-coupled transducer using a flat piezo-electric element with external 'optics'

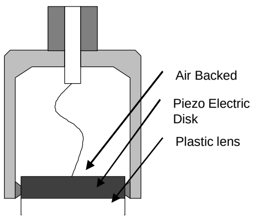

Figure 9: Focused air coupled transducer using a plastic lens bonded to a flat piezo-electric element

The most successful uses a flat resonant disk, and combines the impedance matching layer with a plastic lens as shown in Figure 9

Instrument design

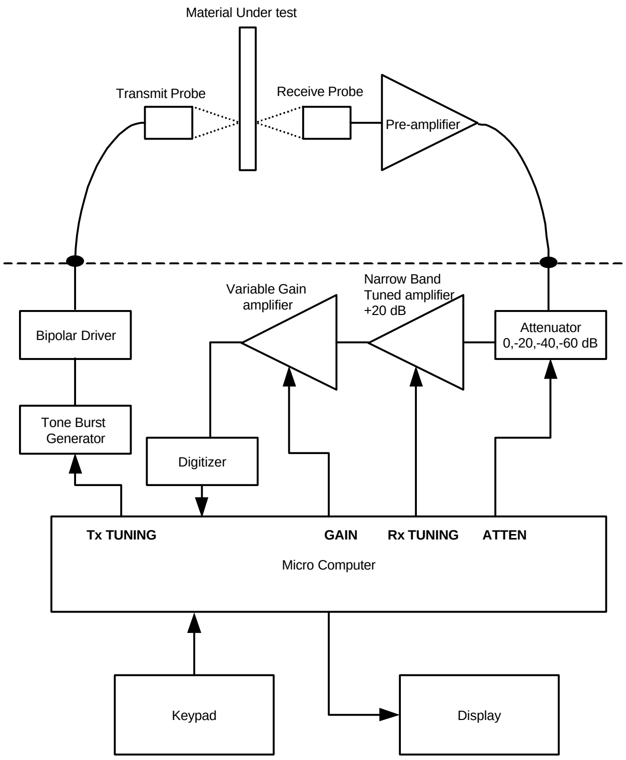

Figure 10: Simlified Block diagram of AIRSCAN system

To match the resonant transducer we require a high power tone-burst generator. It is necessary to be able to adjust the frequency so as to match the resonant frequency of the probe. Typically an adjustment range of +/- 10% from the nominal value is required.

At the receiver end a number of techniques are helpful: A low noise preamplifier, mounted directly on the receive transducer, improves signal to noise ratio towards the theoretical maximum. By using a narrow band amplifier, tuned to match the transmitter tone burst, noise can be further reduced.

Signal processing techniques, for example averaging, can give a worthwhile improvement in signal to noise ratio, but must be used with care since they reduce the effective sampling rate. Since the transmitting pulse rate is already limited by the air path time (echoes must have time to die away before the next pulse) little further reduction can be tolerated if a reasonable scanning rate is to be achieved. These techniques are therefore not suitable in most production applications.

A practical instrument employing this technology is the QMI Sonda 007C shown in figure 11, this employs fully digital circuitry and is well suited to automated operation. The display of the instrument is designed to be similar to a conventional ultrasonic instrument’s ‘A-Scan’ presentation. The only controls unfamiliar to an ultrasonic technician will be the tone burst generator configuration and tuning adjustments.

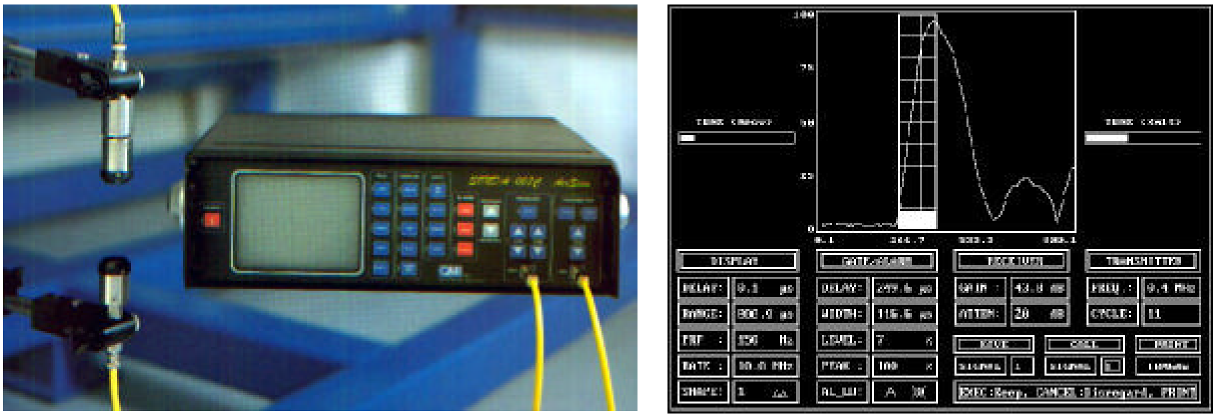

Figure 11: QMI SONDA 007C and display

The last area of sensitivity enhancement comes in the interpretation side. This type of test is best done using a ‘C-scan’ presentation, where a two dimensional ‘map’ of the surface is created. By viewing the results in this way it becomes possible to visually identify patterns and understand what results should be expected. This in turn means that the Airscan should be used with a suitable motorized scanning assembly such as that shown in Figure 12.

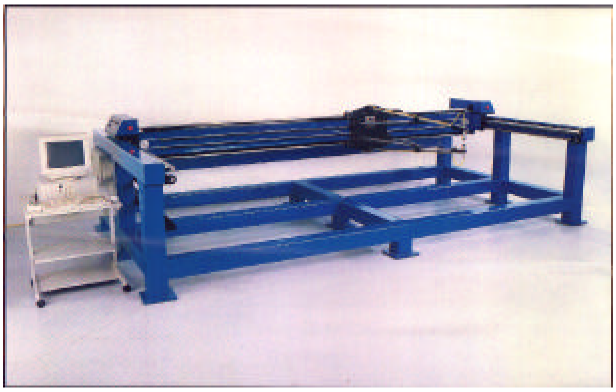

Figure 12: QMI LS12 Aerospace panel Scanner

Typical applications of air-coupled ultrasonics

As already noted, the main advantage of the air coupled inspection method lies where the material to be inspected, or its subsequent processing, is incompatible with water.

A typical example of this is in composite materials where subsequent bonding is intended, or where the presence of water would interfere with the intended use. In these cases conventional ultrasonic methods could be used, but would require subsequent drying out processes

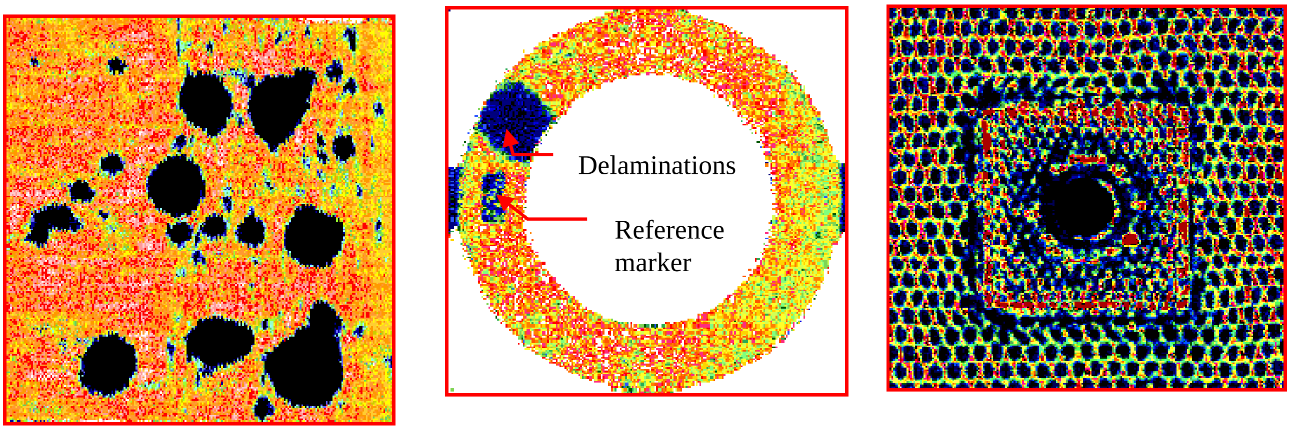

Figure 13 : Three applications where Airscan solves process incompatibility problems.

Figure 13 shows three typical applications:

The first is a carbon phenolic laminate intended for an aerospace application. There is a process advantage here, but the main advantage of using Airscan comes in the fact that delaminations can easily become filled with water by capillary action, this would render them less likely to be detected. This particular panel shows a number of delaminated regions.

The second application is an aircraft carbon brake disc. Again a delaminated region is clearly visible. To assist in locating defects within this part, which is obviously symmetrical an acoustic marker has been attached (typically a piece of 'sticky' foam tape).

The last is a more exotic application, a support panel for a satellite solar array. This is made from an aluminium cored honeycomb material. The structure detail can be clearly seen. The region shown contains a 50mm square strengthener plate at an attachment point. Damage to the honeycomb core adjacent to the plate is clearly visible.

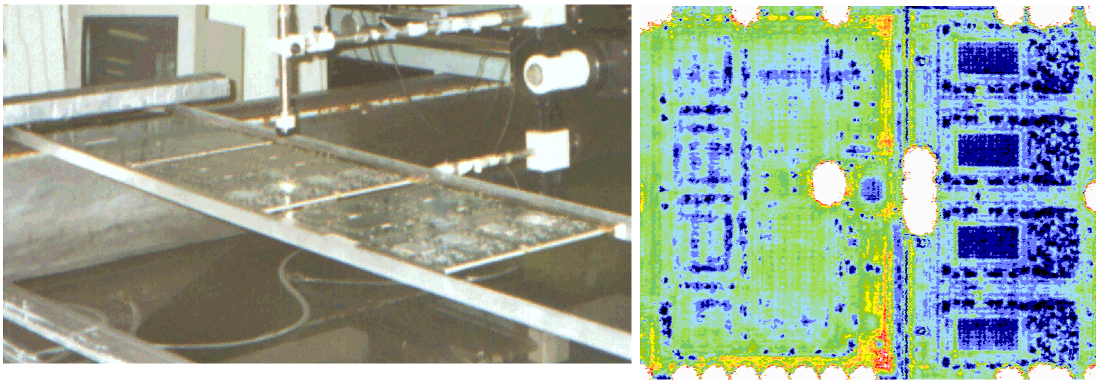

Figure 14 : Scanning arrangement and results from inspection of a satellite printed circuit board.

A different satellite application is shown in Figure 14. Circuit boards for communication satellites cannot, as with terrestrial applications, rely on air to conduct heat away. Therefore they are constructed with a thermally conductive material bonded to the underside of the printed circuit assembly. Any defects in this bonding will compromise the heat conduction efficiency and thus the reliability of the assembly. Airscan can be used to verify these parts, whereas a water-coupled test would be completely unacceptable. Note the large white spots in the centre of the result. These are caused by sound diffraction through mounting holes in the board.

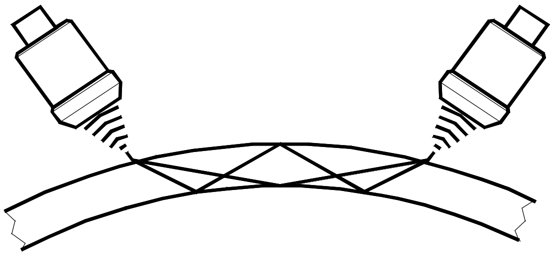

Figure 15 : Guided Plate waves

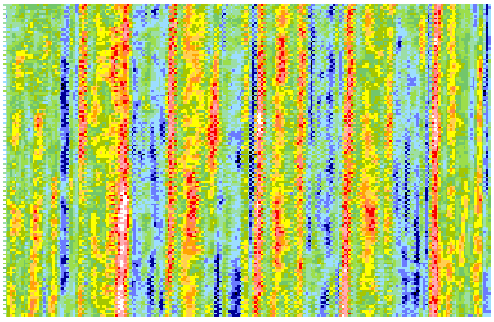

Figure 16: GFRP Pipe, plate wave results

All the applications up to now have employed the through transmission configuration, as shown in Figure 2. Figure 15 shows a different approach, using Ultrasonic "plate waves": If the sound is injected into a thin sheet at the correct angle it will be guided along the plate and can be "picked up" further along. This allows the Airscan technique to be used for some applications where access from both sides is not practicable. An example of this is shown in Figure 16. This shows results from in-process inspection of a Glass fibre reinforced plastic pipe. At the inspection point the materials has a temperature around 150 Celsius, and contact with water would adversely affect curing of the plastic resin.

Conclusion.

As we have seen the air coupled ultrasonic method has moved from being an experimental technique to a mature and reliable technology. Although the inherent losses mean that it can never match the higher sensitivity applications of immersion ultrasonic methods the sensitivity and resolution available can easily match those required for many "production" applications where quick and reliable assessment of bonding quality, rather than microscopic resolution, is the requirement. As a result it is possible to expand the application of ultrasonic techniques into many situations, and possibly industries, where it was not previously appropriate.

This article was presented as a paper at the British Institute of Non Destructive Testing Seminar " Developments in Ultrasonic Transducers" In November 1997.
It draws extensively from two papers

"Airscan Transducers, Technique and Applications" by Grandia W.A., Grandia B, Strycek J, and Loertscher H, (published on the Internet at www.ndt.net)

"NDE applications of Air-Coupled Ultrasonic Transducers" Grandia W.A. and Fortunko C.M. From the 1995 IEEE International Ultrasonics Symposium.

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