# Application of Air-Scan Technology to Ballistic Impact Protective Systems

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## Abstract

The Research and Technology Group of the Defence Clothing and Textiles Agency (R&TG DCTA) have been investigating the application of non-destructive testing (NDT) methods to personal armour components and systems. The research has considered both pre- and post-impact conditions. The application of NDT could not only be used to determine directly the extent of damage after an impact event, but could also be extended to include armour design and quality assurance assessment. This however, relies on the availability of suitable inspection techniques and equipment. The materials and systems that are typically used for personal armour are highly attenuating to ultrasound transmission. Consequently, inspection has required items to be immersed in water. However, due to research into probe technology and signal processing, systems are under development for which this is no longer the case. The findings of an initial study to compare the results from the water and Airscan systems will be presented.

## Introduction

Ultrasonic testing is one of the established methods for the non-destructive testing of materials and structures. It is principally used to locate flaws and discontinuities such as porosity, inclusions, cracks and disbonds in manufactured components. The principle of this method of inspection relies upon the reflection of ultrasound from interfaces between dissimilar materials.

Conventional ultrasonic inspection may be conducted in one of two ways.

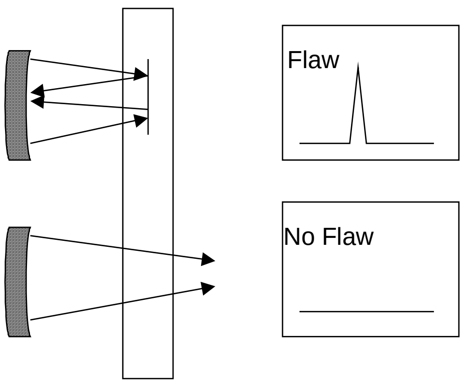


**Figure 1: Pulse-echo inspection configuration**

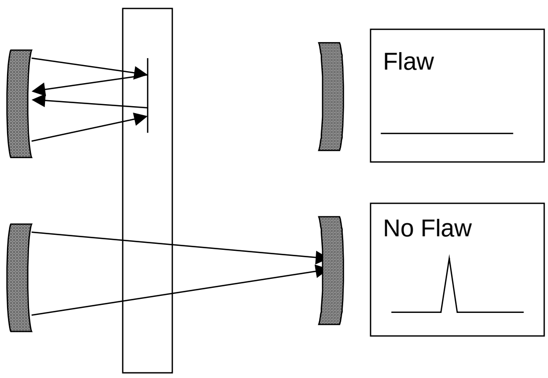


**Figure 2: Through-transmission inspection configuration**

The *pulse-echo* technique utilises a single transducer. A flaw is indicated by the presence of a reflected signal.

The *through-transmission* technique uses separate transmit and receive transducers on opposite sides of the component under test. A flaw is indicated by the absence of a transmitted signal. This technique is particularly suitable for detecting disbonds in multilayer or complex structures where the reflected signal might be difficult to analyse. It also gives very good sensitivity but is limited by the need to access both sides of the component and to co-ordinate the movement of two transducers. Most applications of the Airscan system use the trough-transmission approach.

## The Role of Couplants

Transmission of ultrasound between a probe and a rigid test piece across an air gap is extremely inefficient owing to the large acoustic impedance mismatch between air and solid materials. The employment of a coupling media at the probe/test piece interface usually overcomes this problem. Couplants typically consist of water, glycerine, or a variety of oil and water based gels. The presence of the couplant is important for the sensitivity of the inspection in two ways; (i) the attenuation of ultrasound in a liquid is much less than in a gas, and (ii) the couplant counters the acoustic impedance mismatch between the two materials.

Every material has an acoustic impedance, Z. This is defined by the sum of the material density, ρ and the velocity, v at which ultrasound propagates through it. Hence, dense solids tend to have high acoustic impedance and gasses very low. Consider two materials of acoustic impedance $Z_1$ and $Z_2$ in pressed contact. Ultrasound incident on the interface will be partly transmitted across and partly reflected back from the interface. The amplitudes of these two components are defined by the acoustic impedance mismatch; the greater the mismatch, the smaller the proportion of the ultrasound transmitted. The transmission coefficient [1] is defined in equation 1.

$$T = \frac{2Z_2}{Z_2 + Z_1}$$ **Equation 1**

At a practical, single interface between steel and water, 35% of the ultrasound is transmitted. Across the interface between steel and air, only 0.6% is transmitted. In practical inspection, a minimum of four interfaces are encountered:

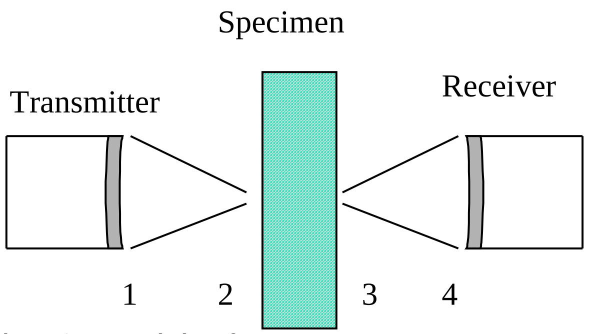


**Figure 3: Acoustic interfaces**

1. From the transmitting probe material (typically a ceramic) to the couplant
2. From the couplant to the test piece
3. From the test piece to the couplant
4. From the couplant to the receiving probe.

Therefore using air as a couplant as opposed to water may result in an increased path loss of 160 dB (i.e. only 1/120,000,000$^{th}$ of the transmitted energy being detected).

## Current Limitations

The advantages of the employment of liquid couplants are clear. However, there are a number of limitations associated with their presence:

- Ultrasonic inspection is often required in circumstances where the test piece material must not become wet or saturated with water. Typical examples include aerospace materials, particularly those that will be sealed by later processing, such as a 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. Indeed, with the increasing use of composites in aerospace and other safety critical structures, the issue of couplant caused contamination is of growing importance.

- Ingress of a liquid couplant into the test piece 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.

Many attempts have been made to overcome these limitations in the form of non-contact techniques. These include sophisticated laser generation and detection systems, electromagnetic acoustic transducers (EMAT's) [2] and air coupled ultrasound [3].

Use of laser systems can cause scorching of the test piece surface due to the high levels of energy involved. Such systems are also very expensive, making practical use unlikely at this time. EMAT probes can only function on electrically conducting test pieces, which eliminates use on composites and other non-metallic structures. Some success has been achieved with use of solid coupling materials such as those described by Billson and Hutchins [4], Drinkwater and Cawley [5-6] and Bourne, et al [7] although these still require contact with the test piece which may be undesirable. Furthermore, such devices are designed for high frequency, pulse echo operation which is often unsuitable for highly attenuative materials such as those used in personal armour.

## Airscan Technology

There is therefore a requirement for a practical technique that enables reliable inspection of highly attenuative materials without the risk of contamination from liquid couplants and the need for expensive immersion tanks. It is into this gap that Airscan technology pitches itself. However, realisation of this goal required a number of technical barriers to be broken, mainly to overcome the huge loss of signal associated with the use of air as couplant. These are summarised below. Buckley [8] gives a fuller description.

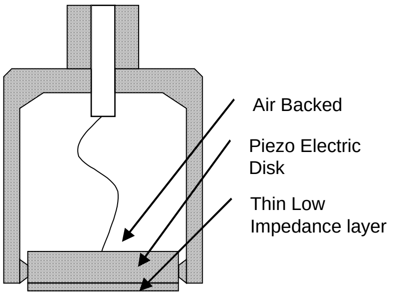


**Figure 4 : Air-coupled probe design features**

**Figure 5: QMI AS400C Air-coupled probe**

- The use of a resonant transducer maximises the conversion between electrical and kinetic energy, making the transducer as efficient as possible.
- A sinusoidal transmitter excitation signal is used rather than a rectangular or 'spike' pulse. In the Sonda 007CX, a 500V peak to peak tone burst of up to 15 cycles is used. Thus the pulse contains much more energy and by matching the toneburst frequency to the transducer resonance, maximum energy transfer is obtained.
- The losses due to the impedance mismatch between the air and the transducer ceramic can be reduced by an acoustic matching layer of a suitable material. Lightweight polymers are used as they have intermediate impedance close to the optimum. In some designs the matching layer performs a dual function, acting also as an acoustic lens to focus the sound beam.
- A low-noise preamplifier is mounted directly adjacent to, or incorporated in, the receiver transducer so as to minimise any noise pickup on the cables.
- Electrical design of the receiver circuitry may also be optimised for best signal to noise ratio. In practice, this is achieved by using tuneable narrow band filters matched to the toneburst frequency.
- Signal averaging and digital filtering techniques may be used to further improve the signal to noise ratio. However, these may limit the effective sampling rate.

By using combinations of such approaches, Airscan technology has now moved from being an experimental laboratory based system to a practical inspection tool, particularly suited to automated scanning of personal armour components.

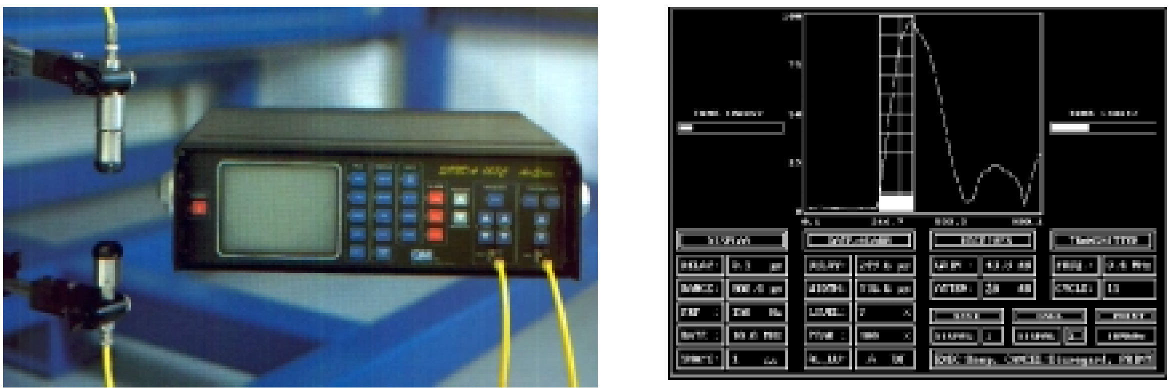

**Figure 6: QMI SONDA 007C and display**

## Discussion

Current research topics being undertaken by the DCTA, R&TG include studies on pre- and post impacted armour material and systems. These are to consider if the presence and form of defects in armour systems influences the ballistic performance and to correlate the extent of delamination in composites and multi-component armour systems after ballistic impact with performance. The most reliable method for quantifying the extent of such internal defects has proven to be by ultrasonic means. This has historically been conducted by through transmission immersion testing, hence water being the couplant. This has generated a number of practical difficulties and has raised questions regarding the reproducibility of results. Firstly, the materials used for personal armour are highly attenuative to ultrasound propagation making conventional frequencies (1-10MHz) impractical. There is also evidence that prolonged contact with water causes deterioration in mechanical properties of such materials [9]. This coupled with the risk of water ingress into defects such as delaminations, which would reduce the reliability of positive identification, the suitability of immersion testing personal armour components is thrown into question. In theory the Airscan system is ideally suited for a number of reasons:

1. It functions at frequencies lower than those typically used in conventional immersion testing (50 – 400kHz) hence reducing the effective attenuation in the materials under test.
2. It uses air as couplant, thus eliminating the risk of test piece contamination.
3. The risk of defects being missed due to water filling defects within the test piece is eliminated.
4. The system is designed to look for large area defects such as those commonly encountered in quality assurance and post failure analysis of personal armour materials.

This led to preliminary investigations into the suitability of Airscan for accurate inspection of personal armour materials and components. A test panel consisting of a ceramic plate bonded to an aramid composite was fabricated for this preliminary trial. Initial inspection was conducted using transducer pairs of two different frequencies. 50kHz was found to penetrate the test panel very well. However, the low frequency limited the size of detectable defect down to approximately 10mm in diameter. 400kHz struggled to penetrate the test piece fully and so was deemed unsuitable for this particular test panel. Subsequent development has resulted in the production of a pair of 120kHz transducers. This arrangement struck a happy medium, combining sufficient penetration with workable resolution, capable of resolving defects of approximately 5mm in diameter. Buckley [10] describes such frequency considerations in more detail.

The second phase of this project involved comparison of Airscan data with that generated by conventional immersion testing on impacted panels. Figure 7 and Figure 8 show the result of inspecting similar aramid plates with both immersion and Airscan methods respectively. These panels were of nominal areal density 6 $kg/m^2$ and were each impacted with a single 9 mm FMJ bullet at velocities in the region of 380 $ms^{-1}$. It is clear that the results are in agreement.

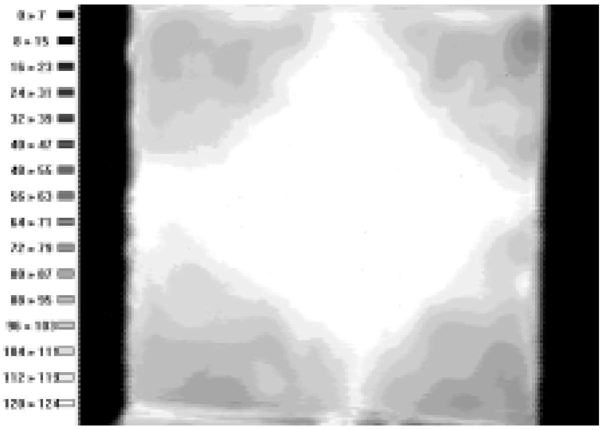

Figure 7. Aramid composite panel after impact. Inspected using immersion through transmission method

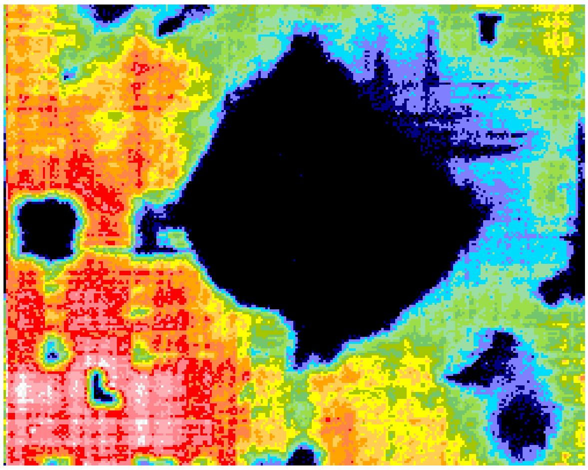

Figure 8: Aramid composite panel after impact. Inspected using Air-coupled ultrasonic method

Such encouraging results gave scope for rapid, non subjective comparrison of post impact damage in different panels. Testing has recently progressed to inspection of contoured components such as the Improved Northern Ireland Body Armour (INIBA) plate. These items have long since been an inspection problem due to their awkward geometry. Figure 9 shows a C-Scan conducted on an INIBA plate using immersion testing. It is evident that signal amplitude is poor, particularly round the edges, and that no meaningfull information is obtained. Figure 10 represents the same component, only this time inspected with the Airscan. Here the signal is much stronger and some detail of the composite is visible. It is noteworthy that in a small area in the top left corner of the plate, no signal was transmitted through the component. This is indicative of a disbond, probably between the ceramic and the composite.

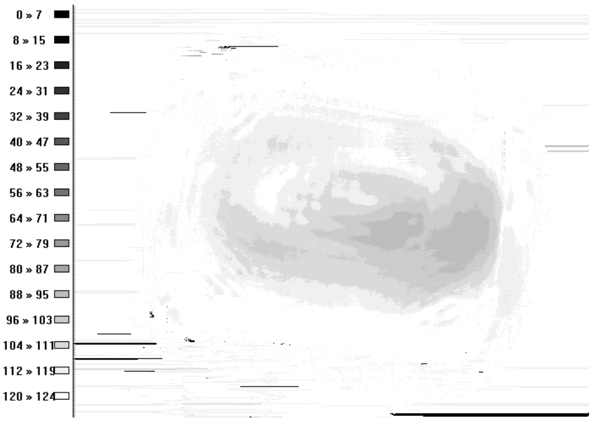


Figure 9. INIBA plate. Inspected using immersion, pulse echo from interface between ceramic strikeface and aramid composite

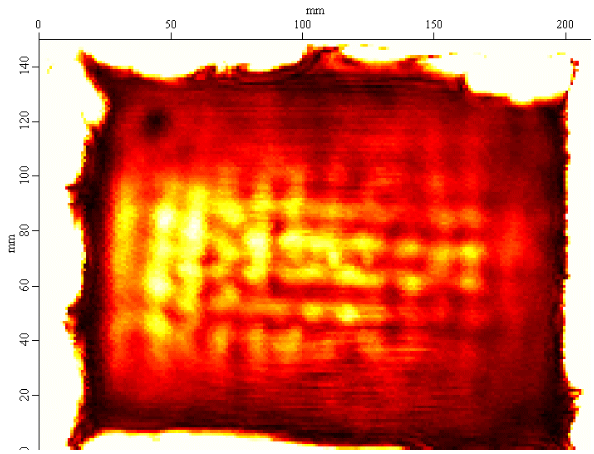


Figure 10. INIBA plate. Inspected using Air-coupled through-transmission at 120kHz. 'Ragged edge' due to sound leakage in experimental setup

Having established that Airscan is suitable for such inspections, work continues to explore feasibility of inspecting many materials and structures used in personal armour that were previously believed to be impermeable to ultrasound and impractical to test. Parallel work is concentrating on comparisons between conventional immersion and Airscan testing to quantify more precisely the benefits gained.

## Conclusions

A number of innovations in transducer and instrument design have enabled air to be used reliably for practical ultrasonic inspection of materials and components. Work conducted between DCTA R&TG and Sonatest Plc has shown that comparable results may be obtained from the Airscan system as from conventional immersion testing of thin composites but without the associated risks of test piece contamination and water filled defects. In addition, the Airscan system has proven successful for pre-impact inspection of more complex components such as the INIBA plate, enabling quality assurance checks to be conducted for the first time. Work is continuing towards establishing the limit of resolution in such components.

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