Air Coupled Ultrasound – A millennial review

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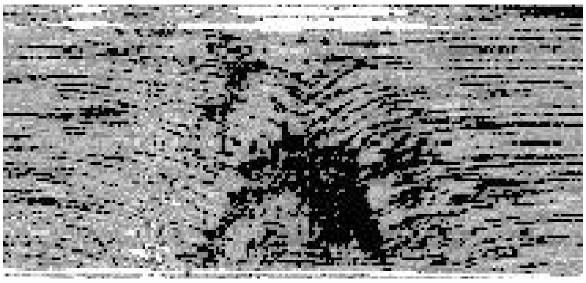
Abstract

During the last decade Air coupled Ultrasonics has advanced from being a laboratory curiosity, of little practical application, to a point where it is a viable technique for many manufacturing inspections.

With appropriate equipment it is possible to perform sensitive inspections for defects such as voids, cracks and dis-bonds in a wide variety of water-incompatible materials. Originally used primarily for Aerospace composites, the applications have been extended to cover a variety of materials where conventional NDT methods are not normally considered suitable.

Diverse applications of the technique include wood, foams and missile propellants. A variety of frequencies can be used, allowing optimization for Resolution or penetration as with 'conventional' Ultrasonics.

Most applications of Air coupled Ultrasound have been for Single channel C-scan systems, testing flat panels. In this context it is normally used as a direct replacement for water-coupled 'squirter' probes, and installing Air-coupled probes and instrumentation on an existing system so as to inspect a wider range of materials is generally a simple procedure. The results are often indistinguishable from those obtained with the water coupling, Figure 1 shows results from inspection of a 'Knot' in timber



More recently the use has been broadened. In particular multi-channel systems have been developed allowing very rapid inspection of large composite panels at a rate approaching $1m^2$ per minute

The current challenge, hopefully completed by the time of presentation, is to overcome the requirements for high transmission power, thus allowing a portable instrument of uncompromised performance to be developed.

This technology shows considerable promise as a solution to a number of currently impractical testing problems.

History of Air-coupled Ultrasound

For many years the users of Ultrasonic techniques have recognized that for some applications the presence of water is undesirable or impractical, and that it would be much better if air could be used as a couplant.

During the 1970's Air-coupled ultrasound was used for some applications such as inspection of wood products[i] and used tyres[ii]. At Sonatest Plc we developed 500 kHz Air-coupled transducers which were used with our UFD1 Flaw Detector for inspection of composites. However, all these applications were severely limited by the technology available, causing undesirable compromises in terms of sensitivity, penetration and resolution.

Towards the end of the 1980's work led by Chris Fortunko of NIST and Bill Grandia of QMI (both now deceased) led to the development of sensitive medium frequency focused ultrasonic transducers and instrumentation. This meant that air-coupled techniques could, at least for some applications, give results comparable to conventional water coupled Ultrasonics, Thus they could become part of the accepted toolkit of NDT techniques, rather than being a specialized curiosity.

Theory of Air-coupled Ultrasound

When sound passes across an interface between two materials only a proportion of the sound is transmitted, the rest of the sound is reflected. The proportion of the sound that is transmitted depends on how close the acoustic impedance of the two materials matches. Water is a fairly good match for most commonly used materials – for example typically around half the sound energy is transmitted at the interface between water and a carbon laminate. After four solid- liquid interfaces (from the probe, to the couplant, to the test piece, and then back again) there is still a few percent of the original energy left so accurate measurement is possible.

Conversely if the sound has to move between the test piece and air (which has very low acoustic impedance) only around 1% of the sound energy is transmitted. Thus after four transitions very little sound energy is left – Typically the overall path loss may be 100 dB higher using air as a couplant than when water is used. The path loss is significantly higher with metals, which have a high acoustic impedance compared to plastics which are lower in impedance.

It is therefore apparent that we must work hard to minimize losses at every stage if we are to achieve acceptable signal to noise for the inspection.

The QMI Airscan technology uses a number of approaches, each of which has its own advantages and in some cases disadvantages. In some applications a particular approach may not be acceptable, or a disadvantage may not be relevant, Thus the 'family' of air-coupled approaches has diverged somewhat to meet particular requirements.

The main techniques used to maximize the performance of the system are:

1. An un-damped Resonant Ceramic transducer, By using this type the conversion between electrical energy and kinetic energy of transducer movement is maximized. Where possible the receive and transmit transducers are 'paired' to match the resonant frequency.

Figure 2: QMI AS400C Air-coupled probe

2. Use of a sinusoidal transmitter excitation signal rather than a single rectangular or 'spike' pulse. In the Sonda 007CX a 500V peak to peak tone burst of up to 15 cycles is used, rather than a single pulse. Thus the pulse contains much more energy, and by matching the toneburst frequency to the transducer resonance, maximum energy transfer is obtained.

   This approach does have the disadvantage that, because of the long sound pulse, accurate measurement of timing is difficult, Most applications of air coupled Ultrasonics employ a through transmission approach, where only amplitude is measured, so this is not normally an issue.

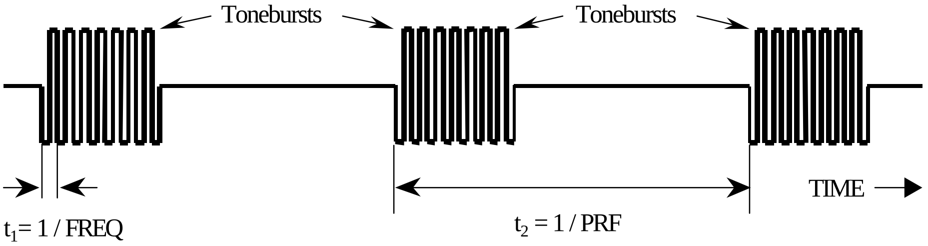


Figure 3 Toneburst wave form

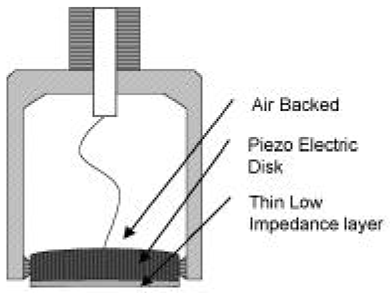


Figure 4: Focused air coupled transducer using a plastic lens bonded to a flat piezo-electric element

3. 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.

4. A low-noise preamplifier is mounted directly adjacent to, or incorporated in, the receive transducer, so as to minimize any noise pickup on the cables

5. Electrical design of the receiver circuitry most also be optimized to get best signal to noise ratio, In practice this is achieved by using tunable narrow band filters, matched to the toneburst frequency.

6. Signal averaging and digital filtering techniques may be used to further improve the signal to noise ratio, however these often degrade the effective sample rate. Since the PRF is normally constrained by the sound path time, which

is much longer in air due to the lower velocity, signal averaging frequently imposes unacceptable reductions in scanning speed. It is however a useful 'tool' when making low speed or static measurements

Test Configurations.

Because of the tremendous difference in transmitted and received signal amplitudes, and the inherent difficulties in achieving adequate transducer/amplifier isolation and recovery, no current air-coupled NDT systems work in single probe mode. Separate transmit and receive transducers are always used.

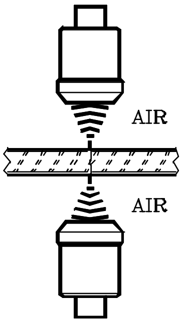


Figure 5: Normal Through Transmission

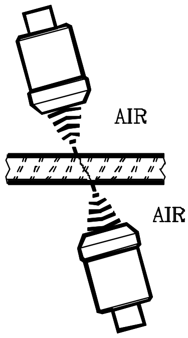


Figure 6: Shear Wave

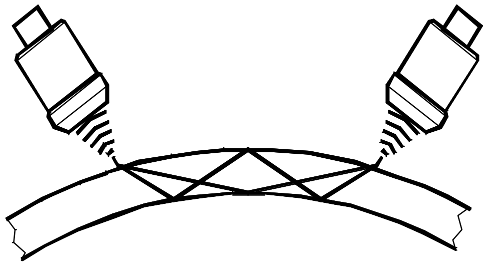


Figure 7: Plate Wave

Where accurate imaging of defects is required the normal through transmission configuration (Figure 5) is most appropriate, as used for conventional water coupled Ultrasonics.

In some materials, particularly laminates, better results are obtained by offsetting the probes and angling them slightly so that shear waves are produced as shown in Figure 6

Because there is no couplant to damp surface vibrations, Air coupling lends itself well to production of Lamb or Plate waves as shown in Figure 7. These can travel significant distance in suitable materials, They have two particular advantages:

- It is possible to have both transmit and receive probes on the same side, or both on the outside of a closed part such as a tube.

- Because the test checks a line, rather than a single point, it is possible to achieve much greater throughput speeds in applications where a precise image is not required.

Effect of Frequency

Air coupled Ultrasound typically operates at frequencies below 1 MHz, above this the sound transmission in air reduces, and more importantly, scattering losses in many materials become unacceptably high. (Typically scattering losses increase with the forth power of frequency) QMI have worked primarily at 50, 120 and 400 kHz. Results at different frequencies are summarized in Table 1

Frequency	Typical spot resolution	Typical Materials	Comments
50 kHz	8-10 mm	Thick structural foams, Complex multi-layer composites, Unprocessed Timber	Will penetrate almost anything, but resolution is inadequate for many purposes,
120 kHz	5 mm	Foam sandwiches, two or three layer honeycombs, medium thickness timber, drywall,	Good compromise where max resolution not required. Can penetrate most 'possible to test conventionally' materials.
400 kHz	1-2 mm	Solid laminates, single layer honeycombs,	Gives results comparable in resolution to practical production tests.

Table 1: Effect of frequency on Air coupled UT tests

The majority of the work carried out by QMI has been at 400kHz, but increasingly lower frequencies are being employed to test more complex composite materials. A previous paper examines this in more detail.[iii]

Applications.

Wood products

As previously noted the timber industry was among the first that employed air coupled ultrasound commercially. Applications of Air-coupled Ultrasound fall into four main groups:

- Assessment of Bulk timber for internal decay and voids prior to processing. This requires extremely high penetration. Currently fully air-coupled inspection has not provided adequate signal to noise ratio, although the technology has been applied with soon success in conjunction with dry pressure coupling

- Detection of delaminations and cracking in composite or processed wood products such as particleboard and pressed wood. This normally involves some form of scanning, although a single line test is sometimes acceptable. By using a lamb wave it may be possible to test the entire width of a board, allowing effectively 100% inspection

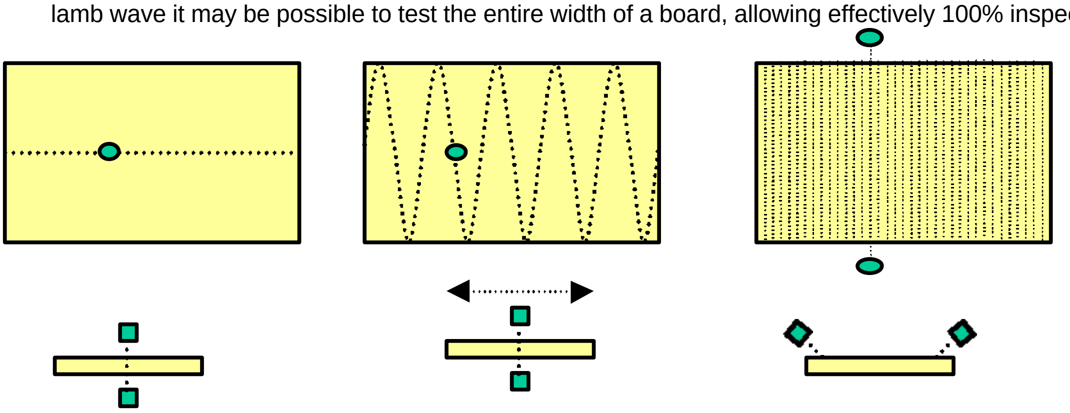


Figure 8: Different approaches to 'scanning' of sheet products

- Assessment of wood quality by measuring sound transmission velocity. This has been quite successful, although the tone burst limits accuracy of timing measurement.

- In-service Inspection of wood products for internal decay and cracking, for example structural beams and utility poles.

Many different configurations are used, with thin wood panels high frequencies can be used, and extremely good imaging can be obtained, as shown in figure 9.

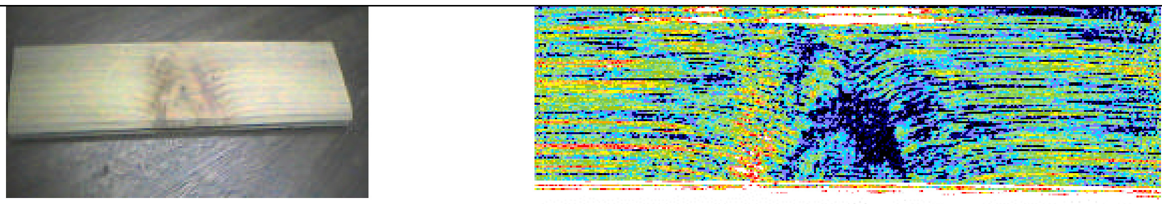


Figure 9: Comparison of photograph and C-scan in wood

Composites

Composite materials, particularly within the Aerospace industry, have been a primary area of application for air-coupled (and dry-coupled) test methods. The following are among the examples of results from inspection of composite parts

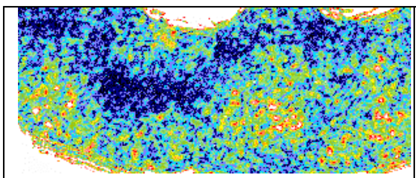


Figure 10: Scan of part of an aircraft brake disk, dark area appears to be disbonded

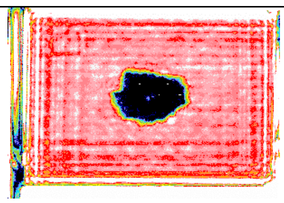


Figure 11: Impact damage in a carbon laminate panel

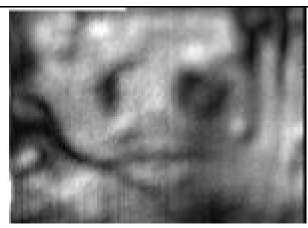


Figure 12: Bonded foam panel, (test at 50 kHz)

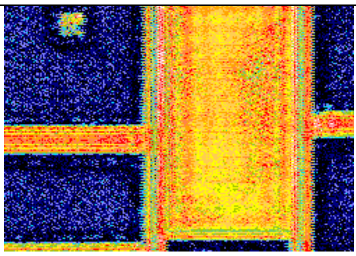


Figure 13: scan of a complex composite satellite part (carbon/carbon & carbon/honeycomb)

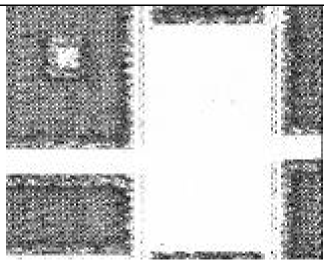


Figure 14: as previous figure, tested at a higher gain to optimize results on honeycomb section.

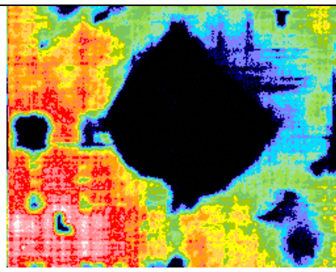


Figure 15: Light weight armor panel, showing disbonding after impact.

These are all through transmission C-scans obtaining results which will be reasonably familiar to users of conventional Ultrasonics, however many production inspections can conveniently use a plate wave configuration, giving simple 'go/no go' quality assessments. This has been particularly applied to pultruded composites.[iv]

Metal parts.

The extremely high acoustic impedance of metals, and the corresponding poor transmission coefficients for sound from air, means that metals are generally poor candidates for Air-coupled inspection, however, when other circumstances are favourable acceptable results may be obtained. A system is currently being manufactured to inspect bonds in a thin (2mm) laminated steel tube that is intended for an aerospace application.

Accurate Timing measurement using Air-coupled ultrasound

Relevant physical properties of a material can often be correlated to the velocity of sound, This can be calculated by measuring the transit time through a reasonably long section of the material. Water would be incompatible with many of the materials (e.g. wood, where properties are significantly affected by moisture) Air-coupled lamb waves lead themselves well to this, since the results are reasonably predictable, there are no coupling arrangements to interfere with production speed, and the experimental setup can often be arranged so that a fairly long distance in the material can be measured, thus minimizing error. However, as noted earlier, the duration of the tone burst can be a limiting factor in measurement precision. To reduce this it is necessary to use a 'conventional' damped probe driven with a spike or square wave pulse. This greatly reduces the overall efficiency. To counteract this extremely high power can be used (a 1200V pulser has been tried, and a 4 kV unit is being developed.) Because these applications do not typically require a rapid sample rate signal processing can be used to further improve signal to noise ratio.

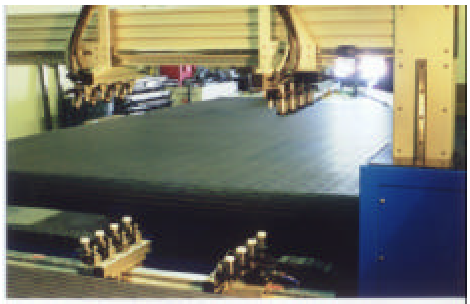


Figure 15: Close-up of probe assemblies

Large Area Scanning.

As noted above the scanning rate of Air-coupled ultrasound is limited by the relatively low PRF which is possible with the long transit times in air. Typically a PRF of around 200 Hz is possible. If we accept a relatively coarse scan pitch of 3mm as acceptable for a production test this implies a maximum linear speed of 600mm / second and in two dimensions, an absolute minimum time of around 10 minutes to scan one square metre. The scanning assembly shown in figure 17 combines the results from 8 channels, each of which carries out a through transmission test. Customized software 'assembles' the results from each probe into a single image. The end result is a combined throughput of around 1 square meter per minute, able to keep up with a high-volume production line for composite panels.

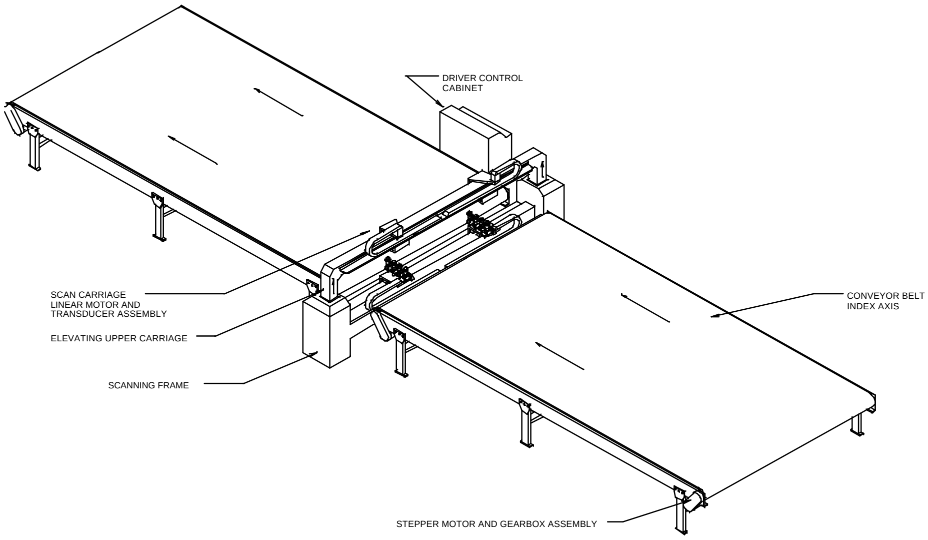


Figure 16: Multiple channel air coupled ultrasonic scanner

Portable Instrumentation.

Because of the high power requirements most air-coupled Ultrasonics requires an AC power source. While commercial air coupled portable units have been available for some time they have been limited to very low frequencies (50 kHz and below) where penetration of most materials is very easy and thus high power is not so necessary. While power is still a limitation, it has recently been possible to develop a portable instrument capable of operation at 120 kHz, This provides discrimination of many types of defect not visible at the lowest frequencies. Work is currently underway to develop field applications.

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[i] Birks, A.S. "Particle board Blow detector, Forest Products Journal, June 1972, Referenced in **The NDT Handbook,** 2nd Edition.

[ii] Lavery *et al*, "Nondestructive Tire testing", Materials Evaluation, July 1975, Referenced in **The NDT Handbook,** 2nd Edition.

[iii] Frequency considerations in air-coupled ultrasonic inspection. J. Buckley, H. Loertscher. BINDT Conference, Sept. 1999

[iv] In-process inspection of pultruded tubular products using air-coupled ultrasound. J. Buckley, J. Strycek, H. Loertscher. 37th Conference of the BINDT, Sept. 1998.