INDUSTRIAL APPLICATIONS OF AIR-COUPLED ULTRASOUND

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ABSTRACT
This paper will described the many applications in which air-coupled ultrasound can be used. The first of these is in the measurement of gas flow. This includes the measurement of hot gas jets, where both the flow and temperature cross-sections can be measured and imaged simultaneously. In addition, high temperature flames can be investigated and their temperature profile estimated. There are also applications in surface measurement, where surface profiles can be determined as images. This uses focussed devices incorporating mirrors or other elements. Such high resolution imaging has other uses. For instance, it is possible to image the internal structure of very thin materials in this way, with examples including packaging and paper products. Finally, air-coupled ultrasound can be used to form images of the internal structure of many types of materials. One very interesting area is food quality inspection.

INTRODUCTION
Air-coupled ultrasound has been investigated by many authors for the imaging of materials, and to make measurements within air and other gases. There are several developments that are important in this area – the availability of wide bandwidth and efficient ultrasonic transducers, and the use of signal processing techniques to recover signals in noisy environments. With both of these aspects being available, many interesting industrial measurements can be made.

Transducers for wide bandwidth measurements are usually of two types. The first are piezocomposites or piezoelectric transducers fitted with an impedance matching layer [1], which can be of various designs. The other approach is to use a capacitive or electrostatic transducer. This is inherently of reasonable bandwidth. For most air-coupled measurements, the devices are constructed with a rigid conducting backplate and a thin, flexible polymer membrane [2]. Both sets of devices have been used in air-coupled measurements, including imaging of solid materials [3], non-destructive evaluation (NDE) applications [4], robotics etc. Figure 1 shows a schematic diagram of a typical capacitive device, and Figure 2 shows the typical output into air. As can be seen, there is a reasonable bandwidth available for measurements.

In this paper, the various applications will be reviewed, and it will be seen that there are many areas to which this technology can be applied. Below, examples are shown of measurements in gases, including hot and flowing gas jets, NDE imaging examples, the inspection of food products, and the measurement of surface profiles.
Figure 1.- A typical capacitive transducer

These devices typically provide waveforms and bandwidths such as that shown in Figure 2 under transient excitation. As will be seen, the ultrasonic waveform is well-damped with a reasonable bandwidth.

Figure 2.- Typical waveform and spectrum from a capacitive transducer

TOMOGRAPHIC MEASUREMENTS OF HOT GASES

There is an interest in measurement of both flow velocity and temperature profiles in hot gas flows. An example is in the exhausts from various types of internal combustion engines and turbines. Using air-coupled ultrasound, it is possible to send ultrasonic signals across the flow in a given plane at various angles, and to use this information to reconstruct tomographic images of cross-sections in flow velocity and/or temperature. This is achieved by measuring the ultrasonic time of flight at some angle to the flow axis, both with and against the direction of gas flow. The sum and difference values along the same path are then used to give the required information: a difference removes the effect of background changes in acoustic velocity due to temperature, leaving just the flow component; the sum gives the temperature information.

Figure 3 shows the result of measuring the properties of a hot gas jet at an angle of 45° to the flow axis. As can be seen, cross-sections in both flow and temperature can be produced from the same set of data. Such reconstructions have many uses in engineering applications.

Figure 3.- Flow (left) and temperature (right) cross-sections of a hot gas jet at three different heights, taken at 45° to the gas jet axis.
In some situations, it is possible to have high temperatures but very low flow velocities. An example is the flame above a Bunsen burner, where the significant contribution is from the temperature effects only. In this case, the reconstruction of temperature is possible directly from the time of flight data, as shown in Figure 4.

Figure 4. Ultrasonic measurements across a Bunsen burner flame. (a) a single lateral scan showing the change in arrival time, (b) tomographic reconstruction of temperature profile.

AIR-COUPLED MEASUREMENT OF MATERIALS AND SURFACES

The above measurements used a typical transient excitation waveform, which because of the use in gases was of sufficient amplitude to give good resolution. However, consider the case where a signal is to be passed through a solid object using gas coupling. In such situations a large amount of energy is lost by reflection at the impedance boundaries, such that transmitted signal to noise levels are very low. In such situations, pulse compression techniques can be used. These drive the source transducer with typically a swept-frequency “chirp” signal, and the received ultrasonic waveform is cross-correlated with a replica of the drive voltage waveform. This can dramatically improve signal detectability, and allows the technique to be used to image the internal structure of a wide range of industrial materials.

Figure 5(a) is a conventional immersion C-scan image of a carbon fibre composite plate containing impact damage. The area highlighted by the blue box was then scanned using air-coupled ultrasound, and the result shown in (b), where it can be seen that similar details were observed, but without the need for a coupling liquid.

Figure 5. - A comparison of C-scans produced by (a) water immersion and (b) air-coupled ultrasound for a composite plate containing impact damage.
High resolution images can be obtained using various focusing elements, including curved transducers, Fresnel lenses and mirrors [5]. Figure 6(a) shows one such device, using an off-axis parabolic mirror to achieve a good focal region in air, as illustrated in Figure 6(b). Such devices can be used to make many interesting measurements.

Figure 6. – An off-axis parabolic mirror for high resolution air-coupled ultrasound. (a) Schematic diagram of mirror geometry, and (b) an experimental scan of the focal region in air.

Figure 7 shows an example of the type of images that can be achieved in thin materials. This shows watermarks in commercial writing paper. The optical through-transmission image is shown on the left, and the equivalent acoustic image is shown on the right. The lettering is seen clearly in both images. Note however, that the acoustic image can be obtained even in the presence of dark ink on the surface of the paper, a fact that may be useful in security applications. Similar images can be obtained of glued joints in cardboard packaging, including long-life food containers. Figure 8 shows two such high resolution images, the one on the left being fully sealed, the one on the right having a break in the glue line.

Figure 7. - Images of watermarks in paper, obtained by (a) optical and (b) ultrasound through-transmission.

Figure 8. - Images of bond lines in cardboard packaging. (a) Good bond; (b) an area of delamination, shown as the darker area.
An interesting feature is that the well-defined focal region can be used to form reflection images. An example is shown in Figure 9, where the parabolic mirror has been used in pulse-echo to scan the surface of a metal sample, in this case a coin. Various features can be extracted from the signal, including received amplitude, time of flight, spectral content etc, which gives a wealth of data concerning surface condition.

![Air-coupled reflection image of a UK coin of the realm.](image)

**Figure 9.** – Air-coupled reflection image of a UK coin of the realm.

### NON-CONTACT FOOD QUALITY INSPECTION

There are many measurements for which air-coupled ultrasound can be used in food materials. The fact that it is non-contact means that it can be used on a production line, for objects such as food cans and containers. Figure 10 shows the results of such an application, where signals were transmitted through a liquid-filled container at various heights, and the pulse compression output recorded. Above the liquid level (at 0 mm), no signal was transmitted, as coupling through the air within the container was poor. However, below this level, the typical rectified and smoothed output signal was detected, giving an indication of fill level.

![Air-coupled ultrasonic detection of liquid fill level in a container.](image)

**Figure 10.** – Air-coupled ultrasonic detection of liquid fill level in a container.

Air-coupled ultrasound is also useful for imaging the internal contents of food, and in particular for detecting non-metallic foreign bodies and other contaminants which can be missed by X-rays and metal detectors. An example is shown in Figure 11 which shows the detection of a single deliberate inclusion of a piece of crushed mint sample into the chocolate. As can be seen, it is clearly detected by the scan, meaning that the concentration of such inclusions can, in principle, be estimated. Experiments by the authors have been performed on many different food products as part of a study funded by the UK government with four major food companies. It demonstrates that air-coupled ultrasound has many uses in food quality inspection.
Figure 11. – Air-coupled ultrasound images of a single mint inclusion in chocolate.

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References