WIDE BANDWIDTH AIR-COUPLED ULTRASONIC TESTING OF FOOD CONTAINERS IN AIR

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ABSTRACT. Air-coupled NDE has been used to perform measurements on food containers. This relies on the broad bandwidth available from polymer-filmed capacitive transducers, combined with pulse compression techniques. The first experiments involve liquids within cylindrical polymer containers. It will be demonstrated that transmission through the drinks bottles can be used to measure liquid level, either from monitoring the through-transmitted signal directly, or by observation of a reflection from the liquid surface. This can be achieved without contact to the container. By scanning the transducers around the container, it is also possible to collect tomographic data. It will be demonstrated that this can be used to reconstruct air-coupled cross-sectional images of such containers, so that contaminants can be located. It is also shown that the temperature of a liquid can be estimated successfully, using time-of-flight measurements. The result is a powerful method for the NDE of such materials, which could be applied to production-line situations.

INTRODUCTION

Much research has been carried out on the use of physical measurements to determine the properties of food [1]. These can be used to determine the physical properties of the foodstuff (e.g. in emulsions, powders and other forms [2]), or to detect foreign objects [3], and surface defects [4]. In particular, there has been recent interest in using ultrasound to investigate the content of food products. One reason for this is that any change in the acoustic property of the test medium could then be related to changes in the food product. Ultrasound has the ability to differentiate between both the propagation velocity within various media, and the differences in acoustic impedance between different regions within a given volume. Thus, using the usual contact or immersion techniques, ultrasound can be used to measure the moisture content of the food products [5] and for liquid level measurement [6]. However, to date these techniques require a coupling medium between the test sample and the transducer surface. In certain cases, the need to use a couplant makes testing difficult, for instance if contamination of the food or container has to be avoided. For these reasons, X-rays have been widely used to detect anomalies or foreign objects present in food [7-9], usually in through-transmission. Other techniques such as Magnetic Resonance Imaging (MRI) can be used to study the temperature distribution in food samples [10], although this is an expensive and complicated method.

This paper describes the use of air-coupled techniques to measure liquids within containers similar to those used in the food industry. It will be demonstrated that various
non-contact measurements are possible, including the detection of liquid level measurement, tomographic imaging and temperature estimation. All these measurements were performed using the pulse compression technique, where the accuracy of time-of-flight measurements is improved, and where a good signal to noise ratio (SNR) should result [11,12].

APPARATUS AND EXPERIMENTAL SETUP

The experimental arrangement used for non-contact liquid level measurement is as shown in Figure 1. The pulse compression approach was implemented using an NCA 1000 pulser/receiver unit. In order to provide initial calibration, the transducers were aligned horizontally, with no sample in place, and separated by 170 mm. The output chirp voltage was superimposed upon a +200V dc bias using a capacitive decoupling circuit, before being applied to a capacitance source of bandwidth 1.5MHz. The longitudinal waves propagated through the air to the sample. Through-transmitted signals were received by the capacitive receiver, input to a Cooknell CA6/C charge amplifier, and pulse-compressed data from the NCA 1000 unit recorded using a Tektronix TDS540 digital oscilloscope with 200 averages.

Initially the transducers were aligned axially ($\theta = 0^\circ$). The aim was to measure through-transmitted signals as the liquid level changed. A cylindrical bottle with an external diameter of 116 mm and thickness 0.6mm was then placed between the transducers. Measurements were obtained by varying the volume (and hence the liquid level) of liquid inside the container, with the transducer location fixed. Each variation of $2.6 \times 10^5$ m$^3$ of water (corresponding to 2.5mm in level) was recorded. A second set of measurements were performed with the transducers tilted as shown in Figure 1, at angle $\theta = 12^\circ$. The aim was to try and obtain a signal that reflected from the liquid surface. Timing the arrival of this signal would give an estimate of liquid depth.

![Figure 1](image-url)

**FIGURE 1.** The experimental setup for liquid level measurement using two broadband capacitance transducers.
Cross-sectional imaging of defects was performed on the same container (Figure 2), using linear and angular translation of the transducer pair to collect data from around the sample. All scanning and data acquisition was controlled by Labview™ version 5.0 software. This software also extracted data (peak amplitude or the time of arrival) from each waveform in the scan, for later input into a tomographic reconstruction program. Data was also collected from containers containing simulated foreign objects.

Temperature measurement can also be performed using air-coupled transducers. This has been demonstrated in two containers: a microwave container (180mm x 110mm x 49mm) and a soft-drinks can. The experimental setup is as shown in Figure 3.

The transducers were separated by 158mm and the container placed between them as shown. The chirp signal was set to have a centre frequency of 800kHz with a bandwidth of 700kHz. An averaging of 400 samples was applied to the signal before it was recorded onto a floppy disk. A typical experiment involved time-of-flight measurements at regular (5 minute) intervals as the liquid within the container cooled from close to 100°C down to room temperature. A thermometer was also used simultaneously to measure the temperature of the water as it cooled.

The transmitted time of flight \((t_{\text{tof}})\) of a chirp from the source across the sample to the receiver was recorded, \(t_{\text{tof,transmit}}\). The measured \(t_{\text{tof}}\) of the reflected signal \((t_{\text{tof,air}})\) from source to the front wall of the sample and bounced back was also recorded for calibration purposes. The measured velocity of sound in water was then used to compute the water temperature using the fifth order polynomial equation reported by del Grosso [13]. This measurement was repeated for both a microwaveable container and a soft drinks can.
RESULTS AND DISCUSSION

Liquid Level Measurement

A polymer drinks container was positioned as shown in Figure 1, with $\theta = 0^\circ$. The water level was then varied in 2.5mm steps, with 0 mm being the transducer axis. Figure 4 shows the recorded waveforms. The received amplitude remained constant as long as the water level remained above 0mm, but as this was approached, the amplitude increased due to signal scattering from the water surface. As the water level reduced further, the peak amplitude reduced to zero as the liquid content was replaced by air. Note that Figure 4 demonstrates an excellent SNR.

![FIGURE 3. Experimental setup of the water temperature measurement in a container.](image)

![FIGURE 4. Variation of the pulse compression output as the transducer was scanned vertically down a circular bottle containing liquid. The transducers were aligned axially, with $\theta = 0^\circ$.](image)
A more practical arrangement would be that with tilted transducers, so that a reflection from the under side of the water surface could be obtained. The transducers were thus tilted to $\theta = 12^\circ$ from the horizontal plane. As before the water level was varied by 2.5 mm for each measurement. The measured waveforms are shown in Figure 5. As the amount of water in the container reduced by a step size of 2.5 mm, the time of arrival of $|P(t)|$ decreased, and the pulse-compressed time peak moved to the left as shown. This was due to the shorter travel time for the signal reflected from the water surface.

The recorded signal shows that the SNR is much lower compared to Figure 4. This was because most of the incident signal was reflected into the air at the interface and only part of the signal was transmitted. However, it is evident that the liquid surface has been detected by reflection, and hence measuring the time of arrival would give a measure of liquid level. The predicted accuracy of this measurement is approximately ±1 mm.

**Tomographic Imaging of Drink Containers**

Tomographic imaging was performed on liquid-filled polymer drinks bottles, to show that the presence of a foreign object in a bottle filled with water could be obtained. Imaging was thus performed on a circular aluminium rod placed inside the cylindrical polymer drink bottle. The image obtained from the peak signal amplitude is as shown in Figure 6. The image was reconstructed using the difference technique mentioned earlier, where each projection was compared to a set of reference data obtained from a sample containing only water. The defect of 10 mm diameter is clearly shown in the figure, but is distorted due to diffraction and refraction effects. However, it can be seen that the rod attenuated the through-transmitted signal. Further imaging was conducted by replacing the circular aluminium rod with a thin plate of length 7 mm and width 1.5 mm. The

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**FIGURE 5.** Change in time of arrival of the compressed pulse signal with variation of liquid level using transducers at $\theta = 12^\circ$. The major peak is a reflection from the liquid surface.
FIGURE 6. Air-coupled tomographic reconstruction of a polymeric drinks bottle, containing a circular aluminium rod of diameter 10mm.

FIGURE 7. Air-coupled tomographic reconstruction of a polymeric drinks bottle, containing a thin plate of length of 7 mm and width of 1.5mm.

reconstructed image using the difference tomography technique is shown in Figure 7. The dashed line in the image highlights the area of the object. Again, the plate has been detected, but the image is distorted by refraction effects. Despite this, both images indicate that an object with a different acoustic impedance to the water could be detected using transducers located in the air outside the container.

Refraction effects are particularly marked in the present experiments, as the longitudinal velocity in the water within the container is over four times greater than in air. In addition, ultrasonic waves are incident at fairly large angles to the circular cross-section of the bottle at the extremes of each projection. Increased imaging accuracy would result if refraction effects were taken into account during the image reconstruction process.
FIGURE 8. Measurements of water temperature in (a) microwaveable container and (b) a soft drinks can. The solid line and data points represent the thermocouple and ultrasonic measurements respectively.

**Temperature Measurement of Liquid in a Container**

The velocity of sound in water is known to increase with temperature up to 74°C but to decrease again thereafter. The dependency on the velocity of sound and temperature conducted here are based on the algorithm given by del Grosso [13] and by using this equation, the velocity of sound was calculated from the measured time of flight. The calculated velocity of sound across water within both a microwaveable container and a soft drinks can is as shown in Figures 8(a) and (b) respectively. The result shows an exponential decay of the sound velocities as the water within the container cooled with time. From the computed sound velocity, the temperature of the water in the container is shown as data points. The results obtained using the ultrasonic measurement show good agreement when compared with the result measured using the thermometer, which is represented by the solid line. There is reasonable agreement, although the slight discrepancy between the ultrasonic and thermometry measurements is thought to arise from the fact that the ultrasound integrated the effect along a line, whereas the thermometer represented a point measurement.

**CONCLUSIONS**

An air-coupled ultrasonic technique has been developed, which can be used to measure properties of interest to the food industry. This was performed using two broadband capacitance transducers together with a pulse compression signal processing technique. The combination has been shown to result in a good signal-to-noise ratio for ultrasonic through-transmission. It has been shown that the level of water within a polymer drinks bottle could be estimated, either by monitoring the amplitude of through-transmission, or by using a reflection from the water surface. Tomographic images of horizontal cross-sections were also presented, although these were distorted by diffraction effects. Measurement of water temperature in containers was also successfully performed and the results show good agreement with those from a thermocouple.
REFERENCES