The Use of Air-Coupled Ultrasound to Test Paper

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***Abstract*—Capacitance transducers containing a thin polymer membrane have been used to transmit ultrasonic signals with frequencies in excess of 1 MHz through various paper products such as paper and cardboard. At normal incidence, a resonance was visible in thicker samples, the frequency of which could be correlated to parameters such as the thickness of the paper sample and the moisture content. It has also been demonstrated that images can be obtained of changes in structure across paper and card samples.**

I. Introduction

The paper industry is constantly seeking new non-contact methods for testing various paper products during manufacture [1]. The most common method for determining the quality of paper involves testing a set of samples off-line. This technique is not always satisfactory, as paper measurements made in the laboratory have to be averaged over the whole surface of the sample because of the uneven nature of the product. These averaging techniques conform to statistical standards, but can be time-consuming and expensive. There are, however, some existing on-line methods for testing paper products. These include optical methods [2], [3], gamma-rays [4], or beta radiation [5]; ultrasound [6]–[12] and even resistance to fungi [13]. They are used to measure parameters such as paper thickness and modulus. Other parameters of interest include the basis weight (or mass per unit area) and moisture content. A common technique for basis weight measurement uses the attenuation of beta or gamma radiation [4], [5]. However, the use of ionizing radiation in an industrial environment is undesirable for safety reasons, and, hence, an alternative technique is much sought after.

The introduction of a non-contact ultrasonic measurement system would offer an improvement, as variations in paper thickness and material parameters could be measured continuously. The conventional technique of using ultrasonic immersion transducers for inspecting moving materials is unsuitable, as the water couplant would alter the composition of the paper sample under test. The acoustic impedance of air is closer to paper than it is to other materials, such as metals and polymers, and, hence, air-coupled ultrasound is a good candidate for the testing of paper products.

Ultrasound is used both at high energies to aid certain paper manufacturing processes and in a non-destructive sense to measure certain parameters of the paper. Areas that have been investigated in the past include the measurement of liquid penetration in paper, delamination defects, and the characterization of the elastic parameters of the paper [6]. Other work investigated the use of Lamb waves [7], [8] to measure paper properties. Habeger and Baum [9] made use of piezoelectric wheel probes to measure the acoustic velocity within the paper as it was being manufactured, this being related to the resultant mechanical properties of the material. The piezoelectric wheel probes were designed to be in constant contact with the paper as it moved along on the paper web. Measurement of the acoustic velocity in paper samples and other thin sheets to determine properties such as thickness and mass per unit area has also been investigated [10], again using piezoelectric transducers. Attempts have also been made to measure the surface roughness of paper [11] using the amount of scattered signal from the paper surface.

With the advent of paper machines running at increasing speeds and producing thinner papers, transducers such as the wheel probe become increasingly difficult to use. A non-contact technique would be more useful for such testing. Previous work in this area has included the use of laser-generated ultrasound [12], [13] and air-coupled piezoceramic transducers [14]. Much work has been published on the use of laser-generated ultrasound for static materials inspection [16]–[18]. However, there would be some concern over damage to the sample [13], which would result from repeated firing of the laser. The use of a laser-based measurement system is also likely to be costly, and there are safety implications. There have been some experiments reported that have used air-coupled piezoceramic composite transducers [19], [20], and some early work with Lamb waves used low frequency capacitive devices [8]. However, because of restricted bandwidth, transducers with different center frequencies would be required to make measurements on paper samples with a variable thickness (e.g., Khoury *et al.* [12] used three pairs of piezoceramic transducers in their experiments).

As mentioned previously, in most cases, the testing of paper products with ultrasound seems to have used contact piezoelectric devices. However, capacitance transduc-

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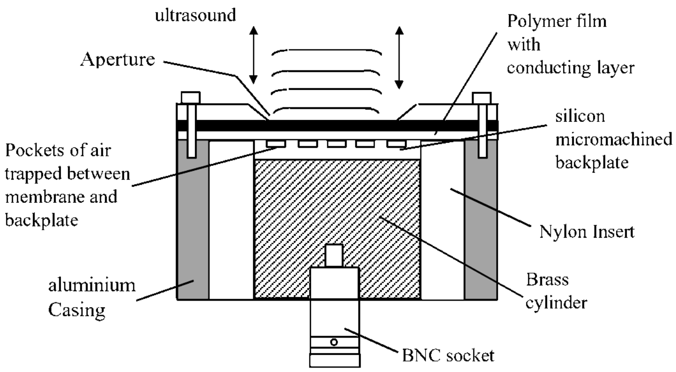

Fig. 1. Schematic diagram showing construction of the capacitive transducer used for these measurements.

ers have been used in air to measure the properties of polymeric materials [21], including carbon fiber composites; the technique was able to identify defect areas caused by delamination of the fiber layers. This paper describes experiments carried out using a pair of high-frequency, broadband, air-coupled capacitance transducers and various paper and card samples. It then proceeds to explore the potential of this technique as a means of analyzing the properties of paper.

II. Experimental Method

The experiments were conducted using a pair of broad bandwidth capacitance transducers similar to those described in previous publications [21]–[24]. The capacitance transducer, as the name suggests, is based on a capacitor with two parallel electrodes. The first electrode is a stationary one and is commonly referred to as a backplate. In many devices, this electrode is a polished or roughened metal surface [25], [26], but, in the devices used here, it is fabricated using silicon micromachining techniques [22], [27]–[29]. The vibrating membrane is usually a thin polymer film with a typical thickness in the range from 2 to 10 μm, with a metal coating on one side, as shown in Fig. 1. The membrane traps pockets of air behind it, which aids the coupling of ultrasound into the air. It is common when using these devices to add a dc bias voltage between the backplate and metal layer of the membrane within both source and receiver, as this helps stiffen the device mechanically and improves the frequency response. (Note that the receiver requires a bias voltage for operation in any case.) A typical waveform and corresponding spectrum detected when using a pair of these devices in air at a separation of 90 mm is shown in Fig. 2. It is clear from this figure that the response is well-damped with frequencies extending up to 1 MHz. Temperature variations and atmospheric turbulence in the laboratory were found not to affect the response unduly.

The first set of experiments was conducted using ultrasound at normal incidence, as shown in Fig. 3. The paper sample was mounted in a frame and held equidistant between the two transducers, which were separated by 90 mm. The transducer, used as a source, was driven with a voltage pulse from the Panametrics pulser, which provided a −250-V pulse with a fast rise-time (<100 ns) and a longer fall, adjustable using the damping controls. The signal detected by a second transducer was then amplified by the Cooknell charge amplifier and subsequently displayed on the oscilloscope. In each of these tests, signal averaging was used to increase signal to noise ratios, as received voltages were typically only a few milliVolts in amplitude (1000 averages was usual with a very good reproducibility). No additional windowing or filtering was necessary. Typical waveforms from two paper samples of different thicknesses are displayed to the left of Fig. 4(a and b). This indicates that a resonant waveform was detected in through-transmission, with the peak in the frequency spectrum corresponding to the through-thickness resonance. Note the presence of a high frequency electromagnetic noise precursor in the waveform of Fig. 4(a), caused by the high amplification used. To the right of each figure is the received frequency spectrum in through-transmission. This was obtained in each case by performing a fast Fourier transform (FFT) of the waveform and dividing this by the FFT of the received signal in the absence of a sample (shown earlier in Fig. 2). This deconvolution procedure suppressed the effect of the frequency response of the instrumentation system, allowing the resonant peaks to be more easily observed. Fig. 4 indicates that the through-thickness longitudinal resonance was at a lower frequency when the thicker paper sample was tested, as would be expected. Note that the sample had to be aligned within a few degrees of normal incidence, but this was not critical. It was important, however, to align the transducers very carefully with each other to maximize bandwidths and sensitivities.

Tests were performed on various sets of paper with different basis weights. These were supplied in the form of A4 white sheets (210 × 297 mm) by Enso Ltd., Finland and were of the type typically used for photocopying. The manufacturer estimated the area, thickness, and mass of each sheet, to give a nominal value of mass per unit area (to ±5%). The thickness of each sample was also measured independently by micrometer by the authors. Three samples were cut from each sheet and tests were performed on all three individually to give an average value of signal amplitude and frequency content for a given sheet.

III. Results and Discussion

A. Through-Thickness Experiments

The first series of experiments used ultrasound at normal incidence to observe the through-thickness longitudinal resonance, such as that shown earlier in Fig. 4, and to determine whether the resonant frequency was related to any of the paper parameters supplied by the manufacturer. There are several parameters of interest. For instance, paper is manufactured by pouring wood pulp and water onto a woven mesh, and this process gives rise to paper with two sides having different roughness and surface pattern. The

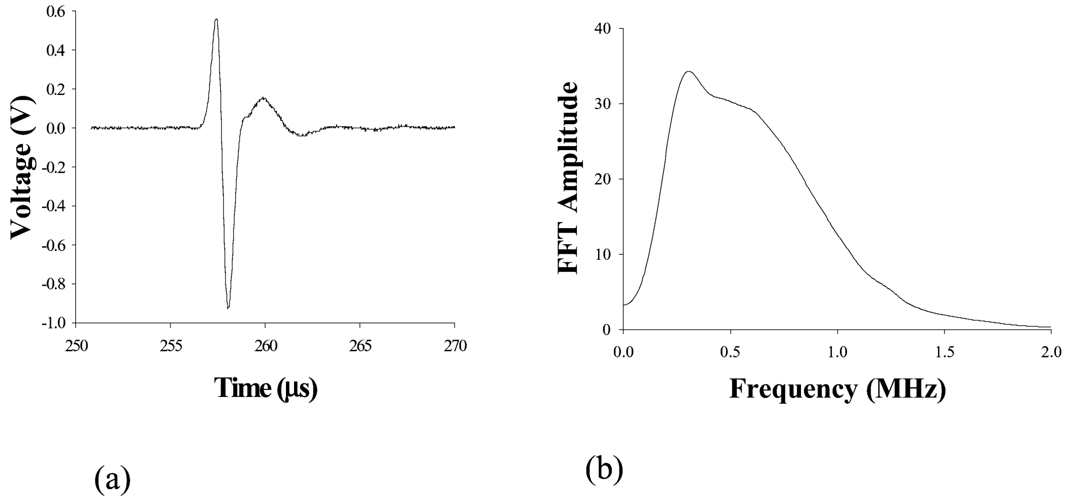

Fig. 2. a) Typical waveform and b) corresponding spectrum obtained when using a pair of the capacitive transducers in air.

two sides are referred to as the 'mesh' side and the 'felt' side, and the manufacturers (Enso Ltd.) measure a water penetration time for each side, known as Vp and Hp, quoted as time in seconds. Procedures for measuring these times during manufacture are described elsewhere [30], but it is usual to employ ultrasound in water immersion. In the present experiments, Hp was measured by the paper manufacturers using a commercial liquid penetration dynamics analyzer (Emtec Electronic GmbH, Germany), again to an accuracy of ±5%.

It was of interest here to see whether a through-transmission signal in air was correlated to this paper-wetting parameter. As an example, Fig. 5(a) plots the through-thickness ultrasonic resonant frequency of a set of paper samples against Hp, where the resonant frequency was measured as the peak frequency within the normalized through-transmitted spectrum. This shows a trend of decreasing resonant frequency with an increase in Hp. A best-fit straight line is also shown with an R^2 of 0.8505. Water absorption is known to be affected by the exact structure of the paper matrix [30]; hence, a correlation of Hp with resonant frequency might be expected, as structural changes will alter the elastic properties within the material and, hence, the longitudinal sound velocity.

Fig. 5(b) shows the changes in through-thickness resonant frequency against the glue content of a set of constant-thickness paper samples (the glue content was estimated by weight during the manufacture of the paper samples). Again, a linear trend with peak detected frequency ($R^2 = 0.8969$) was observed. The addition of glue or other additives changes the elastic parameters of the paper sample, as expected, leading to a change in the ultrasonic velocity for a given paper thickness.

It is interesting to obtain a representative value for the longitudinal sound velocity (V_1) in the paper samples provided for this research. Habeger and Baum [9] state that V_1 is given by

$$V_1 = [E_1 \,/\, \rho\,(1 - \nu_{12}\nu_{21})]^{1/2} \tag{1}$$

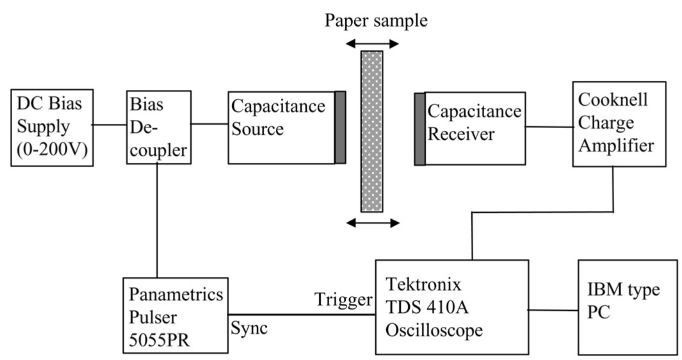

Fig. 3. Experimental arrangement for normal incidence through-transmission experiments conducted with air-coupled ultrasound and paper samples.

where ρ is the density of the paper, E_1 is Young's modulus in paper machine direction, and ν_{12} and ν_{21} are the Poisson ratios in the directions parallel and perpendicular to the paper machine direction, respectively. Because paper is anisotropic, a single through-thickness measurement cannot be used to determine the elastic properties completely but can be used to estimate the value of V_l. The through-thickness resonant frequency [31] can be expressed as

$$f_{\mathrm{resonant}} = V_1 \,/\, \lambda = V_1 \,/\, 2d \tag{2}$$

where λ is the ultrasonic wavelength at resonance, and d is the thickness of the medium.

A representative set of paper samples with basis weights ranging from 80 g/m^2 (typical A4 laser copy paper) to 240 g/m^2 (thin card) were tested to determine V_1 from f_{resonant}. Fig. 6(a) is a waterfall plot illustrating the change in through-thickness waveform for each paper sample in this group. From Fig. 6(a), it can be observed that no resonance was detected in the thinnest samples (i.e., with the lowest basis weight), but that a resonance evolved as the basis weight increased. The absence of a resonance for the thinner samples occurred because f_{resonant} was beyond the high frequency cut-off of the transducer response. The

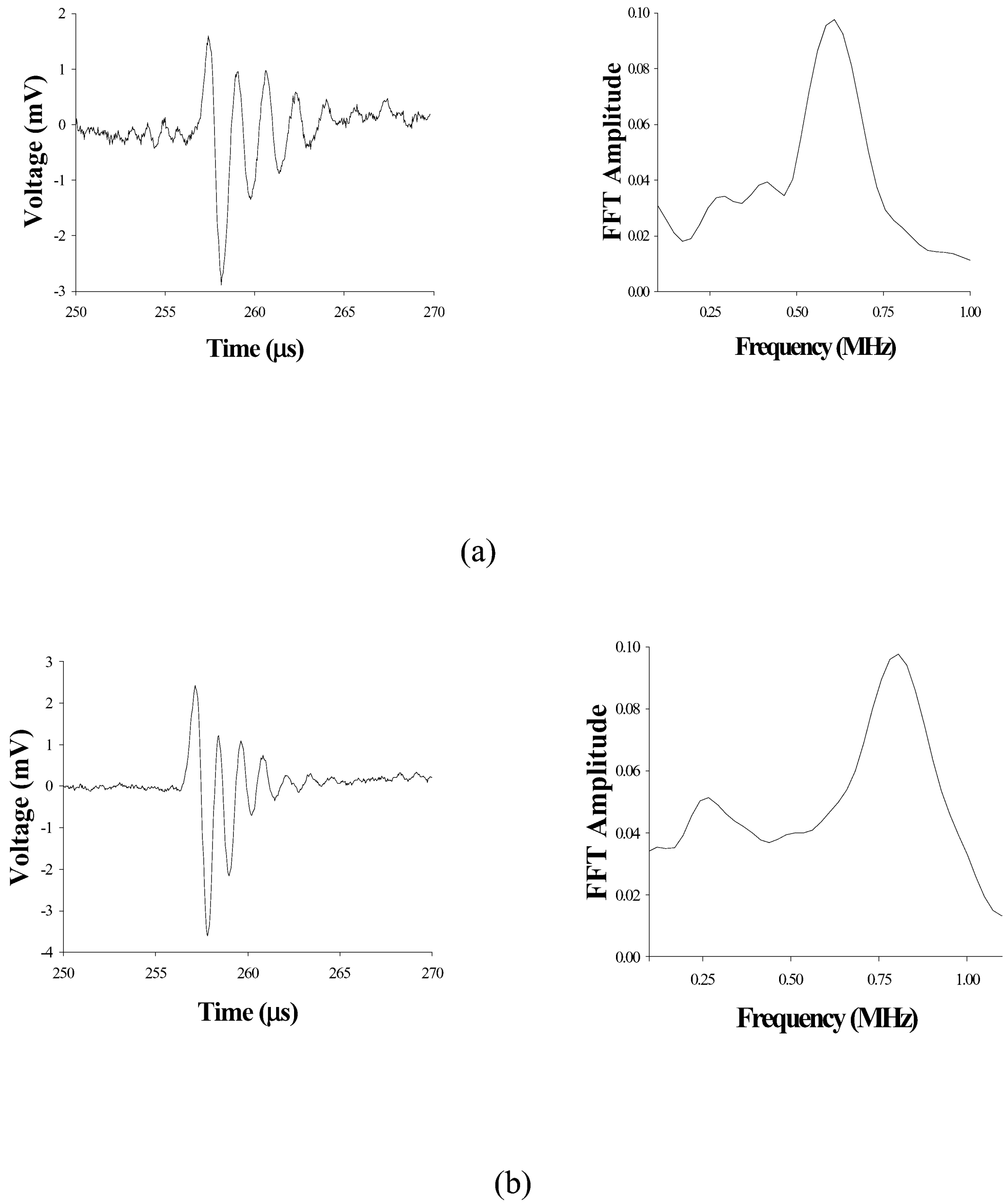

Fig. 4. Typical through-thickness waveforms (left) and corresponding spectra (right) for normal incidence. The spectra have been deconvolved with the spectrum of the waveform recorded in the absence of a sample (Fig. 2). Results are shown for paper samples with a thickness of a) 278 and b) 226 μm.

variation in through-thickness resonant frequency should be inversely proportional to the paper thickness (2), assuming that the longitudinal acoustic velocity is constant for this set of paper samples. Fig. 6(b) shows that this was the case for the higher basis weights. Where a resonance could be observed, the resonant frequency decreased as the basis weight increased, as expected. From these data, a mean ultrasonic longitudinal velocity of 346 ± 9 ms^{-1} was calculated in the paper samples. This is consistent with other measurements on paper [12], where the velocity was measured with contacting wheel probes and was found to vary within the range from 200 to 400 ms^{-1}.

B. Moisture Content Experiments

Another parameter of interest to paper manufacturers is the relative change in moisture content. Some work has been reported in the literature that has examined the relationships between moisture and fibrous materials such as paper [32], [33]. These studies have discussed paper as a natural polymer system with hydrogen bonds. When water or moisture is added to the paper, the fibers tend to absorb the moisture and increase in size [33]. The hydrogen bonds also become weaker and break up. This implies that paper with added moisture has a lower mechanical stiffness. Hence, the absorption of water will alter the me-

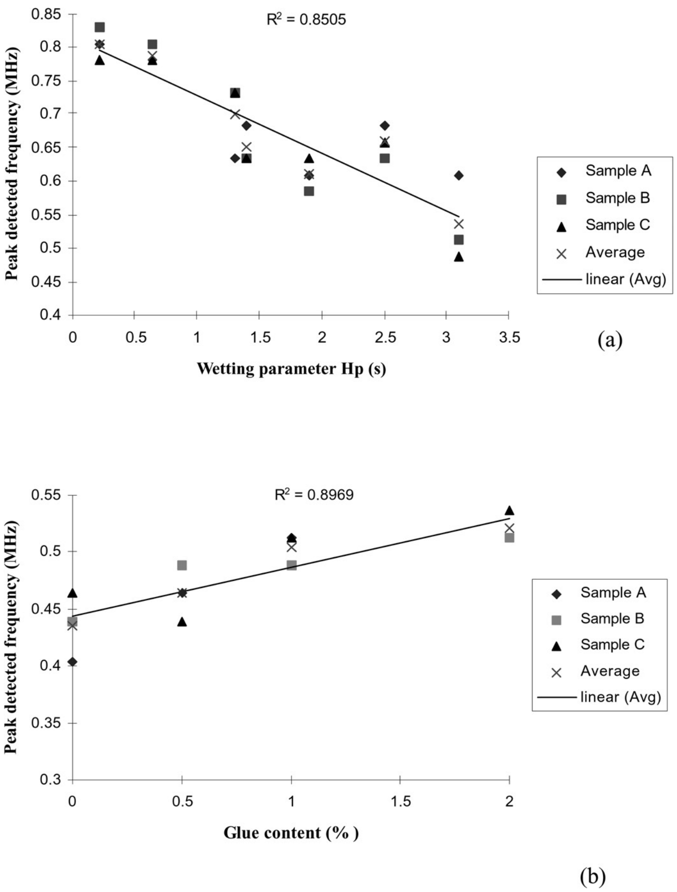

Fig. 5. Typical trend plots showing the variation of through-thickness resonant frequency with a) wetting parameter Hp (related to liquid absorption) and b) glue content.

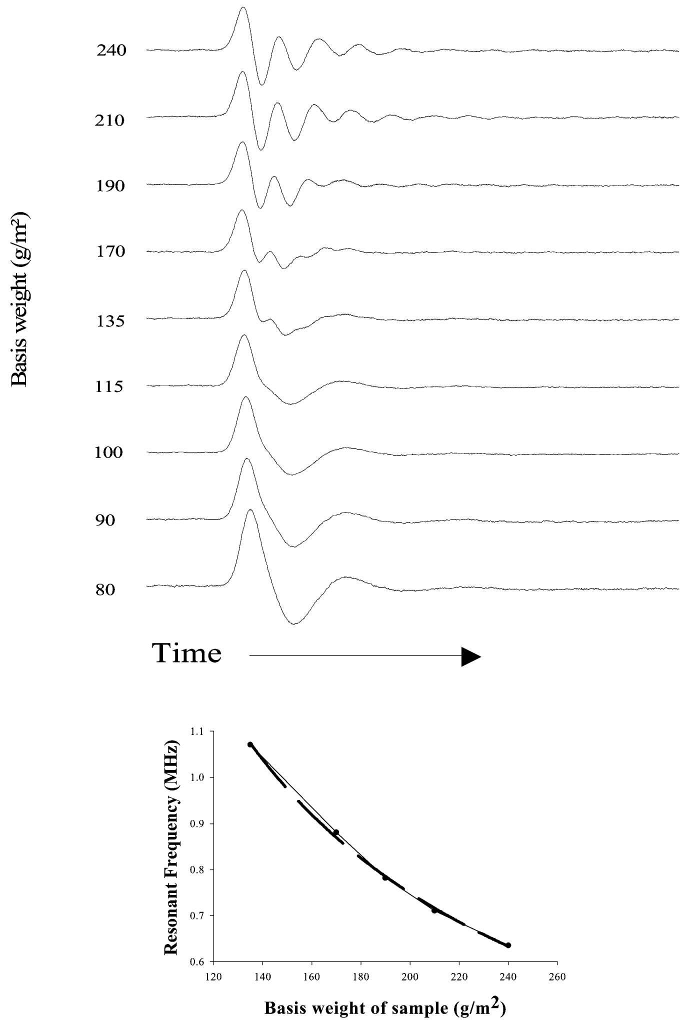

Fig. 6. The variation in through-thickness waveforms as a function of paper basis weight shown by a waterfall plot of time waveforms, each with a total duration of 20 μs (top), and the change in resonant frequency (the dotted line indicates a fitted curve) (bottom).

chanical structure and, hence, the ultrasonic velocity (1). This change in ultrasonic velocity will lead to a shift in the resonant frequency of the ultrasonic waveform propagating through the paper sample (2). An experiment was conducted in which moisture was added to a paper sample, and the through-thickness waveform was monitored periodically as the paper sample dried out under normal laboratory conditions.

The equipment used for this experiment is shown in Fig. 7. The paper sample and the frame in which it was mounted were both weighed continuously on a mass balance (Precisa 310M; sensitivity of 10 μg). The paper sample and frame were weighed before any moisture was added so that a reference mass could be obtained. The paper sample was then sprayed with a fine mist of water, the increase in mass was noted, and the ultrasonic through-thickness waveform was recorded. Therefore, the waveform and total mass were recorded at regular time intervals as the paper sample dried naturally over a period of some hours. Data from the balance were then used to calculate the water content as a percentage of the total mass of the paper sample. Note that the high sensitivity of the balance was required to perform this experiment.

Fig. 8 compares a through-thickness ultrasonic waveform for a paper sample at ambient laboratory conditions

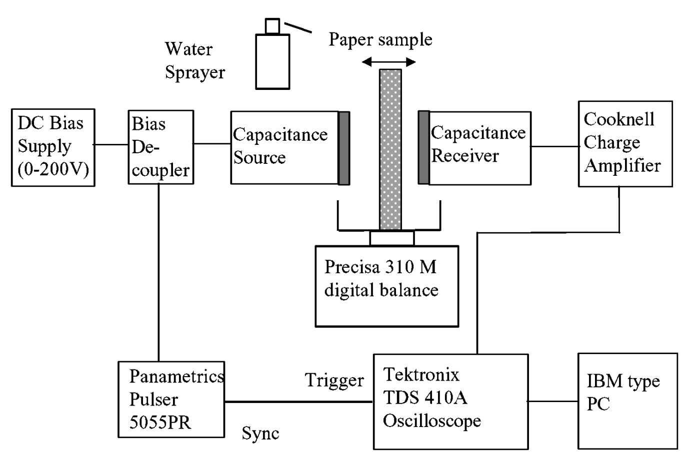

Fig. 7. The experimental set-up for determining the effect of moisture content on the propagation of air-coupled ultrasound through paper samples.

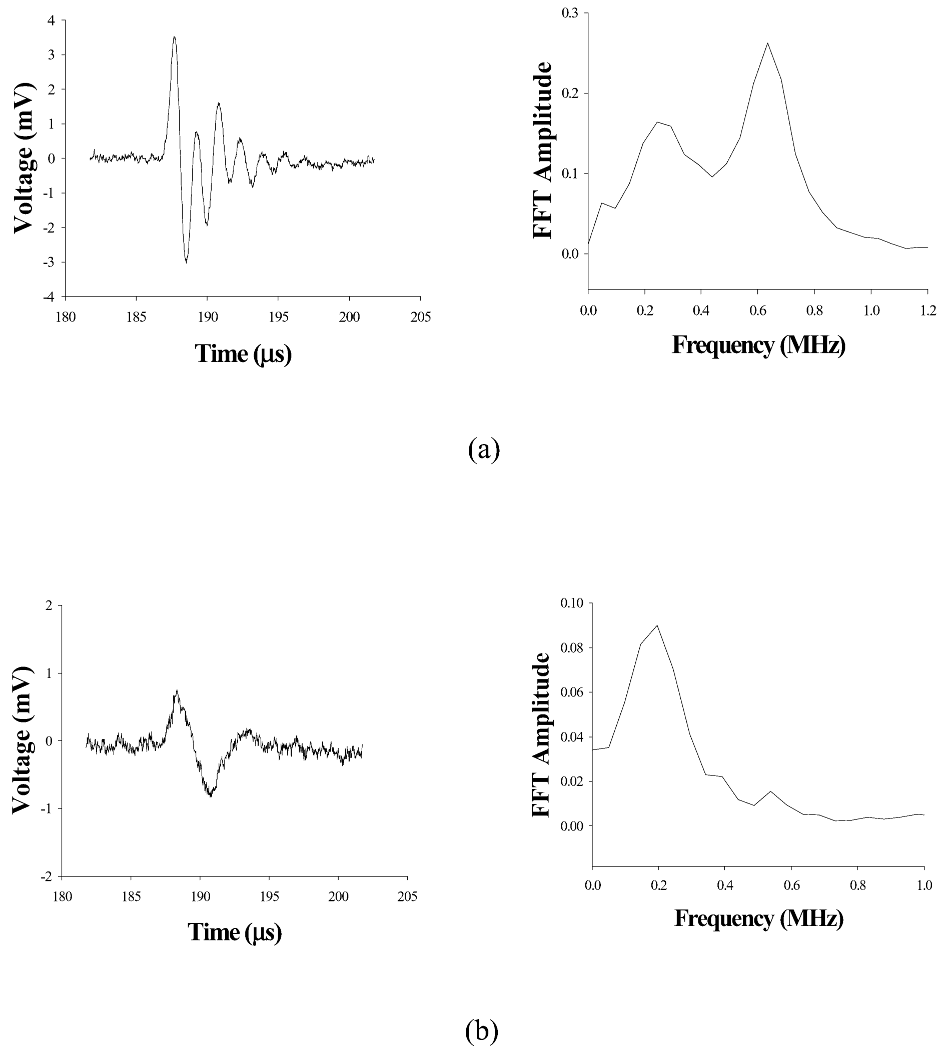

Fig. 8. Through-thickness waveforms (left) and corresponding spectra (right) for the cases when the paper sample a) is dry or b) contains added moisture. The spectra have been deconvolved with the spectrum of the waveform recorded in the absence of a sample (Fig. 2).

and one with added moisture (25% increase in water content by weight). A longitudinal resonance was detected before water was added, whereas the addition of moisture resulted in a non-resonant through-transmitted signal at a reduced amplitude and frequency. Fig. 9 illustrates the change observed in through-thickness waveform as a function of the water content, measured as a percentage increase in weight of the sample. It can be seen that, as the sample dried out, the through-thickness resonance began to reappear. Fig. 10(a) displays the variation of water content of the sample with time as derived from the balance and ultrasonic data. For each of the waveforms displayed in Fig. 9, a peak-to-peak voltage amplitude and a through-thickness peak frequency were measured, as shown in Fig. 10(b and c, respectively). For the higher water content, there was a low detected signal amplitude with a peak frequency of ∼200 kHz. As the water content reduced to less than 10% of the total mass of the paper sample, the peak frequency of the through-thickness waveform was observed to increase. Thus, the peak detected frequency returned to a value of 700 kHz once the sample had lost significant amounts of moisture, which was the value recorded at the start of the experiment before water was added. It is also interesting to note that, for the higher water content (∼25% of the mass), the amplitude detected was <2 mV compared with an amplitude of ∼7.5 mV when the water content was minimal. Thus, an increase in the water content by a factor of four caused a corresponding decrease in amplitude by approximately the same factor.

The processes involved in the absorption of water in paper are complicated, as stated previously, but the main effect seems to be the reduction in stiffness of the material caused by breakage of bonds between fibers. This would simultaneously decrease the acoustic velocity and increase attenuation, especially at high frequencies. Thus, both the transmitted amplitude and resonant frequency would decrease with water content, as observed. The increase in acoustic impedance of the material would also decrease transmitted amplitudes. A further component affecting amplitude would be the increased surface roughness caused by the swelling of fibers. It is thought, however, that

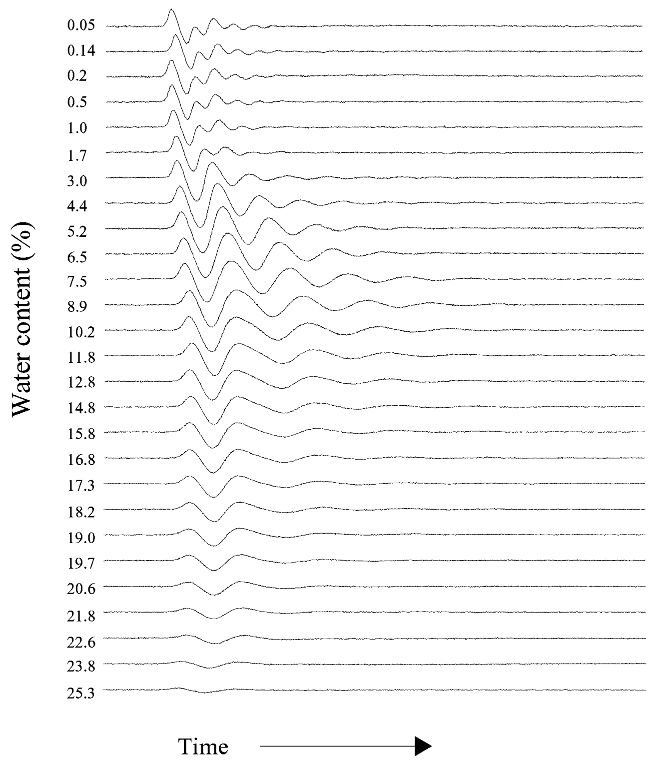

Fig. 9. Waterfall plot illustrating the change in through-thickness waveform of a typical paper sample as a function of water content of the sample.

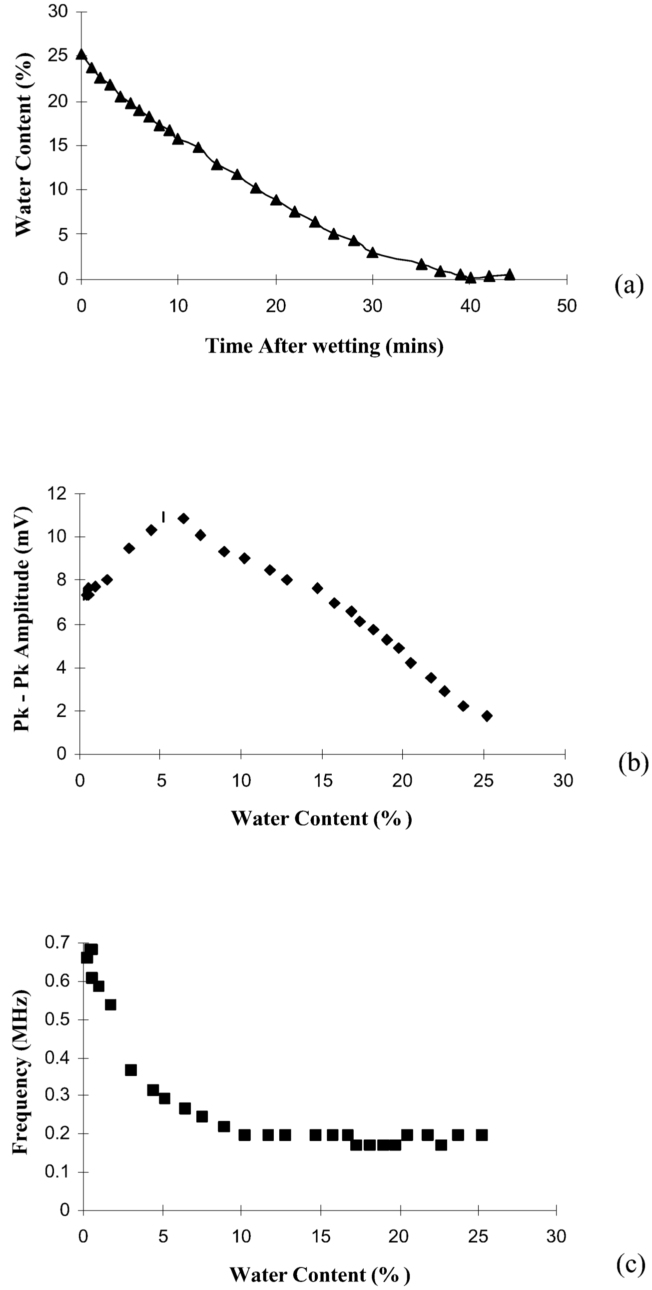

Fig. 10. a) The variation in water content of a paper sample with time and the variation of the through-thickness waveform as a function of water content in terms of b) pk-pk detected amplitude and c) peak detected frequency.

the reduction in stiffness caused by structural changes is the dominant factor, in agreement with previous studies on wetting [30].

The results from the previous two sections have produced some interesting results and demonstrated that the capacitance transducers can be used to measure certain parameters of the paper samples. This allowed the experiments to be taken a step closer toward an automated testing system, where a pair of transducers are scanned across a region of the paper sample. Information from the through-thickness waveforms recorded at each point could then be used to produce images of the paper samples.

Fig. 11 illustrates the equipment used to perform a scan of the paper samples. The source transducer was driven by a Panametrics pulser (type 5055PR). The receiver and receiver transducers were held vertically on opposite sides of the paper sample and were mounted onto an X–Y stage such that they could be moved in unison across the paper. The sample was held in a horizontal plane and supported by clamps. The two linear stages were driven by stepper motors, controlled using a Minicam stepper motor driver unit and software running on an IBM-type PC. Through-transmission waveforms were recorded by the digital oscilloscope and transferred to the PC for storage and later analysis.

A scan was then performed on a paper sample onto which water drops had been adsorbed over a limited area. The idea was to determine whether this area could be identified and imaged successfully using air-coupled ultrasound. It was shown in Fig. 8 that a difference in through-transmission waveform would be expected between wet and dry paper samples, in that both the amplitude and frequency content would be different. The peak signal amplitude and frequency spectrum were recorded at each point in the scan. Fig. 12 displays the variation in peak amplitude of the signal, determined from the maximum amplitude in the frequency spectrum, across the area containing the added moisture. It is evident that the area was identified successfully and is shown in the bottom left of the image.

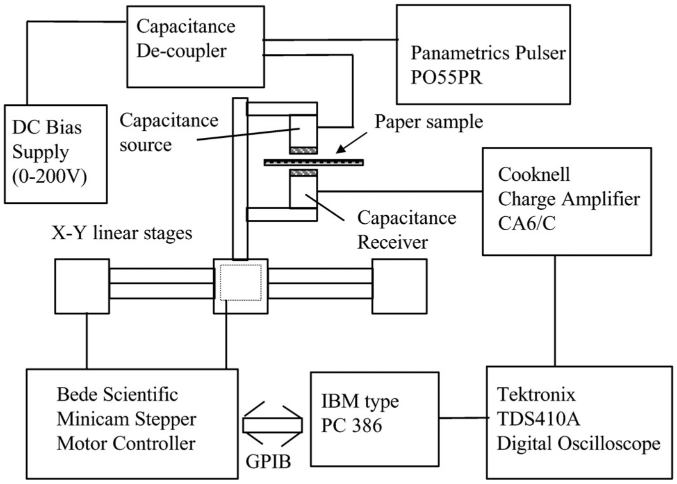

Fig. 11. The experimental arrangement used for the C-scans of the paper samples.

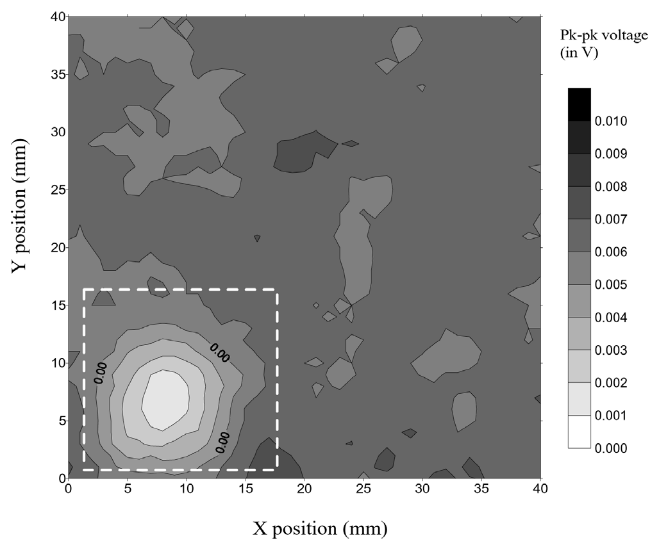

Fig. 12. The result of a C-scan showing the variation in pk-pk amplitude of a through-thickness waveform for a paper sample with a region of moisture (boxed).

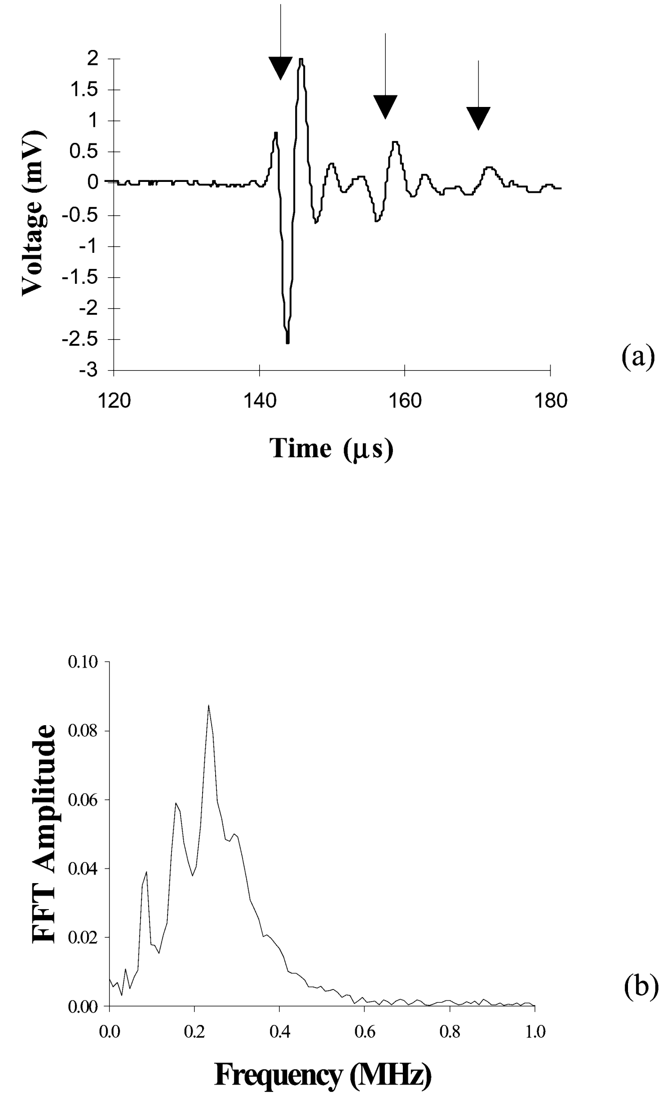

Fig. 13. Typical through-thickness waveform (a) and corresponding spectrum (b) for a cardboard sample showing multiple reflections.

C. Experiments with Cardboard Samples

Further experiments were conducted using a cardboard sample of 1.8 mm thickness (as measured using a caliper gauge). Fig. 13 shows the typical through-thickness ultrasonic waveform detected along with the corresponding spectrum. It is evident from this figure that the broad bandwidth of the capacitance transducers has allowed multiple reflections to be observed.

The cardboard sample was constructed from several layers laminated together with adhesives. The stiffness of the cardboard is reduced greatly if delamination occurs. The ability to quickly assess large areas of cardboard for these delaminations would be of great interest to the manufacturers, and the air-coupled capacitive transducers could be used to perform such an assessment. A scan was thus conducted on a cardboard sample with an artificial 25-mm square delamination defect, again using the equipment described in Fig. 11. This was produced by cutting the sample, delaminating it horizontally with a sharp blade, and rejoining the sample together with adhesive. In the region of the defect, the ultrasound would be severely attenuated because of the break-up of layers within the cardboard, and, hence, a through-transmission signal would be greatly reduced. Fig. 14 displays the through-thickness ultrasonic waveform for both a defect-free region and one containing the delamination defect. It is clear from this figure that the amplitude of the signal for the defect region was greatly attenuated so as to be virtually indistinguishable from background noise, whereas multiple reflections could be observed in areas where the sample was undamaged. Fig. 15 is an image obtained by plotting the variation of the amplitude of the through-thickness waveform across the area of the cardboard sample containing the defect. This figure demonstrates that the defect in the center of the scan is clearly visible using this non-contact technique,

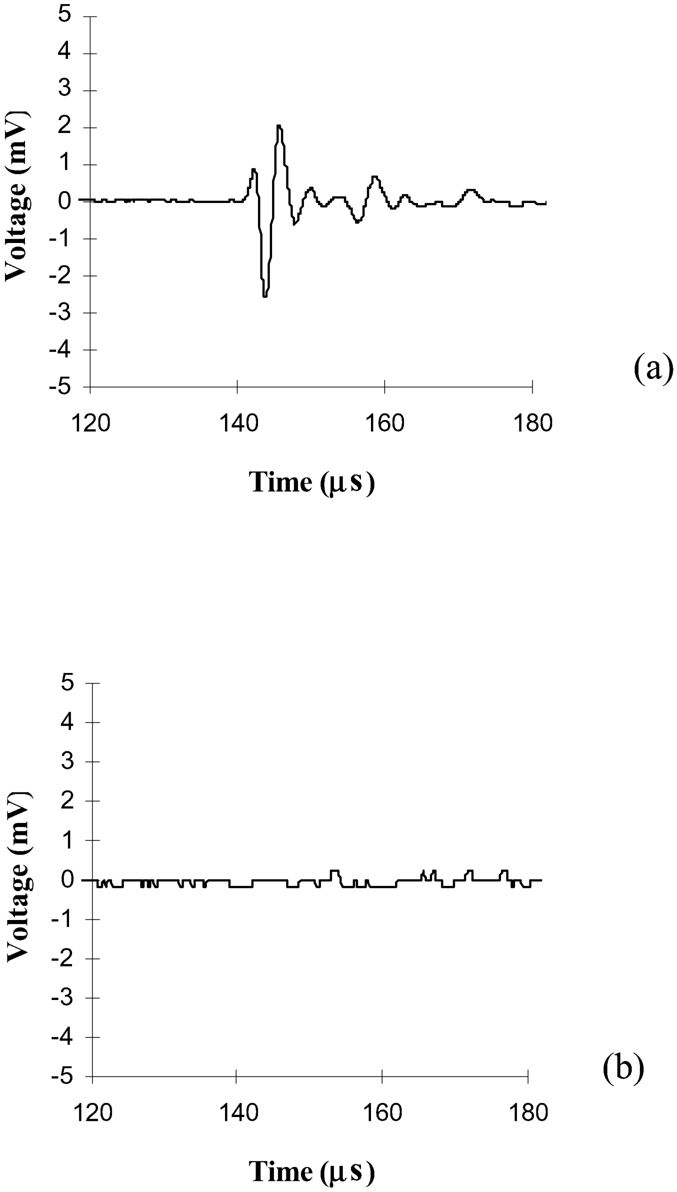

Fig. 14. Typical through-thickness waveform detected by a pair of capacitive ultrasonic transducers when the sample is a a) defect-free region of card and is a b) delaminated area of card.

as is the line where the sample was rejoined after delamination (the straight vertical feature in the image).

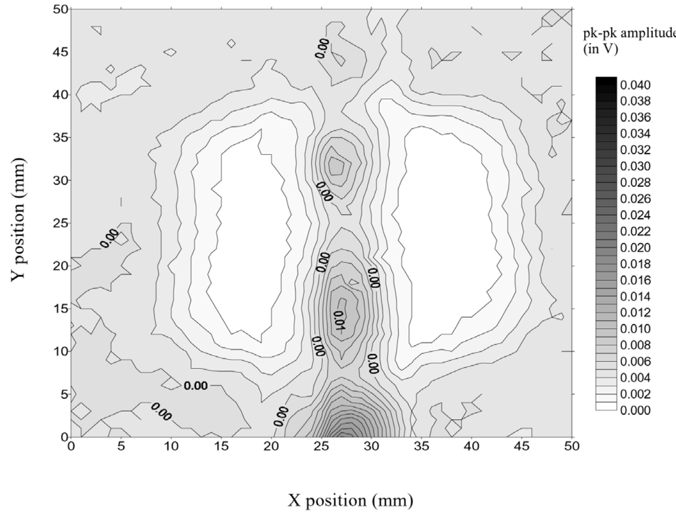

Fig. 15. The result of a C-scan illustrating the variation in pk-pk amplitude of a through-transmission waveform for the cardboard sample with a delamination defect.

IV. Conclusions

The work reported has shown that air-coupled ultrasound may be used to measure certain properties of paper, and hence measurements can be made without the use of a liquid couplant or mechanical contact. A through-thickness resonance was detected, and the value was found to be related to certain paper parameters. In particular, this resonant frequency was also observed to be a good measure of paper thickness (or acoustic velocity if the thickness was already known). The moisture content of the paper was also observed to have an effect on the ultrasonic velocity and was observed to affect the frequency content and amplitude of the through-thickness waveform as a function of water content. It is envisaged that these results could form the basis for potential non-contact measurement of the moisture (or liquid) content of the paper samples. A further experiment was conducted using a pair of scanned capacitance transducers to produce a C-scan image. This technique proved to be useful in assessing changes in moisture content of a paper sample.

The same pair of capacitance transducers was also used with a cardboard sample and, because of the broad bandwidth, the through-thickness waveform contained several reflections from the different layers of the cardboard. The C-scanning arrangement was then used to assess an area of a cardboard sample with a known delamination defect. The result obtained from this experiment illustrated that the non-contact capacitance technique could also be used to detect mechanical defects that could affect the strength of the material.

Acknowledgments

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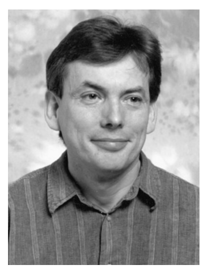

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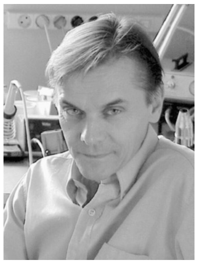
D. R. Billson is a lecturer in ultrasonics in the Department of Engineering and has developed his expertise in ultrasonics in both academic and industrial environments over the last 10 years. After his B.Sc. in physics at Birmingham University and his M.Sc. in optoelectronics at Heriot-Watt University, he started work for TWI in 1988 as a physicist in the NDT Department. In 1990, he took a position in the Department of Engineering at Warwick, where he completed work that he submitted for a Ph.D., which was awarded in early 1995. This work looked at novel techniques for ultrasonically testing difficult materials and was followed by post-doctoral contracts in both Physics and Engineering Departments at Warwick. In 1996, Dr. Billson went on to work for ABB-TRC to develop and evaluate NDT systems for the NDT of nuclear plant. In February 1998, Dr. Billson returned to the Engineering Department at Warwick to work on fully micromachined silicon ultrasonic transducers and transferred to the post of lecturer in September of that year. Dr. Billson maintains an active interest in all aspects of ultrasonics, particularly in the applied field of materials testing. He maintains his links with the NDT industry and is a member of the British Institute of NDT.



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