Ultrasonic measurements in polymeric materials using air-coupled capacitance transducers

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Wide bandwidth capacitance devices have been designed which have a high transduction efficiency in air at frequencies into the MHz range. They are sufficiently sensitive to allow transmission through solid samples, including polymers and fiber-reinforced composites. Examples are presented of experiments showing how such transducers may be used to measure material properties and to perform ultrasonic imaging.

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INTRODUCTION

There are many examples in the literature of ultrasonic transduction methods which do not require contact to the sample. Such methods fall into several categories. Optical methods can be used for both ultrasonic generation and detection. Ultrasonic transients can be generated using pulsed optical energy, either from conventional light sources or lasers. In the latter case, a range of mechanisms can be used, including thermal expansion, material ablation, and the evaporation of coatings.[1] The generation process is well characterized, and wide bandwidths are possible. One property of this source is that it tends to generate several modes simultaneously, which sometimes complicates the subsequent data analysis. Optical detection can be achieved using various types of interferometry and other methods such as optical beam deflection,[2,3] and systems have been described for experiments in solids using optical generation and detection. While there are undoubted advantages to using such an approach in some situations, there is potential for damage at the source. Also, the detection methods often rely on careful alignment with respect to the detection surface, which must have suitable optical characteristics.

Two other methods have also been used to generate and detect wide bandwidth transients in solids. The first of these is a capacitance method, where a conducting biased electrode is positioned within a small distance (typically tens of microns) from the surface. These devices have been used primarily for detection,[4] where changes in the gap cause charge variations on the electrode, although generation is also possible.[5] Alternatively, the electromagnetic acoustic transducer (EMAT)[6,7] can be used as a method for both generation and detection. In detection, a magnetic field is applied to the sample, and the ultrasonic motion causes an eddy current to be generated which is detected by a coil placed a few millimeters from the surface. Ultrasonic generation can also be achieved by passing current transients through the coil. A disadvantage of both capacitance transducers and EMATs is that the surface of the material should ideally be electrically conducting.

There are many situations where it would be advantageous to propagate wide bandwidth ultrasonic pulses through solid samples without contact, but where the application of the transduction method based on optical methods, capacitance approaches, and EMATs would be difficult. Examples include the rapid inspection of large areas of material, where the sample is not electrically conducting, and where the surface finish is not sufficiently smooth for interferometric methods to be successful. An example of such a situation is the detection of defects within fiber-reinforced polymer composites, and in the measurement of the ultrasonic properties of these and other polymer-based materials (e.g., transparent plastics, foams, etc.). Here, a system using air-coupled transducers would be very useful. Consider, however, the problems that would be encountered in such an experiment where a signal was to be transmitted through a plate of material. The ultrasonic transient generated by the source would travel to the first air/solid interface, where the intensity transmission coefficient α_t for a longitudinal plane wave at normal incidence is

$$\alpha_t = \frac{4Z_1Z_2}{(Z_1+Z_2)^2}, \tag{1}$$

where Z_1 is the acoustic impedance of air and Z_2 that of the solid. For typical values of Z_1 and Z_2, for air (430 $\mathrm{kg}^{-2}\,\mathrm{s}^{-1}$ and a polymeric solid (3.2×10^7 $\mathrm{kg}^{-2}\,\mathrm{s}^{-1}$), respectively, only a small fraction ($\approx$0.05%) of the energy would enter into the solid. A similar transmission coefficient would exist at the far solid/air boundary, so that a large decrease in signal would be present when compared to propagation in air alone.

Lamb waves[8] may also be generated and detected in thin plates of material, where the direction of propagation is parallel to the surface of the plate. They exist in two types of modes, symmetric and asymmetric, which are both dispersive (i.e., waves of different frequencies travel at different

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velocities in the material). However, if the wavelength is much greater than the plate thickness, then the dispersion of the symmetric mode is reduced and its velocity tends towards a single value. Lamb waves radiate or "leak" from a plate into air at different angles depending on their velocity, as described by Snell's law, and so a system using air-coupled devices would be ideally suited for both the generation and detection of these waves.

In anisotropic materials such as carbon-fiber reinforced polymer (CFRP) composites, the Lamb waves will have different velocities in different directions, dependent upon the orientation of the fibers and the laminates (cross-ply, unidirectional or quasi-isotropic. Much work has been done recently[9–13] to model the propagation of Lamb waves in composite plates and to calculate the dispersion curves for the material. The two main methods for this approach have been to calculate bulk elastic properties by combining those of the individual layers using classical lamination theory, or to calculate the equations of motion in each layer and apply the appropriate boundary conditions at each layer interface.

An additional factor in all air-coupled experiments at ultrasonic frequencies is attenuation in air which will in general increase with frequency.[14] This will limit the propagation distance in air, but as will be seen, it is not a serious problem at frequencies in the MHz range and propagation distances of a few centimeters.

Despite these difficulties, recent work has investigated the use of transducers operating in air, using the air path to couple ultrasonic energy into the sample. There are several basic designs whereby these devices can be constructed.[15] One of these relies on the use of piezoelectric materials, which can be modified to result in a lower acoustic impedance than that of the normal piezoelectric material. This usually involves the use of a composite piezoelectric/polymer matrix, often with the piezoelectric elements in the form of pillars within an epoxy substrate.[16] These so-called 1–3 connectivity composites can be optimized for either generation or reception in air. Further gains in sensitivity result when a matching layer to air is included. This can either be some form of rubber, or another polymer composite containing air-filled microspheres. Such devices have a reasonable sensitivity, and indeed have been used for experiments in composites and other materials in various configurations, including through transmission.[17–21] Their main drawback seems to be their relatively narrow bandwidth response.

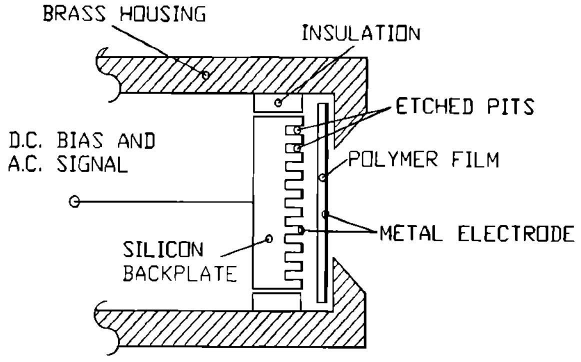


FIG. 1. Schematic diagram of the silicon backplate capacitance transducer.

The devices that are the subject to the present work are a development of previous research into the use of capacitance transducers in air for ultrasonic ranging and manufacturing applications.[22–28] Conventional devices use a metallic backplate over which a thin polymer membrane is stretched. The backplate serves as an electrode to which a dc bias is applied, the membrane having a conducting grounded film on its outer surface. Application of transient voltages to the electrode causes motion of the membrane, and hence ultrasonic generation. Detection occurs via motion of the membrane causing charge variations on the back electrode. Much work has recently been reported on the effect of backplate surface condition and membrane properties on the resulting transduction performance,[29,30] where it was shown that back-

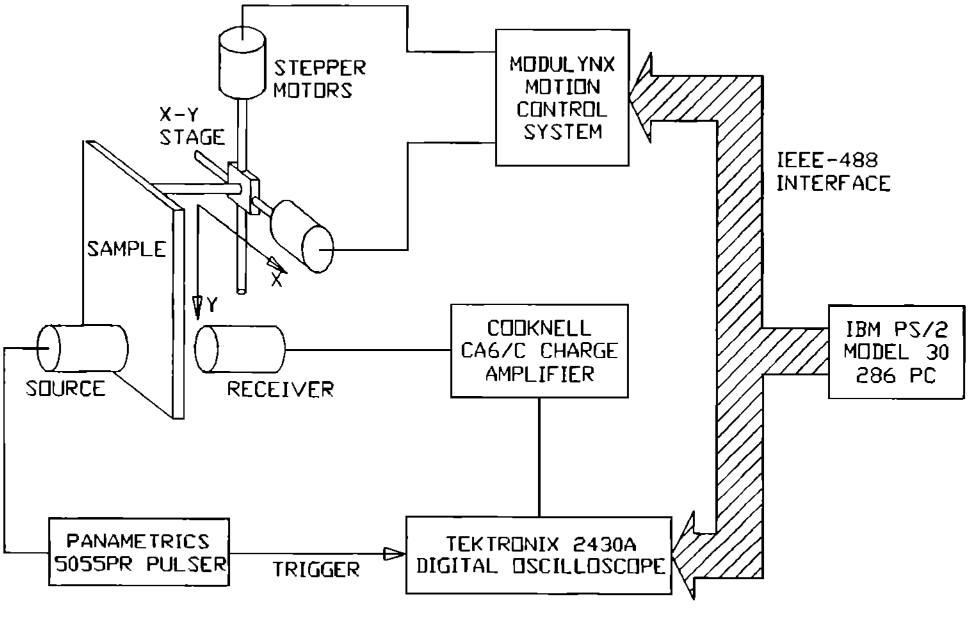


FIG. 2. Diagram of apparatus for through transmission studies.

plate roughness in particular had a pronounced effect on sensitivity and bandwidth. The devices used in the present work use a silicon backplate,[31,32] whose surface features can be precisely controlled (see Sec. I).

In the following, a description of the devices used in these experiments will be given, together with their transduction properties. Experiments will then be described where ultrasonic pulses have been transmitted through polymers and fiber-reinforced composite plates. It is shown that measurements can be made on many such materials, using capacitance-based transducers in air. The imaging capabilities of such a system are also demonstrated.

I. APPARATUS AND EXPERIMENT

The capacitance transducers were developed to be highly efficient generators and detectors of wide bandwidth ultrasonic pulses in air. Their design is shown schematically in Fig. 1. The backplates were constructed from optically flat single crystal silicon wafers. Etching techniques were then used to produce a series of pits in the surface, of 40-μm depth and diameter, spaced at regular intervals of 80 μm over the active area of the device. After etching, the backplate was coated with metal to give a conducting surface. This backplate served as the signal electrode, to which a dc bias voltage of typically 100 V was applied. A thin polymer membrane (Mylar or Kapton) was placed against this backplate; this was metallized on one side only, with the unmet-

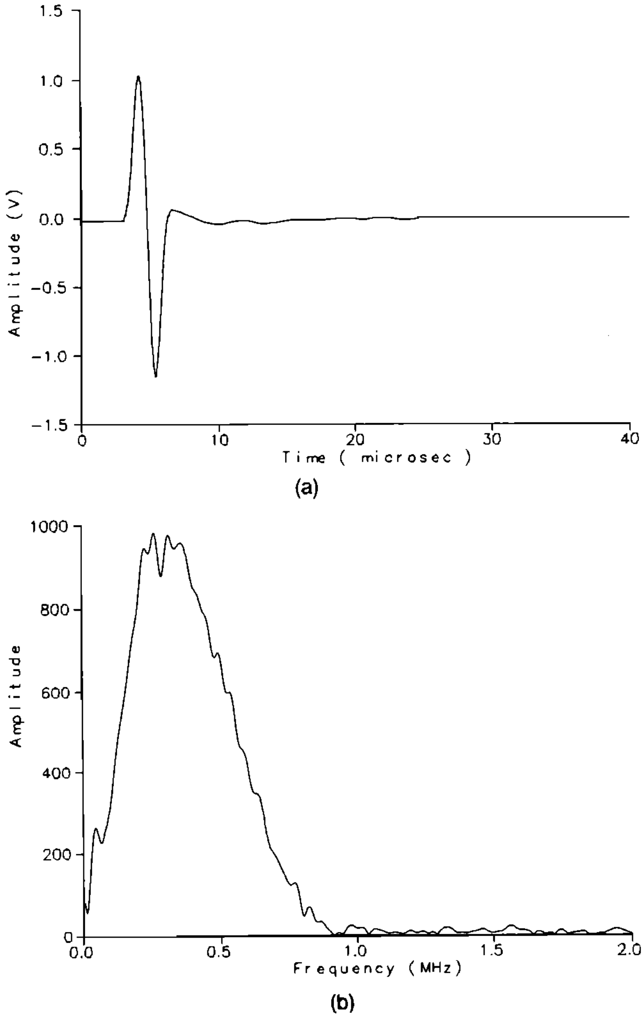


FIG. 3. (a) Waveform transmitted through air. (b) Spectrum of waveform in (a).

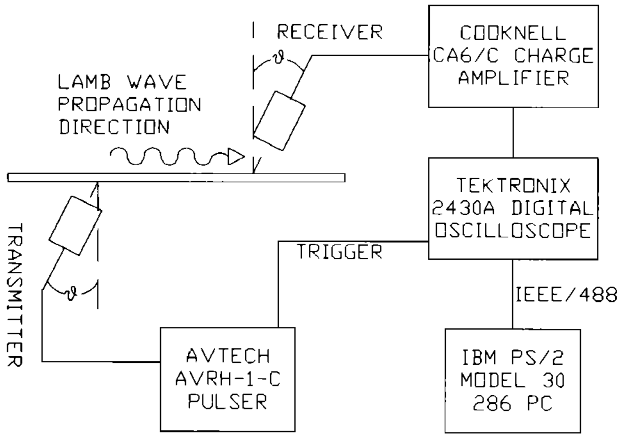


FIG. 4. Diagram of apparatus used for Lamb wave studies.

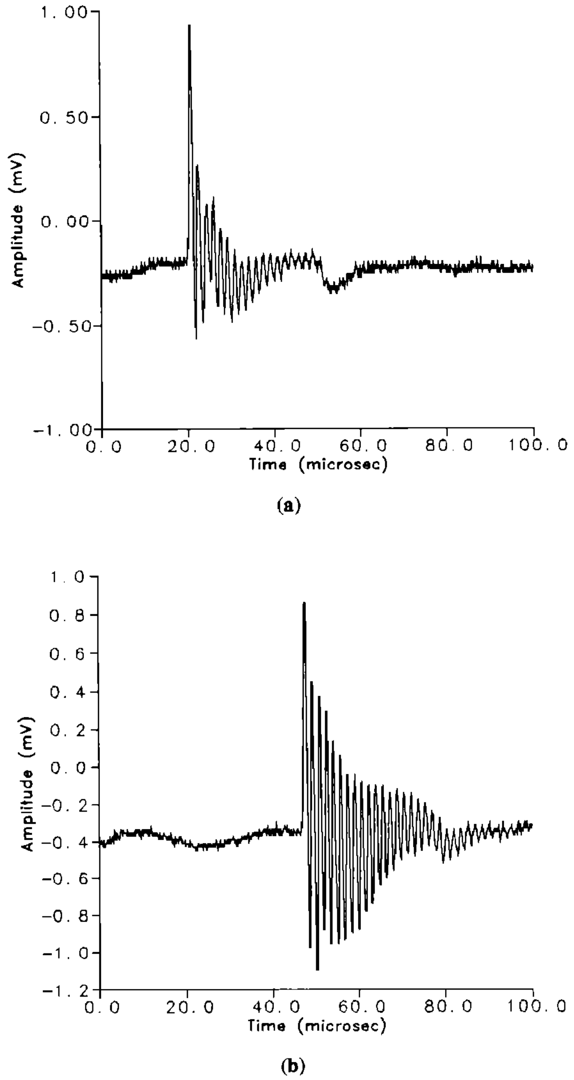


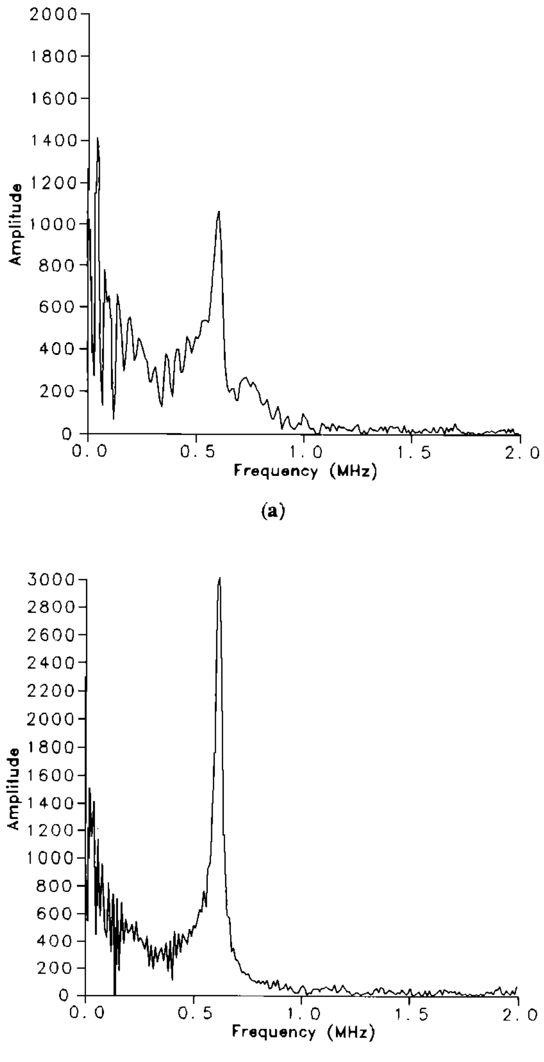
FIG. 5. Waveforms transmitted through (a) unidirectional and (b) cross-ply carbon fiber reinforced composite of 2.2-mm thickness (16-ply).

allized surface against the backplate. The outer electrode was grounded to the case of the transducer, which in turn was insulated from the backplate electrode. Further details of the construction of the device may be found in Ref. 33.

With the dc bias voltage applied, the thin polymer membrane was attracted to the backplate, thus forming an array of tiny air springs. The resonant frequency of the etched pits was designed to increase the high-frequency response of these devices, so that in a typical experiment they had a bandwidth of at least 1 MHz. In generation, a voltage transient was applied to the backplate, causing a force on the polymer membrane and hence ultrasonic generation. In detection, a charge amplifier was attached to the backplate. Changes in the capacitance of the device caused by ultrasonically induced motion resulted in charge variations, which could be modified to produce voltage signals via the charge amplifier. The apparatus used for a through-transmission system using these devices is shown in Fig. 2. A Panametrics 5055 PR pulser acted as the transient voltage source for ultrasonic generation. Ultrasonic transients emitted by the source were transmitted through a parallel plate of the material under study, and on emerging from the far surface, propagated to the receiving transducer where they were detected. Received signals were conditioned using a Cooknell CA6/C charge amplifier, which also applied the 100-V dc bias to the transducer backplate. The resulting voltage waveforms were digitized using a Tektronix 2430A oscilloscope, triggered via the pulser unit, and transferred to a PC for storage and analysis.

For some of the experiments, the sample was mounted on an X-Y translation stage as shown in Fig. 2. This was controlled by an IBM PS2 computer via a Modulynx motion control system and stepper motors. This allows through-transmission waveforms to be recorded as a meander scan, over scan areas of up to 200×200 mm, with a position resolution of 1 mm. The Tektronix 2430A oscilloscope was also controlled from the computer, resulting in a totally automated scanning system that could record full waveforms for imaging purposes.

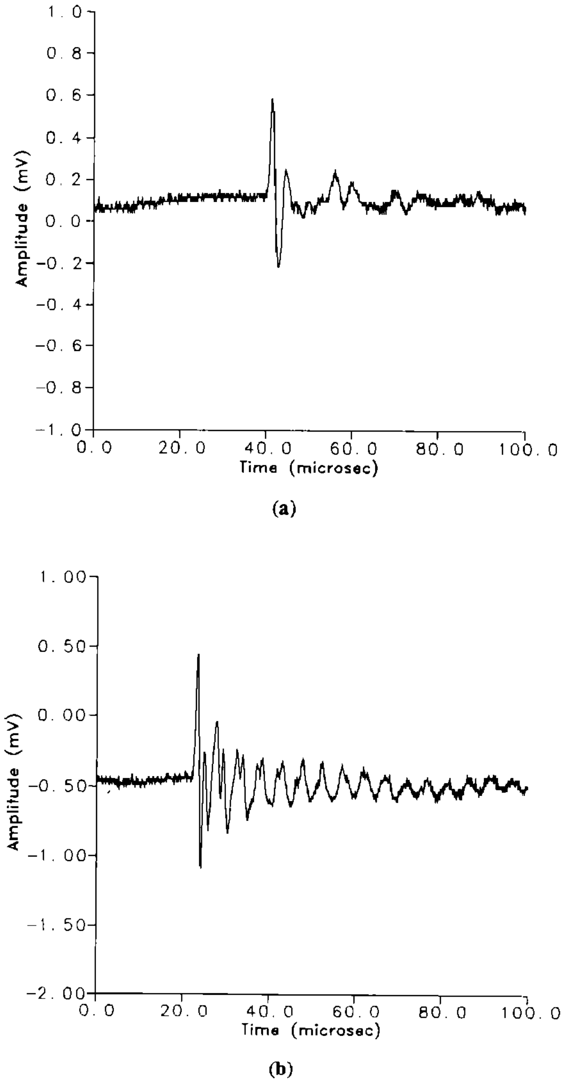
A typical waveform transmitted from source to receiver through air is shown in Fig. 3(a). As can be seen, the signal level is of the order of volts, and is a well-damped wide



(a)

(b)

FIG. 6. Spectra of waveforms shown in Fig. 5.



(a)

(b)

FIG. 7. Waveforms in (a) a 120-ply carbon fiber reinforced plate and (b) a pultruded glass fiber reinforced plate of 6 mm thickness.

bandwidth transient. Note that the Panametrics pulser was not on full power, as at this setting saturation (at 3 V) of the charge amplifier output occurred. A spectrum of the signal is shown in Fig. 3(b). Note the absence of any primary resonances, and the fact that useful energy was available at frequencies of up to 1 MHz and beyond. A series of experiments were conducted on various plate samples with different uniform thicknesses. Waveforms were recorded in through transmission for various materials, including fiber-reinforced composites, foams, and polymers, placed in air between the transmitter and receiver, as will be described below.

Experiments using Lamb waves were also performed, using the apparatus shown in Fig. 4. Ultrasonic waves were generated in air by the Avtech AVRH-1-C pulser, and the angle θ which the transducer made with the surface normal of the plate determined the range of frequencies of Lamb waves which would propagate along the plate to be detected by a similarly orientated transducer connected to a Cooknell CA6/C charge amplifier. Waveforms were captured using a Tektronix 2430A digital oscilloscope, and transferred to an IBM PS2 model 30 286 PC via an IEEE/488 interface for storage and later analysis.

II. RESULTS AND DISCUSSION

A. Longitudinal waveforms and spectra

Consider first thin plates of carbon-fiber reinforced polymer (epoxy) composite. These are available in various lay-up configurations, where subsequent layers are positioned at various angles with respect to each other. If they are all in the same direction, the result is a unidirectional composite, although other configurations are possible. For example, if plies are at angles of 0°, 90°, and ±45° in an alternating sequence, then a quasi-isotropic laminate results, whereas if the plies are alternatively at 0° and 90°, a cross-ply laminate will be formed. The thickness depends on the number of layers used to form the composite, so that a 16-ply plate is nominally 2.2 mm thick.

Figure 5 shows transmitted waveforms through 16-ply samples of (a) unidirectional and (b) cross-ply material. In both cases, it is evident that despite the large loss in signal

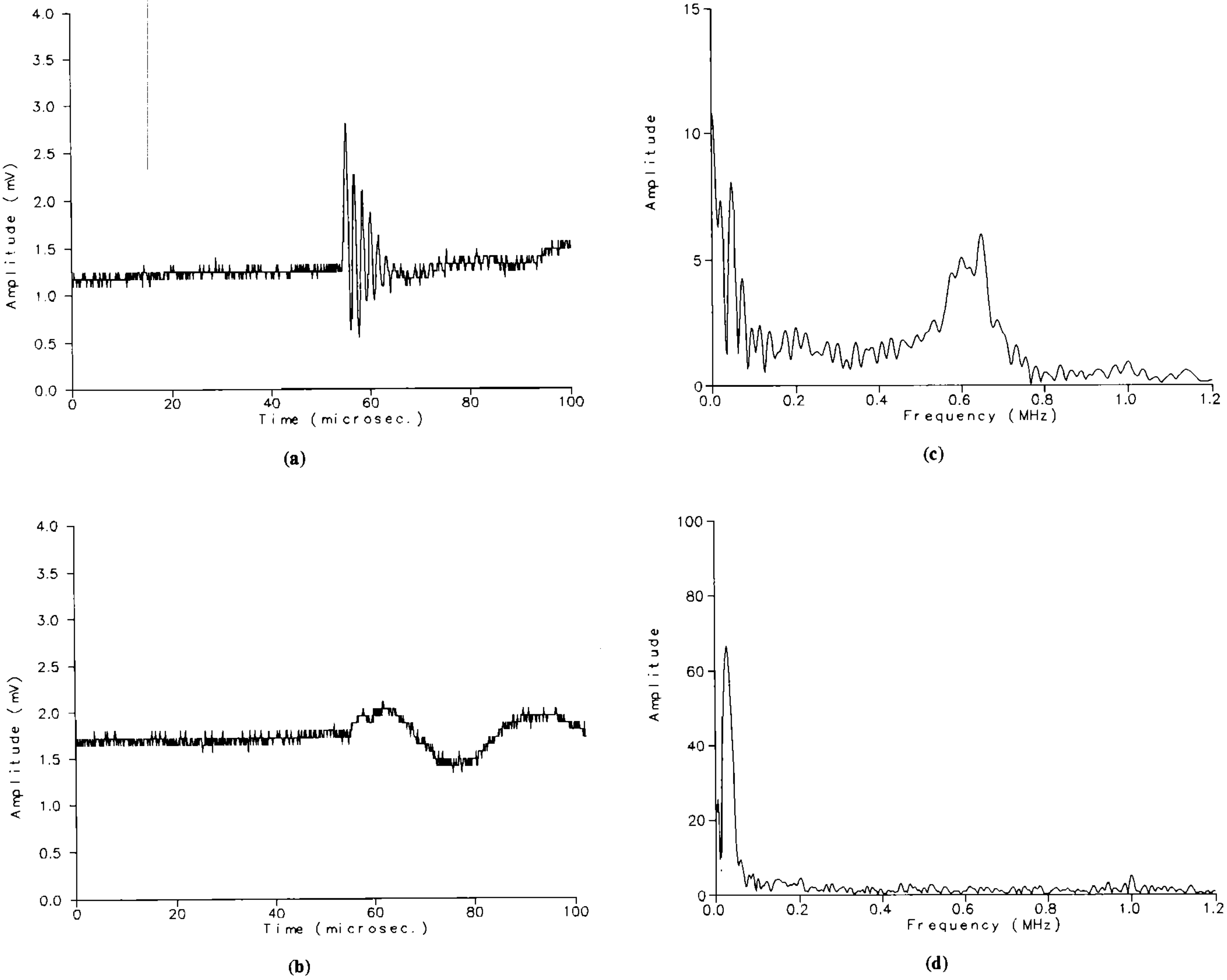


FIG. 8. Waveforms through (a) a defect free area and (b) a Teflon tape defect in a 16-ply unidirectional carbon fiber-reinforced composite plate. (c) and (d) Spectra of waveforms in (a) and (b).

associated with transmission across two air/solid interfaces, waveforms were recorded that contained oscillations which decayed in amplitude with time. The frequency of these oscillations is associated with the round trip transit time of longitudinal waves within the material. This is illustrated further by taking the spectrum of each waveform, obtained using a fast Fourier transform (FFT) and shown in Fig. 6 for both samples. It is seen that peaks appear at the frequencies associated with the damped oscillations, which represent the fundamental for thickness mode vibrations in the plate. These frequencies are seen to be similar for both samples. This is expected from their structures, where velocity differences would be predicted in directions parallel to the plate surfaces, but not in the thickness direction. An interesting feature is that the resonance is less sharp in the spectrum, and the oscillations in time more highly damped, for the unidirectional sample. This could be due to the more anisotropic nature in the unidirectional lay-up configuration, which would tend to promote propagation down the fibers and hence discourage a strong thickness resonance. In each case, however, measurement of the resonant frequency for a known sample thickness leads to an estimate of the through-thickness longitudinal velocity of 2900±50 ms^{-1}, which does not change significantly with the lay-up configuration.

Further evidence for the resonant behavior has been observed in 24-ply and 40-ply samples of quasi-isotropic material, and as would be expected, the thicker material leads to a lower fundamental resonant frequency, but a similar estimate of through-thickness longitudinal velocity. In even thicker material, it was possible to observe discrete multiple

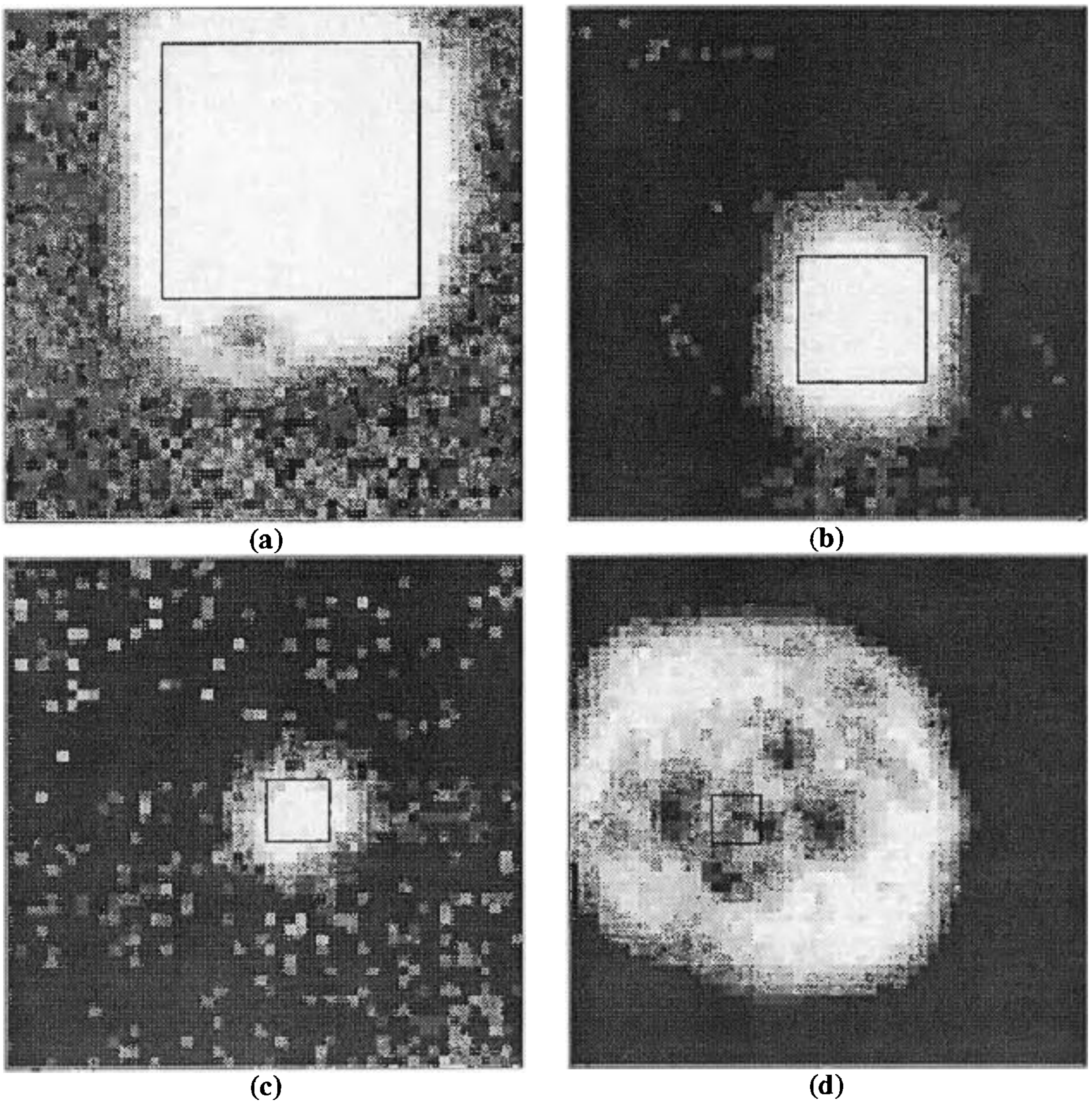


FIG. 9. Images of (a) 1-in. (b) 0.5-in. and (c) 0.25-in. Teflon tape defects in a 16-ply unidirectional carbon fiber-reinforced composite plate. The outlines show that actual size of each defect and their approximate location. (d) An image of a delamination caused by impact in a cross-ply plate. The outline shows the actual 5×5 mm area of impact.

reflections within the solid material. Two examples are shown in Fig. 7, where waveforms are presented for (a) a 120-ply carbon-fiber-reinforced unidirectional plate, and (b) a 6-mm-thick pultruded glass-fiber-reinforced sample. In both cases, the multiple reflections are clearly resolved. Additional waveforms (not shown) were also obtained in other materials, including a 5-mm-thick Plexiglass sheet and a 14-mm-thick open pore expanded polyurethane foam sample. In the latter case the extremely high attenuation of the material meant that the first transmitted longitudinal signal was present, but multiple reflections were highly damped making their identification difficult.

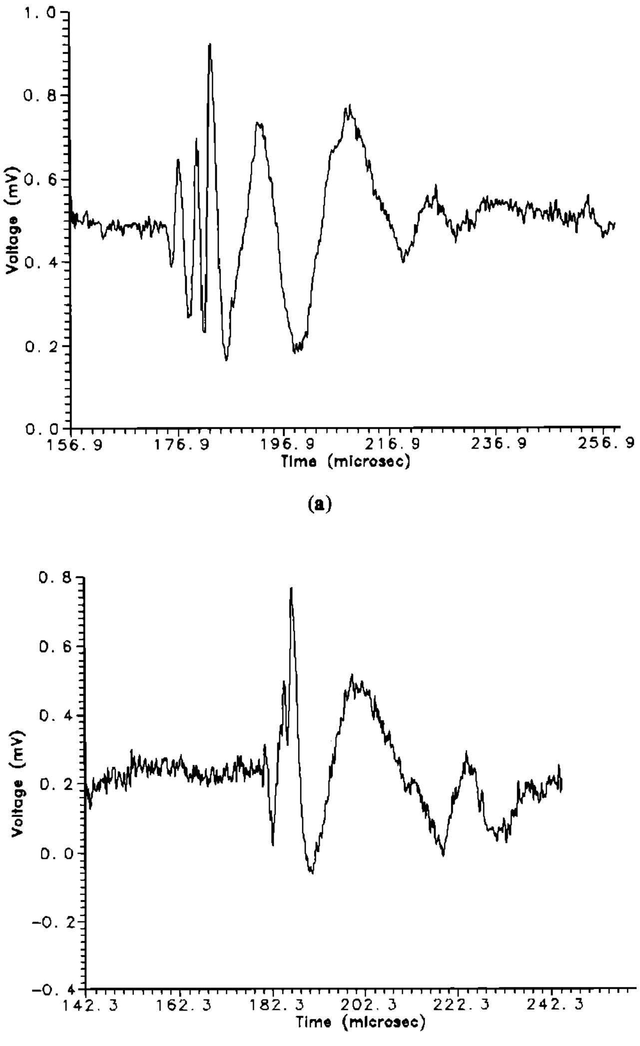
It is evident from the above waveforms and spectra that the air-coupled capacitance devices are able to produce data capable of providing a range of measurements in polymeric materials. In many cases, multiple reflections within the plate thickness lead to a resonance at a certain frequency. As in more conventional immersion schemes, this information can be used to estimate the longitudinal wave velocity in the samples, using normal incidence in air, provided the thickness is known. The bandwidth and sensitivity of the devices have been shown to be high enough to allow such measurements to be performed, despite the high losses induced by the air/solid interfaces.

B. Detection of defects

A major factor affecting the performance of fiber-reinforced polymer composites is the presence of delamination defects. These have been the subject of much interest, as ultrasonic techniques are very useful in detecting such anomalies. For the testing of large composite panels, it is often necessary to scan a transducer pair, operating in the through-transmission mode, in unison over the area of interest. In some cases, an immersion tank cannot be used, and devices such as water-jet transducers have been developed for such applications. These have a limited resolution, due to the low frequencies used and the area of contact that the water column makes with the sample. It was thus thought to be of interest to examine the use of the silicon-based air-coupled devices for the detection of defects. In the present work, two such cases have been investigated—artificial defects, and those caused by impact damage. Data was collected using the through-transmission system shown earlier in Fig. 2. The two transducers were fixed in position, and the sample moved in an X-Y meander scan under computer control. The images presented here were produced over a 50-×50-mm scan area, with a pixel resolution of 1 mm.

The system was first tested on a sample that contained artificial defects, in the form of layers of 15-μm-thick Teflon tape, included in the composite during manufacture. These were of square cross section, and occupied the central 8 layers of a 16-ply unidirectional composite plate. Three defect sizes were available, namely 0.25, 0.5 and 1 in. (6.35, 13.7, and 25.4 mm). Examples of waveforms taken over a defect free area, and over the Teflon tape, are shown in Fig. 8 together with their spectra. As can be seen, the resonant oscillations are present in the defect free data, whereas the data from over the defect contained much lower frequencies and a less prominent spectral resonance peak. This was due to the defect suppressing the strong thickness resonance. One method that could have been used to perform imaging is to time window the waveform (as in a conventional C scan). However, the dc level tended to shift from one position to the next, due to the tendency of the transducers to pick up background low-frequency acoustic noise, although this could be removed by filtering.

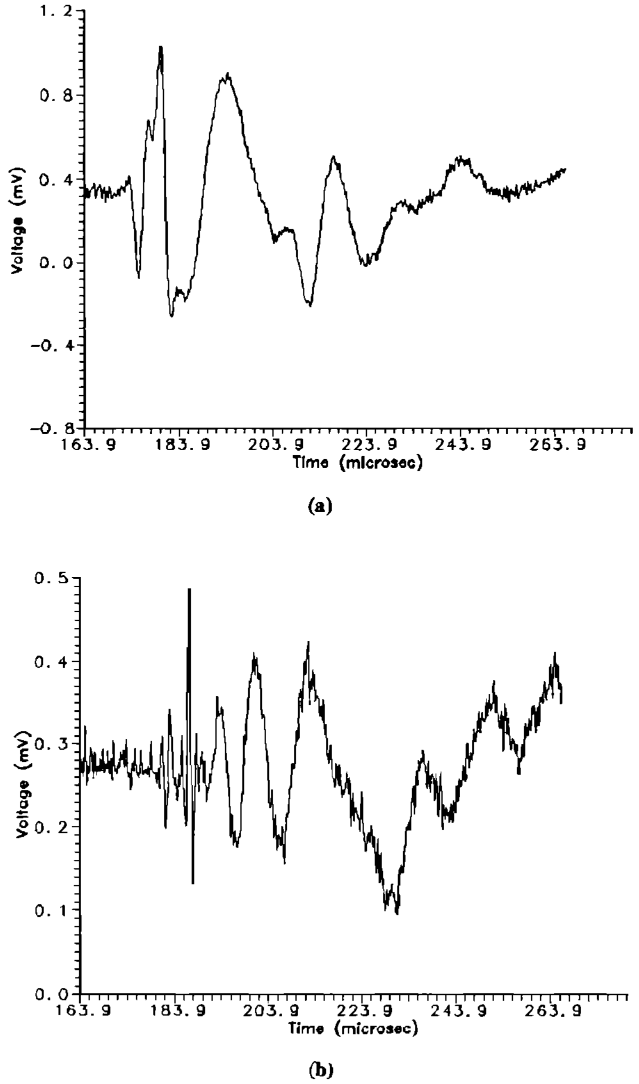
For the above reasons, a different technique was employed which based imaging on a window portion of the spectrum, encompassing the spectral peak at 0.6 MHz. As was seen in Fig. 8, this was a prominent feature in the defect free material but was affected markedly by the artificial defects. Hence, simply plotting the maximum amplitude within the window (or alternatively, some other variable such as total area) led to reasonable images. This is illustrated in Fig. 9(a)–(c) for the three artificial defects quoted earlier. It is evident that the air-coupled ultrasonic system has detected the presence of these delaminations (the solid square outlines) very effectively, and has given a good indication of their size and shape. Note that the transducer aperture of 10 mm was not negligible relative to the defect sizes, and hence



(a)

(b)

FIG. 10. Lamb waves in (a) 1.5-mm "Plexiglass" and (b) 8-ply quasi-isotropic carbon fiber-reinforced composite plates.



(a)

(b)

FIG. 11. Lamb waves in an 8-ply unidirectional composite plate, propagating (a) parallel to and (b) across the fibers.

some distortion of the image would result. It is possible to produce focused transducers[33] to give greater resolution, but it is evident that the images show approximately square defects, of a size close to that expected from the above considerations.

Figure 9 shows the image obtained from an area of delamination caused by impact. The sample was a 100-×150-mm plate of 6.35-mm thickness with a cross-ply lay-up configuration. The area of impact was 5 mm in diameter and it is evident from the image, taken over a 50-×50-mm scan area, that damage was caused over a much wider area than that of the impact.

C. Lamb waves

Lamb waveforms were obtained using the two air coupled transducers in the configuration shown in Fig. 4. Examples are shown in Fig. 10, after passing them through a 2-MHz low-pass filter to remove noise. Figure 10(a) shows the signal obtained in a 1.5-mm-thick Plexiglass plate, in which the dispersive a_0 mode is clearly visible, with the higher frequencies arriving first, as expected from the well-known behavior of this mode in an isotropic plate. A similar waveform was obtained in a 2.2-mm-thick 8-ply quasi-isotropic carbon fiber-reinforced composite plate, as shown in Fig. 10(b). In more anisotropic composites, such as an 8-ply unidirectional plate, different waveforms are obtained when the direction of wave propagation is parallel to the fiber orientation, as shown in Fig. 11(a), and at 90° to it, as shown in Fig. 11(b). The elastic properties of the material, and hence the acoustic velocities, are different for a wave propagating along the fibers, resulting in the slightly deformed waveform which arrives at an earlier time than the waveform transmitted across the fibers. Analysis of such waveforms in anisotropic media is difficult, due to the more difficult wave propagation characteristics in these materials. However, it is proposed that future work could be directed toward the extraction of material properties (such as thickness and possibly elastic constants) from such measurements as those shown in Figs. 10 and 11.

III. CONCLUSIONS

An air-coupled transduction system has been demonstrated which can be used for the ultrasonic inspection of polymeric materials. The system, based on capacitance transducers using a silicon backplate, has sufficient sensitivity and bandwidth to investigate a wide range of materials. Work is now underway to increase the range of application of these devices.

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[1] D. A. Hutchins, "Ultrasonic Generation by Pulsed Lasers," in *Physical Acoustics*, edited by W. P. Mason and R. N. Thurston (Academic, New York, 1988), Vol. XVIII, pp. 21–123.

[2] J.-P. Monchalin, "Optical detection of ultrasound," IEEE Trans. Ultrason. Ferroelec. Freq. Control **UFFC-33**, 485–499 (1986).

[3] J. W. Wagner, "Optical detection of ultrasound," in *Physical Acoustics*, edited by W. P. Mason and R. N. Thurston (Academic, New York, 1990), Vol. XIX, pp. 201–266.

[4] W. Sachse and N. N. Hsu, "Ultrasonic transducers for materials testing and their characterization," in *Physical Acoustics*, edited by W. P. Mason and R. N. Thurston (Academic, New York, 1979), Vol. XIV, pp. 277–406.

[5] D. W. Schindel and D. A. Hutchins, "The capacitance transducer as a standard ultrasonic source in solids," submitted to J. Acoust. Soc. Am.

[6] H. M. Frost, "Electromagnetic ultrasonic transducers: Principles, Practice, and Applications," in *Physical Acoustics*, edited by W. P. Mason and R. N. Thurston (Academic, New York, 1979), Vol. XIV, pp. 179–276.

[7] R. B. Thompson, "Physical properties of measurements with EMAT transducers," in *Physical Acoustics*, edited by R. N. Thurston and A. D. Pierce (Academic, New York, 1990), Vol. XVIII, pp. 157–200.

[8] I. A. Viktorov, *Rayleigh and Lamb Waves—Physical Theory and Applications* (Plenum, New York, 1967).

[9] T. T. Wu and S.-T. Chiu, "On the propagation of horizontally polarized shear waves in a thin composite laminate plate," Ultrasonics **30**, 60–64 (1992).

[10] A. H. Nayfeh and D. E. Chimenti, "Ultrasonic wave reflection from

liquid-coupled orthotropic plates with application to fibrous composites," J. Appl. Mech. **55**, 863–870 (1988).

[11] W. A. Green, "Elastic waves in laminated plates of inextensible material," in *Elasticity: Mathematics, Methods and Applications*, edited by G. Eason and R. W. Ogden (Ellis-Horwood, 1990).

[12] A. K. Mal, "Wave propagation in layered composite laminates under periodic surface loads," Wave Motion **10**, 257–266 (1988).

[13] N. Guo and P. Cawley, "The interaction of Lamb waves with delaminations in composite laminates," J. Acoust. Soc. Am. (to be published).

[14] H. E. Bass, L. C. Sutherland, J. Piercy, and L. Evans, "Absorption of sound by the atmosphere," in *Physical Acoustics*, edited by W. P. Mason and R. N. Thurston (Academic, New York, 1984), pp. 145–232.

[15] W. Manthey, N. Kroemer, and V. Mágori, "Ultrasonic transducers and transducer arrays for applications in air," Meas. Sci. Tech. **3**, 249–261 (1992).

[16] M. I. Haller and B. T. Khuri-Yakub, "1–3 composites for ultrasonic air transducers," Proc. 1992 IEEE Ultrason. Symp., Tuscon, 937–939 (1992).

[17] D. Reilly and G. Hayward, "Through air transmission for ultrasonic nondestructive testing," Proc. 1991 IEEE Ultrason. Symp., Florida, 763–766 (1991).

[18] S. K. Yang, V. V. Varadan, and V. K. Varadan, "Noncontact thickness measurement of wet/dry paint coating using an air-coupled transducer," Mater. Eval. **48**, 471–480 (1990).

[19] A. J. Rogovsky, "Development and application of ultrasonic dry-contact and air-contact C-scan systems for nondestructive evaluation of aerospace composites," Mater. Eval. **49**, 1491–1497 (1991).

[20] C. M. Fortunko, J. O. Strycek, and W. A. Grandia, "Nondestructive testing of "thick" aerospace honeycomb structures using through-transmitted ultrasonic guided waves," Rev. Prog. Quant. NDE **8B**, 1643–1650 (1990).

[21] M. Deka, "Air-coupled ultrasonic transducer for NDE," Proc. 1987 IEEE Ultrason. Symp. 543–546 (1987).

[22] R. Hickling and S.P. Marin, "The use of ultrasonics for gauging and proximity sensing in air," J. Acoust. Soc. Am. **79**, 1151–1160 (1986).

[23] T. Yano, M. Tone, and A. Fukumoto, "Range finding and surface characterization using high-frequency air transducers," IEEE Trans. Ultrason. Ferr. Freq. Control **UFFC-34**, 232–236 (1987).

[24] R. C. Bryant and R. E. Bogner, "Ultrasonic surface imaging in adverse environments," IEEE Trans. Sonics Ultrason. **SU-31**, 373–390 (1984).

[25] J. Löschberger and V. Magori, "Ultrasonic robotic sensor with lateral resolution," Proc. 1987 IEEE Ultrasonic Symp., 547–551 (1987).

[26] M. K. Brown, "Controlling a robot with sonic and ultrasonic means," Proc. 1987 IEEE Ultrason. Symp., 553–561 (1987).

[27] R. W. Smith, R. Walters, J. Carlson, and R. Harris, "High-frequency acoustic systems for robotic applications," Mater. Eval. **46**, 1262–1266 (1988).

[28] W. S. H. Munro, S.Pomeroy, M. Rafiq, H. R. Williams, M. D. Wybrow, and C. Wykes, "Ultrasonic vehicle guidance transducer," Ultrasonics **28**, 350–354 (1990).

[29] M. Rafiq and C. Wykes, "The performance of capacitive ultrasonic transducers using v-grooved backplates," Meas. Sci. Tech. **2**, 168–174 (1991).

[30] H. Carr and C. Wykes, "Diagnostic measurements in capacitance transducers," Ultrasonics **31**, 13–20 (1993).

[31] D. W. Schindel, D. A. Hutchins, L. Zou, and M. Sayer, "Capacitance Devices for the Generation of Air-Borne Ultrasonic Fields," Proc. 1992 IEEE Ultrason. Symp., Tuscon, 843–846 (1992).

[32] D. W. Schindel and D. A. Hutchins, "Air-Coupled Ultrasonic Transducer," U. S. Patent, S.N. #07/966,649 (1994).

[33] D. W. Schindel, D. A. Hutchins, L. Zou, and M. Sayer, "The design and characterization of micromachined air-coupled capacitance transducers," submitted to IEEE Trans. Ultrason. Ferroelec. Freq. Control.