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Air-coupled ultrasonic testing of metals using broadband pulses in through-transmission

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Abstract

A pair of air-coupled electrostatic ultrasonic transducers with polished metal backplates have been used to test metals using broadband pulses in non-contact through-transmission. A range of aluminium samples between 1.7 mm and 12.9 mm thick were successfully tested using entirely air-coupled non-contact bulk waves. Individual longitudinal reflections and mode-converted shear waves could be seen in the signals obtained through the thicker samples. The results demonstrate that it is possible to both generate and detect discrete broadband pulses in metals using air-coupled transducers, making entirely air-coupled through-thickness NDT of metals an achievable goal. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Air-coupled ultrasound; Electrostatic transducer; Non-destructive testing; Metals; Through-transmission

1. Introduction

Ultrasonic transducers which use air as the coupling medium [1] have been widely investigated, with many different transducer designs being employed. Such devices may be broadly classified as either piezoelectric or capacitive in nature. Piezoelectric devices generally have a narrow bandwidth and operate in a resonant mode due to an impedance matching layer [2–4], although piezocomposite [5,6] and piezopolymer [7,8] transducers have shown some promise as broadband devices. Capacitive or electrostatic devices [9–13] are generally broadband and so may operate as either resonant [10,13] or non-resonant devices, depending on their construction and the driving signal used.

Ultrasonic non-destructive testing of materials using air as the coupling medium has been studied for many years, with early efforts restricted to low frequencies and guided waves [14,15], primarily due to the lack of suitable transducers. However, with the recent advances in air-coupled transducer design, bulk wave modes have been successfully used by a variety of authors to test both polymeric materials [16–18] and metals [18,19].

Air-coupled ultrasonic NDT using bulk waves is difficult, primarily due to the large impedance mismatch between air and most solid materials. The energy transmission coefficient T for an interface between two materials with acoustic impedances Z_1 and Z_2 may be found from the well known formula [20]:

$$T = \frac{4Z_1Z_2}{(Z_1+Z_2)^2}.$$

For each interface between air ($Z_1 \approx 420$ kg m^{-2} s^{-1}) and aluminium ($Z_2 \approx 17\times10^6$ kg m^{-2} s^{-1}), T is approximately 10^{-4}, so for an aluminium plate in air, T will be 10^{-8}, i.e. a total loss of 80 dB. However, this is based on the assumption that both air–aluminium interfaces are acting independently, i.e. the thickness of the sample is large when compared to the longitudinal wavelength. For the frequency range 200 kHz to 1 MHz typically encountered in air-coupled ultrasonic NDT, the wavelength of longitudinal waves in aluminium (assuming $v = 6320$ ms^{-1}) will be between 31.6 mm and 6.3 mm. So in many situations this assumption is not valid and the situation is less simplistic. For a 'thin' sample the transmission coefficient may be found using [20]:

$$T = \frac{1}{1 + \frac{1}{4}\left(\frac{Z_1}{Z_2} - \frac{Z_2}{Z_1}\right)^2 \sin^2\left(\frac{2\pi d}{\lambda_2}\right)}$$

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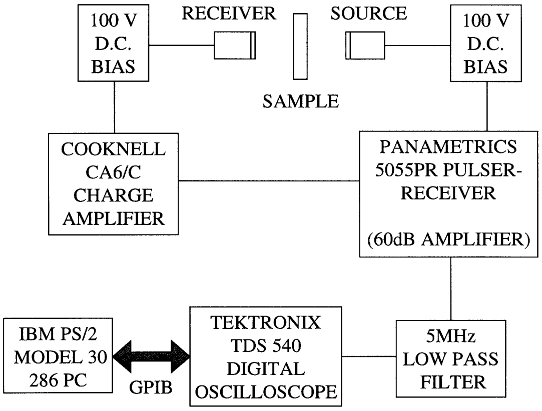

Fig. 1. Schematic diagram of the experimental apparatus.

where d is the thickness of the sample and λ_2 the wavelength in the solid. It can be seen that T will be at a first maximum when

$$d=\frac{\lambda_2}{2},$$

i.e. when the sample is an integer number of half wavelengths thick, and a minimum when the sample is an odd number of quarter wavelengths thick. For an aluminium sample in air, T would then vary between a maximum of 1 and a minimum of 5×10^{-5}, making air-coupled inspection easier for 'thin' samples, in theory at least.

It is this improved transmission, when the sample is acting as a half-wavelength resonant layer, which has been utilised by previous successful attempts [19] to ultrasonically test metals in air using bulk waves in through-transmission. A resonant signal (as a toneburst applied to a broadband device) was used to stimulate the sample at its half-wavelength frequency. These results require some prior knowledge of the sample itself, so that the correct narrowband frequency range may be selected to maximise transmission.

By using a broadband pulse, the sample itself will 'select' its own resonant frequency and act as a narrow-band filter. Despite the reduced signal levels expected when compared to the resonant techniques, as the available energy will be spread over a much wider frequency range, a wide variety of samples of different thickness may be tested using the same transducers, as will be shown in the work to follow.

2. Experiment

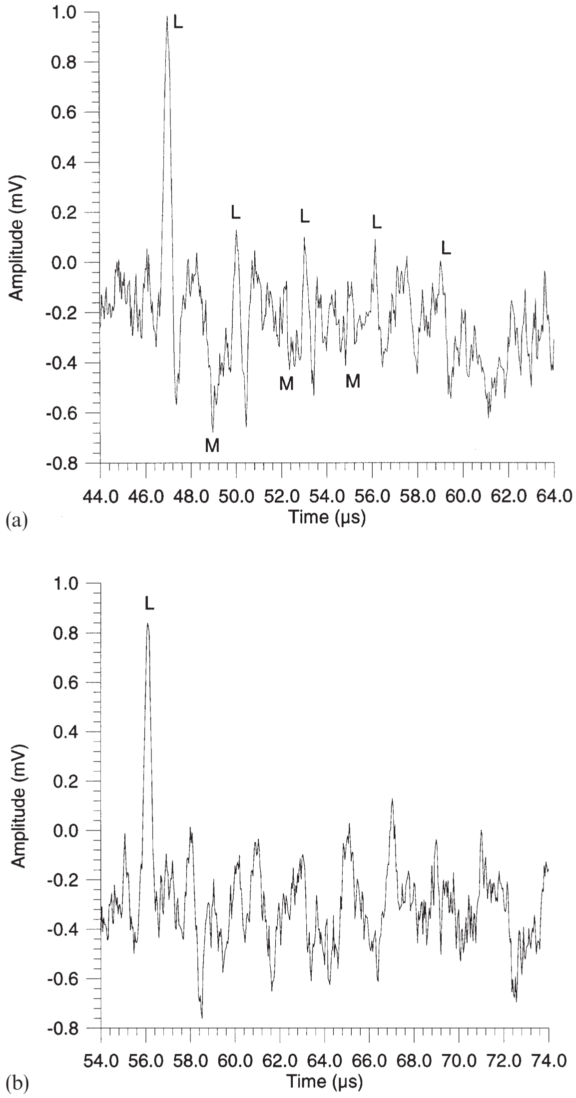

Fig. 2. Air-coupled waveforms through (a) 9.7 mm and (b) 6.4 mm thick plates of aluminium. Longitudinal echoes L and mode converted shear waves M can be seen.

The equipment used for the air-coupled through thickness experiments is shown schematically in Fig. 1. A pair of capacitance transducers, each consisting of a brass backplate polished to a surface roughness R_a of 0.1 μm and a metallized Mylar membrane 2.5 μm thick, were separated by a 25 mm air gap. The source transducer was driven by a Panametrics 5055PR pulser receiver, which delivered a −300 V transient with a rise time of <10 ns. A d.c. bias voltage of 100 V was also applied between the film and backplate of the transducer using a simple capacitive decoupling circuit. The receiver was attached to a Cooknell CA6/C charge amplifier, which had a sensitivity of 250 mV pC^{-1} and applied a well regulated d.c. bias of 100 V to the transducer. An additional 60 dB of gain was obtained by passing the signal through the amplifier stage of the Panametrics unit. The received signals were captured on a Tektronix TDS540 digital oscilloscope and then transferred to a

PC via an IEEE-488 GPIB interface for storage and analysis.

3. Results

Fig. 2(a) shows the air-coupled waveform transmitted through a 9.7 mm thick sample of aluminium, and a similar waveform was obtained in a 12.9 mm thick sample. Individual longitudinal echoes *L* and mode converted shear waves *M* can clearly be seen, and the waveforms are very similar to those obtained in earlier work by the authors using laser-generated ultrasound [21]. Fig. 2(b) shows the signal obtained through a 6.4 mm thick aluminium plate, and it is now more difficult to resolve individual longitudinal echoes. In thinner samples the half-wavelength resonance could be measured more accurately in the frequency domain, and Fig. 3 shows fast Fourier transforms (FFTs) of the waveforms obtained through aluminium plates (a) 6.4 mm, (b) 5.0 mm, (c) 2.7 mm and (d) 1.7 mm thick, with resonant peaks at 458 kHz, 580 kHz, 1.099 MHz and 1.794 MHz respectively, which correspond to the half-wavelength resonances for longitudinal waves in each sample. It is difficult to clearly discern the peak at 1.794 MHz in (d) as this is approaching the upper frequency limit of the transducer pair, as can be seen from the overall frequency response of the transducer pair, shown in Fig. 3(e). It should be noted that, due to the low signal levels, it was necessary to average the waveforms over 10^4 times to remove noise. However, this averaging can easily be reduced by using both a more powerful pulse generator and more sensitive amplifiers.

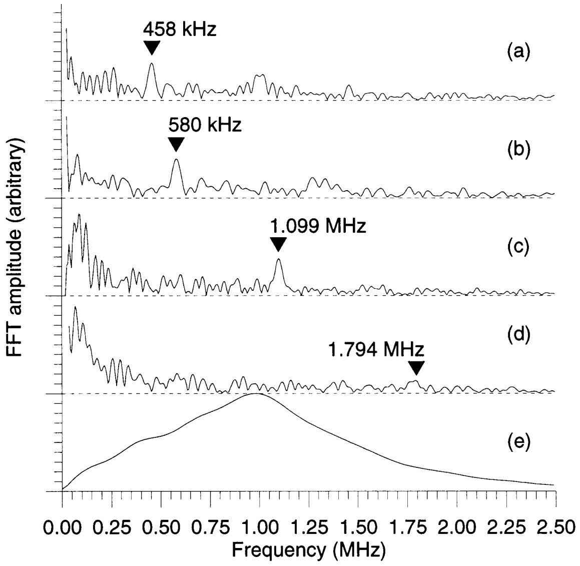

Fig. 3. Frequency spectra showing the resonant frequencies of (a) 6.4 mm (b) 5.0 mm (c) 2.7 mm and (d) 1.7 mm thick aluminium plates. (e) shows the overall bandwidth of the system.

4. Conclusions

From the results presented here, it has been shown that individual broadband longitudinal reflections and mode-converted shear signals may be generated and detected in aluminium using entirely air-coupled waves, and used to test samples of different thickness in through-transmission. With improvements in amplifier sensitivity and pulse energy, the technique could easily be applied to a number of applications where air-coupled NDT of metals is required.

References

[1] W. Manthey, N. Kroemer, V. Mágori, Ultrasonic transducers and transducer arrays for applications in air, Meas. Sci. Technol. 3 (3) (1992) 249.

[2] L.C. Lynnworth, Ultrasonic impedance matching from solids to gases, IEEE Trans. Sonics, Ultrason. 12 (1965) 37.

[3] M. Tone, T. Yano, A. Fukumoto, High-frequency ultrasonic transducer operating in air, Jpn. J. Appl. Phys. 23 (6) (1984) L436.

[4] O. Krauß, R. Gerlach, J. Fricke, Experimental and theoretical investigations of SiO_2–aerogel matched piezo-transducers, Ultrasonics 32 (3) (1994) 217.

[5] J.A. Hossack, G. Hayward, Finite-element analysis of 1–3 composite transducers, IEEE Trans. Ultrason. Ferroelec. Freq. Contr. 38 (6) (1991) 618.

[6] M.I. Haller, B.T. Khuri-Yakub, Micromachined 1–3 composites for ultrasonic air transducers, Rev. Sci. Instrum. 65 (6) (1994) 2095.

[7] A.S. Fiorillo, PVDF ultrasonic sensors for location of small objects, Sensors and Actuators A 4142 (1994) 406.

[8] B.J. Martin, A.F. Collings, An efficient airborne ultrasonic transducer, Ultrasonics International 93 Conference Proceedings, 1993, p. 209.

[9] H. Carr, C. Wykes, Diagnostic measurements in capacitive transducers, Ultrasonics 31 (1) (1993) 13.

[10] M.I. Haller, B.T. Khuri-Yakub, A surface micromachined electrostatic ultrasonic air transducer, IEEE Trans. Ultrason. Ferroelec. Freq. Contr. 43 (1) (1996) 1.

[11] M.J. Anderson, J.A. Hill, C.M. Fortunko, N.S. Dogan, R.D. Moore, Broadband electrostatic transducers: Modeling and experiments, J. Acoust. Soc. Am. 97 (1) (1995) 262.

[12] D.W. Schindel, D.A. Hutchins, The design and characterization of micromachined air-coupled capacitance transducers, IEEE Trans. Ultrason. Ferroelec. Freq. Contr. 42 (1) (1995) 42.

[13] I. Ladabaum, B.T. Khuri-Yakub, D. Spoliansky, Micromachined Ultrasonic Transducers – 11.4 MHz transmission in air and more, Appl. Phys. Lett. 68 (1) (1996) 7.

[14] A.J. Rogovsky, Development and application of ultrasonic dry-contact and air-contact C-scan systems for nondestructive evaluation of aerospace composites, Mat. Eval. 49 (12) (1991) 1491.

[15] M. Luukkala, P. Heikkila, J. Surakka, Plate wave resonance – a contactless test method, Ultrasonics 11 (10) (1971) 201.

[16] D.A. Hutchins, W.M.D. Wright, D.W. Schindel, Ultrasonic measurements in polymeric materials using air-coupled capacitance transducers, J. Acoust. Soc. Am. 96 (3) (1994) 1634.

[17] D.E. Chimenti, C.M. Fortunko, Characterization of composite prepreg with gas-coupled ultrasonics, Ultrasonics 32 (4) (1994) 261.

[18] R. Farlow, G. Hayward, Real-time ultrasonic techniques suitable

for implementing non-contact NDT systems employing piezoceramic composite transducers, Insight 36 (12) (1994) 926.
[19] D.W. Schindel, Air-coupled generation and detection of ultrasonic bulk waves in metals using micromachined capacitance transducers, Ultrasonics 35 (2) (1997) 179.
[20] J. Krautkrämer, H. Krautkrämer, Ultrasonic Testing of Materials, 4th fully revised edition, Springer-Verlag, Berlin, 1990.
[21] W.M.D. Wright, D.W. Schindel, D.A. Hutchins, Studies of laser-generated ultrasound using a micromachined silicon electrostatic transducer in air, J. Acoust. Soc. Am. 95 (5) (1994) 2567.