REVIEW OF CRACK DEPTH MEASUREMENT BY ULTRASONICS

P.A. Doyle and C.M. Scala
Aeronautical Research Laboratories
Box 4331,GPO Melbourne, Australia

ABSTRACT

Research concerning bulk and surface wave methods for the measurement of the depth of surface-breaking cracks will be reviewed. This review will examine techniques for measuring crack depths which are based on the scattered pulse amplitude, time-of-flight methods, and ultrasonic spectroscopic analysis. Measurement of the transit time of bulk waves appears most likely to provide simple and reliable depth measurement in the near future. Promising directions for future research will be discussed.

INTRODUCTION

Ultrasonic methods are widely used in the detection of both internal and surface defects in structural materials. Because of increasing design complexity, e.g., the application of fracture mechanics concepts to aircraft design,[1] there is a special motivation to develop quantitative, rather than simply qualitative, techniques for non-destructive evaluation (NDE).

This paper reviews recent ultrasonic research directed towards the measurement of the depth of surface-breaking cracks which have already been located by ultrasonic or other NDE methods. Both bulk (P or S) and surface (R) wave techniques are included. The first general approach considered is the relationship between crack depth and the strength of the signal scattered by a crack from an ultrasonic beam. Next, depth measurement based on the transit times for waves following various paths around the crack is reviewed. Finally, the potential of ultrasonic spectroscopic analysis to measure small cracks and indicate crack morphology is discussed. When it helps clarify the state of the art for surface flaws, brief consideration is given throughout the paper to related work dealing with the ultrasonic examination of internal flaws. The potential of ultrasonic and acousto-optical imaging techniques is not discussed in this review.

SCATTERED AMPLITUDE METHODS

The Pulse-Echo Technique

The most common use of an ultrasonic probe is in the simple pulse-echo technique which detects the return signal scattered by a flaw situated beyond the 'dead zone' of the transducer.[2] The strength of the signal gives some indication of the size of the flaw, but quantitative estimation of size requires careful interpretation. One approach to this analysis is to compare the signal with that scattered by a known standard defect. Hitt[3] introduced flat-bottomed holes in test blocks made from the same material as the specimen under test as reference standards for scattering by internal defects. While flat-bottomed hole standards are still used, Hislop[4] argued that the so-called AVG (distance-signal voltage-defect size) diagram of Krautkrämer,[5] which quantifies the flatreflector system without actually needing sets of test blocks, provides a simpler standard for internal flaw measurements.

For the surface cracks of primary interest in this paper, reference standards often consist of spark eroded slots or saw cuts produced in a position geometrically similar to that for the crack to be measured. However, many difficulties are associated with the use of artificial reference defects.[6] Even after transducer coupling variations are avoided, the return signal is influenced by crack shape, crack surface roughness, and mode conversion upon reflection. The signal also varies with the frequency mode and bandwidth of the probe. Further, much of the ultrasonic intensity can be transmitted across an unloaded fatigue crack, causing the return pulse to depend on the state of stress in the region of the crack.[7] For an assembled structure, this state of stress is determined by material type, crack growth history, the amount of stress relaxation, and induced stresses.[8] Finally, ignoring interference effects, which depend on crack size and orientation, can cause under-estimation of crack depth. These effects prevent the intensity of the reflected pulse from always increasing monotonically with crack depth, as is assumed in simple theory.[9,10]

Corbly et al[7] overcame some of the above difficulties by using a known fatigue crack, in the same material and geometrical configuration as the unknown crack, as a reference standard for the pulse-echo technique. They employed S-wave reflection to find the depths of fatigue cracks as small as 0.5 mm to ± 0.2 mm. While this accuracy is excellent, the unknown cracks were prepared by the same constant amplitude loading cycle as the standard crack. Further work is needed to establish if and when the varying loading history of cracks encountered in practice significantly alters their reflectivity, thereby influencing the reliability of this technique.

Depth Measurement from First Principles

In parallel with the development of empirical methods which rely on reference standards, a more fundamental approach to crack depth measurement is being sought through more detailed consideration of the scattering processes involved. The complexity of the interaction of a beam with a surface flaw has been graphically illustrated by Baborovsky et al,[11] who used Schlieren visualization to demonstrate the interaction of an S-wave pulse with a slit. They describe fourteen possible main P and S scattered pulses produced by various combinations of mode conversion and diffraction from a single incident pulse. Not all of these scattered pulses are strong for any one crack orientation and incident pulse direction, although a strong return will occur for almost any of them at suitable incident angles. Figure 1 sketches as an example the field produced by a 2 MHz shear wave pulse incident at 35° on a slit two wavelengths deep in steel. It is possible for the back-scattered pulse to disappear altogether at suitable angles and depths, which emphasizes the caution needed in applying the pulse-echo technique.

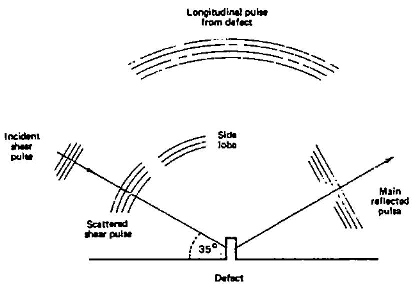

Fig. 1 Sketch of a cross-section through the field produced by a 2 MHz shear wave pulse incident at 35° on a slit two wavelengths deep in steel.[12]

The more fundamental and general approach to depth measurement would be to solve rigorously for the interation between the beam and the flaw, then determine depth by comparing theory and experiment at suitable scattering angles. A major obstacle to development along these lines is the difficulty of obtaining exact solutions for the scattering of elastic waves; even for scatterers in infinite media, solutions exist for only a few simple geometrical shapes.[13] This difficulty has led to a search for suitable approximate solutions. For the case of internal spheroidal and cylindrical defects, calculations based on the first Born approximation[14,15] have been compared with experiments by Tittmann[16] who found good agreement for back-scattering from small obstacles. Tittmann[16] and Adler and Lewis[17] used Keller's geometrical theory to approximate the scattering from disc-shaped flaws (which resemble internal cracks), and found good agreement with experiments for the larger scatterers for which Keller's theory is valid.

For surface cracks, multiple scattering due to the proximity of the surface to the obstacle is a further serious complication. Bennett[18] expressed the total field for a set of scatterers due to all multiple scattering in terms of the field reflected by each scatterer in isolation. He calculated as an example the field in the neighborhood of a cylinder adjacent to a plane free surface, which required numerical approximation by steepest descent of some integrals. Extending this work to the case of a crack at a surface would be valuable, though the formulation is complicated. A useful, but less rigorous, approach was adopted by Baborovsky et al[19], who numerically treated each point on the illuminated crack face as a Huygen's source radiating in all directions (Fig. 2). The calculated field at an exit point includes up to eighteen contributions from wave s undergoing one to three scattering events, having due regard to mode conversion. Empirical corrections are included for head waves, surface waves and waves generated at the crack tip. These authors found broad agreement between computed scattered fields and Schlieren photographs of the type sketched in Fig. 1. They made a preliminary study of the pulse-echo technique by concentrating on the back-scattered part of the field, and found encouraging agreement between calculated and measured curves of intensity versus defect depth. The value of further work along these lines may depend on the validity of the approximations inherent in the numerical calculations for the near field of the scatterer.

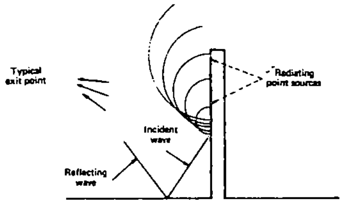

Fig. 2 Illustrating the model of Baborovsky et al[19]; for clarity only radiated waves of one mode caused by direct illumination are shown.

The approach to crack depth measurement from first principles, as discussed here, is providing the necessary understanding of the interaction between ultrasound and defect, which in itself is sufficient motivation for its continued pursuit. It may be that, for the next few years at least, simpler and more reliable crack depth measurement will be based on other approaches, particularly the timing methods discussed below.

Other Amplitude Methods

A number of other methods using scattered amplitude to measure crack depth have been proposed. Böttcher et al[20] arranged two angle probes on opposite sides of a slit in mild steel (Fig. 3); a signal dependent on slit depth reaches the receiver due to scattering by those grain boundaries beyond the slit edge. Silk and Lidington[21] pointed out that diffraction by the edge also contributes to the signal. Crack depth could be measured by comparing the signal received from an unknown defect with those from known slits, provided the calibration could be reliably established. However, there are significant differences between measurements by the two groups of authors, and further work would be needed to improve the calibration. Silk and Lidington indicate a number of disadvantages of this method; these include commonly occurring random errors caused by scattering from inclusions in the steel and by probe coupling variations. Also, the technique is limited to cracks at least 3-4 mm deep, due to the physical size of transducers and probe beam width and to the need to eliminate interfering surface waves. They found that a more accurate and reliable depth measurement can be made with this probe configuration by using a timing technique, as discussed below.

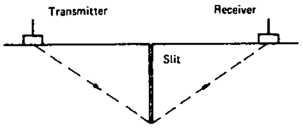

Fig. 3 The two-probe configuration used by Böttcher et al.[20]

During a study by photoelastic visualization of the interaction of surface waves with slits, Reinhardt and Dally[22] noted that the variation of transmission and reflection coefficients with crack depth might provide a basis for the measurement of small cracks less than half a wave-length deep. The transmission of surface waves past a crack in a fatigue test specimen has in fact been used[23] to monitor crack growth from an initial precrack 1.2mm deep. The reflection coefficient for surface waves, which varies more markedly than the transmission coefficient for cracks much smaller than the wavelength, may prove more useful for the measurement of very small cracks; this possibility does not yet seem to have been thoroughly investigated.

Finally, we consider a rather different technique proposed recently by Silk.[24] When a surface wave is directed towards a crack, part of the energy travels down the crack face and is radiated over a wide range of angles as S-waves from the tip (Fig. 4). An S-wave detector of known angle Ø should give maximum response at two positions, one at each side of the crack tip. Once these two positions are located (for one surface of the specimen), the crack depth can be readily found geometrically. This technique has the advantage of requiring neither a reference standard nor a detailed study of the scattering process. Silk measured fatigue crack depth greater than 8 mm to an accuracy of 13% with this method, though it is unsuitable for application to small cracks.

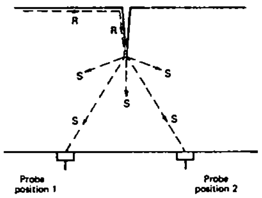

Fig. 4 Depth Measurement be detecting S-waves produced by mode conversion of R waves at the tip using an S-wave detector of known angle Ø.

TIMING METHODS

Bulk Wave Timing Methods

Di Giacomo et al[25] directed an S-wave towards a crack at an angle by reflection from the back face of a plate (Fig. 5), then shifted the probe away from the crack face until the position shown in Fig. 5a was reached, at which the back-scattered pulse was about to disappear. They measured the time lag between generation and reception of the reflected pulse, as well as that when the transducer was moved back through the maximum amplitude to the point where the signal was again about to disappear (Fig. 5b). The crack depth was found from these two measurements by eliminating the effective beam divergence from the calculation. The technique gave the depth of tight fatigue cracks in plate specimens within a standard error of 2-3 mm for cracks up to about 30 mm deep.

Di Giacomo et al described an alternative method having similar accuracy which is suitable for deep cracks ($\gtrsim$ 10 mm), in which they replaced one of the measurements by moving the probe close to the crack, and measured the transit time corresponding to disappearance of the direct reflection from the crack tip. A focussed beam probe could improve both variations of the technique by giving greater sensitivity for tight cracks and by resolving more abrupt changes in crack edge profile.

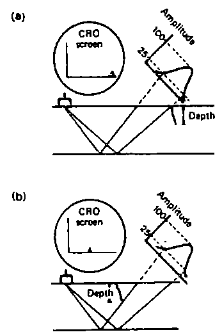

Fig. 5 The technique developed by Di Giacomo et al.[25] (a) and (b) show the two positions at which readings were taken.

Although these authors did not discuss the possibility, their methods could be readily modified to provide depth measurement for cracks opening onto inaccessible surfaces. While use was made of signal amplitude to eliminate the finite beam width, the self-normalization implicit in the technique led Di Giacomo et al to find values for depth almost independent of the absolute magnitude of the scattered pulse. Thus this technique provides a bridge between those methods described above which depend on signal amplitude, and those which are solely variations on the time-of-flight approach.

Silk and Lidington[21] used the configuration of Fig. 3 to determine the depth of artificial slits by measuring the time delay between the transmission of a short longitudinal pulse, and its reception after scattering by the crack edge. With a knowledge of probe separation and wave speed in the specimen, elementary geometry relates crack depth to this time. A shallow angle of 20° for beam entry was required to achieve a scattered pulse height significantly above noise level; this geometry causes a loss in the accuracy of depth measurement proportional to sin 20°. However, given this sufficiently strong diffracted P-wave, the required pulse was easily identified, since it preceded any other pulses arriving at the receiver, such as mode converted S-waves or possibly surface waves. Slots 10-40 mm deep were measured to an accuracy of ± 0.5 mm. Silk and Lidington[26] later used this technique, making meaningful time measurements as short as 20 ns, to measure the depth of artificial slite 1-30 mm deep to within ± 0.25 mm. For slits of varying depth, they measured the profile of the edge. A very shallow beam entry angle of 10° was necessary for the smaller slits, in order to maximize the diffracted pulse by causing the centre of the beam to impinge more nearly on the edge of the crack.

Recently, actual fatigue crack depths in steel have been measured[27] to ± 0.2 mm using 2.5 MHz longitudinal probes, though in all cases reported the cracks were at least 6 mm deep. Since the measured depth is a weighted average over the beam spread along the crack edge, less accuracy is obtainable near sharp changes in depth along the crack profile. The principal limitation on accuracy is the change in pulse shape, which complicates identification of corresponding points in the transmitted and received waveforms. Tests carried out under compressive load demonstrated the continued accuracy of this technique even for tight cracks, whose ability to transmit ultrasound is a serious problem for both amplitude techniques and for the surface wave methods discussed below. This P-wave technique has been developed at Harwell to the point where visual estimation of transit time has been replaced by an electronic measurement system. Hence, an automatic accurate crack depth meter could become available in the near future. In addition, different probe arrangements suitable for a wide variety of specimen geometries are being investigated.[28]

One particularly simple method is to mount a single probe on the face opposite the crack, and to use time measurement to determine distance from the crack tip to the opposite face of the specimen. This approach was used by both Hunt[29] and Winters[30] to measure the depth of fatigue cracks opening on the inside of large gun barrels. The observed weak signals were attributed to reflections by facets near the crack tip; some cracks tending to be normal to the surface were missed by this method.[29] The technique was reliable only for cracks deeper than 2-4 mm. Both authors reported a systematic depth indication 0-1 mm below the true values. Silk and Lidington[28] also found considerable variations in the success of this technique when applied to fatigue cracks. They discussed in an oversimplified way the relative contributions to the signal from diffraction, refraction and scattering by micro-defects near the crack tip. A more detailed theoretical study of these mechanisms including the effect of mode conversion is needed to establish when this single probe timing method is reliable. This study would be doubly valuable if carried out in conjunction with photo-elastic or Schlieren visualization experiments.

The use of the slower S-waves rather than P-waves increases the accuracy in converting from time delay to crack depth by a factor of about two. This advantage is not easily realized in practice with conventional S-wave probes, due to difficulty in identifying the relevant S-wave echoes among interfering signals.[27,28] However, using a specially constructed short pulse S-wave probe arranged as in Fig. 6, Lloyd[31] measured the depth of artificial slits 0.75-4.5 mm deep to ± 0.25 mm. His method is based on the theory of Freedman[32], which shows that the return signal consists predominantly of pulses scattered from discontinuities, in this case the base and the tip of the slit. Further work directed towards exploiting the lower speed of S-waves for other probe configurations could prove profitable, particularly if more attention is paid to probe design to reduce spurious signals.

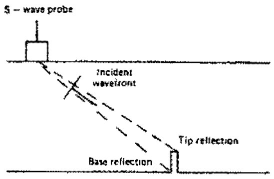

Fig. 6 The S-wave method of Lloyd;[31] the base reflection is coincident with the specular reflection.

Surface Wave Timing Methods

Several authors have recently investigated the use of surface waves for crack depth measurement. Because they follow the crack profile, surface waves measure the length L along the crack face to its tip, rather than the more useful crack depth of the tip below the specimen surface (Fig. 7a); however, as we shall see later, more complicated experiments can eliminate this restriction. Also, the greater ability of these waves to penetrate small gaps often requires tight cracks, or cracks with solid or liquid filled gaps, to be opened by suitable loading of the specimen if depth measurement is to be achieved.

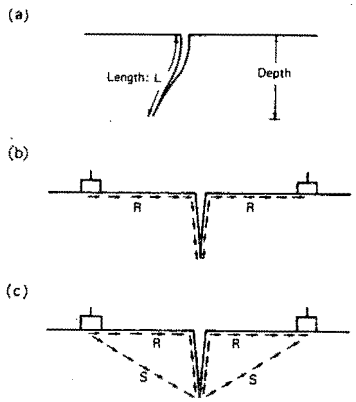

Fig. 7 Crack length measurement using surface waves.
a) Distinction between crack depth and the crack length L.
b) Crack length measured by the surface wave propagating around the crack.
c) The three main pulses expected at the receiver. Note that P, S and both reflected and transmitted R-waves are in general all produced at each discontinuity.

When a surface wave reaches a discontinuity such as a crack opening or tip, part of the energy will be radiated as P or S waves into the body of the specimen and part will be reflected back as a surface wave, leaving the remainder to bend around the corner and continue as a surface wave. Cook[33] found the crack length L by measuring the time taken for the surface wave to pass around the crack between two transducers (Fig. 7b). This method was later found to be accurate for most fatigue cracks having L above 2 mm, provided the transmitted signal could be unequivocally identified.[34] Unfortunately, attenuation of the surface wave caused by the crack morphology and the roughness of the surface finish prevented this method being accurate in some cases, and perhaps more importantly, it was not possible to know beforehand which cracks would be unsuitable. Hall[35] further clarified this technique by using photoelastic visualization of the interaction between a surface wave and notches in glass specimens. He demonstrated that three main pulses are expected at the receiver - the R-wave transmitted around the crack, a mode converted S-wave propagating from the tip over a range of directions including that towards the receiver, as well as a diffracted S-wave caused by an unwanted bulk wave produced at the transmitter (Fig. 7c). This insight facilitated the measurement of 9 mm deep fatigue cracks in steel using specially designed 4.2 MHz Rayleigh wave probes. Notches down to about 1 mm were indicated by broadening of the received pulse, though quantitative depth measurement by simple timing only becomes possible when the three main signals are resolved.

Hudgell et al[34] introduced an alternative method suitable for parallel-sided specimens (Fig. 8), which uses only a single probe. This method is less accurate than that originated by Cook[33], but more reliable because it more consistently provides an identifiable signal. Total transit time is measured for that part of the surface wave which is converted to an S-wave at the tip, reflected from the opposite face of the flat specimen, then reconverted to a surface wave due to glancing incidence at the tip, and finally travels back to the probe. Because of the relatively small difference between R and S wave velocities, this method required measurement to ± 10 ns by time interval averaging to estimate fatigue crack edge profiles only to within about 1 mm. An inherently more accurate single probe technique measures the time between R-wave reflections from the crack opening and tip. Lidington and Silk[36] used this approach to measure the depth of an artificial slit up to 30 mm deep to an accuracy of ± 0.2 mm. They were not able to deal with slits below about 4 mm, since for smaller depths the tip reflection was not resolved from the moderately short pulse from the slit opening. For a fatigue crack profile in steel, their accuracy in measuring L dropped to ± 0.8 mm, possibly due to a large inclusion concentration giving greater background intensity in the signal. Some spuriously high and low readings were found for this real crack, probably caused by changes in the crack angle and by regions of cracking parallel to the plate surface.

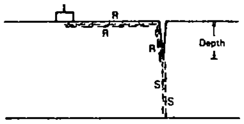

Fig. 8 Crack length measurement using the difference between speeds for R and S waves.

Silk[24] proposed several methods aimed at finding depth rather than length for a real crack. The most interesting of these first measures the times of flight between two transducers for the surface wave propagating around the crack, and for the mode converted S-wave originating at the tip (Fig. 9). Next, the roles of transmitting and receiving probes are reversed, and the measurements repeated. With these four readings, the time delay involving surface waves can be eliminated altogether, leaving the algebraic equivalent of the bulk S-wave timing method of Lloyd.[31] Silk used this method to find the depth rather than L for conveniently deep (22-30 mm) fatigue cracks to ± 0.5 mm.

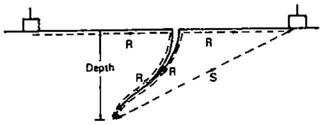

Fig. 9 Elimination of R-wave transit times to find crack depth.[24]

The surface wave techniques described here have generally not been able to measure such small fatigue cracks as have the more successful of the bulk wave methods considered above, nor have they usually been so accurate, reliable, or versatile. Nevertheless, the approach is at a comparatively early stage of development, and as Silk[24] pointed out, may not yet have reached its full potential, particularly if viewed in the light of the more sophisticated treatment of the received pulses discussed in the following section.

ULTRASONIC SPECTROSCOPIC ANALYSIS

The transit time techniques considered so far rely on one or more pulses being identified at the receiver without any need for processing the total signal. One approach to extending these methods to smaller cracks and to mapping the morphology of the crack face is to pursue further analysis of the signal, either in the time domain or in the frequency domain, that is, to adapt the development of ultrasonic spectroscopy[37,38] to signals from surface flaws. Work in this field has to date been mainly directed towards the study of internal defects. We shall briefly discuss this work, as it will help guide the development of the spectroscopic study of surface defects.

Because of the difficulty in developing the theoretical analysis, Gericke[37] and Wüstenberg and Mundry[39] suggested empirically forming an atlas of signatures for reflections from different types of internal flaws, to which one could refer to interpret the spectral traces obtained from unknown defects. However, ultrasonic spectroscopy has developed along rather more manageable lines through experimental and theoretical studies of the spectral traces from simply shaped objects. This work includes a method for the determination of the size of arbitrarily oriented flaws of two-dimensional (crack-like) geometry[40,41] and studies of cylindrical inclusions[42-44] and of spheroidal cavities[17] in elastic solids.

The same general approach described above for internal defects was adopted for surface flaws by Morgan.[45] He applied spectroscopic analysis techniques to the study of surface wave reflections from a slot milled in aluminum. The reflections from this slot using a broad-band (0.5-10 MHz) interdigital transducer were as in Fig. 10a. Each corner in the slot, whose shape is shown in Fig. 10b, acts as a scattering center. He introduced two methods - the time reconstitution method and the cepstral method - which allow later signals to be resolved from each other, provided the signal from the first scatterer can be separated. The time reconstitution method requires that both amplitude and phase of the reflected signal be retained for analysis. For this method, Morgan wrote the impulse response function for the surface crack in terms of reflection and transmission coefficients for a set of scatterers, which in this case were the corners in the slot. He assumed no change in pulse shape upon reflection, thereby neglecting dispersion. Fig. 10c shows the experimentally reconstituted time signal for the artificial slot and illustrates the correlations with the five scattering centres. The cepstral method, which does not require the phase of the reflected signal, gave results almost identical to Fig. 10c for the artificial slot. For this alternative method, analogue spectrum analyzers are applicable, instead of the digital processing requires to obtain phase information for the time reconstitution approach.

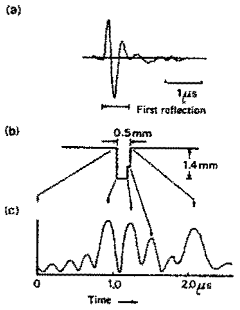

Fig. 10 The spectroscopic analysis carried out for surface waves by Morgan.[45]
a) The original reflected signal.
b) The geometry of the slot.
c) The experimentally reconstituted time signal.

In defining his original impulse response function, Morgan did not consider the effect of internal cycles between scatterers in the series. To improve the correlation between signal and slit morphology, these contributions to the signal should be evaluated and compared with the errors inherent in the computational procedures. The future development of his methods also depends on their extension to the morphologies of real surface cracks.

The energy carried by a surface wave is spread over a finite depth below the surface, governed by the wavelength. Therefore, the time taken to pass around a crack whose depth is of the order of the wavelength is frequency dependent. Silk[24] suggested developing a technique for crack depth measurement based on this dependence which, while being less accurate than conventional transit time measurements, would be largely independent of the angle of the crack. We believe that a study of this frequency dependence may prove most valuable in the analysis of broadened pulses received in the interrogation of shallow cracks, such as have been reported by Hall.[35] In any case, a more rigorous treatment of the frequency dependence than has been given to date is required.

DISCUSSION

From the techniques considered in this review, bulk wave transit time measurements appear to hold the main hope for the near future to provide simple and reliable quantitative crack depth measurement. Surface wave timing methods are also promising, though they are perhaps at a slightly earlier stage of development. Further fundamental scattering studies such as those described will be valuable in providing the necessary general understanding of the basic processes involved, particularly if applied to the scattering in the region of the crack tip.

Not only greater accuracy and reliability of depth measurement are desirable, but also the ability to measure smaller cracks; for example, cracks 0.5mm deep are often critical in high strength steels in aircraft components. Research in ultrasonic spectroscopic analysis, possibly along the lines suggested, should contribute to the study of small cracks. For some specimen geometries, another approach which may be developed to provide quantitative measurement is the use of guided ultrasonic waves. These waves have been used to detect cracks down to 0.05 mm in thin tubes.[46]

The ultrasonic probes used are another area for development. Greater accuracy and sensitivity in measuring the depth of the profile of small cracks may be possible by the use of focused probes,[47] and particularly by the use of single pulse generation.[48-51] Again, improved probe design may allow exploitation of the inherent advantage of shear waves over pressure waves for timing techniques. Finally, we should mention that only single cracks have been studied to date; multi-branched cracks and close clusters of cracks are subjects for future study.

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DISCUSSION

John Brinkman, Chairman (Rockwell International Science Center): Let me ask a question. On your last chart you showed an experimentally reconstituted signal.

Peter Doyle: (Aeornautical Research Lab): Yes.

John Brinkman, Chairman: Can you comment on the reconstitution?

Peter Doyle: Yes. What we did was simply to write the impulse response function in terms of the reflection and transmission coefficients and then, provided that you can identify the reflection in the first corner, you can go to the answer.

John Brinkman, Chairman: Okay.