ULTRASONIC MEASUREMENT OF CRACK-LIKE DEFECTS IN METALS

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ABSTRACT Ultrasonic methods for sizing crack-like defects in metal are reviewed. Techniques include the amplitude method, the timing method and ultrasonic spectroscopic analysis.The timing method provides the most simple and reliable measurement by far. However, spectroscopic analyses do have a certain potential for sizing cracks of the order of a wavelength.

INTRODUCTION

Ultrasonic methods have been widely used to detect and locate crack-like defects in structural materials. Quantitative techniques have been developed for crack sizing. These techniques include the scattered amplitude method, the timing method and ultrasonic spectral analysis. A brief review of all these three methods was given by Doyle and Scala [1] in 1978.

The amplitude-sizing techniques rely on the observation of the amplitude of reflected or transmitted ultrasonic bulk waves from a crack. However, the ultrasonic signals received are a combination of several separate echoes which can overlap and interfere with each other; their amplitudes also depend on other factors not related to the crack size, such as surface roughness, transparency and orientation. Furthermore, the varying acoustic pressure in the beam profile of the transducer and the variations in coupling efficiency between the transducer and the material add to the inherent amplitude variability. For these reasons, the amplitude method for crack sizing is considered unreliable. It should be noted that unfocused transducers were used. Focused transducers have only been used recently to size cracks. It has been shown that the echo amplitude, together with the transducer scanning distance and measurement of travel time of ultrasonic echoes, can, in some instances, provide accurate sizing of cracks. These techniques will be discussed later.

The timing method is by far the most reliable method for the location and sizing of cracks. It is based on the measurement of the travel time of sound waves diffracted or reflected from the crack. M.G. Silk [2] reviewed the research carried out on the timing method up to 1976. Bulk waves (longitudinal and shear) and surface (Rayleigh) waves or a combination of all of these waves can be used in the timing method.

The timing methods rely on the pulses being identified at the receiver without there being the need for processing the total signal. To size smaller cracks and to map the morphology of the crack face, further analysis of the signal has to be pursued by spectroscopy. While timing methods have been applied to practical ultrasonic problems, ultrasonic spectral analysis is still confined to laboratory testing applications.

AMPLITUDE METHODS

The most common use of an ultrasonic transducer is in the pulse-echo technique which detects the return signal scattered by a defect situated in the far field region of the transducer. The amplitude of the signal is compared with that scattered by a known standard defect and some quantitative estimation of the defect size is deduced [3]. For crack sizing, reference standards often consist of EDM slots or saw cuts fabricated in a position geometrically similar to that of the crack to be measured. This method is considered unreliable as the amplitude of the return signal is influenced by crack shape, crack surface roughness and mode conversion upon reflection [1].

However, focused transducers have been used to scan across a crack and it has been shown that this method is applicable to crack sizing. When an ultrasonic beam scans the surface of a sharp-edged plane crack sufficiently misoriented with respect to the beam axis, it has been observed that the amplitude of the back-scattered signal reaches a local maximum when the beam axis hits the defect edge (Fig. 1). If the crack orientation is known, crack size can be determined from the position of the local maximum [4]. If not, the size and orientation of the crack can be determined from the differences in travel time $t_2 - t_1$ and the transducer scanning distance Δx [5, 6].

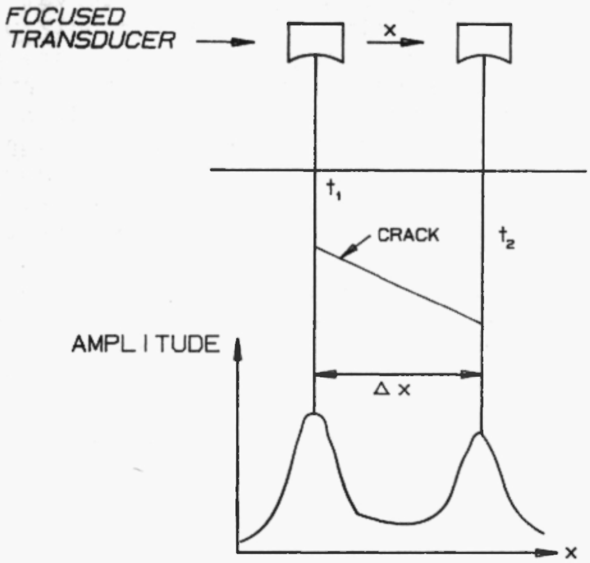

Fig.1 Schematic shape of the amplitude of the diffracted ultrasonic signal when a normal focused probe is scanning a crack along direction x [5,6].

TIMING METHODS

A. Longitudinal and/or Shear Waves

1a. One transducer; one scan position. The simplest method uses one transducer as transmitter/receiver. Sound waves diffracted from the crack tip and reflected from the crack root are assumed to travel in parallel rays back to the transducer (Fig. 2). The probe angle θ has to be used to calculate the crack depth d.

$$d = \frac{v\Delta t}{2\cos\theta} \qquad (1)$$

where v = velocity of sound wave and Δt = difference in the round trip travel time between the crack tip and crack root.

The crack was assumed to be oriented normal to the surface. This method has been used by Lloyd [7] to measure a slit using an unfocused shear wave probe. Hayman [8] found that it was difficult to identify any echoes from the crack tip when unfocused transducers were used to inspect real cracks, and that focused transducers considerably improved the effectiveness and ease of using the method. However, focused transducers can only be used for sizing shallow (<3 mm) cracks because of their limited beam width.

Instead of measuring relative travel time, absolute travel time between the transducer and the crack tip can be measured. If the transducer is located directly above the crack tip, the crack depth can be determined. This technique has been used by Silk and Lidington [9] to estimate the depth of fatigue cracks (Fig. 3).

1b One transducer, two scan positions. Date et al [10] measured the difference in travel time from the tip and root of an inclined slit in one scan position. Measurements from two scan positions, one from the right side and one from the left side of the slit were

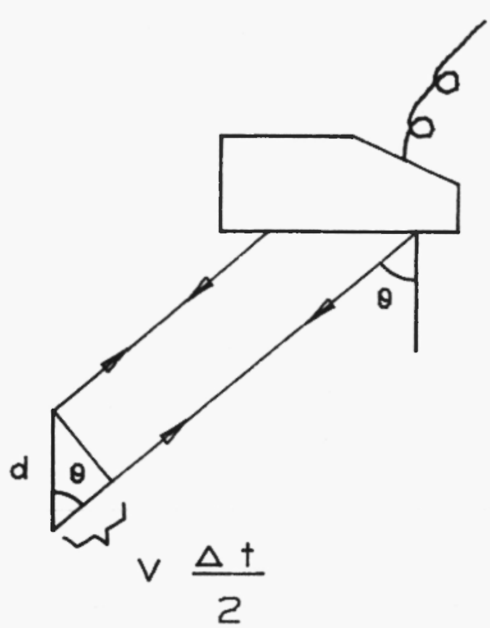

Fig 2 Measuring the depth of a vertical crack with a single transducer in one scan position.

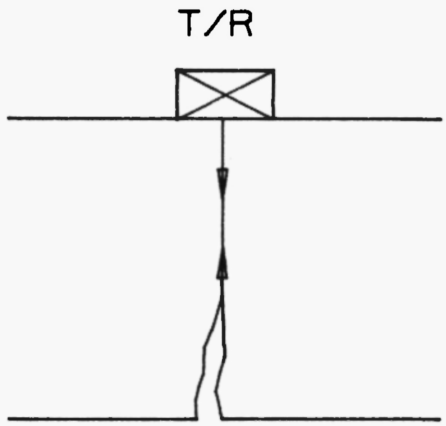

Fig. 3 Sizing a crack with a normal transducer.

then used to calculate the length of the slit by simply using Pythagoras's theorem. A 45° probe had to be used (Fig. 4).

It is not difficult to derive the equation for sizing an inclined slit when the probe angle is not 45°. The orientation of the slit to the normal of the surface α can be calculated from (Fig. 5):

$$\tan\alpha = \frac{d_1 \cos\theta_2 + d_2 \cos\theta_1}{d_2 \sin\theta_1 + d_i \sin\theta_2} \qquad (2)$$

$$\text{where } d_i = v\frac{\Delta t_i}{2} \qquad i = 1,2 \qquad (3)$$

v is the sound velocity. Δt_i is the difference in round trip travel time from the tip and root at the ith scan position. θ_i's are the probe angles. For the sake of generality, θ_1 does not have to be equal to θ_2.

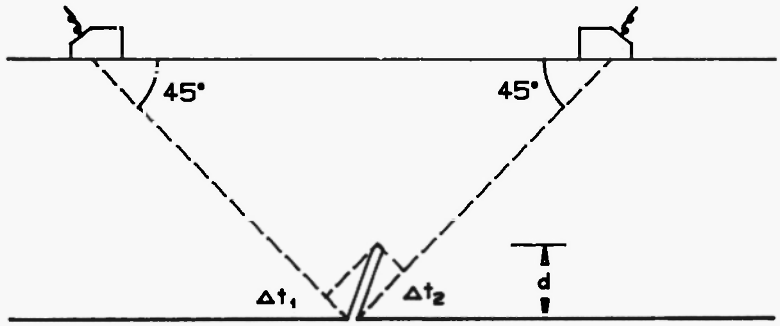

Fig 4 Sizing an inclined slit with a 45° transducer in two scan positions [10].

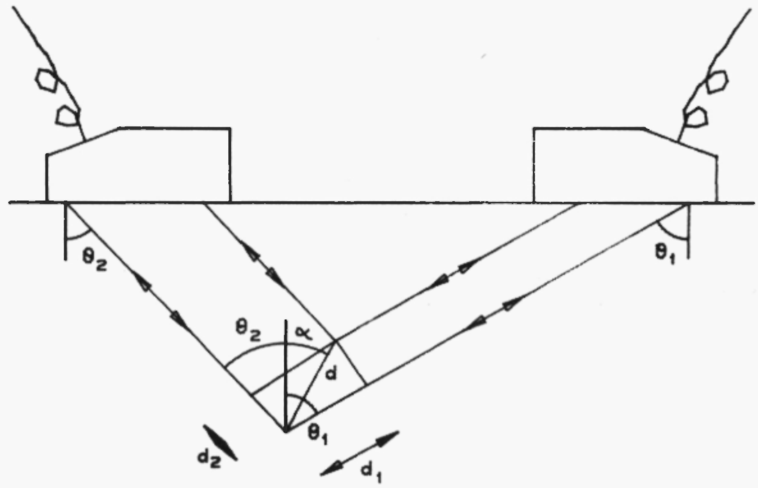

Fig. 5 Sizing an inclined slit with a transducer in two scan positions. $\theta_1 = \theta_2$. $\theta_1 \neq \theta_2$ would imply that two transducers were used.

The crack length d can be calculated from

$$d = \frac{d_1}{\cos(\theta_1 - \alpha)} \quad (4)$$

or

$$d = \frac{d_2}{\cos(\theta_2 + \alpha)} \quad (5)$$

The above methods assume that the sound beams striking the tip and the root are parallel. This is a good assumption if the crack size is much smaller than the distance between the crack and the transducer. A method that assumes that sound beams radiate from the transducer exit point has been described by Mak [11]. Travel time from the exit point to the tip or root has to be measured (Fig. 6). Either trigonometry or analytical geometry can be used.

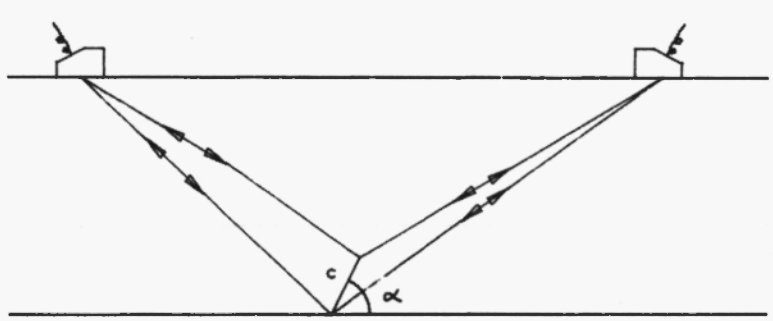

Fig. 6 Sizing an inclined slit. The sound beam is assumed to radiate from the transducer wedge exit point.

1c One transducer, multiple scan positions. For a transducer scanning linearly along the z = 0 plane, the travel distance l between the transducer exit point (x,0) and a point defect located at (x_o, z_o) is given by

$$l^2 = (x - x_o)^2 + z_o^2 \qquad (6)$$

which can be rewritten as

$$\frac{l^2}{z_o^2} - \frac{(x - x_o)^2}{z_o^2} = 1 \qquad (7)$$

This is the equation of a hyperbola whose apex is given by (z_o, x_o). At different scan positions x, travel time can be measured and travel path l deduced. A numerical method of minimization can be used to deduce the location of the point defect.

Alternatively, Eq. (6) can be rewritten as

$$l^2 - x^2 = -2xx_o + (x_o^2 + z_o^2) \qquad (8)$$

Plotting $l^2 - x^2$ against x will yield a straight line with gradient = $-2x_o$ and intercept = $x_o^2 + z_o^2$.

Again, the location of the point defect (x_o, z_o) can be calculated.

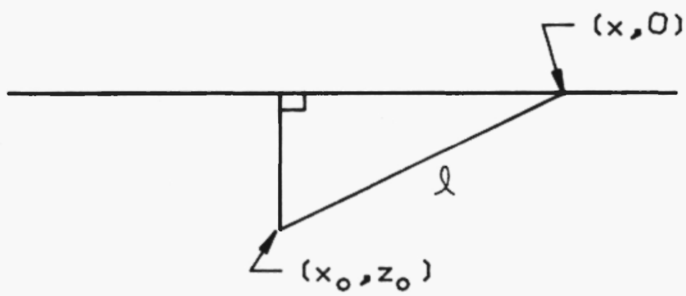

Fig. 7 The relationship governing the transducer position (x,0) and the point defect position (x_0, z_0). l is the travel path.

These two methods have been used to locate the tip and root of inclined slits [12]. Crack length and orientation can then be calculated easily.

2a Two transducers, one scan position. The two transducers are placed symmetrically about the crack tip (Fig. 8). A pulse from the transmitter is diffracted at the crack tip and arrives at the receiver. If the beam entry points are separated by a distance 2S, the crack depth is given by

$$d = \left[\left(\frac{c\Delta t}{2} \right)^2 - S^2 \right]^{1/2}$$

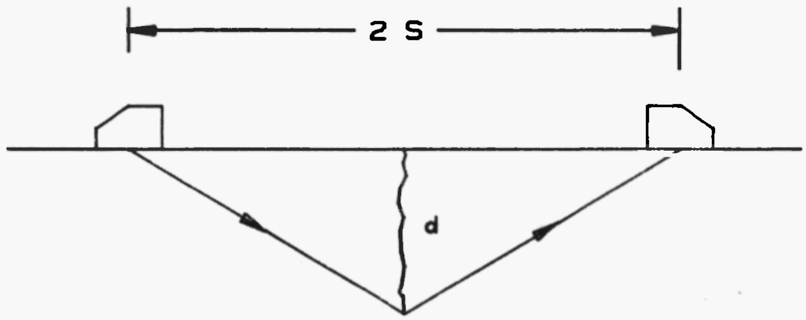

Fig. 8 Sizing crack depth with a symmetrical probe arrangement.

where Δt is the travel time in the metal.

Measurement of absolute travel time can be inaccurate because of the delay between the trigger pulse and the ultrasonic pulse and the delay in the transducer wedges. Therefore, the transit time of the diffracted wave is sometimes measured relative to the transit time of another wave, either a reflection from the back wall of the piece of metal or a direct signal from the transmitter to the receiver on an uncracked part of the piece of metal [14] .The latter signal is a wave travelling at the bulk longitudinal velocity just under the surface and is referred to as a 'lateral wave'.

A method in which the two transducers do not necessarily have to be located symmetrically with respect to the crack tip is described in references [15, 16, 17]. The probe angle of the transmitter has to be used to calculate the crack depth. Lateral longitudinal waves were used as a reference signal. The method also considered situations where sound waves were mode-converted at the crack tip.

A specially designed multimode transducer which yielded a mode-converted diffracted signal from the crack tip, has been used to size fatigue cracks in cladded pressure vessels [18].

<u>2b Two transducers, two scan positions.</u> When two transducers are used as a transmitter-receiver system, for every beam of identical travel time running from the transmitter location to the receiver location, the scattered points must lie on an ellipse with foci at the transmitter and receiver locations. In order to locate a point scatterer, the two transducers have to be moved to another scan position and the travel time measured and another ellipse drawn. The intersection of the two ellipses inside the material will yield the location of the point scatterer (Fig. 9). The method can be performed analytically [19] or by simply drawing the two loci [20]. It is usually assumed that the beam entry point in the metal is fixed and lies along the acoustical axis of the transducer. Because of the diverging beam profile of a transducer, this assumption is not quite correct. A beam entry point correction should be made for locating the crack tip, either by using numerical analysis [21], or graphically from intersection of two loci [22].

<u>2c Two transducers, multiple scan positions.</u> The two-transducer technique has a certain advantage over the single transducer technique. Signals scattered from the crack surface, which might

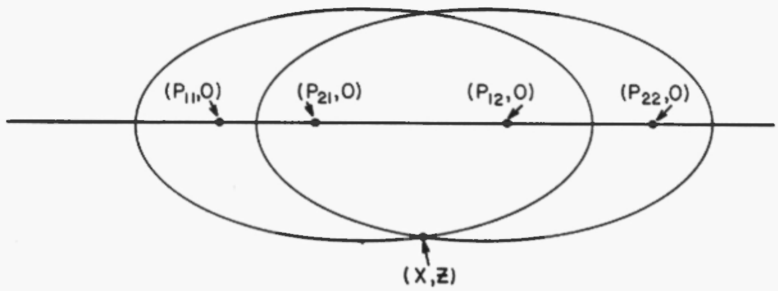

Fig. 9 The location of the crack tip, (x,z), is given by the the intersection point of the two ellipses inside the material. The foci of one ellipse are $(p_{11},0)$ and $(p_{12},0)$. The foci of the other ellipse are $(p_{21},0)$ and $(p_{22},0)$

lead to underestimation of crack size, are blocked by the crack and not received. A crack, however, can be partly transparent [23,24], but the signal scattered from the crack tip usually has a larger amplitude than the signals transmitted through the crack.

The two-transducer technique has proven to be quite satisfactory for detecting diffracted waves from crack tips and then sizing the cracks from the arrival times of these diffracted waves. The NDT Centre at Harwell has developed a general purpose portable digital data collection and analysis system using this technique. [22, 24, 25] At each scan position, the data are digitized. For a linear scan, a B-scan type presentation can be generated using the digital data collection system which provides a visual display of the overall situation. However, the B-scan retains the effect of beam spread. Each defect signal is curved due to contributions from the extremities of the beam arriving later than those travelling along the beam axis. This effect can be reduced by using a synthetic aperture focusing technique [22,25]. The technique simulates a beam which is focused at all depths of the material. The data processed provide a much better resolution and signal-to-noise ratio than the raw data.

<u>3 Three transducers</u> A method using three transducers was described by Bond and Punjani [26]. A normal compressional probe with a shear wave probe on each side, was located on the opposite surface of a surface-breaking crack (Fig. 10). Each shear wave probe was used as a transmitter/receiver. Signals reflected or diffracted from the crack root and tip could be detected. They also transmitted shear waves which were mode-converted into longitudinal waves at the tip and root. The longitudinal waves were detected by the normal compressional probe. The two shear wave probes could also be used as a transmitter-receiver pair, detecting shear waves diffracted from the crack tip. By combining all this travel time information, the difference in travel time from the crack tip and root could be established and the crack depth deduced. The advantage of this method is that the distance between the transducers need not be known.

<u>4 Four transducers</u> As mentioned earlier, the two transducer technique has proven to be quite successful in crack sizing. However, a basic limitation to the application of the technique has been the need to employ two probes physically linked together so

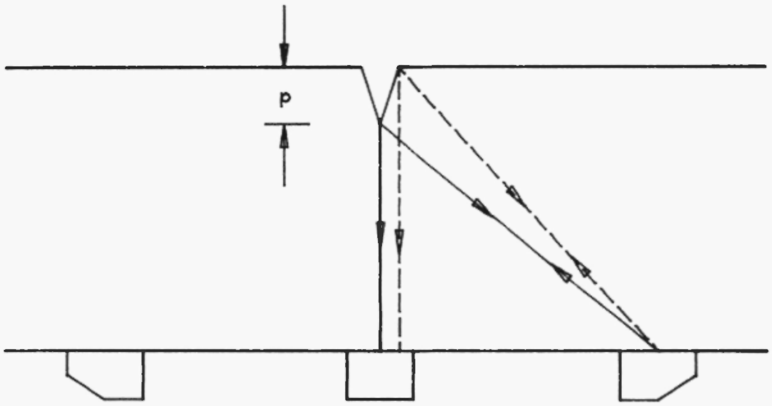

Fig 10 Measuring crack depth d with a three transducer configuration [26].

that their separation remains constant within reasonable limits. In some applications like crack sizing in T-butt welds, the physically linked probes provide a serious drawback.

Silk [27] has described a technique where the restriction of physically linked probes has been relaxsd. Four transducers were required. The transmitting probes were separated from the receiving probes. The distance between the inner transmitter-receiver probe pair need not be known, but they have to be symmetric with respect to the crack tip. A backwall echo was needed as a reference signal (Fig. 11).

Dalberg [28] described a method where the requirement of symmetry about the crack tip was eliminated. The transmitter (one probe) and the receiver (three probes) were physically unlinked. The distance between the transmitter and receiver need not be known. A lateral wave was used as a reference and had to be measured on an uncracked part of the test object (Fig. 12). The separation between the probes in the receiver unit had to be known precisely in order for the crack to be sized accurately.

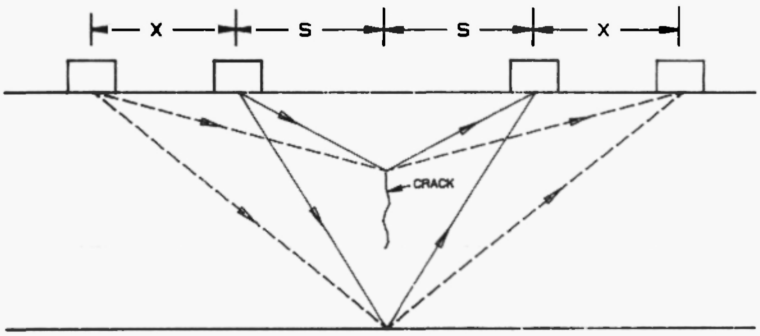

Fig 11 A symmetric four probe system for sizing a crack [27]. x has to be known while s need not be known.

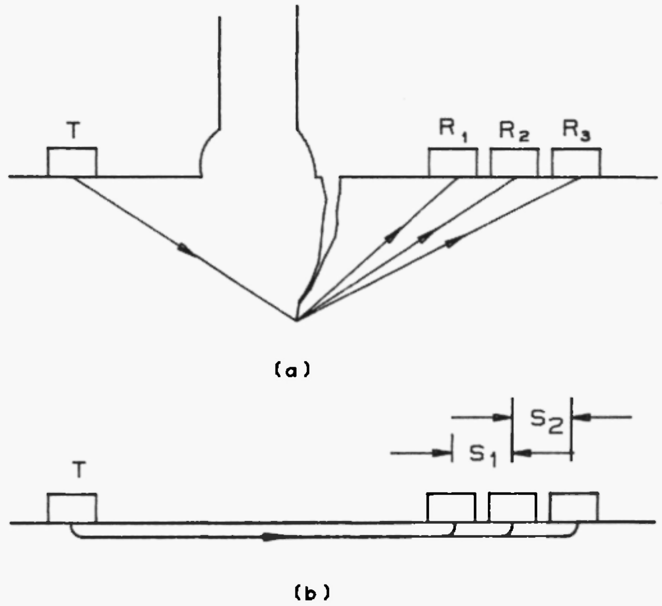

Fig. 12 (a) The crack sizing method using four transducers and (b) the lateral wave as reference.

SURFACE WAVES

A general treatment of the properties of a surface wave is described by Viktorov [29]. The wave travels along the surface of the test material provided the surface is acoustically unloaded, as is the case with an air/metal interface. When a surface wave strikes a crack, it is partially reflected back at the crack opening and partially transmitted along the face of the crack (Fig.13). When it reaches the crack tip, part of it is reflected back and part of it is transmitted as a surface wave. Some of it is also mode converted to shear wave. Using a single-probe technique based on the reflection of surface waves from the crack opening and crack tip, the crack depth of cracks perpendicular to the metal surface could be measured [2]. This technique has been applied to

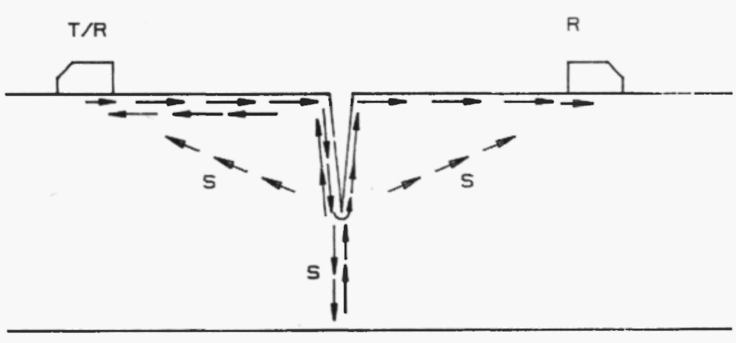

Fig. 13 Behaviour of an ultrasonic Rayleigh wave impinging on surface-breaking crack. s stands for shear wave.

measuring surface-breaking cracks in railway wheels [30]. However, the reflection from the crack tip is usually weak.In an alternative approach the delay between the crack opening reflection and the mode-converted shear wave reflected from the opposite surface of the metal was timed[31]. These two methods can easily be modified to the transmission mode when two tranducers are used (Fig.13). Another through transmission method monitors the time of travel of the surface wave between two probes held at a fixed distance apart [2]. The presence of a crack increases the observed transit time by causing the surface wave to travel along the crack faces. The increase in transit time Δt, is a direct measure of the crack depth d

$$d = C_R \frac{\Delta t}{2}$$

where C_R is the velocity of the surface wave.

A mode-converted shear wave at the crack tip can travel directly to the transducer(s) (Fig. 13). This wave has been used in several methods which use either one or two transducers [2,32]. Crack length, depth and orientation can be measured. A three transducer configuration located at the same surface has also been used by Silk [2, 32] (Fig.14). One of them was used as a transmitter and all three were used as receivers.The relative travel time of the mode-converted shear wave received by two transducers had to be measured.

Another three transducer technique was discussed by Bond and Saffari [33]. A normal probe, either longitudinal or shear wave was placed on the back face of the test-piece to insonify the crack. Two surface wave probes placed on opposite sides of the crack on the front face act as receivers (Fig 15).

Because of the usually weak signal from the crack tip, it is sometimes difficult to identify it in the presence of other interfering pulses arising from defect irregularities. This technique has mostly been confined to laboratory testing and there have only been a few attempts to apply the method to practical ultrasonic problems. Surface wave signals are also easily damped by any liquid on the metal surface. This makes automation of inspection using surface waves rather difficult.

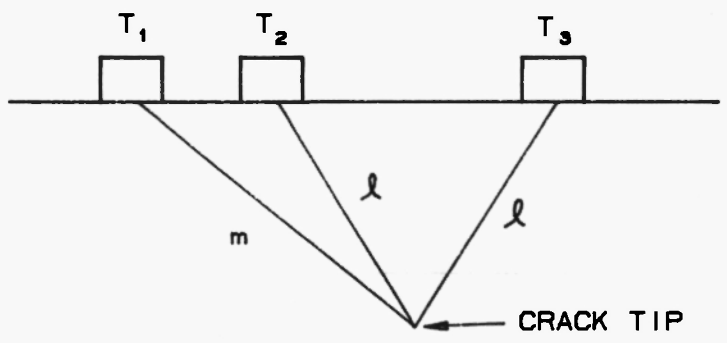

Fig. 14 Transducers T_2 and T_3 are symmetric with respect to the crack tip. The time delay between the mode-converted shear wave arrival at T_1 and T_2 are measured.

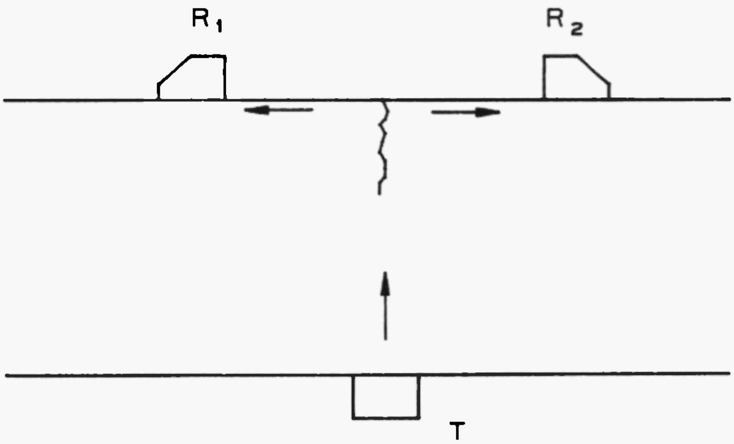

Fig. 15 T is a normal transmitter. The mode-converted Rayleigh waves are received by R_1 and R_2.

ACCURACY OF TIMING METHODS

The accuracy of crack sizing depends on the accuracy in measuring travel time, i.e. relative travel time or absolute travel time. Relative travel time can be measured from the peak of the pulse from a crack to the peak of a reference pulse. Depending upon whether the two pulse shapes are similar to each other, relative travel time can be measured to an accuracy of 1/100 of a wavelength. Measuring absolute travel time is a more involved process. The travel time should be measured at the zero crossing point of the leading edge of the pulse and not at the peak of the pulse. However, interfering noise can make it difficult to determine where the leading edge is. Another problem that affects accuracy is that the output pulse from the pulser to the transducer is usually not synchronized with the triggering pulse to the oscilloscope. But, correction can be made by noting the time difference on the oscilloscope between the two pulses. For an angled probe, the travel time through the wedge has to be measured. One method is to put a thin metal plate against the beam exit point of the wedge and measure the reflected travel time from it on an oscilloscope. Another method is to calibrate the wedge travel time from a slit of known depth. However, because of beam divergence, the beam exit point marked on the wedge may not necessarily correspond to the beam entry point in the piece of metal. Beam entry point correction has been studied [34, 21] but the study assumes sound waves are radiated from the centre of the transducer crystal. Further studies need to be done. Another source of error arises from ignoring the transit time in the acoustic coupling medium between the wedge and the metal surface. This error has been considered in Ref. 2 and 35. The time is of the order of a nano-second and will only contribute to the error in crack sizing of much, much less than a wavelength.

The error in crack sizing is also affected by the error in measuring the location of the transducer(s). The uncertainty in crack size can be estimated from the uncertainty in the determination of various parameters by using the rules of error propagation [36]. An example is given in Ref. 11. The error is approximately 0.2 of a wavelength.

Spectrum Analysis

The time of flight techniques considered so far rely on the pulses being separated from each other such that their travel times can be measured accurately. For a crack size of the order of a wavelength the pulses are often cluttered together. Further analysis of the signal has to be pursued, either in the time domain or in the frequency domain. Ultrasonic spectroscopy can be applied to size cracks and to map the morphology of the crack face. A good reference book on ultrasonic spectral analysis for nondestructive evaluation in general has been written by Fitting and Adler [37].

Up to now, spectral analysis on cracks has only been applied to surface cracks. In most experiments, the Rayleigh wave was used. Signals reflected from the crack were deconvolved so that the crack characteristics can be more easily interpreted. The output signal $s_2(t)$ can be formulated as a convolution between the incoming signal $s_1(t)$ and the impulse response h(t) from the crack [38]:

$$s_2(t) = h(t) * s_1(t)$$

After Fourier transformation, the convolution is reduced to a complex multiplication in the frequency domain:

$$S_2(f) = H(f)\ S_1(f)$$

As the transfer function H(f) of the crack is required, it can easily be obtained from

$$H(f) = \frac{S_2(f)}{S_1(f)}$$

$S_1(f)$ can be determined by observing the echo from a large flat smooth surface that is perpendicular to the interrogating beam. In the case of a vertical surface breaking slot or crack, the first Rayleigh wave signal reflected can be used [39]. Alternatively, a Rayleigh wave reflected from a sharp 90°-corner could also be used as a reference [40]. The periodicity of modulation in the transfer function H(f) is measured and an inversion formula is used to relate the periodicity to crack depth [40, 41]. An inverse Fourier transform can be applied to H(f) to transform it back to the time domain [39, 31]. The reconstituted time signal yields a better resolved signal than the original time signal. The travel time from each corner in the slot can be identified (Fig 16).

The property of a broadband Rayleigh wave, whereby its frequency spectrum varies with depth below the surface, can be used to measure the depth of cracks. The spectrum loses its higher frequencies as the wave goes deeper into the material because the higher frequencies cannot penetrate as deeply as the lower frequencies. Spectroscopic procedures were applied to the transmitted wave after a Rayleigh wave interacted with a surface crack [42]. The cutoff frequency was determined from the spectrum. An empirical linear relation between the cutoff wavelength and the crack depth could be deduced.

Barna [43] attempted to model the interaction of a transducer sound field with an EDM notch. The transducer was treated as a rigid piston source. A shear wave was generated in the metal. The notch was considered to be located in the far field of the transducer. Computational results from the Fourier spectrum of the wave scattered from the notch were compared with experimental data from the "root" signal for EDM notches of depth ranging from 0.75 mm to 6 mm. A qualitative agreement in amplitude and peak frequency was obtained.

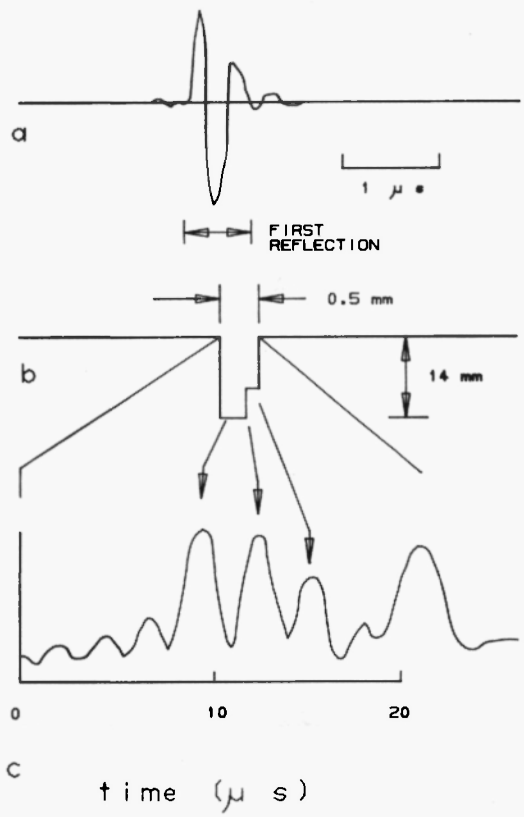

Fig. 16 The spectroscopic anlysis for suface wave: a - the original reflected signal; b - cross-sectional view of the milled slot; c- the experimentally reconstituted time signal.

CONCLUSIONS

Of all ultrasonic methods for sizing crack-like defects in metal, the timing methods are the most reliable and of all the transducer configurations, the two transducer arrangement employing bulk waves has been used most frequently.

This last method has the advantage that signals scattered from the crack surface, which might lead to underestimation of crack size, are blocked by the crack and not received. The position of the transducers can also be arranged such that the mode-converted waves are detected [18].

The single transducer arrangement is also a popular technique. It has the advantage that the handling of one transducer is much more convenient and mutual alignment is not needed. Recently, focused transducers have been used with the single transducer technique. They increase the signal-to-noise ratio, making the crack more easily recognizable and more accurately sized. For a crack size smaller than 3 mm, the crack can be sized in one scan position as both its tip and root lie within the beam width [8]. For a larger size crack, the transducer has to be scanned to measure the difference in travel time from the tip and the root [6,44] in order for the crack to be sized.

Multitransducer techniques have also been attempted for crack characterization. Any one transducer can be used as a transmitter/receiver, and any two transducers can form a transmitter-receiver pair, thus increasing the information gathered. Because of the larger amount of data, the distances between transducers may not need to be known. Mode converted waves are sometimes measured as they can provide better signal-to-noise ratios.They are used as a transmitter-receiver system to detect diffracted waves from crack tips. The cracks are sized from the arrival times of these diffracted wave.

For small cracks, sound waves diffracted from the tip and the root overlap and interfere with each other, making the application of the timing method difficult. Ultrasonic spectroscopic analysis may provide an answer. Up to now, the methods have been applied to surface-breaking notches. More research needs to be performed in this area to make the technique more practical.

REFERENCES

1. Doyle, P.A. and Scala, C.M., "Crack depth measurement by ultrasonics: a review" Ultrasonics, 16, 164-170, (1978).

2. Silk, M.G., "Sizing crack-like defects by ultrasonic means", Research Techniques in Nondestructive Testing, 3, 51-99, (1977).

3. Krautkramer, J. and Krautkramer, H., Ultrasonic testing of materials, third revised edition. Springer-Verlag (1983).

4. Bouami, D. and de Vadder, D., "Automatic tracking of crack growth with ultrasonic focused probe in CT specimen", Conference Proceedings of Ultrasonic International 85, 751-756, (1985).

5. de Vadder, D., Azou, P. and Saglio, R., "Determination of orientation and size of badly oriented defects by means of focused probes", Proceedings of the First International Symposium on Ultrasonic Materials Characterization, June 1978, 11-16, (1980).

6. Paradis, L., Serruys, Y., and Saglio, R. "A time-of-flight method for crack evaluation using focused ultrasonic probes", Materials Evaluation, 44, 568-570, (1986).

7. Lloyd, E.A., "An ultrasonic short-pulse shear-wave method for measuring the depth of surface-breaking cracks", Brit. J. NDT, 17, 172-175, (1975).

8. Hayman, A.J., "An improved ultrasonic tip-corner timing method for sizing shallow surface-breaking cracks", Brit. J. NDT, 27, 295-299, (1985).

9. Silk, M.G. and Lidington, B.H., "An evaluation of single probe bulk-wave time-delay techniques in sizing cracks in steel", NDT International, 10, 129-134, (1977).

10. Date, K., Shimada, H. and Ikenaga, N., "Crack height measurement - an evaluation of the accuracy of ultrasonic timing methods", NDT International. 15, 315-319, (1982).

11. Mak, D.K., "Ultrasonic methods for measuring crack location, crack height and crack angle", Ultrasonics. 23, 233-226, (1985).

12. Mak, D.K., "The use of an unfocused transducer to determine accurately the positions of point scatterers in defect mapping", CSNDT Journal. 8,42-44, (1987).

13. Silk, M.G. and Lidington, B.H. "Defect sizing using an ultrasonic time delay approach", Brit. J. NDT. 17, 33-36, (1975).

14. Charlesworth, J.P., Lidington, B.H. and Silk, M.G., "Defect sizing using ultrasonic flaw diffraction", Proceedings of the first European Conference on Non-Destructive Testing. 4/55-4/62, (1978).

15. Golan, S., "Sizing of cracks with scattered ultrasonic waves", Proceedings of the First International Symposium on Ultrasonic Materials Characterization, June 78, 29-36, (1980).

16. Sachse, W., and Golan, S., "The scattering of elastic pulses and the non-destructive evaluation of materials", Elastic Waves and Non-Destructive Testing of Materials. 11-31, (1978).

17. Golan, S., "Optimization of the crack tip ultrasonic diffraction technique for sizing of cracks", Material Evaluation. 39, 166-169, (1981).

18. Gruben, G.J., Hamlin, D.R., Grothues, H.L. and Jackson, J.L., "Imaging of fatigue cracks in cladded pressure vessels with the SLIC-50", NDT International. 19, 155-161, (1986).

19. Mak, D.K., "Ultrasonic measurement of crack depth", CSNDT Journal. 6, 36-40, (1985).

20. Poulter, L.N.J., "Signal processing methods applied in the ultrasonic inspection of PWR inlet nozzles", NDT International ,19, 141-144, (1986).

21. Mak, D.K., "Correction of beam entry point for the pitch-catch technique in ultrasonic testing", CSDNT Journal. 7, 22-34, (1986).

22. Curtis, G.J. and Hawker, B.M., "Automated time-of-flight studies of the defect detection trial plates 1 and 2", Brit. J. of NDT.25. 240-248, (1983).

23. Golan, S., Adler, L., Cook, K.V., Nanstad, R.K. and Bolland, T.K., "Ultrasonic diffraction technique for characterization of fatigue cracks", Journal of Nondestructive Evaluation. 1, 11-19, (1980).

24. Silk, M.G., "The use of diffraction-based time-of-flight measurements to locate and size defects". Brit. Journal of NDT. 26, 208-213, (1984).

25. Carter, P., "Experience with the time-of-flight diffraction technique and an accompanying portable and versatile ultrasonic digital recording system". Brit. Journal of NDT. 354-361, (1984).

26. Bond. L.J. and Punjani, M. "New multitransducer techniques for crack characterization". Review of Progress in Quantitative Nondestructive Evaluation. 3A, 297-307, (1984).

27. Silk, M.G., "A separate probe technique for accurate crack sizing using ultrasonic diffraction". Conference Proceedings of Ultrasonic International 79. 415-426, (1979).

28. Dalberg, P., " A four probe technique for accurate sizing using ultrasonic diffraction". Conference Proceedings of Ultrasonic International 81, 384-389, (1981).

29. Viktorov, I.A., Rayleigh and Lamb Waves. Plenum Press,(1967).

30. Fahr, A., Kotanen A.R. and Charlesworth, A.M. "Ultrasonic surface wave measurement of surface-breaking cracks in a railway wheel", CSNDT Journal. 7, 44-49, (1986).

31. Hudgell, R.J., Morgan, L.L. and Lumb, R.F., "Non-destructive measurement of the depth of surface-breaking cracks using ultrasonic Rayleigh waves". Brit. Journal of NDT. 16, 144-149, (1974).

32. Silk, M.G., "The determination of crack penetration using ultrasonic surface waves", NDT International. 9, 290-297, (1976).

33. Bond, L.J. and Saffari, N., "Mode-conversion ultrasonic testing", Research Techniques in Nondestructive Testing, 7, 145-189, (1984).

34. Mak, D.K., "Beam entry point correction for crack tip measurement", Conference Proceeding of Ultrasonics International 85. 655-660, (1985).

35. Mackiewicz, S., Gorzny, J., Kiersnowski, M., and Pawlowski, Z., "Ultrasonic detection and depth measurements of cracks in thick welds" Proceedings of the 11th World Conference on Non-destructive Testing. 2, 1124-1129,(1985)..

36. Bevington, P.R, Data Reduction and Error Analysis for the Physical Sciences. McGraw Hill, (1969).

37. Fitting, D.W., and Adler, L., Ultrasonic Spectral Analysis for Nondestructive Evaluation. Plenum Press, (1981).

38. Nabel, E., and Mundry, E., "Evaluation of echoes in ultrasonic testing by deconvolution". Materials Evaluation. 36. 59-61, (1978).

39. Morgan, L.L. "The spectroscopic determination of surface topography using acoustic surface waves", Acoustica 30, 222-228, (1974).

40. Fitting, D.W. and Adler, L., "Frequency dependent interaction of ultrasonic waves with surface-breaking cracks", New Procedures in Nondestructive Testing, 203-212, Springer-Verlag, (1983).

41. Fitting, D., Adler, L., and de Billy, M., "Bulk and surface wave scattering from surface breaking cracks", Review of Progress in Quantitative Nondestructive Evaluation, 1, 525-535, (1982).

42. Testa, A.J. and Burger, C.P., "Rayleigh spectroscopy for characterizing surface cracks", Review of Progress in Quantitative Nondestructive Evaluation, 1, 557-564, (1982).

43. Barna, B.A., "Modelling of real UT transducer field/flaw interactions", Review of Progress in Quantitative Nondestructive Evaluation, 4A, 73-82, (1985).

44. Kittmer, C.A., Hallet, J.B. and Sycko, V.N., "Capabilities/limitations of focused ultrasonic beams for sizing pipeline girth weld defects" Fifth Canadian Conference on Nondestructive Testing, 104 -114, (1985).