ULTRASONIC SIZING OF CRACKS IN WEB GEOMETRIES

T. A. Gray and R. B. Thompson

Ames Laboratory, USDOE
Iowa State University
Ames, IA 50011

INTRODUCTION

Evaluation of the critical nature of interior cracks in turbine rotor component web regions in order to assess the remaining service life of the parts requires accurate determination of the crack sizes in order to perform fracture mechanics analysis. This analysis is important both in order to retire critically defective parts and in order to return components to service if detected flaws are sub-critical. The purpose of this paper is to evaluate several techniques for sizing internal cracks in planar geometries.

Four techniques for obtaining size estimates for interior cracks from ultrasonic backscattering data will be described and their implementation will be briefly discussed. These methods are:

1) the ka=1.05 resonance method (RM),
2) the flash-point technique (FPT),
3) an adaptation of the 1-D inverse Born approximation (IBA),
and 4) the 1-D inverse Kirchhoff approximation (IKA).
(The abbreviations in parentheses above, e.g., (RM) will be used in the sequel to identify these techniques).

The RM is based upon the occurrence of a "resonant peak" at ka=1.05 in the magnitude of the scattering amplitude for back-scatter from a circular crack, where k is the longitudinal wavenumber and a is the crack radius. This peak has been observed in theoretical calculations of Opsal (1), for example, in which this peak was found to persist for all angles of illumination and for rough simulated cracks as well. This technique thus provides an immediate estimate of the crack radius as a $1.05/k_o$ where k_o is the wavenumber corresponding to the resonant peak (2).

The FPT is based upon the existence of two crack edge-diffracted signals from the points of stationary phase (flash points) (3). At other than normal incidence to a flat crack, these two signals will be received at different times, separated by a time delay of Δt. An estimate of the projection of the crack radius onto the incident direction is readily found to be $a\sin\theta = v\Delta t/4$ where θ is the angle between the incident direction and the crack normal and v is the acoustic velocity of the wave mode (L or T) which illuminates the crack. The actual crack radius can be obtained only if the crack orientation is known a priori or if several incident angles are considered.

The IBA is an adaptation of the 1-D inverse Born approximation (4) for crack sizing applications. In this technique, a "characteristic function" γ_B is defined by

$$\gamma_B(u) = \text{constant} \times \int_o^\infty \text{Im}(A_o(k)) \frac{\sin 2ku}{2ku}\, dk \tag{1}$$

where $A_o(k)$ is the pulse-echo scattering amplitude from a crack and $u = r\sin\theta$ with the distance r measured along the scattering direction with r=0 at the crack center (2). The function $_B$, properly normalized, has a value of roughly unity for r<a and is small for r>a. An estimate of $a\sin\theta$ can be obtained, e.g., as the value of u at which $\gamma_B(u) = 0.5$ (2).

The IKA is similar to the IBA but is based upon the elastodynamic Kirchhoff approximation (2,5) to scattering from flat cracks. In a manner similar to the IBA, a "characteristic function" γ_K is defined as

$$\gamma_K(u) = \text{constant} \times \int_o^\infty \text{Im}(A_o(k)\; J_o(2ku)dk \tag{2}$$

where J_o is the zero-order ordinary Bessel function of the first kind (2). This characteristic function has been found to have a sharper drop in amplitude at $u=a\sin\theta$ than does the IBA (2). An estimate of $a\sin\theta$ can be obtained as in the IBA from the $\gamma_K(u)$ = 0.5 contour.

The RM and FPT are quite straightforward to implement with possible constraints imposed only by transducer bandwidth. The RM requires significant energy at frequencies such that ka=1.

The FPT must have sufficient energy at wavelengths comparable to or smaller than $a\sin\theta$. Implementation of the IBA or IKA is somewhat more difficult for two reasons. First, these two methods require a phase reference for the scattering amplitude, A, at the crack center (r=0) and so some method for appropriately correcting the phase of experimental data is needed. Second, the 1-D inverse Born approximation, which was developed to size volumetric flaws (4), requires a transducer bandwidth of at least $0.5<kb<2.5$ where b is a characteristic flaw dimension (5). It is expected therefore that the IBA and IKA for crack sizing will need similar bandwidths, namely $0.5<ka\sin\theta<2.5$.

EVALUATION OF TECHNIQUES

Each sizing technique was used to produce crack size estimates from both numerically exact scattering amplitudes for a smooth circular crack (1) and from experimental data. The experimental data were obtained from two samples - a cast thermoplastic disk containing an approximately circular crack induced by a laser (6) and an optically bonded fused quartz plate containing a machined simulated crack in the bond plane. The theoretical results and data from the plastic sample were for L→L backscatter while both L→L and T→T backscattering data were obtained from the glass sample. The experimental data were corrected for the effects of diffraction, attenuation, etc. according to the model of Thompson and Gray (7) to yield approximations to the crack scattering amplitudes.

Evaluation of the RM against experimental data yielded only inconclusive results. For example, Fig. 1 shows a comparison of the theoretical scattering amplitude (1) for L→L backscatter at a 30° incident angle relative to the crack normal and the corresponding experimental data from the plastic sample. Although the overall agreement between these curves is good, there is no definite peak in the experimental data at ka=1.05 (f=1.93 MHz). Similar results were obtained experimentally at other incident angles (see Ref. 8 for additional comparisons). Since the frequency of the expected resonant peak is near the low-frequency bandwidth limit of the available transducers, more definitive results from the in-house samples might be obtained using transducers with more low frequency content.

Theoretical and experimental results using the FPT for sizing are given in Fig. 2. In this figure, the dotted line corresponds to the ideal response $r = a\sin\theta$, the solid curve is the result for the theoretical (MOOT) data, and the vertical bars give the range of estimated sizes from the two lab samples using various transducers. As can be seen, the theoretical and experimental results provide good sizing response for all angles of incidence.

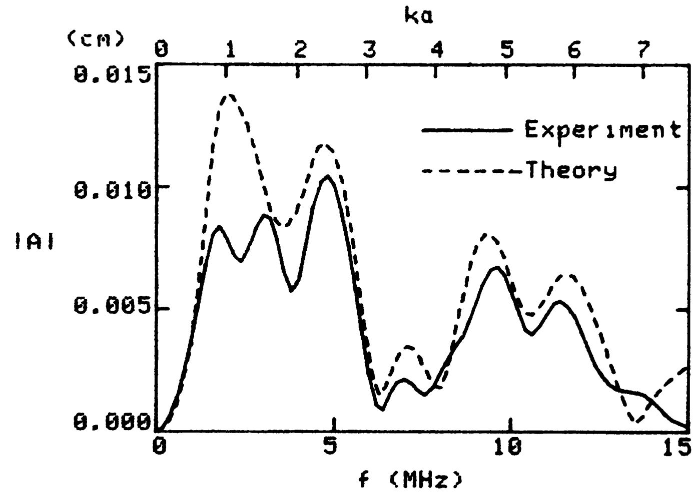

Fig. 1. Comparison of theoretical (dotted line) and experimental (solid line) scattering amplitude from a 220µm radius crack in thermoplastic at a 30° incident angle.

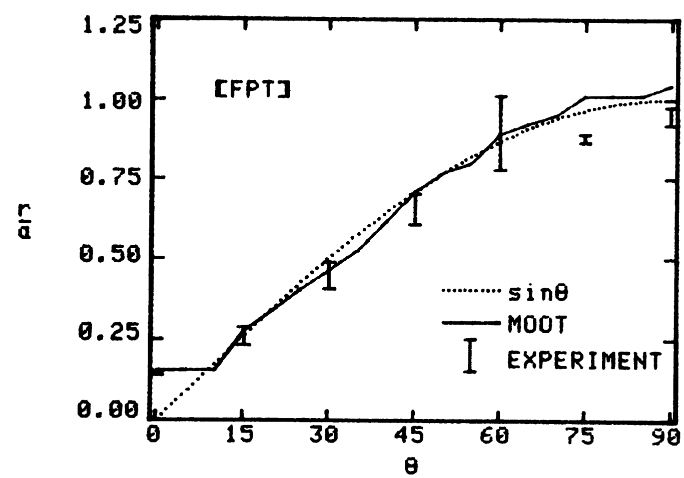

Fig. 2. Sizing results for FPT. Dotted line is r/a=sinθ, solid line is results for theoretical data and vertical bars are ranges of results for experimental data.

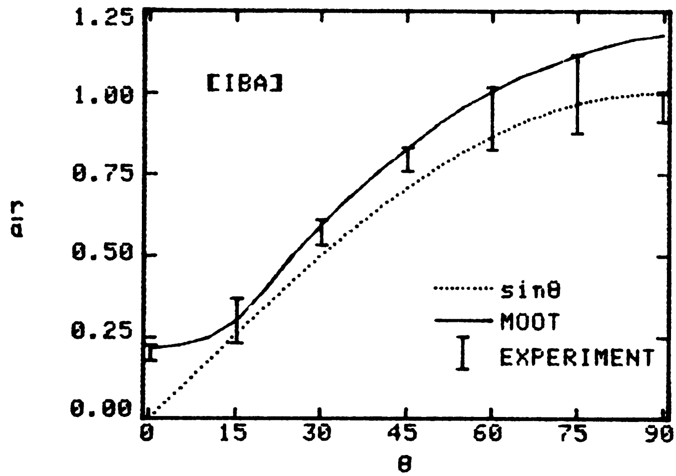

Fig. 3. Sizing results for IBA. Dotted line is r/a=sinθ, solid line is results for theoretical data and vertical bars are ranges of results for experimental data.

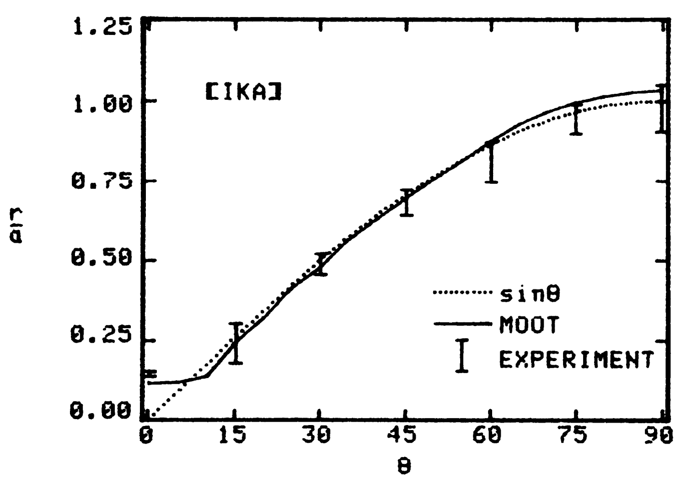

Fig. 4. Sizing results for IKA. Dotted line is r/a=sinθ, solid line is results for theoretical data and vertical bars are ranges of results for experimental data.

Similar results for the IBA and IKA are given in Figs. 3 and 4. Size estimates were obtained from the characteristic functions using the 50% contour as described previously and the zero-of-time determination was made by using the midpoint of the flash-point arrival times. It should be noted that other techniques for estimating the crack radius from the characteristic function can be used - e.g., the area under the characteristic function divided by its peak value. Although that approach gave more accurate sizing results for MOOT data (see, e.g., Fig. 2.4 of Ref. 2) better rsults from the experimental data were obtained using the 50% contour approach, particularly at incident angles greater than 45°.

SUMMARY

Experimental evaluation of the RM did not provide conclusive results. Since this technique has the possibility of providing the true crack radius, it would be highly beneficial for additional investigation to be pursued. In particular, additional theoretical analysis for the cases of non-circular and rough cracks and for T→T scattering should be considered. Further experimental testing against well characterized cracks is also in order. The remaining three techniques considered here gave experimental sizing results of comparable accuracy. Although the FPT proved to be simplest in terms of implementation, the IBA or IKA may prove more useful when the flash-point signals are poorly distinguishable. However, these latter two methods require precise determination of the crack center. Methods for such determination, e.g., the probabilistic approach used by researchers at the Rockwell Science Center (9) should be pursued.

ACKNOWLEDGEMENT

The work was sponsored by the Center for Advanced Nondestructive Evaluation, operated by the Ames Laboratory, USDOE. for the Air Force Wright Aeronautical Laboratories/Materials Laboratory and the Defense Advanced Research Projects Agency under Contract No. W-7405-ENG-82 with Iowa State University.

REFERENCES

1. J. Opsal, private communication.
2. J. H. Rose, T. A. Gray and R. B. Thompson, in, Review of Progress in Quantitative Nondestructive, 2, D. O. Thompson and D. E. Chimenti, eds., Plenum Press, New York (1982).
3. J. D. Achenbach, A. N. Norris, L. Ahlberg and B. R. Tittmann, ibid.
4. J. H. Rose and J. A. Krumhansl, J. Appl. Phys. 50, 2951 (1979).

5. L. Adler and J. D. Achenbach, J. Nond. Eval., 1, 87 (1980).
6. D. K. Hsu, C. Y. She and Y. Li, these proceedings.
7. R. B. Thompson and T. A. Gray, J. Acoust. Soc. Am., 74(4), 1279 (1983).
8. R. B. Thompson and T. A. Gray, these proceedings.
9. K. A. Marsh, J. M. Richardson, R. C. Addison and R. K. Elsley, in, Review of Progress in Quantitative Nondestructive Evaluation 2, D. O. Thompson and D. E. Chimenti, eds., Plenum Press, New York (1982).