Use of Ultrasonic Models in the Design and Validation of New NDE Techniques [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1986 **320**, 329-340
doi: 10.1098/rsta.1986.0122

Phil. Trans. R. Soc. Lond. A **320**, 329–340 (1986)
Printed in Great Britain

Use of ultrasonic models in the design and validation of new NDE techniques

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In implementing fracture mechanics based techniques for the design and life extension of structural components, it is necessary to establish the reliability with which various flaw sizes and types can be detected and characterized. Traditionally, this has been accomplished through extensive experimental demonstration programmes. This paper discusses present efforts to use model predictions to reduce the required amount of experimentation, and hence the cost, of such programmes. Formalisms whereby the extensive elastic-wave theoretical scattering effort of the last decade can be applied to practical problems are first reviewed. This is followed by several specific examples which have occurred in the nuclear and aerospace industries. The paper concludes with the identification of some important remaining theoretical problems and a discussion of possible strategies for future implementation of model calculations as tools in structural integrity programmes.

INTRODUCTION

The need to quantify the reliability of non-destructive evaluation techniques is a major consequence of modern structural life-prediction methodologies. A useful historical perspective, in the context of the nuclear industry, has been provided by Nichols (1980). He notes, with respect to the NDE of welds, that:

> '. . . their main application in the past has been to control the overall level of quality, often on a sampling basis. The role of NDE was rather like that of a policeman on the beat, who, by catching some of the wrongdoers frightens away others. The adoption of fracture mechanics as part of the pressure vessel integrity assessment has led to the use of NDE in a different way; that is, to draw attention to any and every defect which would be sufficiently large to be critical in that structure. This new role of NDE is now like the putting up of a security fence with a security guard to stop any faulty character from getting inside the structure.'

This adoption of fracture mechanics as a life-prediction tool has had important consequences in a number of industries, two of the most visible of which are the nuclear and military aircraft industries. In each, the ability to unambiguously demonstrate the suitability of a structure for additional service life has been shown to have enormous economic benefits. For example, the shutting down of a typical nuclear power plant for unnecessary repairs costs approximately U.S. $500000 per day in replacement power alone (Dau 1980). In the aircraft business, considerable attention has been given to the extension of the lives of both air frames and engines. A programme known as 'retirement for cause' (RFC) is presently under way, to construct a fully automated system for the NDE of engine components in the maintenance depot environment. Successful application of this programme has been projected to save U.S. $250000000 in replacement part costs for the F100 engine (Annis *et al.* 1983).

The realization of these cost savings requires that the NDE systems satisfy certain performance criteria, which are often specified statistically (Fertig 1985). This is often accomplished in a two-stage procedure (Yang & Donath 1983), consisting of a fast, sensitive, search mode followed by a slower, more accurate, evaluation mode, to determine the type of flaw (crack, inclusion, etc.) and its size, shape, and orientation. The search mode is intended to have a high probability of detecting all unacceptable flaws. However, speed may be achieved at the cost of precision, yielding an unacceptably high false rejection rate. To avoid the resulting economic losses, the (ideally) small number of rejected parts are subjected to the more careful evaluation mode to assess the severity of the initial indications. The performance of the sequential implementation of the two techniques can thus maintain the sensitivity to unacceptable defects while reducing the probability of discarding acceptable parts.

Traditionally, one establishes NDE system reliability through an experimental demonstration programme, wherein the performance of the NDE system is measured on a statistically significant number of samples. However, the costs of producing these samples and performing the necessary tests can be great. Thus, a major economic benefit could be realized by using models to predict NDE performance in conjunction with a reduced number of samples and experiments. This paper explores the present status of this approach.

Modelling can be used in three distinct stages in the evolution of an NDE technique (Thompson *et al.* 1984). The most direct is in the verification of the performance of a previously defined NDE system. A second, closely related, application lies in the selection and design of the NDE system to be used in a new inspection problem. Here, performance trade-off studies could be made before committing resources to the construction and evaluation of hardware. The third, and ultimate, use of NDE models is during the design of the structure itself. Presently, fracture mechanics is used as a tool in designing damage-tolerant structures. However, little or no systematic attention is given to the detectability of the specified flaws at the design stage. Therefore, engineering models of flaw detectability, such as will be discussed in this paper, should be developed to the point that they can be used routinely by the designer. This would place NDE and fracture mechanics on an equal footing, as they must be if damage-tolerant and inspectable structures are to be fully realized. Models of manufacturing processes can also be introduced to optimize performance, cost of manufacture and inspectability. Modelling the maintenance process is also conceivable; the retirement for cause programme discussed below is an initial step.

General principles of models

Figure 1 illustrates the elements of a model for the ultrasonic detection of flaws. The model must be built around scattering theories of the ultrasound–flaw interaction, such as those developed over the last decade (Thompson & Thompson 1979). To these, theories for the other physical processes which determine the strengths of flaw signals and noise should be added. Thus models for illumination of the flaw and detection of its scattered signals must include transducer characteristics; relative positions of the probe, part, and flaw; transmission through interfaces; attenuation; and wave propagation effects such as refraction, diffraction and focusing. The scattering itself is a function of the flaw parameters such as size, shape, orientation, surface roughness, branching, and closure. Noise can be determined by a number of physical processes such as scattering from microstructural inhomogeneities in the material, reflection from interfaces or part surfaces, or electronic noise in the receiver.

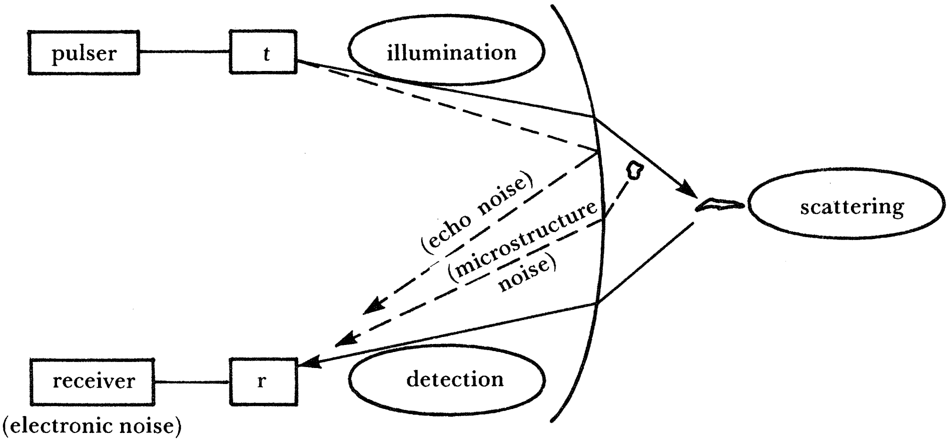

FIGURE 1. Elements of a detection model.

In principle, the formulation of such a model is straightforward. Reciprocity relations (Kino 1978; Auld 1979) allow one to extend the familiar Green function representation of the scattering problem to one that explicitly includes the radiation patterns of the transducers. In the notation of Auld (1979), the flaw-induced change in the electrical reflection coefficient of the transducer (i.e. signal with flaw minus signal without flaw) is given by Achenbach *et al.* (1985):

$$\delta\Gamma = -\frac{i\omega}{4P}\int_A (u_i^{tr}\tau_{ij} - u_i\tau_{ij}^{tr})\, n_j\, dA, \tag{1}$$

where A is the surface of the scatterer, and a time-harmonic variation of the form $\exp(-i\omega t)$ has been assumed. Also, P is the electrical power incident on the transducer; u_i^{tr}, τ_{ij}^{tr} are the displacement and stress fields induced by the transducer in the absence of a flaw; u_i, τ_{ij} are the displacement and stress fields induced by the transducer in the presence of a flaw; and n_j are the components of inward-directed normal to A.

For a crack that is free of surface tractions, we have $\tau_{ij}n_j \equiv 0$, and (1) reduces to

$$\delta\Gamma = \frac{i\omega}{4P}\int_{A^+} \Delta u_i\, \tau_{ij}^{tr}\, n_j\, dA, \tag{2}$$

where A^+ is the illuminated face of the crack, and Δu_i is the crack-opening displacement induced by the transducer field:

$$\Delta u_i = u_i^+ - u_i^-. \tag{3}$$

This result can be readily generalized to two transducer situations.

Equations (1) and (2) provide a framework for combining models of transducer beam fields (u_i^{tr}, τ_{ij}^{tr}) and their interactions with flaws (u_i, τ_{ij}). Direct advantage can then be taken of many of the advances in scattering theory that have occurred in the last decade (Thompson & Thompson 1979).

APPLICATIONS

In practice, the challenge lies in making approximations such that the computations become tractable while retaining sufficient accuracy for the engineering applications not to be compromised. In the last few years, successful formulations for several specific problem areas have been reported.

(*a*) *Pressure-vessel weldments*

Several models have been formulated for application to the problem of the inspection of nuclear pressure-vessel weldments. These applications have required the development of suitable formalisms to allow (2) to be meaningful yet efficiently implemented. For instance, various scattering theories to compute the crack-opening displacement must be used which allow prediction of such physically observed phenomena as tip-diffracted waves. Because of the possibility of relatively large flaws whose sizes could be comparable with or exceed the beam widths, detailed beam patterns must be incorporated into the computation. In addition, procedures must be developed for computing the results of calibration as well as flaw detection experiments so that the levels of the signals with respect to code-mandated thresholds can be predicted.

At the Berkeley Laboratories of the Central Electricity Generating Board (Haines 1981*a*; Haines & Green 1981; Langston 1981), a set of models have been developed based on an approach that is essentially equivalent to combining (2) with the scalar Kirchhoff approximation to scattering (Haines & Langston 1980). Beam patterns were empirically introduced into the models based on the results of calibration experiments. After the successful validation on geometrical reflectors incorporated into small laboratory test blocks, as described in the above references, these models were used in the analysis of manual inspection data, particularly those data developed during a series of round-robin tests (P.I.S.C. 1) evaluating the reliability of the inspection of welded plates following the n.d.e. procedures specified in section XI of the A.S.M.E. Boiler and Pressure Vessel Code (Haines 1981*b*; Haines *et al.* 1982).

The application of the models can be broken down into three steps. The models were first used to establish the strengths of signals independent of human or instrumental errors. Assuming this to define the mean of a distribution of signals that would be observed in practice, the models were then used as a basis for determining the relation between defect detection probability and experimental parameters. It was concluded that four factors had primary importance; ratio of mean defect signal to threshold, number of independent scan lines intersecting the defect, and constants describing interteam and intrateam variabilities in observed defect signals. The last two must be deduced from experimental data and consequently depend on the conditions under which the inspection is performed. Given the resulting functional form for the defect detection probability, prediction of the results of other inspections performed under similar conditions can be made (Haines 1981*b*).

Applications of scalar Kirchhoff models for flat cracks to experimental data obtained from real defects are limited by the neglect of the effects of surface roughness and mode conversions losses (Langston & Wilson 1984), which in unfavourable situations can produce errors of the order of 20 dB. The effects of mode conversion can be introduced through the use of elastodynamic theories, as has been done by Chapman (1982, 1984) and Chapman & Coffey (1982). Their models are formally based on (2) and use the elastodynamic Kirchhoff scattering theory (Adler & Achenbach 1980) for near-specular directions, or the geometrical theory of diffraction (Achenbach *et al.* 1982) for non-specular directions. The use of the diffraction theory offers an improved description of the amplitudes of the signals diffracted from the crack edges. The transducer radiation patterns used in these elastodynamic models were obtained from theoretical predictions. Figure 2 presents the results of an experimental validation of the Kirchhoff version of the model. Here the experimental C-scan response from a geometrical reflector is compared with the model predictions, with excellent agreement.

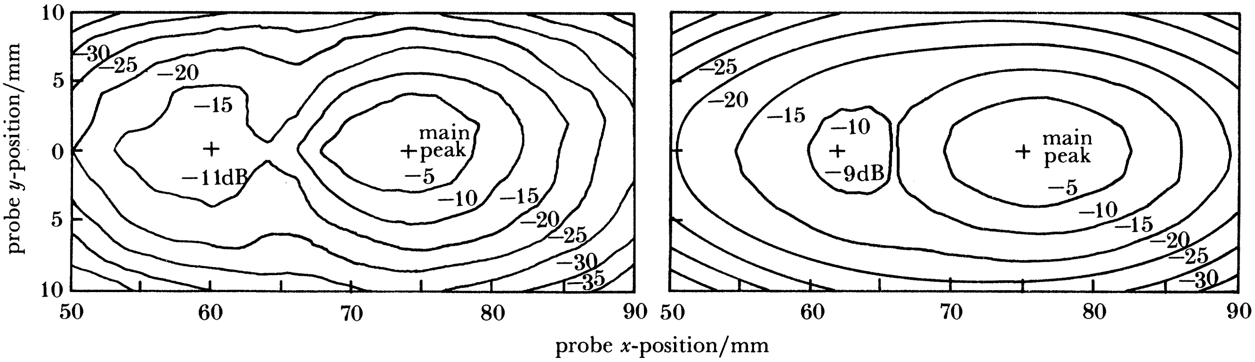

FIGURE 2. (*a*) Experimental and (*b*) theoretical C-scan plots of the response of a 55°, $2\frac{1}{2}$ MHz pulse–echo shear-wave probe to a 10 mm diameter flat-bottomed hole at a depth of 46 mm and tilted at 30° to the vertical (Coffey & Chapman 1983).

The formal model deals only with smooth cracks. The effects of crack roughness, beam propagation through austenitic cladding, and variable coupling are introduced through estimated corrections. The resulting capability has then been used to predict the results of ultrasonic defect detection in the proposed Sizewell B pressurized water reactor (Coffey *et al.* 1982; Coffey & Chapman 1983). Particular emphasis is placed on establishing the detectability of a postulated 'worst case' flaw, as distinct from making statistical predictions of reliability.

(*b*) *Intergranular stress corrosion cracking in piping*

As discussed in the introduction, the establishment of a capability for detecting possible flaws, as represented by the search mode, does not guarantee a successful NDE technique because of the possibility of excessive false rejections of good parts. Often a second evaluation mode is required to provide the classification and size information. A model has recently been developed in the United States for the scattering from intergranular stress corrosion cracks (IGSCC), as have developed in the piping of some B.W.R. power plants (Achenbach *et al.* 1985). This has then been used to compare the effectiveness of competing techniques for depth determination.

Figure 3 illustrates the geometry of the calculations. An ultrasonic transducer, mounted on a wedge, is assumed to generate a 45° shear wave propagating through the wall thickness. The resulting waveform illuminates a Y-shaped crack model of an IGSCC, breaking the opposite surface. The computations are again based on (2). A scalar gaussian beam theory, which includes the effects of beam spread (Thompson & Lopes 1984), is used to describe the radiation pattern. The scattering is modelled by the elastodynamic Kirchhoff approximation (Adler & Achenbach 1980). This would be expected to provide an accurate description of the corner reflection at the base of the crack and an approximate description of the tip-diffracted signals (A. Norris, unpublished results; Gray & Thompson 1983). The calculation is performed in two dimensions, with the distance from the probe to the crack treated as an independent variable.

The model has been used to compare the accuracy of two sizing techniques. In the decibell-drop technique, the depth estimate is obtained by first positioning the transducer to obtain the peak amplitude from an IGSCC and then moving the transducer to each side of the crack until the amplitude has been reduced by a nominal amount (−3 dB in the computation). In the pulse-arrival-time method, the difference in arrival times of the signal diffracted from the crack tip

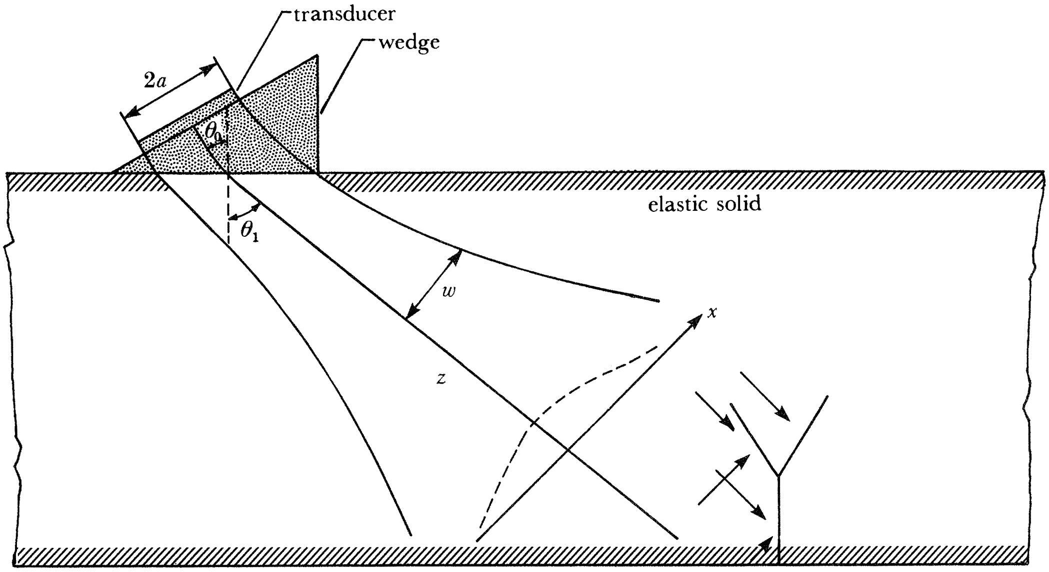

FIGURE 3. Geometry of IGSCC calculation. Variables include probe geometry and frequency, probe position and crack geometry. Illuminating rays are indicated by arrows.

and the corner reflection from the base of the crack are used to make the depth estimate. Figure 4 presents typical results, which show the relative accuracy of the two techniques for a set of model cracks in which the parameters shown in figure 3 were varied. Also shown are experimental results obtained with a variety of probes and samples (Dau & Behravesh 1984). It can be concluded unambiguously for these situations that the pulse-arrival-time technique provides much more accurate sizing results, whereas the decibel-drop response is primarily determined by the beam width.

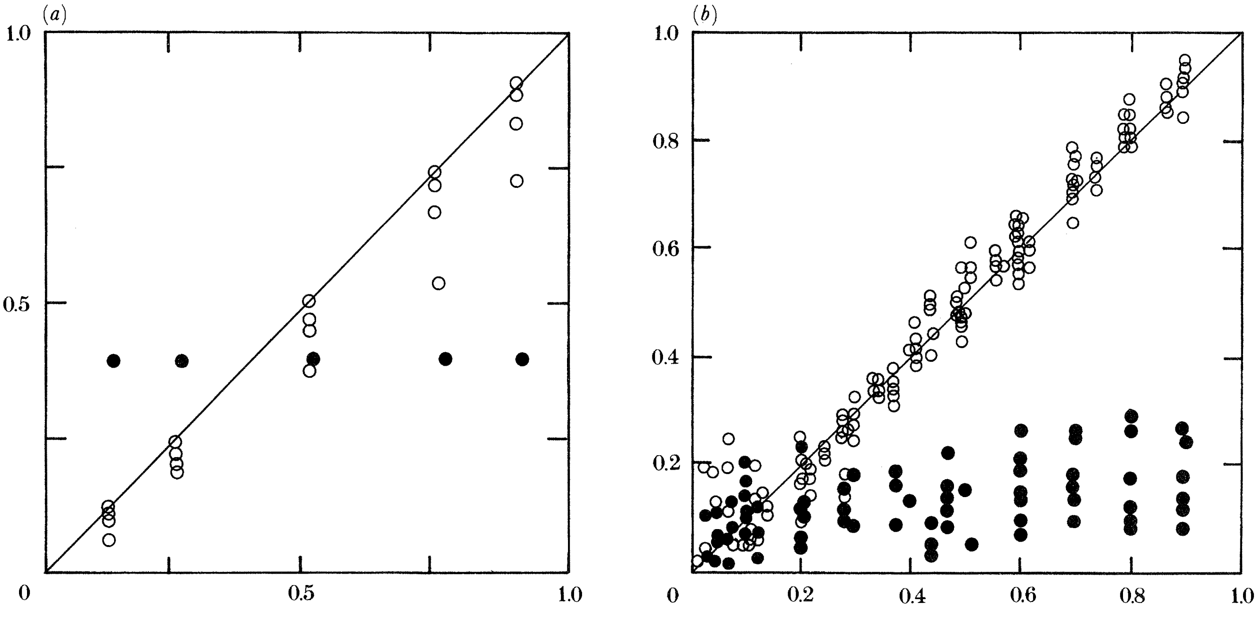

FIGURE 4. Estimated against actual heights for IGSCC sizing. (a) Theory; (b) experiment (Dau & Behravesh 1985). ○, tip diffraction; ●, decibel drop. (1 in = 2.54 cm.)

(*c*) *Aircraft engine components*

In the military aircraft industry of the United States, probabilistic fracture mechanics plays a major role in structural integrity programmes. An important current example is the retirement for cause (RFC) programme (Annis *et al.* 1981). Therein periodic inspection is to be used to extend the lives of individual turbine engine rotor components beyond the initial design goal, based on the statistical behaviour of a set of similar parts undergoing fatigue. An essential step to ensure that the probability of failure in a particular service interval is less than a prescribed value is that the probability of flaw detection (POD) has an acceptably high value for flaws of a critical size and larger. Typically, the POD is evaluated through an experimental demonstration programme. However, the aforementioned high costs of such an approach makes the use of models quite attractive.

Fertig & Richardson (1983) have recently formulated a model for ultrasonic flaw detection in the rotating components of aircraft turbine engines. The geometry of the computation is the same as in figure 1. A penny-shaped crack is assumed to be oriented in a plane near normal to a cylindrical surface, representing the bore of a rotor component. Because fracture critical flaws can have dimensions of 1 mm or less, the flaw size is taken to be small with respect to the beam dimension. For flaws on the beam axis, a measurement model (Thompson & Gray 1983*b*) based on (2) was used to combine analytical expressions for the axial fields of refracted beams (Thompson & Gray 1983*a*) and the elastodynamic Kirchhoff approximation (Adler & Achenbach 1980) to predict absolute signal amplitudes. Variability in the flaw signal was introduced by assuming that the flaws were randomly oriented with a mean orientation in the radial direction. Noise signals due to gas porosity were introduced through a second, additive model. The pores were assumed to be randomly positioned throughout the beam, whose variation in cross section was approximated by a gaussian. Scattering from the pores was based on the solution of Ying & Truell (1956). Predictions of the POD were based on a Monte Carlo comparison of the signal level to threshold. A major emphasis of this work was the search for signal processing algorithms to improve crack detectability. Figure 5 compares the predicted POD for detection of the video signal with that which would occur when the data was processed by a statistically based 'detection filter', designed to improve signal to noise through the suppression of high-frequency noise (Fertig *et al.* 1984). In each, the threshold was set so that noise-only waveforms would produce a false alarm rate of probability less than 0.01. The improved performance of the 'detection filter', designed with the aid of the p.o.d. model, was confirmed experimentally (Elsley *et al.* 1984, 1985). Extension to simultaneous processing of data obtained on multiple scans has also been considered (Fertig *et al.* 1985).

Gray *et al.* (1986) have reexamined the POD modelling problem from the perspective of predicting the performance of an automated, scanned ultrasonic system such as will be used in the RFC programme. Variabilities in the flaw signal are considered to be caused by two degrees of misorientation freedom (tilt and skew), two degrees of translational freedom with respect to the beam axis, as well as additive noise. The beam profiles needed for off-axis flaws are described by a scalar gaussian model (Thompson & Lopes 1984) and the elastodynamic Kirchhoff equation is used to describe the scattering. Experimental confirmation has been obtained for both the gaussian approximation to the beam profile in appropriate régimes such as the far-field or near-focal points (Gray *et al.* 1985; Newberry *et al.* 1986), as well as for the ability of the measurement model to predict absolute signal levels (Thompson & Gray 1983*b*; Gray & Thompson 1984; Thompson & Gray 1984; Gray *et al.* 1985).

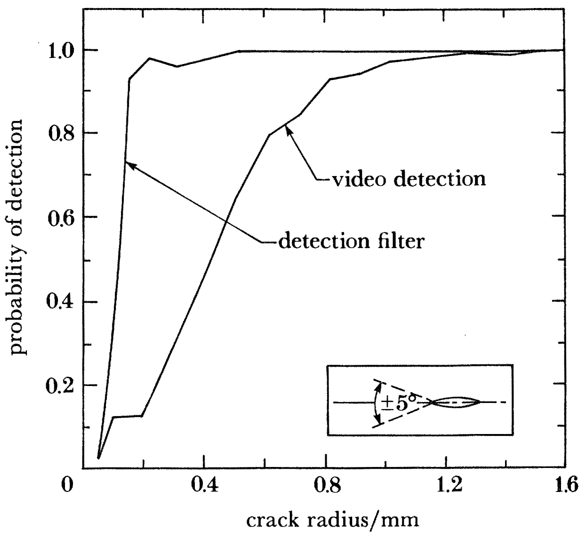

FIGURE 5. Probability of detection of radially oriented circular cracks in IN100 (Fertig *et al.* 1984).

The philosophy of the POD calculations has been to develop a simple, flexible model that can be applied to a wide range of situations in a survey sense. When conditions dictate, slower, more accurate approaches could be used. Fast computation of the POD is achieved by replacing the previous Monte Carlo calculation by a series of analytical approximations. In essence, the dependence of the signal upon the random variables is fitted to simple functional forms. Assuming a uniform distribution of the orientation and scan variables and a gaussian distribution of noise, the POD is determined by finding the fraction of state space in which the video signal exceeds a selected threshold. By using a VAX 11/780 computer, computations costs are one U.S. dollar per POD point at local rates.

Figure 6 presents the results of a preliminary experimental test of the POD model. Here a focused, 45° refracted longitudinal wave probe has been used to detect simulated circular cracks in IN100 through a planar surface. The simulated cracks were thin cylindrical cavities embedded in the interior of the sample by diffusion bonding. Theory and experiment are compared for four different scan increments in one dimension (with continuous scanning in the second dimension). With one adjustable parameter needed to correct a 3 dB absolute signal amplitude error in the present formulation of the measurement model for this parameter régime, general agreement is observed, with both plots showing the improvements in POD performance that would be expected as scan increment is decreased.

Figure 7 illustrates the use of the model to evaluate and improve a hypothetically proposed, 45° refracted shear-wave inspection. By using a 1.27 cm (0.5 in) diameter, 10 MHz probe, a scan plan of a cylindrical bore of 7.6 cm (3 in) radius was postulated, having increments of 0.254 cm (0.1 in) in both axial and circumferential directions. The flaw tilt and skew were each assumed to vary between ±10°. By using a threshold corresponding to 50% of a 0.16 cm diameter, radially oriented crack response, POD curves at three flaw depths were computed, as shown in figure 7*a*. At the depths of 1.27 cm (0.5 in) and 3.81 cm (1.5 in), very similar POD values are predicted. Near the focal plane at a depth of 2.54 cm (1.0 in), the POD is found to be considerably lower, although the axial beam intensity is greatest at this depth. However,

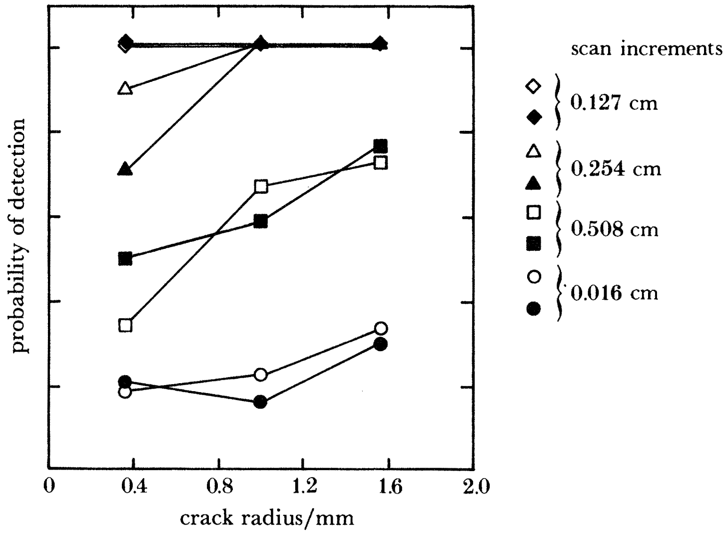

FIGURE 6. Comparison of experimental and model POD for x–y scan of a simulated circular crack in IN100 below a planar surface. Open symbols show theoretical and filled symbols show experimental results.

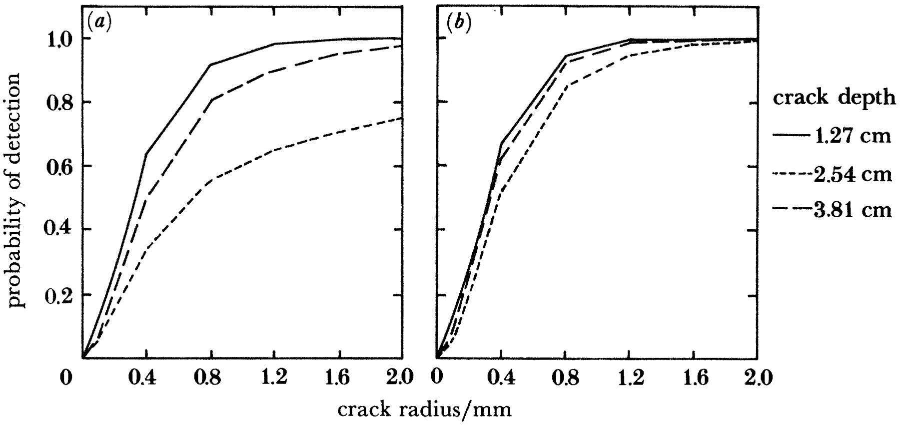

FIGURE 7. Predicted influence of scan plan on POD (*a*) POD at three depths for axial and circumferential scan increments of 0.254 cm; (*b*) POD at three depths for axial and circumferential scan increments of 0.508 and 0.127 cm, respectively.

the focusing in the circumferential direction caused by propagation through the curved interface reduces the beam width to approximately 0.173 cm (0.07 in) at this point. Hence, in the postulated 0.254 cm (0.1 in) scan increment, there is a significant probability that the flaw would fall in a weak portion of the beam. Figure 7*b* shows how these results could be improved by increasing the axial scan increment to 0.508 cm (0.2 in) and decreasing the circumferential scan to 0.127 cm (0.05 in). Hence, use of the model in setting up the scan plan would allow an improved inspection to be achieved with no loss in inspection time.

(*d*) *Future directions*

The directions for future work can be divided into two major categories: model refinement and model implementation. The present models provide good descriptions of the experimental signals observed from smooth reflectors in simple geometries. However, real flaws may have complex structures and surrounding geometries. Early theoretical work has dealt with the effects of surface roughness (DeBilly *et al.* 1980; Roberts *et al.* 1981), contacting asperities (Achenbach & Norris 1982; Buck *et al.* 1985; Punjani & Bond 1986), and beam aberrations owing to refraction of focused beams (Frohly *et al.* 1983; Thompson & Lopes 1986). Further work in these areas is required.

However, application of the models should not be delayed until these factors are fully described theoretically. Such a strategy would guarantee that the benefits of the modelling approach would never be realized. Instead, the available results for simple cases should be used in an appropriate manner. A useful analogy can be made to fracture mechanics. The stress intensity factor of a penny-shaped interior crack or half-penny surface-breaking crack is the starting point of many calculations. Refinements for geometrical stress modifications, crack closure, and environmental effects are then added as dictated by experience.

Such a philosophy has been adopted by several groups concerned with NDE modelling. Thompson *et al.* (1984) have proposed that models can be calibrated on a limited set of measurements and then used to evaluate the effects of other factors, such as crack orientation or ellipticity, on inspection reliability. Coffey & Chapman (1983) added correction factors to the ideal theory to account for the effects of crack roughness and propagation through clad surfaces. As part of a corporate reliability programme, Sturges *et al.* (1986) have described a data base defining the effective reflectivity of naturally occurring flaws in engine materials with respect to that of flat bottom holes. Hybrid models of various forms, in which some of the parameters are experimentally derived, will probably play an important role in future applications.

As noted in the introduction, NDE models should find three distinct applications; the evaluation of existing NDE systems, the design of improved NDE systems, and the design of structural and machinery components themselves. This latter, most powerful goal, could be realized through an extension of computer-aided design capabilities (Gray & Thompson 1985). Consider the design of a complex-shaped part such as a turbine rotor component. This will, in general, have a variety of ultrasonic entry surfaces, ranging from planar to bicylindrical. The POD which can be obtained after beam entry at each of these points will be strongly

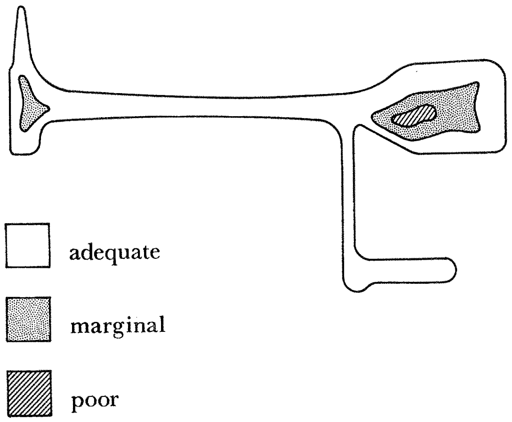

FIGURE 8. Conceptual use of POD modelling in design, showing hypothetical variation of inspection adequacy as could be predicted by model.

influenced by degree of curvature. At each point on the part surface, the POD as a function of flaw depth could be computed by using techniques such as those in this paper. By comparing the results with the variation of critical flaw size with depth, the adequacy of the inspection in various regions of the part could be determined, with results displayed in the form of a contour map, such as the conceptual example in figure 8. It is believed that such a methodology would contribute significantly to the reduction of the classical problem of parts which are uninspectable because of neglect of NDE in the design process.

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Discussion

A. Rogerson (*U.K.A.E.A., Risley*). Dr Thompson's model describes the physics of the interaction of ultrasound with a flaw and the physics of the inspection system and how it is used to develop inspection procedures. Does he think that, to get meaningful values of POD, he should attempt to include factors governing the equipment reliability and ergonomic aspects of an inspection?

R. B. Thompson. I fully agree that these influences on total performance must be included if meaningful estimates of PODs are to be obtained. We have not considered ergonomic aspects because our work has been motivated by problems encountered in fully automatic inspections. Assuming that the automation has been properly done, the human influences should be minimized. Of course, for manual inspections, the human influences are much greater and must be explicitly included (Haines 1981; Haines *et al.* 1982).

Equipment reliability, on the other hand, must be considered in all situations. In actual application to an existing system, we have advocated a hybrid approach (Thompson *et al.* 1984). Experiments should be performed on a few samples to determine the equipment reliability, for example, its ability to reproduce a given signal level. This information should be augmented by model simulations of the responses to other variables, such as flaw orientation, scan plan, etc. as discussed in this paper, to get a complete estimate of the overall POD. In the design mode, when a physical system is not available for measurement, estimates of equipment reliability should be included.