USE OF MODELS TO PREDICT ULTRASONIC NDE RELIABILITY

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INTRODUCTION

The need to quantify and predict the probability of detection (POD) of defects by ultrasonic nondestructive evaluation (NDE) techniques is driven by the growing importance of damage tolerant design and maintenance philosophies. Experimental demonstration programs, while costly, are useful in assessing NDE system reliability for existent inspection hardware and for "typical" test specimens. However, such an approach is not effective for prediction of optimal inspection protocols nor for improving the inspectability of components at the design stage. There is, thus, a need for computationally efficient analytical models for such applications.

This paper describes the current status of the development of models to predict the POD of small cracks as might be performed by an automated ultrasonic inspection of a jet engine turbine disk. There are three goals to this modeling work, as are illustrated in Fig. 1. First, the reliability (POD) of a specified inspection of a given component can be predicted. Second, the ability to quantify the POD for different inspection configurations can allow optimization of the inspection reliability with respect to such inspection parameters as probe frequency and focal length, and scan plan. Finally, models can be used to guide the actual design of components themselves to guard against uninspectability.

POD MODEL

The formulation of the POD model derives from the electromechanical reciprocity integral of Auld [1]. The resulting measurement model provides an absolute, but approximate, relationship between a measured ultrasonic signal from a defect and the far-field scattering amplitude of that scatterer [2]. For the work discussed here, the ultrasonic beam patterns are modeled by a Gaussian approximation to piston-source radiation which incorporates the effects of transmission through a liquid-solid interface possessing two independent principal radii of curvature [3,4,5]. The elastodynamic Kirchhoff approximation [6] is used to model the scattering from circular cracks which are assumed to be small with respect to the ultrasonic beam width. In this form, the measurement model is expected to be most accurate at predicting the backscattered signals from cracks which are nearly normal to the beam axis and well into the far field of...
the beam, such as near a focal point [3]. Currently under development is a model for ultrasonic scattering and attenuation due to grains, which is an extension of the results of Goebbels [7].

To attack the problem of ultrasonic NDE detection reliability, the approach of the radar community to video (envelope) detection, namely, the use of so-called Rician statistics [8], was chosen. Although this method is strictly valid only for narrow band analysis, it does provide a first order approach to detectability for broadband analyses. If a RMS noise power $N$ is assumed, the probability $p$ that a video signal $E$ will exceed a threshold $E^*$ is approximated by [8]

$$p = \int_{E^*}^{\infty} \frac{r}{N} e^{-\frac{r}{N}} \left( \frac{E}{N} \right)^2 / 2 i_0 \left( \frac{rE}{N^2} \right) d \frac{r}{N}$$

where $i_0(z) = \exp(-z) I_0(z)$ with $I_0(z)$ the modified Bessel function of the first kind, order zero.

For application to scanned ultrasonic systems, it has been assumed that the signal amplitude $E$ in Eq. 2, for a given crack at a certain depth, is a function of four random variables: the tilt ($\theta$) and skew ($\phi$) angles of the crack and two lateral degrees of misalignment freedom $(x, y)$ with respect to the beam axis. These random variables are further assumed to be uniformly distributed. The POD for the given crack size and depth is then
where \( p = p(x,y,\theta, \phi) \) is given by Eq. 2 and the terms in the denominator represent the assumed ranges of the random variables.

In this form, the large number of evaluations of the measurement model required to numerically integrate Eq. 3 would prohibit its use. Therefore, an approximate closed form function was fit to the measurement model. This function \( E' \) was chosen to be

\[
E' = e^{-(ax+bx^2+cy^2)}(1+d\theta+e\theta^2)(f+g\phi+h\phi^2)
\]

where \( a, b, c, d, e, f, g, h \) are parameters which can be varied so that \( E' \) provides a best least-squares fit to \( E \), the video signal computed by the measurement model. In practice, 81 evaluations of the measurement model, corresponding to all combinations of three values each for the random variables \( x, y, \theta \) and \( \phi \), were made to produce the fit of \( E' \) to \( E \). For the ranges of the random variables in the studies presented here (e.g., \( \pm 10^\circ \) for \( \theta \) and \( \phi \); \( x \) and \( y \) within scan grid) agreement between Eq. 4 and the measurement model is essentially exact. Finally, computation of \( p \) in Eq. 2 is rendered more efficient by rewriting Eq. 2 in terms of a proper integral,

\[
p = 1 - \int_0^1 \frac{E^*/N}{E^*/N} e^{-(r/N - E^*/N)^2/2} \frac{r}{N^2} \frac{E}{N} d(r/N) \]

Note that the integral in Eq. 5 can be expressed in terms of the dimensionless terms \( E^*/N \) and \( E/N \) so that computation of a POD point can be speeded considerably by using look-up tables for specified threshold-to-noise ratios \( (E^*/N) \). Using this approach, one POD point can be computed in approximately 2 minutes of CPU time on a VAX 11/780, which translates to a cost of one dollar at local rates.

To test this model, experiments were performed using a focussed (4 inch focal length) probe and 45° refracted longitudinal waves to detect simulated circular cracks in a diffusion-bonded IN100 specimen [9]. The simulated cracks were thin cylindrical cavities parallel to the sample surface. Scans were performed with four different scan increments in one direction and continuous scanning in the perpendicular direction. For each simulated defect and for each scan increment, twenty scans were performed with random starting positions. The detection threshold was chosen to be 50% of the peak amplitude of the smallest crack. Although model predicted signal amplitudes were 3dB lower than experimental values, (which is believed to be due to the crack lying beyond the beam's focal point (see Ref. 9)), the model predicted POD's are quite close to those measured experimentally, as is shown in Fig. 2. Note that for the smallest scan increment, \( \Delta x=0.05 \) inch, results are not shown in Fig. 2 since both model and experiment gave a POD of unity for the three crack sizes.
COMPUTATIONAL RESULTS

As indicated in the introduction, three uses of modeling are envisioned for ultrasonic NDE reliability: system performance assessment, inspection optimization, and enhancement of component design. As an example of the first use, consider a proposed inspection of a component with an 8.89 cm (3 1/2 inch) cylindrical curvature using 45° SV waves. Figure 3 shows the configuration. Assume that the defects of interest are circular cracks, nominally oriented perpendicular to the interface with a possible ±10° variability in tilt and skew angles. Further, assume that the inspection is to be performed in a raster-type scan with 0.254 cm (0.1 inch) spacing between grid points in both the axial and circumferential directions.

Detection threshold values for these simulations were determined by first computing the signal amplitude from a radially oriented, 0.08 cm radius (.063 inch diam.) crack as a function of its depth below the surface (configuration shown in Fig. 3). The solid curve in Fig. 4 shows the results of model computations of this amplitude vs. distance relationship. The dashed line, which is 50% of the solid line, was chosen as the detection threshold. (Note that the peak amplitude at a depth of roughly 2.5 cm is due to focusing effects of the cylindrical interface).

Figure 5 shows the results of model computation of the POD as a function of crack size for three different crack depths, 1.27, 2.54 and 3.81 cm (0.5, 1.0 and 1.5 inches). A somewhat unintuitive result is that the poorest overall reliability occurs for cracks located 2.54 cm below the surface which is where the illuminating beam intensity is the greatest.

Fig. 2. Comparison of experimental and model-predicted POD for 2-D scans of simulated circular cracks below a planar surface.
Fig. 3. Geometry used for POD simulations.

Fig. 4. Simulated signal amplitude as a function of depth for a radially oriented, .08cm diameter circular crack below a cylindrical surface. (Dashed line is 50% of solid line).
due to focussing (cf. Fig. 4). At this depth the beam width is computed to be approximately 0.17cm (0.07 inch) which is narrower than the postulated 0.254cm (0.10 inch) scan mesh. Therefore, there is a significant probability that the defect will lie in a low-amplitude lateral position of the beam and thus escape detection.

To apply modeling to inspection reliability optimization, we can attempt to improve the preceding scenario. For example, to counterbalance the focussing effects, the in-plane scan mesh can be reduced to 0.127cm (0.05 inch). To retain the same scan rate, the out-of-plane mesh can be increased to 0.508cm (0.2 inch). Results for this case are shown in Fig. 6. Indeed, the reliability of detection at the 2.54cm depth has improved greatly with no reduction of POD at other depths.

Finally, we turn our attention to utilization of the POD model to alter component design. For example, consider the case of inspection for cracks below a bicylindrical fillet, such as might be found on a diffusion bonded IN100 turbine blade-to-turbine disk junction. For this hypothetical inspection, we assume a nominal fillet radius of 0.635cm (0.25 inch) and disk radius of 25.4cm (10.0 inches). Inspection is to be performed with a 0.318cm (0.125 inch) radius focussed (1.27cm (0.5 inch) focal length) probe using 45° SV mode illumination. The probe is positioned with its focal point on the component and the scan plan is to be 0.025cm (0.01 inch) in both in-plane and out-of-plane directions. For this example, an 0.08cm radius (.063 inch diam.) circular crack located 0.635cm (0.25 inch) below the surface was assumed with a nominal orientation perpendicular to the fillet with ±10° of possible tilt and skew misorientation. Figure 7 shows simulated POD for such cracks as a function of fillet

Fig. 5. Simulated POD curves for circular cracks at three depths below a cylindrical surface. Scan mesh: \( \Delta x = \Delta y = 0.254 \text{ cm} \) (0.10 inch).
Fig. 6. Simulated POD curves for circular cracks at three depths below a cylindrical surface. Scan mesh: $\Delta x = 0.127 \text{cm} \ (0.05 \text{ inch}), \ \Delta y = 0.508 \text{cm} \ (0.20 \text{ inch})$.

Fig. 7. Simulated POD for a 0.08cm diameter circular crack below a bi-cylindrical fillet, as a function of fillet radius of curvature.
radius of curvature. As can be seen, a significant variation in detection reliability is observed for rather modest changes of design parameters. Although other factors should also be considered in such a design application, this illustration does show that model-based reliability prediction can play a role in the design process.

SUMMARY

This paper has presented a model-based approach to ultrasonic NDE reliability assessment and illustrates its potential for impact upon NDE system performance prediction, inspection optimization and component design. Several areas of additional work should be addressed. First, implementation of more accurate ultrasonic beam models, such as Gauss-Hermite expansions of the ultrasonic fields [5, 10], and scattering theories, such as the method of optimal truncation [11], should be considered where practical. Second, development of a predictive model for noise and attenuation due to microstructure of the host medium must be completed. Third, techniques to allow more realistic probability distribution functions for the random variables should be explored. Finally, and most importantly, additional experimental trials are required.

ACKNOWLEDGEMENT

This 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 under Contract No. W-7405-ENG-82 with Iowa State University.

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