INTRODUCTION

The push for higher reliability of structures requires that components be adequately inspected for critical flaws. In this computer age, however, it is becoming ever easier to design and develop high performance components with little regard for their inspectability. Time worn inspection "rules of thumb" often are just not good enough to assure the inspectability of a structure which embodies a combination of new geometries and new materials. What is needed is an on-line, analytical tool for the designer which provides quantitative assessment of inspectability levels and predicts the sensitivity of inspectability measures to NDE (nondestructive evaluation) system and component design parameters.

In this paper, one approach to such a methodology for ultrasonic inspection will be described. This "tool" is an approximate, analytical model which simulates the probability of detection (POD) of small flaws in isotropic, elastic media for scanned ultrasonic pulse-echo measurements [1,2,3]. The model realistically treats the radiation from typical rigid piston-type ultrasonic transducers and propagation through curved fluid-solid interfaces [4,5]. Both crack-like and volumetric flaws can be modeled [6,7]. A "proof of principle" illustrative test application of this ultrasonic POD model in conjunction with a commercially available, full-featured computer-aided-design (CAD) package [8] has been performed and will be reported here. Implementation of computer models for other NDE techniques, such as x-ray radiography [9] and eddy current inspection [10] is also in progress and similar CAD/NDE applications for these methods are being developed.

CAD/NDE INTEGRATION CONCEPT

The integration of CAD and NDE elements is intended to provide design-level solutions to a number of possible problems related to the inspectability and ultimate reliability of components and structures. The most basic of these problems is the uninspectable component. In some cases, the combination of design parameters, such as component geometry or material properties, and inspection methodology lead to the inability to reliably detect critical flaws in a component. If this situation is not identified until after the component is in production or operation, the only solutions may be to reduce the performance specifications of the component so that those flaws which are detectable define the safety envelope, or to scrap the components and pursue a redesign to alleviate the inspectability limitation. These cures are expensive. A better solution is to identify the inspectability problem during the design stage when modifications can be effected easily and relatively cheaply. This solution requires that quantitative estimates of inspectability and its dependence upon design and inspection system variables be on hand at the designer's workstation, in much the same manner that stress analysis tools (e.g., finite element methods) are available.
CAD/NDE integration can also provide an important part of the answer to the problem of optimizing the life-cycle costs of a component. In this arena, the adequacy of inspection of the original component is only part of the picture. At the component manufacture stage, an ultrasonic inspection may be performed upon a "near-net shape" forging whose geometry has been defined in such a way that flaws in critical regions of the final part can be easily detected. For example, the near-net shape may be marginally thicker than the final shape, to allow detection of flaws which would ultimately reside on the part's surface, and may have fairly gradual surface curvature. However, when such a component is reinspected during maintenance operations, these allowances no longer exist. Another factor which impacts the overall cost picture is the relationship between detectability levels and false rejects. That is, in general, increases in detection sensitivity generally lead to increases in the number of good parts that are rejected. There are also tradeoffs between the sensitivity of an inspection and the time required to perform it or the cost of the inspection equipment. Optimization of the life-cycle costs of a component must consider quantitative assessments of a number of such inspection-related details. Such analysis would be most easily performed if the inspectability parameters were considered as part of the design process.

APPROACH

The main objective in the development of the CAD/NDE interface is to generate an inspectability assessment tool for use by the designer to augment currently available design capabilities. This tool, therefore, must be quantitative and must interact with the existing CAD-package structure, including the design database and the analysis and visualization features. In the approach taken here, inspectability prediction is performed by an analytical model of ultrasonic measurements, which will be described in the next section, that estimates the POD for small flaws in isotropic, elastic components of complex shape. Design parameters, such as component geometry and material properties, are explicit inputs to the model. These design parameters are obtained from the CAD design model, which exists either as a wireframe or solid model. Another feature needed in the integration is the capability for generating spatial points within a component at which inspectability analyses will be performed. A convenient method for doing this is to utilize the finite element mesh generation capability common to many CAD packages. A finite element mesh is created within the component. The nodes of the elements are spatial points which lie within the component and whose coordinates in space are part of the finite element mesh database. These are the points at which POD values are to be calculated. These POD values are then passed back into the finite element model as scalar data at the nodes. (This would be the format for a temperature distribution calculation, e.g., in a more typical finite element analysis.) The CAD package's post-processing utilities can then be used to display the POD results to the designer in a familiar presentation format.

ULTRASONIC INSPECTABILITY MODEL

The ultrasonic inspectability model is a computer simulation of ultrasonic pulse-echo measurements. The measurement model is based upon the electromechanical reciprocity integral of B. Auld [1]. This integral is exact but evaluation even for fairly simple cases is computationally intense. However, if it is assumed that flaws are small, so that the illuminating ultrasonic fields are effectively planar (quasi-plane wave approximation), and that the scattering amplitude of a flaw is slowly varying over the range of scattered directions which impinge upon the transducer, then the reciprocity relationship can be significantly simplified [2]. Specifically, the ultrasonic beam and scattering effects can be separated. The resulting model is shown in Eq. 1:

$$\Delta \Gamma_P = \beta \left[ T_a C_a P_a \right] \left[ T_b C_b P_b \right] \frac{2 A \rho_1 v_b}{j k_0 \sigma^2 \rho_0 v_0}$$

(1)

where subscripts "a" refer to fields in the vicinity of the flaw assuming that the flaw is present, subscripts "b" are the fields in the vicinity of the flaw assuming that the flaw is absent. For pulse-echo measurements, these "a" and "b" solutions are identical. The
subscripts "0" and "1" refer to the fluid (couplant) and solid (component) media, respectively. The other terms in Eq. 1 are:

\[
\delta \Gamma_f = \text{simulated flaw spectrum}, \quad 
\beta = \text{ultrasonic system response (efficiency factor)}, \quad 
T = \text{plane wave (Fresnel) interface transmission coefficient}, \quad 
C = \text{amplitude of transducer radiation pattern relative to a plane wave}, \quad 
P = \text{propagation phase and attenuation term}, \quad 
A = \text{far-field scattering amplitude}, \quad 
\rho = \text{density}, \quad 
v = \text{acoustic velocity}, \quad 
k = \text{wave number}, \quad 
\sigma = \text{transducer radius}.
\]

In order to use Eq. 1 to simulate an actual ultrasonic measurement, the factors $\beta$, $T$, $C$, $P$, and $A$ must be determined. (The density, $\rho$, and velocity, $v$, terms are standard material properties.) The efficiency factor, $\beta$, is typically determined from a calibration experiment. Ref. [2] describes such a calibration method which has proven to work well in practice for planar (unfocused) piston probes. For focused transducers, other methods for model calibration must sometimes be employed [11]. The interface transmission term, $T$, is computed as the standard Fresnel plane-wave coefficient for velocity or displacement transmission through a planar fluid-solid interface. The factor $C$ is derived from a model for ultrasonic field generation by piston probes and propagation through liquid-solid interfaces. This term also implements the modifications to the ultrasonic radiation pattern, such as focusing or defocusing, caused by the local curvature of the component's surface. In the current implementation of the model, this beam model is based upon a Gaussian-Hermite eigenfunction expansion of the fields in conjunction with a paraxial interface transmission relationship [4,5]. This beam model accurately predicts the radiation of piston probes (planar or focused) and transmission through curved interfaces for incident angles sufficiently away from critical angles. In this beam model, the probe is characterized by its radius and geometric focal length, and the surface is defined by two principal radii of curvature at the intersection of the probe's central ray with the interface. The propagation factor, $P$, contains both the linear phase variation due to wave propagation and ultrasonic attenuation. The form of this term is

\[
P = e^{-2j(k\sigma_0 + kz) - 2(\alpha_1 + \alpha_2 z)}
\]

where $\alpha$ is ultrasonic attenuation (e.g., nepers/cm), $k$ is wavenumber, and $z$ refers to distance measured along the central ray of the ultrasonic beam. The scattering amplitude, $A$, in Eq. 1 is approximated by elastodynamic Kirchhoff approximations both for cracks [6] and for volumetric flaws [7]. It is well known that these approximations have fairly restrictive regions of validity -- i.e., near specular scattering for cracks and "early" time scattering (e.g., front surface reflection) for volumetric flaws. However, they are quite useful in these regions and the resulting computational schemes are quite efficient. There are, of course, other more accurate, and time consuming, means for scattering amplitude determination, but these will not be addressed here. Finally, a measured RF waveform can be simulated by an inverse fast Fourier transform of Eq. 1.

The ultrasonic response obtained from a given type of flaw will typically exhibit significant variability due to such factors as the flaw's orientation relative to the component surface, its position with respect to scan lines, irregular surface features of the flaw, scattering noise from the component's microstructure, etc. Therefore, detectability is most appropriately described from a probabilistic standpoint, e.g., through the use of probability of detection (POD) analysis. In ultrasonics, the typical detection criterion is based upon the magnitude (e.g., video signal) of signal plus noise compared to a predetermined detection threshold. One approach to modeling POD for this type of measurement is based upon analysis typical of detection of radar signals using the so-called Rician probability distribution [12]. This approach predicts the probability, $p(S,N,t)$, that the magnitude of a given (rectified) signal, $S$, in the presence of noise with an RMS level $N$, will exceed a threshold amplitude, $t$. This probability is given by
\[
p(S,N,t) = \frac{r}{N} \exp \left[ -\frac{(r - S)^2}{2N^2} \right] i_0 \left( \frac{rS}{N^2} \right) \frac{dr}{N}
\]

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

Eq. 3 provides a detection probability estimate for a single signal amplitude, \( S \). However, a given size and type of flaw can generate a variety of different measured responses, due to random variability of the flaw's position and/or orientation. If the orientation and position of a given size and type of defect are described formally by the variables \( \Theta \) and \( X \), respectively, both of which are assumed to be 3D vectors (i.e., \( \Theta = (\theta, \phi, \psi) \) and \( X = (x, y, z) \)). The components of \( \Theta \) and \( X \) are assumed to be random variables. The probability that the signal from all flaws of the given size and type is given by

\[
POD = \int_X \int_{\Theta} p(S(X,\Theta),N,t) \, d\Theta \, dX
\]

where \( S(X,\Theta) \) is the signal amplitude for the specified flaw state, \( p(S,N,t) \) is given by Eq. 3, and the integration is over the probability distribution functions for orientation and positional variability of the flaw. In practice, the measurement model, Eq. 1, is used to calculate \( S(X,\Theta) \) for a relatively small number of position and orientation values and that resulting set of amplitudes is best fit in a least-squares manner to a simple quadratic function of the components of \( \Theta \) and \( X \). This allows the integration in Eq. 4 to be performed more quickly than if the full measurement model were used to evaluate \( S(X,\Theta) \) at each point in a numerical integration mesh used to evaluate the equation. It should be noted that \( S(X,\Theta) \) is implicitly a function of many variables other than the orientation and position of a flaw, as can be seen in Eq. 1 and its subsequent discussion. The ultrasonic signal measured from a flaw is a function of scan plan and component geometry parameters, and hence, so is POD.

EXAMPLE

In this section, an example of the CAD/NDE technique will be presented. The component to be considered is illustrated in Fig. 1, which is a rendition of a wireframe display of an axially symmetric "disk". (Throughout this section, the figures will be artist's renditions of actual hardcopy output from a CAD package. The CAD package used was SDRC I-DEAS [8].) One area of possible inspectability problems would be below the fillet region indicated in the figure, e.g., if the radius of curvature of the fillet is too small. Fig. 2 shows a cross-section view of the disk with a finite element grid superimposed upon it. This grid consists of a number of elements, or sub-areas of the cross-section, and corresponding nodes, which are the vertices of the elements. (In this example, the elements selected in the mesh generation procedure of I-DEAS were axially symmetric, solid, linear quadrilateral elements. Each element would actually be an annulus whose cross-section is seen in Fig. 2.) In this example, a relatively coarse mesh was selected for simplicity. The coordinates of each of the nodes in the cross-section were obtained from the finite element model and surface curvature values were derived from the solid model. These data were used as input to the POD model for subsequent inspectability analysis. Following the inspectability analysis, POD values were entered into the finite element model as nodal data values and the post-processing features of I-DEAS were used to display the results.

In Fig. 3, the result of a combination of "nominal" scan plan and component design parameters is seen. It was assumed that component was scanned on a turntable using a 10 MHz transducer with a 7.62 cm (3 inch) focal length, focused on the surface at normal incidence. Critical flaws were assumed to be 0.032 inch diameter spheroidal inclusions. As can be seen in the figure, the coarse scan index (0.25 cm) and tight fillet radius (0.5 cm) combined to yield poor inspectability, as is indicated by the darker shades, near the surface of the part (due to small spot size) and below the fillet. By improving the scan plan, (the scan index was reduced to 0.10 cm) the near-surface detection was improved significantly, but poor POD persists below the fillet as is shown in Fig. 4. Finally, in Fig. 5, the improved
Fig. 1. Example of wireframe or solid model of an axially symmetric disk generated using a CAD package.

Fig. 2. Cross section of the disk in Fig. 1 showing finite element discretization into a number of elements and nodes.
Fig. 3. POD contours superimposed on the disk cross-section shown in Fig. 2. The scan increment was 0.25 cm and the fillet radius was 0.50 cm in this simulation. Note the poor POD around the edges and below the fillet. (Low POD values are assigned darker shades in this display.)

Fig. 4. POD contours for the same fillet radius (0.50 cm) but a finer scan increment (0.10 cm) compared to Fig. 3. Note that the POD is higher near the edges of the cross-section, but is still poor below the fillet.
Fig. 5. POD contours for both a larger fillet radius (1.0 cm) and a finer scan increment (0.10 cm) compared to Fig. 3. Now the POD is higher near the edges of the cross-section and below the fillet.

Scan mesh is used again, but the fillet radius is increased to 1.0 cm. Since this reduces the beam divergence in the solid, signal amplitudes are increased and POD is greatly improved. Although no real attempt was made to fully optimize the inspection procedure in this example, the concept of evaluating the impact of inspection modifications and component design changes upon component inspectability at the design stage is clear.

**SUMMARY**

This paper has described a means for integrating ultrasonic inspectability assessment and optimization into the component design process. The method utilizes analytical, physically based computer models of POD for small flaws in isotropic, elastic media, including realistic treatment of ultrasonic transducers and ultrasonic propagation and transmission through complex component surfaces. Input to the POD models was derived from a combination of the solid model and its finite element discretization, two natural elements of a CAD database. The resulting POD calculations were subsequently displayed using the built-in post-processing features of the CAD package. The feasibility of this approach was demonstrated by an example test case which consisted of a simulated axially symmetric forging. The demonstration included application of the models to quantify a nominal NDE inspection technique, to optimize the inspection in order to improve inspectability, and to suggest component design modifications needed to achieve adequate POD in critical locations in the part. A key feature of the approach is that the scan plan is an explicit element of the analysis which can, therefore, be extracted as part of a design database, similar to the manner in which numerical control code for manufacturing a component is created. The demonstration was, however, only one of feasibility. The actual implementation of POD code within a CAD package or as an easily accessed data source for the designer has not yet been achieved.

**ACKNOWLEDGMENT**

This work was supported by the Center for NDE at Iowa State University and was performed at the Ames Laboratory. Ames Laboratory is operated for the U. S. Department of Energy by Iowa State University under Contract No. W-7405-ENG-82.

**REFERENCES**

8. I-DEAS™ is an integrated CAD package developed and marketed by Structural Dynamics Research Corporation.
9. F. Inanc and J. Gray, these proceedings.
10. N. Nakagawa and R. E. Beissner, these proceedings.
11. F. Amin, T. A. Gray, and F. J. Margetan, these proceedings.