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Simulating UT Measurements from Bolthole Cracks

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Abstract. Analytical computer models of UT measurements are becoming more prominent in evaluating NDE methods – a process known as Model Assisted Probability of Detection, or MAPOD. As inspection requirements become more stringent, the respective models become more complex. An important application for aerospace structures involves inspection for cracks near boltholes in plate and layered structures. This paper describes a project to develop and validate analytical models for bolthole crack inspection, as well as to implement and demonstrate those models within an integrated graphical interface which can be used to simulate these inspections. The work involves a combination of approximate, paraxial, bulk-wave models as well as more rigorous, analytical models that include both bulk and surface/plate modes. The simpler models have greater flexibility and efficiency for handling complex geometry, while the more exact models are useful for benchmarking and assessing the accuracy of the paraxial versions. Model results will be presented for bolthole cracks in single layered components. Extensions of the models to multiple layers and to more complex geometries and materials will also be discussed.

INTRODUCTION

Model-assisted probability of detection (MAPOD) is an approach to evaluate NDE reliability at reduced cost and effort by using model calculations to supplant some of the typical empirical data used in conventional POD analyses. This approach has been demonstrated successfully for ultrasonic (UT) inspection of rotating jet engine components [1]. Further development and testing of the MAPOD approach is needed for application to aerospace structural members, including bolted and layered components. Evaluation of inspection reliability for structural components is particularly challenging due to the number of factors that can influence the detectability of flaws and to the inherent statistical variability of those factors. For example, Lindgren et al. [2] identified no less than twenty two separate factors that can influence nondestructive evaluation (NDE) of a two-layer bolted structure. Those factors include UT test parameters, properties of the component and geometry, as well as characteristics of the flaws themselves. Clearly, a fully empirical regimen to evaluate the individual effects of this myriad of properties is daunting, at best, and would certainly be prohibitively expensive and time consuming. A rational approach is to use analytical, computer models to estimate the effects of some of the competing factors.

This paper presents the status of a project to develop and deploy analytical and computer models of UT inspection of layered aerospace structural components that are fastened with bolts. The defects of interest in the simulations are cracks breaking from the surface of the bolthole and, potentially, from the face(s) of the layer. The models are being...
developed for multiple layers, including solid layers, such as aluminum, as well as layers of sealant between the solid layers. The work reported here will describe results for a single layer. The models include both a general purpose approximate Simulation Model and a theoretically more exact Benchmark Model. This breakdown into separate models was done because the use of approximations increase the general purpose applicability and computational efficiency of a computer code. It is feasible to represent many effects approximately, including component geometry, material properties, UT inspection and beam characteristics, flaw scattering, etc. However, engineering decisions require understanding of accuracy and validity of those approximations. In some cases, rigorously accurate models may be available to simulate practical inspection scenarios, but those models can frequently be limited in their applicability to complex geometries and may be computationally intractable due to excessive mesh sizes, e.g., a hybrid approach using elements of approximate Simulation Model for flexibility and employs a more rigorous Benchmark Model for evaluating the limitations of the approximations.

**APPROACH**

**Simulation Model**

The Simulation Model, which embodies a general purpose approximate software tool to predict bolt-hole crack responses, is based upon an adaptation of the Thompson-Gray ultrasonic measurement model [3] and applies to bulk wave propagation in multiple isotropic elastic or acoustic layers. The Gaussian-Hermite (GH) model is employed to compute the UT wave fields for longitudinal or shear wave propagation with typical plane-wave transmission and reflection coefficients at layer boundaries. In the current example, the layers are assumed to be planar and beam propagation is via bulk waves in all layers. The bolt-hole and crack are represented as stress-free faceted surfaces. The Kirchhoff approximation is used to compute the scattering from individual facets, which are assumed to be small with respect to the UT beam width; this is a quasi-plane wave assumption for each facet [4]. The total response from the bolt-hole and/or crack is the superposition of the individual facet responses summed over all incident wave modes and illuminating ray paths. The ultrasonic transducers are modeled as ideal piston radiators with broad bandwidth that can be coupled via a wedge or in immersion. The probes can be either planar or focused.

From a practical standpoint, the Simulation Model is a combination of elastic ray tracing, which determines and enumerates the illuminating ray paths from the probe to the bolt-hole and crack. The GH model uses those ray paths to deduce the illuminating UT fields on each of the facets. Electromechanical reciprocity, via Auld’s integral [5], then computes the scattered responses for the individual ray paths, which are then summed for the total response.

**Benchmark Model**

The Benchmark Model is intended primarily to provide a referee computation for evaluating the Simulation Model predictions. The ultrasound response to scattering by a crack extending from a bolt-hole is formulated by applying principles of elastodynamic reciprocity, using the Green function for the hole-free multilayer structure, in conjunction with Auld’s electromechanical reciprocity relation.[5,6] The Green function is the response of the multilayer system to a point body force acting within one of the layers, constructed to satisfy boundary conditions of continuity of normal tractions and displacements at the layer interfaces. Elastodynamic reciprocity seeks to construct the ultrasound scattering response to the bolt-hole and crack as a superposition of Green function responses. The end product of the formulation is an integral equation defined over the bolt-hole and crack surfaces for determination of wave motion displacements on these surfaces. The integral equation is solved through application of the Boundary Element Method (BEM), which converts the integral equation into a linear matrix equation. The ultrasound measurement response voltage is computed by employing the BEM-obtained bolt-hole and crack surface displacements in Auld’s reciprocity relation. The Green function for the multi-layered system is evaluated by exploiting the planar symmetry of the laminate, through application of Fourier integral analysis. The Green function is thereby expressed as a radial 1-D Fourier integral, having an integrand determined through solution of the matrix equation for plane wave interaction with the multilayer structure. Singularities in the integrand determine the guided wave structure associated with the laminate. The 1-D Fourier integral is evaluated numerically using a complex-valued integration contour which circumvents non-analytic behaviors. Employing the Green function in the BEM solution of the governing integral equation leads to coupled scattering matrices for the bolt-hole and crack. The matrix equation input vector (right-hand-side) is given by the wave motion displacements over the geometric surfaces of bolt-hole and crack when the bolt-hole and crack are absent, i.e., the incident field. The incident field is computed by prescribing an incident wave motion
on the outer surface of the laminate over the footprint of an insonifying transducer. Application of elastodynamic reciprocity with the laminate Green function determines the displacements and tractions on the bolthole and crack surfaces via an integration over the incident ultrasound beam footprint: the incident displacement serves as input to the BEM matrix equation, whereas the incident traction is employed in evaluation of Auld’s reciprocity relation.

**MODEL RESULTS**

**Simulation Model**

The Simulation Model was used to predict conventional pulse-echo UT inspection of a 3mm (0.12”) thick aluminum plate with a 4mm (0.16”) diameter bolthole. The inspection configuration is shown in Fig. 1, illustrating the inspection from both a side and a top view. The calculations assumed a 6.35mm (0.25”) diameter circular transducer with a center frequency of 5 MHz and 50% bandwidth. The probe is mounted on a wedge to produce a refracted 45 degree vertically polarized shear (SV) wave in the aluminum plate. Smooth notches (cracks) can be present on the bolthole surface at an angle θ around the hole. The notch is normal to the incident plane when θ is 90 degrees, as shown.

A typical simulation result is shown in Fig. 2 for the case of a 2mm (0.08”) wide through-wall notch at an angle of 90 degrees. The probe was raster scanned across the top of the plate with a total scan length of 30mm (1.2”) and index width of 10mm (0.4”). The physical location of the hole in relation to the scan coordinates is shown as a dotted circle superimposed on the bottom right c-scan image. The broadband calculation yielded RF waveforms of 16 microsecond duration, as shown in the top left image. The bottom right c-scan image shows maximum rectified amplitude of the full 16 microsecond waveforms. The b-scan displays at the top right and bottom left are rectified amplitudes along the horizontal and vertical dashed crosshair lines in the c-scan image. The waveform at the upper left is from the intersection of the crosshairs. For this calculation, the response from the notch (crack) is larger amplitude than that from the bolthole.

![Figure 1](image)

**FIGURE 1.** Illustration of the UT measurement scenarios for bulk wave Simulation Model calculations for a bolthole and crack (notch) in a single aluminum layer.
FIGURE 2. Simulation Model result for scan of a 3mm thick aluminum plate with a 4mm diameter hole and a 2mm wide through-wall notch at 90 degrees. The location of the hole is shown in the c-scan image by the circle and the UT indications from the bolthole and notch are indicated. Representative b-scan images are shown along the crosshair lines in the c-scan image, and a representative a-scan waveform is at their intersection.

The next set of Simulation Model results in Fig. 3 compares the response of the bolthole with no notch (a) to several sizes of notches located at 90 degrees on the bolthole. It should be noted that the color maps in these c-scan images are all self-normalized – i.e., their respective minimum amplitudes are mapped to white, and their maxima to red. In all five images, the peak amplitudes of the bolthole indication are the same. The images for the notched boltholes include a through-wall notch in (b), and half-thickness notches at the bottom (c), mid-wall (d), and top surface (e). There is a clear difference in the c-scan indication from the through-wall notch (b) compared to the top and bottom corner crack results in (c) and (e). However, the difference is not so clear between the through-wall and the mid-wall cracks, where the only clear distinction is in their peak amplitudes.

In Fig. 4 the width and angle of the notch are varied. The width of a notch at 90 degrees is reduced from 2mm (0.08") in image (a) down to 0.5mm (0.02") in (b), with the latter showing a significant reduction in amplitude for the notch indication. This is similar to the difference between the through- and mid-wall notches in Fig. 4. However, the width of the small notch is smaller in Fig. 4(b). In the next two images, (c) and (d), the notch is the same size as in (a), but the angle around the bolthole is changed to 75 and 60 degrees, respectively. For the latter two cases, the notch is no longer perpendicular to the incident plane of the UT beam, and the top and bottom surface corner trap indications are significantly reduced in amplitude and their indications have moved toward the unilluminated back of the bolthole. At 60 degrees, the Simulation Model predicts that the notch response has nearly disappeared. This is most likely a result of the use of the bulk wave beam model and the Kirchhoff approximation scattering model, since that combination does not include creeping waves on the bolthole surface and does not fully capture the diffraction effects at the crack edge.

Finally, in Fig. 5, a comparison is made between results from the 5 MHz transducer used in the previous computations and a 2.25 MHz transducer with 12.7mm (0.5") diameter. Both calculations assumed the same 2mm (0.08") wide through-wall notch at 90 degrees. The resolution is clearly poorer for the second transducer. Note that the 3mm (0.12") plate thickness is roughly 5 wavelengths at 5 MHz, and 2 wavelengths at 2.25 MHz. For the lower frequency case, the validity of the assumed bulk wave inspection is not clear.
FIGURE 3. Simulation Model c-scan results for 4mm bolthole in a 3mm aluminum plate - without notch (a), with 2mm wide through-wall notch at 90 degrees (b), and with a 2mm wide 2and 1.5mm tall notches at 90 degrees located at the bottom surface (c), mid-wall (d), and at the top surface (e). The color maps for each image are self-normalized; the bolthole amplitudes in all images are the same.
FIGURE 4. Simulation Model results for a 3mm thick aluminum plate with a 4mm diameter bolt hole, and through-wall notches of different widths, (a) and (b), and angles, (c) and (d).

Benchmark Model

The BEM scattering matrices for Benchmark Model calculation of the UT responses in the bulk wave regime described above were unworkably large using a typical desktop computer. In order to demonstrate the Benchmark Model’s capability versus that of the Simulation Model, the operating characteristics of the simulated inspection were adjusted. The results here assume a zeroth order antisymmetric Lamb plane wave - A0 mode – in the same 3mm (0.12”) thick aluminum plate and the same 4mm (0.16”) diameter fastener hole. The surfaces of the plate are assumed to be traction free. The frequency spectrum of the beam is assumed to have a 1 MHz center frequency with 100% (Hanning) bandwidth. The BEM calculation employs the Green’s function for an infinite plate. The maximum boundary element size is 0.1 times the shear wavelength at center frequency. When included in the calculations, the notch is assumed to be through-wall, 2mm (0.08”) wide with a 0.3mm (0.01”) opening. Figure 6 shows the measurement configurations represented in the results. All results are pulse-echo responses.
Figure 7 shows results for the bolthole alone with no notch and compares responses from the BEM calculation and from a simple Kirchoff approximation for the reflection from the hole. The full BEM calculation shows the leading specular response followed by creeping wave response around bolthole. The Kirchhoff approximation shows only the specular response with somewhat higher amplitude.

Next, in Fig. 8, the notch is included at \( \theta=0 \), which is in the shadow of the bolthole. The BEM result is nearly identical to that of the bolthole alone in Fig. 8. This is due to reflection of creeping waves from notch having virtually the same travel time. Since the notch is in shadow, the Kirchhoff result in Fig. 9 shows only the bolthole contribution, which is identical to that in Fig. 7 and somewhat larger than the BEM prediction.

Results for the bolthole plus a notch at \( \theta=45 \) degrees are shown in Figure 9. In both the BEM and Kirchhoff cases the specular response from the bolthole and the response from the notch are clearly visible and temporally resolved. The BEM result exhibits more features, representing creeping waves and far tip diffraction from the notch.

**FIGURE 5.** Simulation Model results for a 3mm thick aluminum plate with a 4mm diameter bolthole with a 2mm wide through-wall notch at 90 degrees inspected by (a) a 5 MHz, 6.35mm transducer or (b) 2.25 MHz, 12.7mm transducer.

**FIGURE 6.** Illustration of Benchmark Model calculation setup. Incident field is a 100% bandwidth, 1 MHz broadband A0 mode plate wave with planar phase front.
FIGURE 7. Benchmark Model calculations for a 4mm bolthole with no crack. BEM calculation (a) and Kirchhoff approximation (b) for bolthole surface.

FIGURE 8. Benchmark Model calculations for a 4mm diameter bolthole with 2mm wide through-wall notch at 0 degrees, in the shadow of the hole. Results are for a (a) BEM calculation and (b) Kirchhoff approximation for bolthole and notch surfaces.

Finally, the results for the notch located at $\theta=90$ degrees are presented in Fig. 10. In these results, the bolthole and notch responses are not fully resolved in time. The early time components of the BEM and Kirchhoff results, which correspond to the bolthole reflection, are similar to those in the previous figures with the Kirchhoff amplitude somewhat higher than the BEM. Overall, the two results have nearly the same amplitude.
**SUMMARY AND PLANS**

The Simulation and Benchmark modeling approaches shown here are significant in their ultimate use in MAPOD analysis of aerospace structural components. The joint capability of a flexible, general purpose Simulation Model and a referee Benchmark Model can readily allow analysis of complex structures along with assessment of the theoretical accuracy of the modeling results. Further testing and experimental validation of these models are needed, of course.
Extensions of both approaches are continuing for application to multiple layers, including anisotropic (homogeneous) lamina.

One current challenge is to develop the Benchmark Model’s BEM implementation to permit computations in meaningful component thicknesses and at typical UT inspection frequencies. Presently such applications result in prohibitively large scattering matrices. We are currently developing high performance computing approaches, involving multiple CPUs as well as graphics processing units (GPUs), to enable bulk wave multiple layer applications in the Benchmark Model and to speed up all calculations in general. Work this coming year will address the multi-layer cases for both Simulation and Benchmark Models and will include more extensive model testing and validation.

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