DISTANCE AMPLITUDE CORRECTION FACTORS FOR IMMERSION ULTRASONIC MEASUREMENTS THROUGH CURVED SURFACES

Tim Gray and Mike Garton
Center for Nondestructive Evaluation
Iowa State University
Ames, IA 50011

Paul Zombo
Westinghouse Electric Corporation
4400 Alafaya Trail
Orlando, FL 32826-2399

INTRODUCTION

Near net-shaped forgings offer significant advantages for component manufacture, including less material waste and reduced costs for machining to final shape. However, curved entry surfaces on near net shape forgings create complications for ultrasonic inspection methods. In immersion ultrasonic testing, entry surface curvature causes ultrasonic beam focusing or defocusing, which affects the detection sensitivity to interior material flaws, such as voids and inclusions, as compared to inspection through planar surfaces.

Typically, immersion ultrasonic inspection specifications require the generation of distance-amplitude curves (DAC) that define the sensitivity to a standard reflector, such as a flat-bottomed hole (FBH), as a function of depth within a material. The problem with near net-shaped forging inspection is that every different surface geometry will require a unique DAC. One approach to determining the needed sensitivity levels involves the use of multiple curved surface calibration standards whose geometries mimic those found in regions of the components to be inspected. For a complex forging shape, this clearly entails the need for many different calibration blocks. An added difficulty is that a new forging geometry then requires fabrication of new calibration blocks. An alternative, and less costly, approach is to measure flat surface DAC levels and then to account for different surface geometries based upon analytically derived curvature correction factors (CCF) obtained from well-validated computer models. This has the benefit of simplicity, since calibration measurements need only be made on simple, standard blocks, and of generality, since a model can easily be used to compute CCF for new surface curvatures.

Such a model has been developed that predicts the ultrasonic response from a FBH measured through a curved surface using an immersion ultrasonic system. Model validation was performed on a set of curved surface specimens manufactured by

Westinghouse, each containing FBH reflectors at several metal depths. Ultrasonic measurements were made using planar immersion transducers with various standard crystal diameters and center frequencies and using both normal incidence L-wave and 45-degree shear wave modes. In this paper, we will review the analytical model, summarize the validation tests, and apply the model to the generation of curvature correction factors for immersion ultrasonic measurements through curved surfaces.

ULTRASONIC MEASUREMENT MODEL

The UT measurement model is based upon Auld's electomechanical reciprocity relationship [1]. Flaws are assumed to occur within the bulk of an isotropic, homogeneous, elastic medium. It is further assumed that the flaw dimensions are small with respect to the ultrasonic beam size and that their scattering amplitudes do not vary significantly over the range of angles subtended by the transducer. The ultrasonic inspection method is assumed to be pulse-echo. This results in a relatively simple ultrasonic measurement model in which the ultrasonic beam propagation effects and the scattering effects are separable [2]. The model predicts the time harmonic (single frequency) response caused by the presence of a scatterer in the ultrasonic beam.

Ultrasonic beam propagation and transmission and/or refraction through curved liquid-solid interfaces are represented by the Gaussian-Hermite beam model, in which a time harmonic ultrasonic displacement or velocity field is represented as a summation of Gaussian-Hermite functions [3]. This model employs paraxial approximations, whose accuracy is best near the beam axis and for cases where incident angles in the beam footprint on the component surface are not near critical angles. This model is used to predict bulk propagating waves only. Scattering amplitudes for circular flat-bottomed holes are modeled using the elastodynamic Kirchhoff approximation [4]. This model accurately predicts the specular reflection from a planar reflector, but does not correctly represent edge diffraction or surface waves on the face of the reflector.

To predict broad bandwidth waveforms, the time harmonic results just described must be convolved with the system response of an ultrasonic instrument. This is accomplished by extracting a system efficiency factor [2] from a reference waveform, such as the echo from a planar surface, and multiplying its frequency components times the time harmonic components representing the beam and scattering amplitudes. The resulting spectrum is inverse Fourier transformed to generate a time domain RF waveform.

VALIDATION RESULTS

A set of test blocks was designed to have a variety of cylindrical and bicylindrical surface curvatures with 0.125 inch (0.3175 cm) diameter FBH oriented for normal incidence longitudinal wave and for 45-degree shear wave inspections. The faces of the FBH were designed to be perpendicular to the respective incident directions. The blocks were machined from 4340 steel forging stock and supplied by Westinghouse. The range of surface curvatures is representative of turbine disk curvatures.

Ultrasonic measurements were performed using a Panametrics Automated Systems Division MultiScan system possessing a rotary turntable and two independent 5 degree of freedom bridges (x, y, z, gimbal, swivel). The ultrasonic transducers used were Panametrics A-S or V series planar immersion probes with nominal center frequencies of 2.25 or 5.0 MHz and crystal radii of 0.375 inch (0.9525 cm) or 0.5 inch (1.27 cm) diameter. For normal incidence longitudinal wave measurements, the water paths were chosen to be

0.25 inches (0.635 cm) plus the larger value of (1) the nearfield distance in water or (2) the ratio of water to steel acoustic velocities times 11 inches (27.94 cm). This ensured that the nearfield occurred in the water and that no multiple water path echoes would interfere reflections from flaws with metal depths up to 11 inches (27.94 cm). For shear wave measurements, probe tilt angle was set to 19.09 degrees and the water paths were 0.25 inches (0.635 cm) plus the nearfield distance in water.

For the model calculations, the transducers were assumed to be planar, circular piston probes whose effective radii were equal to the nominal values stamped on the case. Fifty Gaussian-Hermite expansion coefficients were used in both dimensions of the crystal to ensure good convergence. Ultrasonic attenuation was neglected for both the water and steel media. Reference waveforms for system efficiency factor determination were front surface, normal incidence echoes from flat portions of the test blocks with water paths chosen according to the longitudinal wave specification described above. Sample comparisons between model and experiment will be shown.

Figure 1 shows results of measurements from #5 flat bottomed holes (i.e., 5/64 inch or 0.198 cm diameter) in a set of ASTM standard test blocks made of 4340 steel. The data in the figure were obtained using a 2.25 MHz, 0.5 inch (1.27 cm) diameter immersion probe, and signal amplitudes are shown as open circles in the figure. Model simulation of the same measurement configuration is represented by the solid line. Amplitudes were converted to dB by dividing both the measured and the simulated signal amplitudes (peak-to-peak voltages) by the measured amplitude from the 1 inch (2.54 cm) deep FBH. Thus the results in Figure 1 are an absolute comparison between model and experiment. It is interesting that the test block with the 3 inch (7.62 cm) deep FBH, which gave rise to the outlying data point, was not part of the same set as the other test blocks.

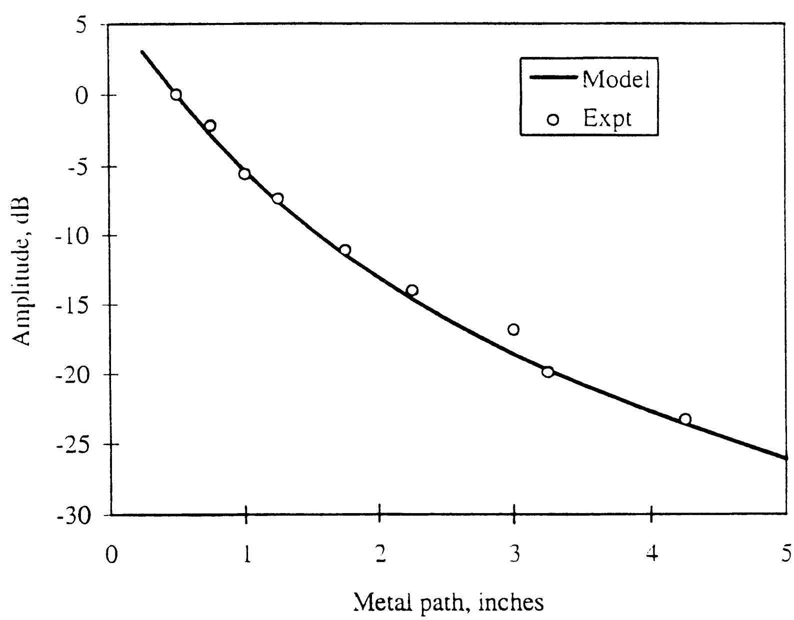

Figure 1. Comparison between experimental and model predicted signal amplitudes for 0.078 inch (0.198 cm) diameter FBH below a planar surface using a 2.25 MHz, 0.5 inch (1.27 cm) diameter probe.

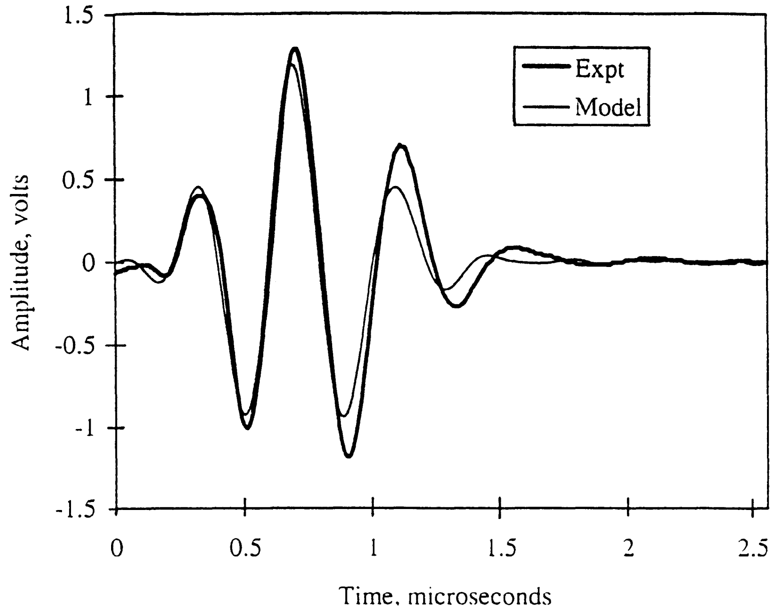

Figure 2. Comparison between experimental and model predicted RF waveforms for a 0.125 inch (0.318 cm) diameter FBH below a 1.5 inch (3.81 cm) radius groove with a swept radius of 14 inches (35.56 cm) using a 2.25 MHz, 0.375 inch (0.9525 cm) transducer.

Figure 2 shows a comparison between an experimental waveform and the corresponding model predicted signal from a 1 inch (2.54 cm) deep, 0.125 inch (0.3175 cm) diameter FBH obtained using a 2.25 MHz, 0.375 inch (0.9525 cm) transducer at normal incidence. The entry surface was a surface of revolution generated by a 3.0 inch (7.62 cm) radius semicircle whose center is 14 inches (35.56 cm) from the axis of revolution. The entry point was at the bottom of the trough. The waveforms in the figure were not normalized or scaled in any manner.

Figure 3 shows a comparison between experimental and model predicted normal incidence longitudinal wave signal amplitudes for #8 FBH (8/64 inch, or 0.318 cm diameter) in one of the Westinghouse fabricated test blocks with a bicylindrical surface. The entry surface was a surface of revolution generated by a 1.5 inch (3.81 cm) radius semicircle whose center is 14 inches (35.56 cm) from the axis of revolution. The entry point was the bottom of the trough. Only 1 inch (2.54 cm) and 3 inch (7.62 cm) deep FBH reflectors are contained in the test block. The amplitudes for both the model and the experimental data in the figure are expressed in dB relative to the amplitude (peak-to-peak voltage) of the experimental signal at the 1 inch (2.54 cm) metal path. This is, thus, an absolute amplitude comparison.

CURVATURE CORRECTION FACTORS

For use as part of an immersion inspection specification, the surface curvature effects need to be quantified in such a way as to allow an operator to set the sensitivity level (gain) on a UT instrument. It is assumed that an operator measures a DAC curve for FBH reflectors of a given size at various depths below a planar surface, consistent with standard operating procedures. Model results are then employed to define the depth dependent

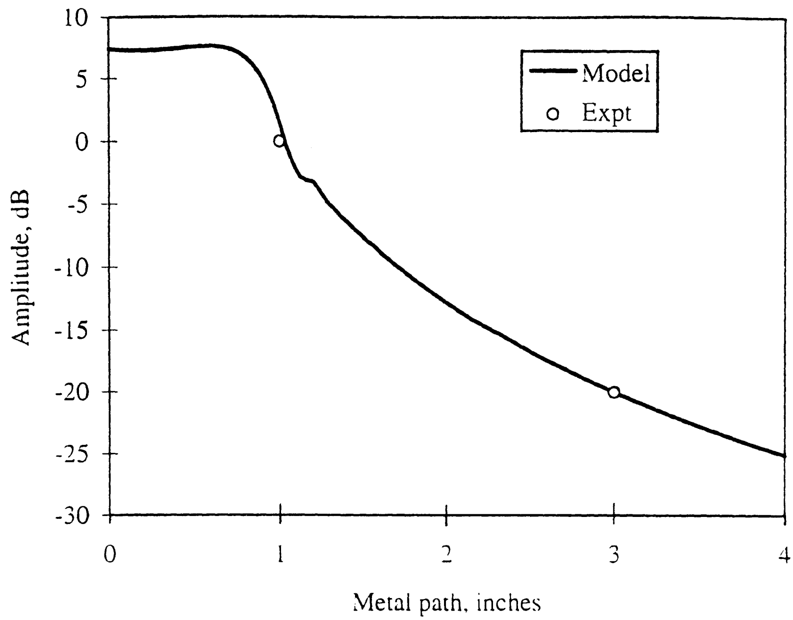

Figure 3. Comparison between experimental and model predicted signal amplitudes for 0.125 inch (0.318 cm) diameter FBH below a 1.5 inch (3.81 cm) radius groove with a swept radius of 14 inches (35.56 cm) using a 2.25 MHz, 0.375 inch (0.9525 cm) transducer.

changes in gain setting needed to achieve the same DAC curve for hypothetical FBH reflectors below a curved surface. To compute the CCF, two waveforms were simulated at each metal path length -- one for a FBH below a planar surface, and one for the same FBH below a curved surface. The CCF is the difference in peak-to-peak voltage amplitude between the two waveforms, expressed in dB. That is, CCF = 20log(Vp/Vc), where Vp is the planar surface signal voltage, and Vc the amplitude measured through the curved surface.

For the results to follow, probes were assumed to be circular, planar piston probes and to have 40 % bandwidth (i.e., -6 dB bandwidth is 40 % of center frequency) as measured from the reflection from a planar surface at the nearfield distance in water. Water paths were set according to the nearfield vs. multiple water echo criteria described above.

Figure 4 shows simulated CCF results for normal incidence, L-wave measurements below three different cylindrical grooves using a 2.25 MHz, 0.375 inch (0.9525 cm) diameter transducer. It is interesting to note that curvature correction values for concave surfaces are generally negative. That is, to achieve the same sensitivity as for a planar surface measurement, the gain setting is lower for the curved surface condition. This can be understood by realizing that a concave, cylindrical groove acts like a cylindrical acoustic lens and focuses the beam within the metal. For the 1 inch (2.54 cm) radius groove, the focal depth appears to be around 0.5 inches (1.27 cm), which is the location of the minimum in the respective curve in Figure 4. Beyond the focal depth, the beam spreads out more rapidly than the planar surface beam, and the CCF value for that groove becomes positive at metal depths greater than about 2 inches (5.08 cm). For the larger groove radii represented in the figure, the focusing effects of the surface curvature are less pronounced and no positive CCF values are obtained.

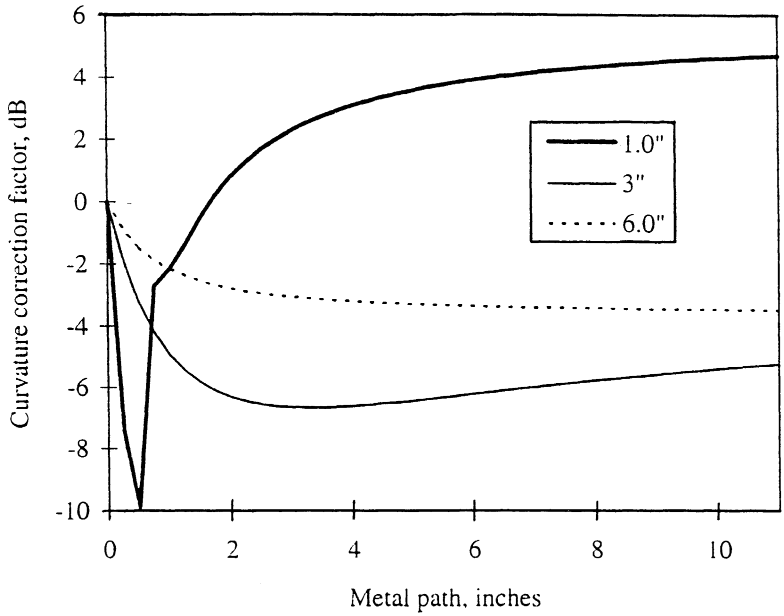

Figure 4. Model predicted curvature correction factors for cylindrical grooves using normal incidence L-wave inspection using a 2.25 MHz, 0.375 inch (0.9525 cm) diameter transducer.

Figure 5 shows CCF results for the same probe and cylindrical groove radii as in Figure 4, except in this case the UT measurement is via mode-converted, 45 degree refracted shear waves where the probe is tilted axially with respect to the groove. The tilt angle is 19.09 degrees. As seen in Figure 4, the CCF values tend to be negative because of the focusing tendency of the surface curvature, although positive values are seen beyond the focal zone for the 1 inch (2.54 cm) radius groove. Note that the focal depth here occurs roughly twice as deep as for the L-wave case in Figure 4 because of the difference in longitudinal versus shear wave speeds in the metal.

Figure 6 shows the simulated effects of "out of plane" curvature on CCF values. This figure shows results for the same 1 inch (2.54 cm) radius groove and normal incidence L-wave probe combination as found in Figure 4, and also shows additional results for two bicylindrical grooves. The latter grooves have one principal radius of curvature of 1 inch (2.54 cm) and the other principal radius of curvature of concave or convex 14 inches (35.56 cm). The dominant geometrical effect in each case is seen to be the 1 inch (2.54 cm) groove radius. The out-of-plane curvatures only contribute roughly +/- 1.2 dB at the greatest metal path length. In some inspection scenarios, therefore, it might be admissible to neglect the out-of-plane curvature effects and perform curvature corrections solely on the basis of the groove radius.

CONCLUSION

The use of analytical models has shown to be an effective and efficient means for specifying inspection sensitivity levels for immersion ultrasonic inspection of near net-shaped forgings of steam turbine disks using planar ultrasonic transducers. Similar applications are envisioned for similar scenarios, such as jet engine forgings. Models can

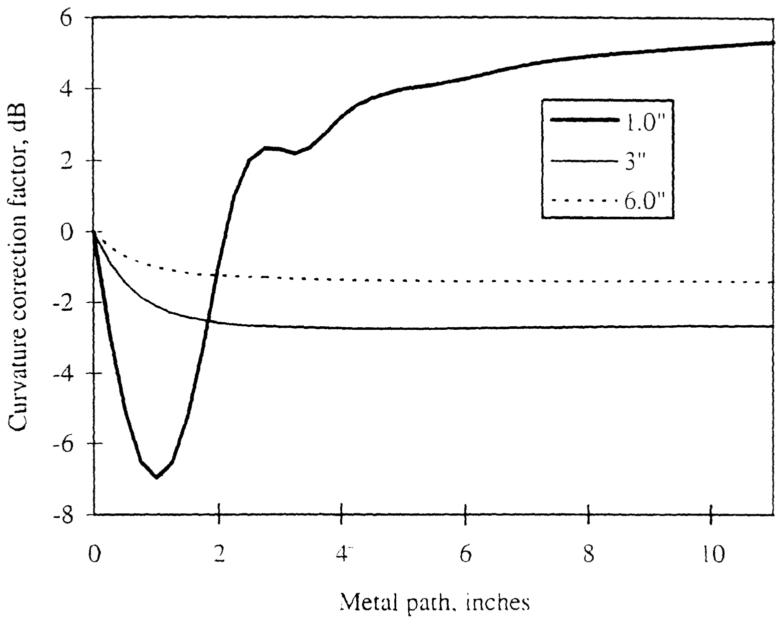

Figure 5. Model predicted curvature correction factors for cylindrical grooves using 45 degree refracted shear-wave inspection using a 2.25 MHz, 0.375 inch (0.9525 cm) diameter transducer.

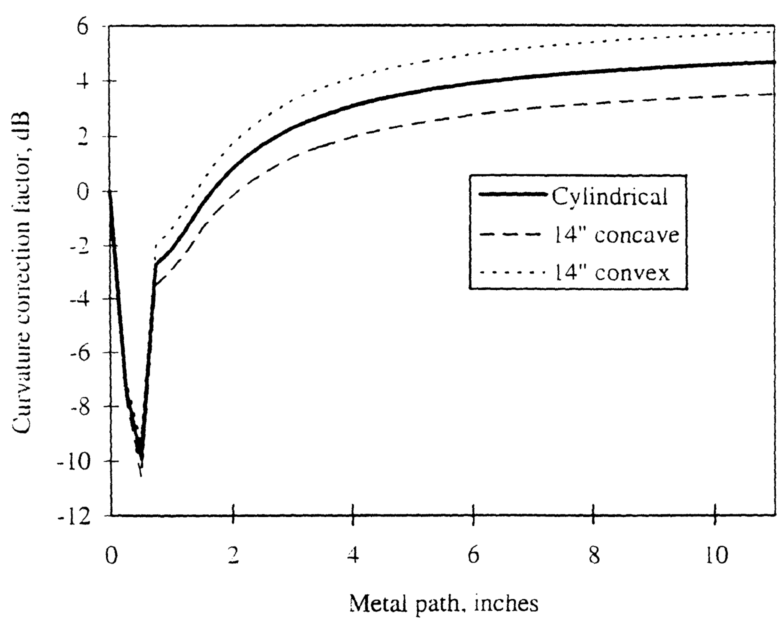

Figure 6. Model predicted curvature correction factors for 1 inch (2.54 cm) radius grooves with out-of-plane curvature as shown in the legend using normal incidence L-wave inspection using a 2.25 MHz, 0.375 inch (0.9525 cm) diameter transducer.

be extremely useful when focused ultrasonic transducers are employed, since simulation results can be used to design the appropriate transducer focal characteristics, as well. In the future, it is expected that this approach to "electronic standards" for ultrasonic inspection specification will result in more reliable, versatile and economical testing procedures.

ACKNOWLEDGMENT

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