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THE EFFECT OF CRACK MORPHOLOGY ON ULTRASONIC RESPONSE

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ABSTRACT. A numerical study is presented of the influence of crack morphology on ultrasonic pulse-echo response. Crack morphology is described as a planar crack onto which a random normal direction deviation is imposed with a specified tangential correlation length. Pulse-echo responses for ensembles of random crack profiles are computed as a function of profile height, correlation length, crack length, angle of incidence, wave mode type and signal bandwidth. Mean and variance of signal peak amplitude are compiled. Limits of validity of a Kirchhoff scattering approximation are observed through comparison to boundary element method (BEM) predictions.

Keywords: Ultrasonics, Crack Morphology

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INTRODUCTION

Ultrasonic inspection sensitivity is most often quantified as the response to a reflector having a canonical geometry such as a flat bottomed hole or EDM notch. It is well understood that the reflectivity of an actual flaw can vary substantially from that of a canonical reflector of comparable size, due in large part to variation in flaw morphology. In previous work, model predictions using the actual measured morphology of a surface breaking half-elliptical fatigue crack resulted in an 8 dB drop in signal response below that of an ideal planar crack of the same dimensions.[1] This result emphasizes the importance of accounting for flaw morphology when assessing probability of detection (POD), and indicates the need for a systematic study of the influence of flaw morphology on inspection sensitivity. To this end, a numerical study was performed which examines the influence of crack roughness on ultrasonic signal amplitude. A planar crack face is distorted by imposing a random crack profile, parameterized by profile height and correlation length. By generating ensembles of crack realizations for fixed profile height and correlation length, mean and variance of signal amplitude are compiled as a function of these crack roughness parameters.

The model formulation used in [1] applied approximate scattering theory in which wave motion on the crack surface is evaluated locally using non-diffracting ray theory, referred to as the Kirchhoff approximation. Limits of model validity arise as a concern when employing such approximations. This concern is examined in the numerical study by comparing Kirchhoff-based predictions with results obtained by the Boundary Element Method (BEM), which provides exact solutions in the limit of numerical convergence. To facilitate this comparison, it is noted that the phenomena which determine Kirchhoff limits of validity function equivalently in 3D and 2D scattering problems (a 2D scattering problem can be viewed as a 3D problem with no dependence on one dimension).
Restricting consideration to 2D scattering enables practical application of the BEM to much larger crack dimensions, correspondingly expanding the establishment of Kirchhoff limits of validity. Results are presented here which compare 2D Kirchhoff and BEM predictions of pulse-echo crack response amplitude mean and variance as functions of random crack profile height and correlation length, crack length, angle of incidence, wave mode type, and signal frequency bandwidth.

**COMPUTATIONAL MODEL FORMULATION**

Model predictions of pulse-echo signals in this work are based on evaluation of Auld’s reciprocity theorem for scattering by a crack, expressed as

\[
v(\omega) = E(\omega) \int_{\text{crack}} u_{i}^{\text{tot}}(x, \omega) \tau_{ij}^{\text{inc}}(x, \omega) n_j(x) \, dx
\]

where \(v(\omega)\) is response voltage as a function of frequency \(\omega\), \(E(\omega)\) is the pulse-echo system frequency response of the measurement (including transducer and electronics), \(u_{i}^{\text{tot}}(x, \omega)\) is the total motion on the crack face as a function of position \(x\), and \(\tau_{ij}^{\text{inc}}(x, \omega) n_j(x)\) is the traction (contraction of stress and surface normal) on the crack face associated with the incident wave field (field in the absence of the crack). The numerical study assumes plane wave incidence of either longitudinal (L) or vertically polarized transverse (T) motion, and a system response function \(E(\omega)\) in the form of a Hanning window having bandwidth characterized by the ratio of 6 dB bandwidth to center frequency. Time domain signals are obtained by Fourier transformation of eq.(1) in frequency \(\omega\). The heart of the scattering calculation is the determination of the surface displacements \(u_{i}^{\text{tot}}\) for a given incident field. An approximation of the surface displacement is obtained through application of non-diffracting ray theory, leading to the Kirchhoff evaluation of eq.(1). An integral equation exactly determining the motion of the crack surface is obtained through application of elastodynamic reciprocity with the associated Green function. The solution to the integral equation is projected onto a basis set defined over the crack surface (boundary elements), thereby transforming the problem to a matrix equation, which is inverted numerically to obtain an exact (to within numerical convergence) expression of the crack face motion, for use in eq.(1). In the present work, the basis was specified as a mesh of constant elements, with 10 elements per transverse center frequency wavelength.

An ensemble of crack profiles is generated by filtering sequences of pseudo-random numbers with a Hanning window. By definition of the original random sequence, the mean of the profile autocorrelation over the ensemble approaches the autocorrelation of the window function. The correlation length of the profile is therefore designated as the half-amplitude half-width of the filter window autocorrelation, denoted \(\gamma\). Realizations of crack profiles having unit maximum peak-to-valley roughness height are shown in Fig.(1) for \(\gamma=0.13\) and \(\gamma=0.25\). It is seen that shorter correlation length results in sharper crack features, whereas the crack transitions into a “wavy” profile at long correlation lengths. Ensembles with up to 1000 entries were compiled for a range of correlation length \(\gamma\) and profile height \(h\). Pulse-echo frequency spectra were computed for each ensemble entry, as a function of angle of incidence, wave mode type, and crack length \(L\). Time domain responses were evaluated through Fourier transformation for each ensemble entry, over a range of frequency bandwidths. The mean and variance of the peak time signal amplitudes were then compiled by summing over the ensemble.
NUMERICAL RESULTS

Numerical results are presented showing the dependence of pulse-echo signal amplitude on crack profile roughness height and correlation length, for a crack contained in aluminum ($c_L=6320$ m/s, $c_T=3080$ m/s) under plane wave incidence. Results are first shown for the case of perpendicular incidence on a crack with length $L=6.32 \lambda_L$ (longitudinal wave length at center frequency), corresponding to a 4 mm crack at 10 MHz. In all that follows here, all lengths are specified in units of $\lambda_L$. The mean and standard deviation (square root of variance) of signal amplitude are plotted, for both exact (BEM) and approximate (Kirchhoff) calculations. These results, and all that follow, are normalized by the response at perpendicular incidence on a smooth crack of corresponding length. Figure(2) plots the mean and standard deviation of peak signal amplitude for 100% bandwidth L-wave incidence as a function of roughness height, for roughness correlation lengths of $\gamma=0.13$ and $\gamma=0.25$. The statistics were compiled using 100 entry ensembles. For the longer correlation length of Fig.(2a), the Kirchhoff and BEM results are nearly indistinguishable in both mean and standard deviation, until they start to diverge above profile height $h=0.9$. A modestly greater disagreement is seen for the shorter correlation length of Fig.(2b), corresponding a greater crack roughness. The corresponding result for T-wave incidence is shown in Fig.(3). Compared to L-wave incidence in Fig.(2), it is seen that the mean amplitude decreases more rapidly with increasing roughness. In Fig.(2a), the mean amplitude is half the smooth crack amplitude at a profile roughness of $h=0.35$, whereas in Fig.(3a) the mean amplitude is half the smooth crack amplitude at a profile roughness of $h=0.16$. It is noted, however, that the transverse wavelength is approximately half the longitudinal wavelength, hence it is seen that in both cases the half-amplitude mean value occurs at a height of approximately 0.35 incident wavelength. It is seen that the exact BEM and approximate Kirchhoff predictions agree closely for profile roughness height up to $h=0.25$, beyond which the predictions diverge. As with L-wave incidence, results for the shorter roughness correlation length in Fig.(3b) diverge somewhat more quickly.

Since it is generally easier to compute single frequency responses, it is of interest to compare broadband and single frequency predictions to assess the viability of a single
FIGURE 2. Mean and standard deviation of pulse-echo signal amplitude: comparison of 100% bandwidth broadband exact (E) BEM and approximate (A) Kirchhoff predictions for perpendicular L-wave incidence. Crack length L=6.32, roughness correlation length a) $\gamma=0.25$, b) $\gamma=0.13$.

FIGURE 3. Mean and standard deviation of pulse-echo signal amplitude: comparison of 100% bandwidth broadband exact (E) BEM and approximate (A) Kirchhoff predictions for perpendicular T-wave incidence. Crack length L=6.32, roughness correlation length a) $\gamma=0.25$, b) $\gamma=0.13$.

frequency approximation to a broadband response. Figure(4) compares 100% bandwidth broadband and single frequency (at the broadband center frequency) predictions for perpendicular L-wave incidence, crack length L=6.32, and roughness correlation length $\gamma=0.25$. It is seen in this configuration that the single frequency result provides a reasonable approximation to the broadband result. In contrast, Fig.(5) compares 100% bandwidth broadband and single frequency L-wave incidence predictions as a function of incidence angle, for a crack of length L=6.32 having both a smooth and rough profile with $h=0.35$ and $\gamma=0.25$. The single frequency result for the smooth crack displays pronounced minima over the 90 degree angular range, associated with interference between crack tip diffracted signals. In contrast, the broadband response displays a monotonically decreasing angular dependence. It is significant to notice that the BEM prediction approaches -30 dB at 90 degrees, where as the Kirchhoff prediction decreases to zero amplitude at 90 degrees. The structure seen in Figs.(5a,b) is readily explained by examining associated time domain responses, plotted in Fig.(6) for 24 degree incidence. The BEM calculation of Fig.(6a) reveals numerous component signals, the interference of which gives rise to the single frequency structure seen in Fig.(5a). Two dominant signals are noted, arising from

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diffraction at the near and far crack tips. Other smaller signals are noted, corresponding to
diffraction into two Rayleigh surface waves types. Significantly, it is noted that the
Kirchhoff prediction of Fig.(6b) displays only edge diffracted signals, with amplitudes
having compromised accuracy. Note that the far tip diffracted signal is about 1dB less than
the near tip signal in the BEM computation, whereas the Kirchhoff theory predicts tip
signals of comparable amplitude. This observation explains why the spectral peaks in
Fig.(5a,b) exceed the broadband predictions by 5db and 6db for the BEM and Kirchhoff
results, respectively. Attention is turned to the effect of roughness in Figs.(5c,d), which
compare 100% bandwidth and single frequency L-wave pulse-echo angular responses from

FIGURE 4. Mean and standard deviation of pulse-echo signal amplitude: comparison of single frequency
($\omega_0$) and 100% bandwidth (broadband) predictions for perpendicular L-wave incidence. Crack length
$L=6.32$, correlation length $\gamma=0.25$, for a) BEM computation and b) Kirchhoff computation.

FIGURE 5. Comparison of single frequency (time harmonic) and broadband mean amplitude predictions for
crack length $L=6.32$. a) Smooth crack BEM, b) Smooth crack Kirchhoff, c) Rough crack BEM d) Rough
crack Kirchhoff. Roughness correlation length $\gamma=0.25$, roughness height $h=0.25$. 
FIGURE 6. Time domain signals contributing to fig.(5). 100% bandwidth broadband L-wave pulse-echo signals at 24 degree incidence: a) flat crack BEM prediction b) flat crack Kirchhoff prediction c) rough crack BEM prediction d) rough crack Kirchhoff prediction.  L=6.32, γ=0.25, h=0.25.

a rough crack having correlation length γ= 0.25, roughness height = 0.25, and crack length L=6.32, for both BEM and Kirchhoff computations. The structure arising from component signal interference is seen to be much less pronounced in the single frequency result than that noted in Figs.(5a,b). It is still seen, however, that the time harmonic result exceeds the broadband prediction by up to 6dB. As with the flat crack, this is attributed to constructive interference between multiple signal components. BEM and Kirchhoff time domain signals are plotted in Figs.(6c,d) for a selected ensemble member at 24 degree incidence in the compilation of the statistics of Figs.(5c,d). Comparing Figs.(6c,d) to Figs.(6a,b), it is evident that numerous randomly arriving signal components are received between the arrival of the near and far tip diffracted signals, and that these signals exceed the tip diffracted signals by ~8 dB. It is to be expected that the mean spectra of these randomly arriving signals would not display coherent spectral minima.

Mean signal amplitudes for broadband L-wave incidence are plotted as a function of incidence angle in Fig.(7) for h=0.25, h=0.5, and γ=0.25, γ=0.13. Kirchhoff and BEM predictions are compared. It is seen that increasing roughness reduces the angular directivity of pulse-echo scattering. It was previously observed in Fig.(5a,b) that the Kirchhoff approximation under-predicts the signal at off-perpendicular incidence for the smooth crack, with under-prediction most pronounced near grazing. Fig.(7) shows how the validity of the Kirchhoff approximation improves at off-perpendicular incidence with increasing roughness, until a point is reached at which the Kirchhoff result begins over-predicting the mean signal. This transition with increasing profile height is seen to occur more rapidly for the shorter roughness correlation length. Corresponding results for T-wave incidence are presented in Fig.(8). Figure(8a) compares BEM and Kirchhoff 100% bandwidth pulse-echo T-wave peak amplitude responses as a function of angle, for a flat crack of length L=6.32. A greater angular directivity than that for L-wave incidence in Fig.(5) is seen, arising from the shorter wavelength. Similar under-prediction of the
Kirchhoff result at off-perpendicular incidence is also observed. A notable phenomenon is the peak in the BEM response prediction at 30 degree incidence, arising from the far crack edge reflection of the leaking surface wave which is generated near the L-wave critical angle. This reflection results in a pronounced amplitude enhancement of the far-edge tip diffracted signal, corresponding to the second dominant signal in Fig.(6a). The Kirchhoff approximation by design does not include this phenomenon. The introduction of roughness having profile height h=0.35 and correlation length $\gamma=0.13$ results in Fig.(8b). A lessening of angular directivity is noted, as is an improvement in agreement between the BEM and Kirchhoff predictions. Note that the enhancement of the far-tip diffracted signal is still observed, although to a lesser extent than the flat crack.
FIGURE 9. Comparison of broadband L-wave BEM (E) and Kirchhoff (A) mean amplitude predictions as a function of angle for crack lengths L=6.32 and L=1.57. a) h=0.0, b) γ=0.25, h=0.35.

Differences in angular scattering arising from varying crack length are examined in fig.(9). Kirchhoff and BEM L-wave incidence pulse-echo responses are plotted for two crack lengths, L=6.32, and L=1.57, and for two roughness heights, h=0.0 and h=0.35 with γ=0.25. As expected, a lesser degree of angular directivity in scattering is seen for the shorter crack. As observed in preceding results, the introduction of roughness further decreases the angular directivity, and brings the Kirchhoff and BEM predictions into closer agreement.

SUMMARY

A study of the effect of crack morphology on ultrasonic response was presented. A randomly rough crack profile is characterized by profile height and correlation length. The mean and variance of ultrasonic response is compiled by computing pulse-echo signals for ensembles of crack realizations, as a function of crack length, angle of incidence, wave type, and frequency bandwidth. Selected results reveal good Kirchhoff performance near perpendicular incidence, and a general improvement in Kirchhoff predictions at non-perpendicular incidence with the introduction of roughness.

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