PREDICTIONS OF PULSE-ECHO ULTRASONIC SIGNALS FROM INNER WALL CRACKS IN BWR NOZZLES

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INTRODUCTION

Formation of cracks on the inner walls of nozzles of Boiling Water Reactors would be of great concern for nuclear power industry. These nozzles, which connect the piping to the pressure vessel of the nuclear reactors, are therefore inspected periodically using ultrasound. However, there are complications in ultrasonic inspection of such nozzles due to the curvature of these components. Such curvatures can greatly influence the wave propagation through them. Therefore, there is a need for practical beam models to study such complications in these kinds of geometries.

Last year we reported on propagation of Gaussian beam through curved surfaces when the plane of incidence does not contain a principle radius of the curvature of the interface [1]. This year we continued that study and investigated the effect of the curvature on the ultrasonic response from cracks when they are observed through such interfaces.

THEORETICAL BACKGROUND

Effects of Transmission Through the Interface

The theoretical discussion of the interaction between the ultrasonic beam and the interface was presented in detail last year [1]. Basically, in that study a Taylor series expansion was used to define the surface of the interface. Then, both amplitude and phase of the incident and transmitted beam were defined on that surface. Consistent with the paraxial approximation, coefficients of linear and quadratic terms were required to be equal for both incident and transmitted beams on the surface of the interface. By equating same order terms of the amplitude and the phase, the parameters of the transmitted beam were computed.

The results of last year's study showed that by injecting a beam with incident angles out of the plane of symmetry of curved interfaces, beam width and radii of curvatures are changed. Furthermore, the principal axes of constant contours of amplitude and phase are not be aligned anymore.

Propagation of the Beam

To propagate an elliptical Gaussian beam whose principal axes of amplitude and phase are not aligned, the angular spectrum of the plane wave approach was used [2]. The results showed that the far field behavior was dominated by focusing and defocusing effects closely aligned with the principal radii of the interface.

Ultrasonic Response from a Crack (Auld's Reciprocity Relation)

To predict the electric voltage signal which arises from backscattering of an ultrasonic beam from a crack, Auld's reciprocity formula [3] is used. In that formula, Auld uses a single, dimensionless reflection coefficient Γ which is directly proportional to electromagnetic fields in the cable. Then, for nonpiezoelectric elastic media and general pitch/catch geometries, he derived a relationship for the change in Γ that is produced by present of a flaw.

$$\Gamma_{flaw} - \Gamma_{no\ flaw} = \frac{1}{4P} \int_S \left(\mathbf{V}_1 \cdot \mathbf{T}_2 - \mathbf{V}_2 \cdot \mathbf{T}_1 \right) \cdot \hat{n}\ dS \tag{1}$$

In the above equation, $\mathbf{V}_1$ and $\mathbf{T}_1$ are time-independent velocity and stress fields which occur in the absence of the flaw. $\mathbf{V}_2$ and $\mathbf{T}_2$ are the fields which would occur in the presence of the flaw under the same conditions. Vector $\hat{n}$ is an outward normal vector to the surfaces of the flaw.

Since the net stress must vanish on the surface of the crack, $\mathbf{T}_2 \cdot \hat{n}$ is equal to zero in the integrand of the equation (1). Thus, the equation (1) reduces to

$$\Gamma_{flaw} - \Gamma_{no\ flaw} = \frac{-1}{4P} \int_S \mathbf{V}_2 \cdot \mathbf{T}_1 \cdot \hat{n}\ dS \tag{2}$$

Figure 1 shows the crack location and coordinate systems used in this study. It must be mentioned that both interfaces in Figure 1 are curved with different radii of curvature in each plane. As it is shown in Figure 1, each point on the surface of the crack, S, is illuminated by both direct rays coming from the top interface (solid arrows) and rays reflected

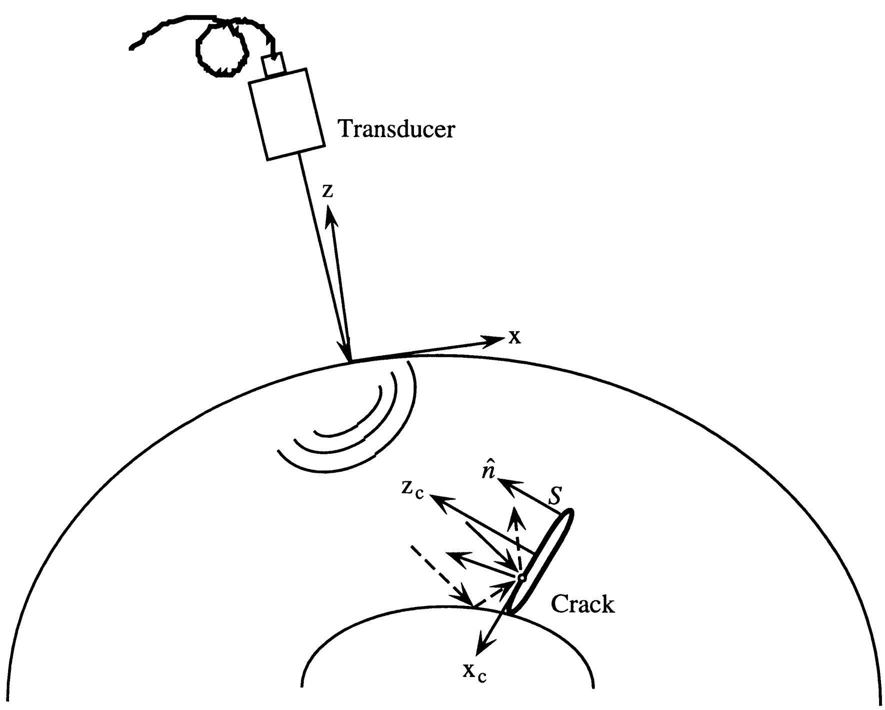


Figure 1. Geometrical configuration of the interfaces, the crack and the coordinate systems.

from the bottom interface (dashed arrows). The coordinate system associated with the crack (x_c,y_c,z_c) is centered in the middle of the rectangular crack, where z_c axis is normal to the plane of the crack and x_c and y_c are along width and length of the crack. The vector $\hat{n}$ is then along z_c. Equation (2) can then be written in crack coordinate system as

$$\delta\Gamma(\omega) = \frac{1}{4p} \int_S (V_x \ \sigma_{xz} + V_y \ \sigma_{yz} + V_z \ \sigma_{zz}) \ dS \tag{3}$$

In equation (3), V_x,V_y and V_z are velocities which occur in the presence of the flaw, and σ_{xz}, σ_{yx} and σ_{zz} are stresses which occur in absence of the flaw. To compute the integral in equation (3), Kirchhoff approximation is used, and it is assumed that only one side of the crack is isonified by the transducer. It must be noted that in the formulation presented here, the tip diffraction is not considered, and Kirchhoff approximation would fail if the crack is isonified at large angles with respect to z axis of the crack (z_c).

The stresses and velocities in equation (3) can be presented as

$$\sigma_{xz} = C_{55} \left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x} \right) \tag{4}$$

$$\sigma_{yz} = C_{44} \left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y} \right) \tag{5}$$

$$\sigma_{zz} = C_{13} \frac{\partial u_x}{\partial x} + C_{23} \frac{\partial u_y}{\partial y} + C_{33} \frac{\partial u_z}{\partial z} \tag{6}$$

$$C_{33} = \rho \ V_l^2 \ , \ C_{44} = C_{55} = \rho \ V_s^2 \ , \ C_{13} = C_{23} = C_{11} - 2 \ C_{44} \tag{7}$$

$$V_{x,y,z} = -i \ \omega \ u_{x,y,z} \tag{8}$$

where u_x, u_y and u_z are displacements in x_c, y_c and z_c directions of the crack coordinate system, and V_l, V_s and ρ are longitudinal and shear velocities and the density. The displacement fields are computed using the numerical procedure described last year [1].

<u>Reference Signal</u>

The change in reflection coefficient $\delta\Gamma$ is frequency dependent. Therefore, to predict the response from a crack, the Fourier spectrum of that signal must be used. To determine the observed voltage, this reflection coefficient must be multiplied by the spectrum of a signal emitted by the transducer, which can be determined from a reference, pulse-echo signal from a known surface (see Figure 2). A measurement model is then used to correct for the effects of beam diffraction, reflection coefficient, attenuation and phase changes on the reference signal. The output of the measurement model would be the spectrum of the signal emitted by the transducer. Finally, this spectrum is convolved with the crack model to predict the signal observed in the laboratory.

EXAMPLE PROBLEM

A model problem was chosen, and the above equations were used to find the effects of curved interfaces on the response from a crack. A 2 MHz, 1.27 cm diameter planar transducer with Gaussian radiation pattern was chosen to excite a beam which propagated through a cylindrical interface with a radius of curvature of 10 cm. The transducer was assumed to be radiating from water to a steel cylinder with a water path of 5cm. Figure 3

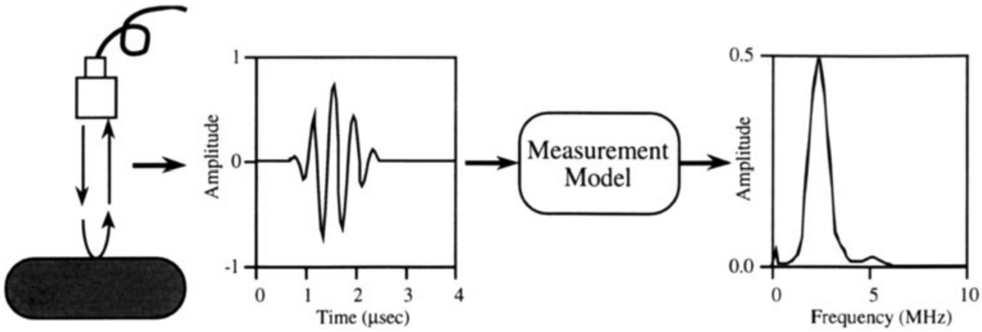


Figure 2. Schematic drawing of finding frequency spectrum of signal emitted by a transducer.

shows the schematic drawing of the model problem. The bottom of the sample was assumed to be flat, and a surface-breaking crack was considered to be located perpendicular to the bottom surface, and always facing the incoming beam. The incident angle, θ_i, was chosen such that the transmission angle, θ_t remained at 45 °. The azimuthal angle ϕ_i was changed from 0° to 90° to investigate the effects of propagation through planes other than the plane of symmetry of the interface. The crack size was also changed to explore its influence on the ultrasonic response.

To simulate an experiment using our model, an input reference signal is needed. A pulse-echo signal reflected from the top surface of a steel sample was used. The measurement model embedded in our model corrected that reference signal to achieve the signal emitted by the transducer. The other input to the model are the geometry of the sample, incident and reflected angles, and the location of the crack.

RESULTS

To observe the changes in ultrasonic response from the crack due to variation in azimuthal angle, simulations were done using ϕ_t equal to 0°, 30° and 90°. Also, in each case both the length and depth of the crack were changed. Figures 4 to 6 show the results of the simulations using our model for each azimuthal angle. In the figures, graphs "a" show the effects of increase in the crack depth, and graphs "b" show the effects of increase in crack length. Also, in each graph the incident beam pattern normal to the propagation direction in the vicinity of the crack is shown. The horizontal axes shown in the beam patterns are along the length of the crack (in the plane of the surface).

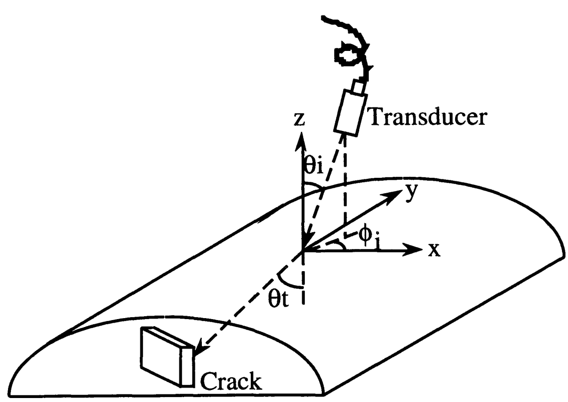


Figure 3. Schematic drawing of example problem.

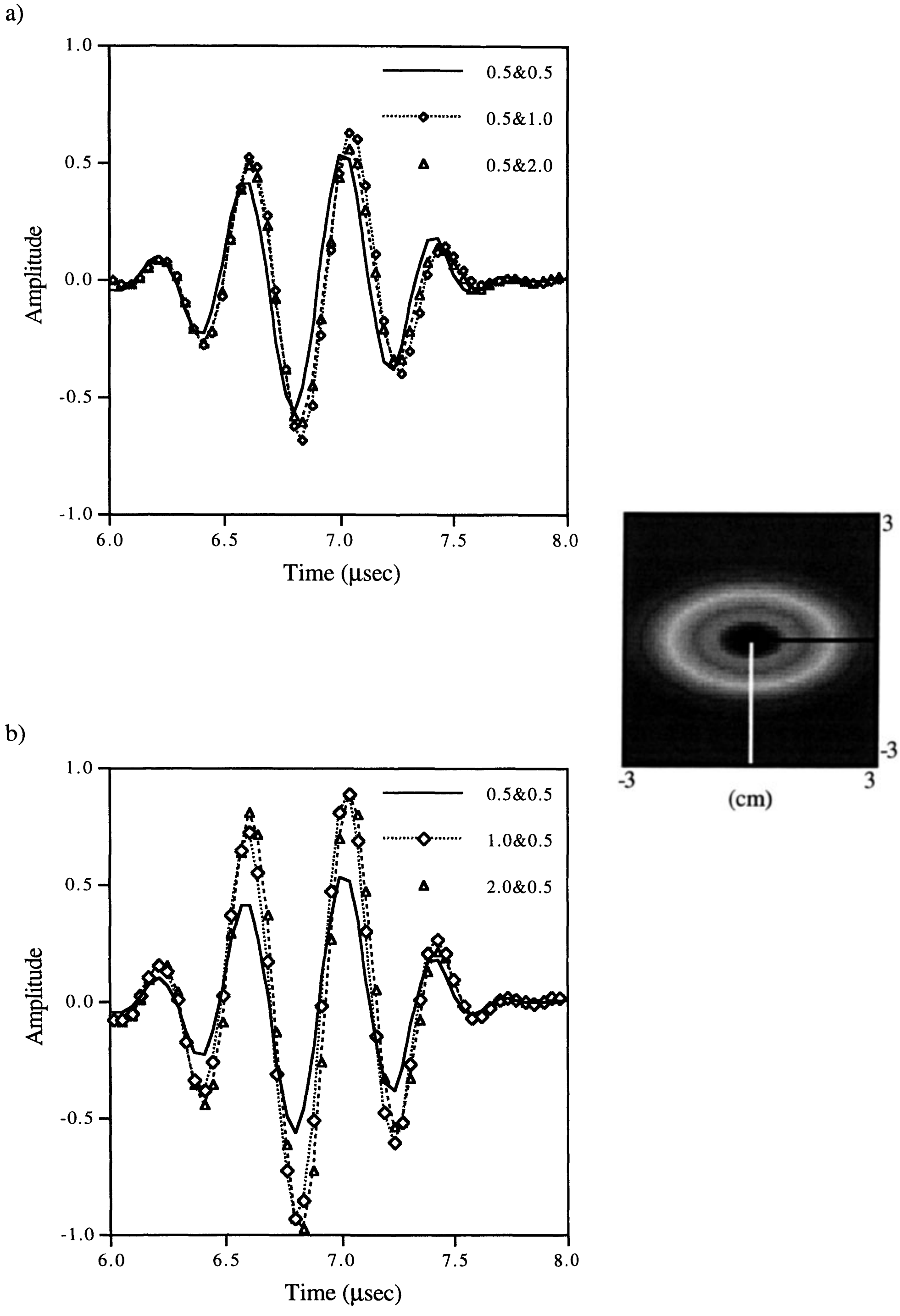
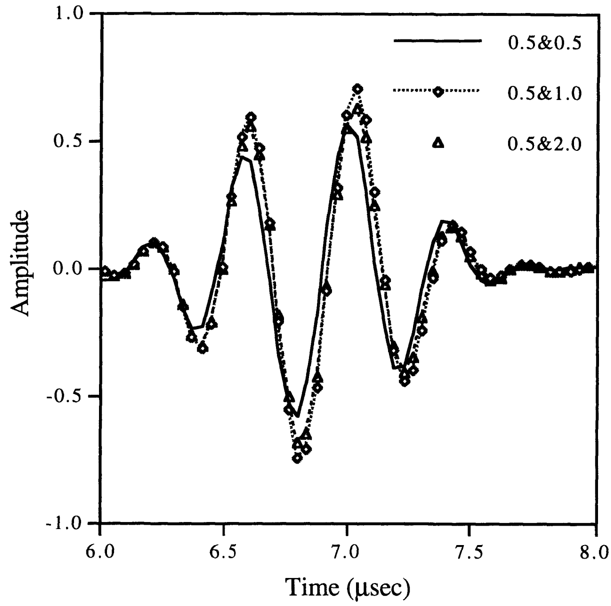
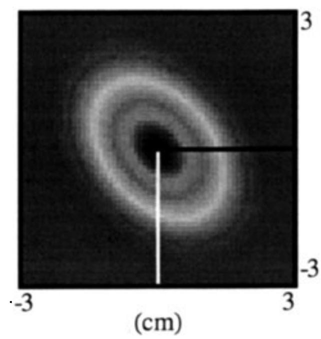


Figure 4. Response from the crack for 0° azimuthal angle, a) variation with crack depth in centimeters , b) variation with crack length in centimeters.

a)





b)

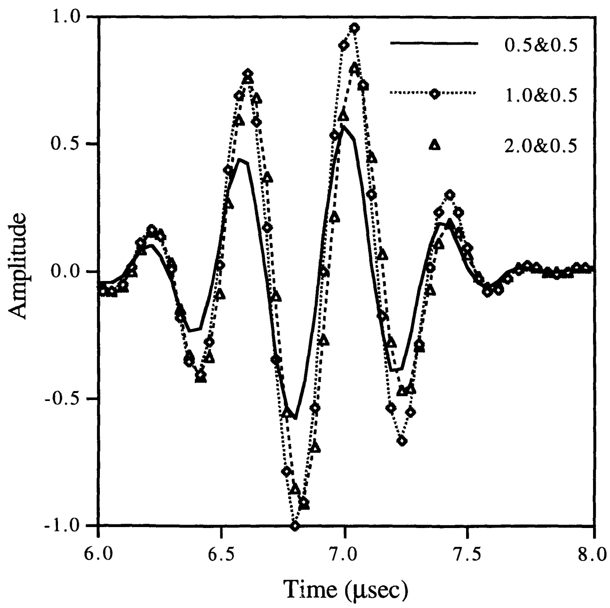
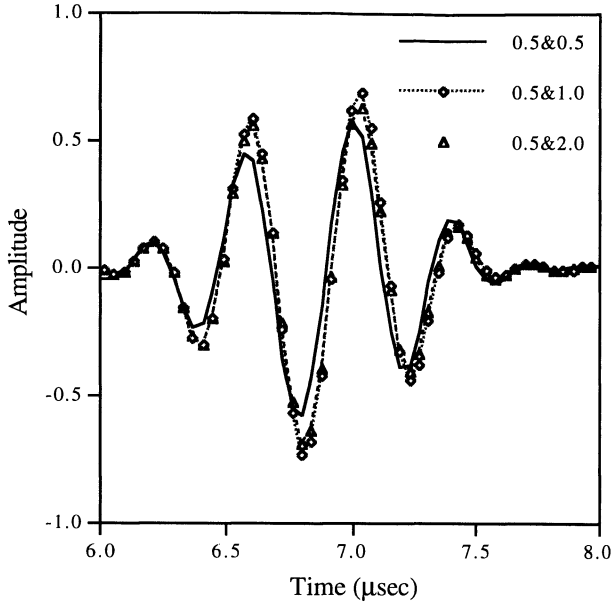
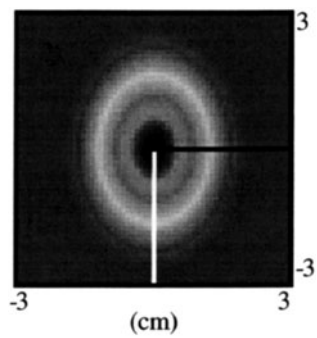


Figure 5. Response from the crack for 30° azimuthal angle, a) variation with crack depth in centimeters , b) variation with crack length in centimeters.

a)





b)

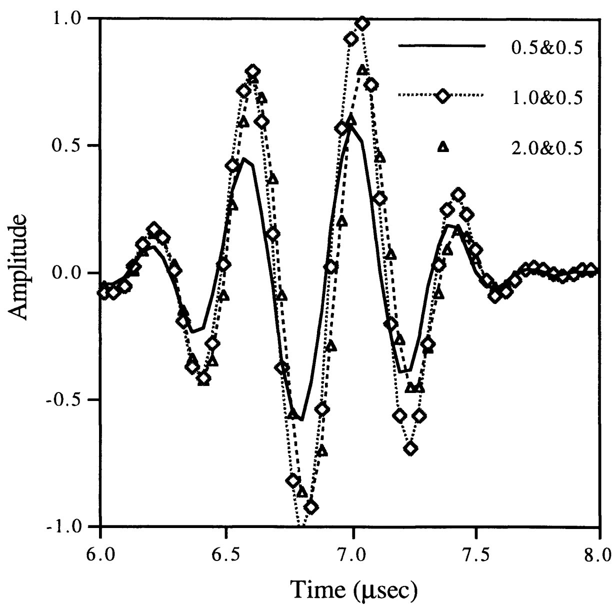


Figure 6. Response from the crack for 90° azimuthal angle, a) variation with crack depth in centimeters , b) variation with crack length in centimeters.

DISCUSSION

The beam profile shown in Figure 4 (0° azimuthal angle) shows elongation of the beam along the length of the crack, and Figure 6 (90° azimuthal angle) shows contraction of the beam along the length of the crack. Therefore, it was expected to see more increase in signal from the crack when the crack size is increased along length in 0° case, and along depth in 90° case. However, it was noticed that the response from the crack is more complicated. In particular, there are cases in which the crack response varies with crack size in an oscillatory fashion. If the beam interacting with the crack contained planar wavefronts (parallel rays), then all points on the crack face would contribute to the corner trap signal in phase. Due to the proximity and finite dimension of the transducer, the rays are not parallel and the beam does not contain planar wavefronts. Consequently, all points on the crack face do not contribute in phase. The oscillations in signals as crack size increases are the results of partial interferences in those regions. This explains why there are some decrease in signals when the size of the crack is increased.

CONCLUSION

In this study, the pulse/echo ultrasonic response from inner wall cracks with arbitrary orientation was modeled. This model considers the propagation of Gaussian beams incident in planes not containing the principle radii of curvature of an interface. The results showed that an important factor in predicting signals is the curvature of the phase of the beam interacting with the crack. In some cases this phenomena caused the signal to decrease when crack size increased.

The future work will be to refine the existing software for predicting the response from the crack and to study the physical significance of such phenomena. Furthermore, experiments will be performed to validate the presented results.

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