PREDICTION OF SURFACE INDUCED ULTRASONIC BEAM DISTORTIONS

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INTRODUCTION

One factor which influences the performance of ultrasonic examinations is the condition of the surface of a component through which the ultrasound must pass to enter the material. Often in nuclear reactor components, factors such as weld overlays, claddings, and diametrical shrink can give part surfaces a wavy, corrugated, or abruptly stepped topography. Having to pass an ultrasonic probe over such a surface during an inspection can result in a redirection of beam energy, beam partitioning, or possibly a partial truncation of the beam. These factors could leave regions of the part uninspected or give rise to mislocation of defects or geometrical reflectors.

Based on a review of the literature and ASME Codes, Good [1] has provided estimates of what surface conditions are likely to exist in the field. One such condition, illustrated in Fig. 1, is an abrupt discontinuity due to an unground or partially ground circumferential weld. Good estimates that there may exist in the field steps of this nature as large as 1.5 mm. The object of this work has been to develop a model to quantify the effects of irregular surface conditions such as this on ultrasonic beams and ultimately on the performance of ultrasonic examinations. The initial effort has been directed at modeling beam transmission through a surface with a step discontinuity, the results of which are reported here.

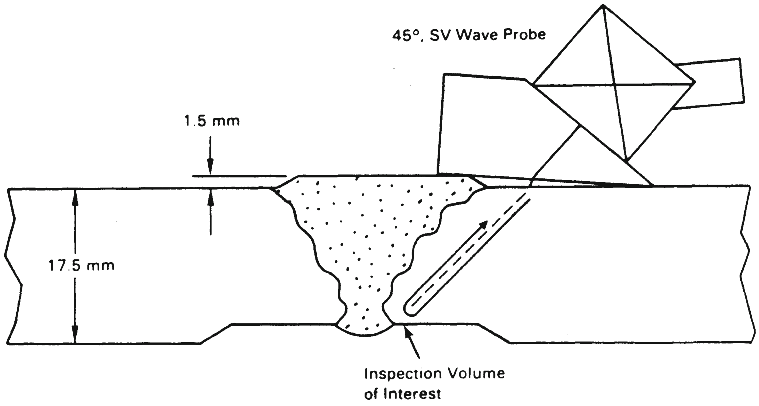


Fig. 1. A 1.5 mm Abrupt Surface Discontinuity Causing Ultrasonic Field distortion (after Good [1]).

ELEMENTS OF MODEL

The model is based on the Gauss-Hermite beam theory which has been developed over the past several years for ultrasonic beam propagation in fluid, isotropic solid, and anisotropic solid media [2-6]. Briefly, the radiation pattern of an ultrasonic beam propagating in the z-direction is represented in the form (harmonic time dependence assumed)

$$u(x,y,z)=\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}C_{mn}U_{mn}(x,y,z) \tag{1}$$

where the U_{mn} are Gauss-Hermite eigenfunctions which have the form of complex Gaussian exponentials in the transverse coordinates multiplied by Hermite polynomials in the transverse coordinates, with amplitude, phase, and width parameters varying in the axial coordinate. The C_{mn} are complex constant coefficients which are found by utilizing the orthogonality property of the Gauss-Hermite functions along with the knowledge of the radiation pattern in some source plane, z=0. Generally, this is the plane containing the transducer face.

When a beam is incident on an interface between two different media, there are reflected and transmitted beams generated which generally contain aberrations due to the interface. A hybrid method of modeling the refraction and aberration of transmitted beams at planar and cylindrical interfaces has been developed and reported [3, 4]. This method uses the Gauss-Hermite model in conjunction with a ray tracing scheme in order to propagate the beam through an interface. Here, this method has been extended to a stepped interface.

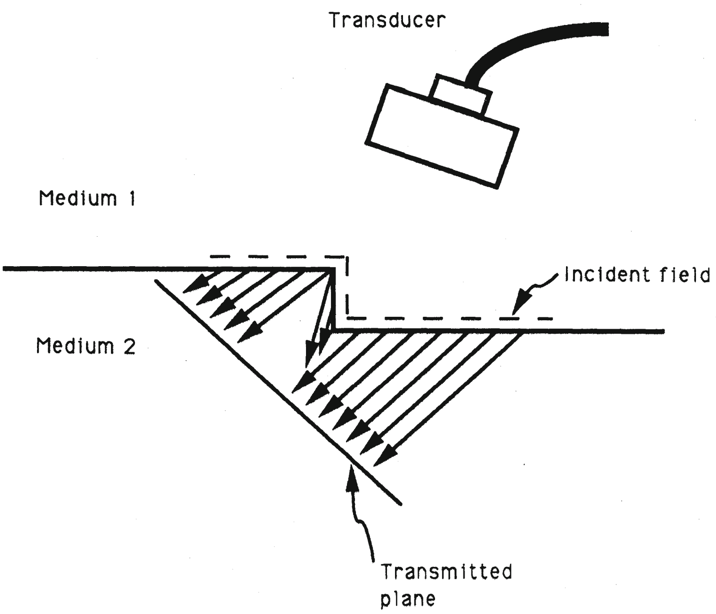


Fig. 2. Schematic illustration of ray tracing through abruptly stepped interface.

The technique is illustrated schematically in Fig. 2. The Gauss-Hermite model is used to compute an incident field at an interface which is produced by a transducer. The incident field consists of beam amplitude and phase on a grid of points at the interface. Each point on the grid is assigned a ray pointing in the direction of beam propagation. These rays are allowed to refract through the interface according to Snell's Law. These refracted rays are then traced to their intersection with an imaginary plane called the TRANSMITTED plane. The change in phase of each ray is computed based on its path length and the amplitude is modified via the transmission coefficient appropriate for its refracted angle as well as by considering the change in cross-sectional area of a "flux tube" surrounding the ray as it refracts through the interface. The details of this procedure are given in [3].

The result is that a grid of points now exists on the TRANSMITTED plane, each point having an amplitude and phase assigned to it. This data is treated as a source plane for an expansion of the beam in a Gauss-Hermite series. A set of coefficients, C_{mn}, is determined and the beam pattern may be computed anywhere in the solid via Eq. (1).

COMPARISON OF MODEL AND EXPERIMENT

As an initial test of the model, a simple experiment was conducted using a 1.85 cm thick stainless steel plate with a 0.63 mm (25 mil) step machined into it. A 0.635 cm radius broadband, planar transducer with a 5 MHz center frequency was used to insonify the plate at normal incidence in an immersion tank. This is illustrated in Fig. 3. The ultrasonic beam transmitted through the plate was mapped out using a microprobe receiver positioned below the plate directly underneath the step. The microprobe was positioned under the step since it was assumed that, for this normal incidence scan, this would be the spot most affected by the presence of the step.

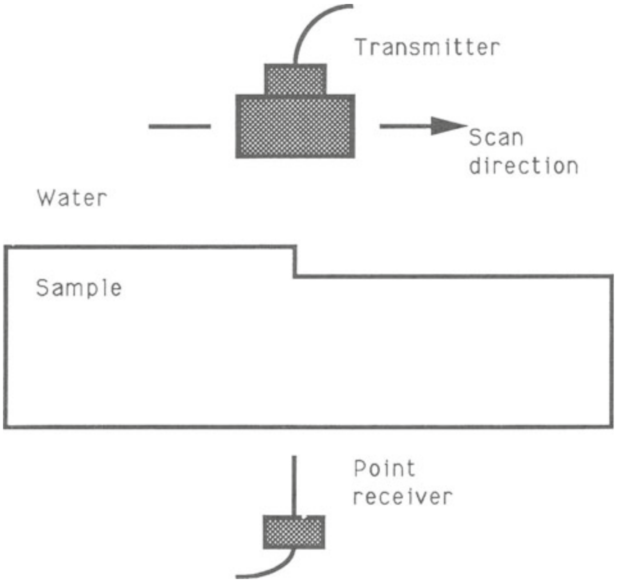


Fig. 3. Experimental scan through stepped interface.

The transmitting probe was scanned parallel to the surface with the signal received at the microprobe recorded at small increments in the scan. As a reference, the same procedure was carried out with both transmitter and receiver positioned in an area of the plate well away from the step. The recorded signals were fast-Fourier-transformed and plots were made of through transmitted amplitude vs. transmitting probe position for several frequencies. Figures 4-7 show a comparison of experiment and theory for 2, 3, 4, and 5 MHz, respectively. Both the step and reference (no step) scans are shown. The agreement between theory and experiment is good for all cases.

There is significant beam distortion at 2 and 5 MHz but very little at 3 and 4 MHz. This is understood by examining Fig. 8, which is a plot of through transmitted amplitude vs. frequency when the transmitter is positioned directly over the step and receiver. This data is normalized to the reference (no step) case. As can be seen, there are periodic nulls of amplitude with frequency (NOTE: 0-1 MHz and 8-10 MHz are outside bandwidth of transducer).

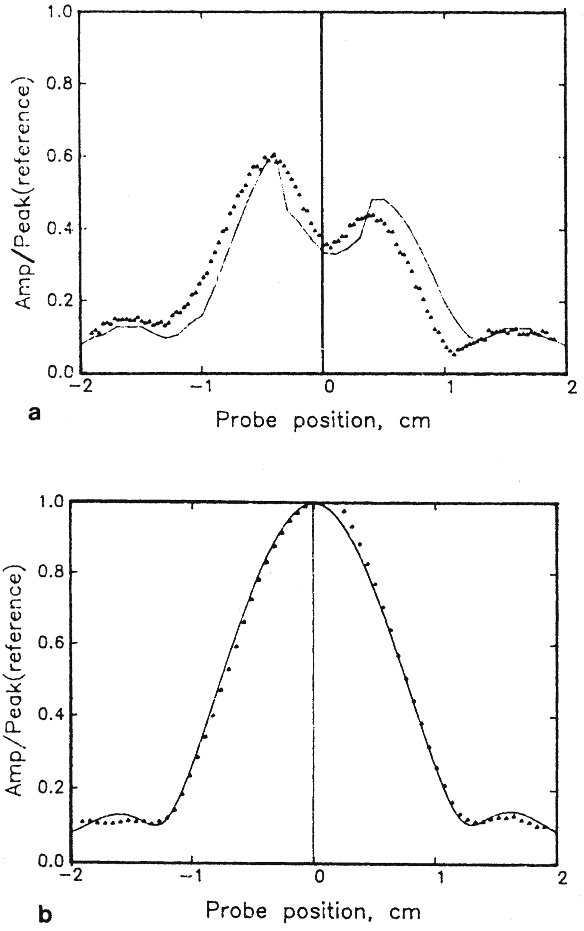
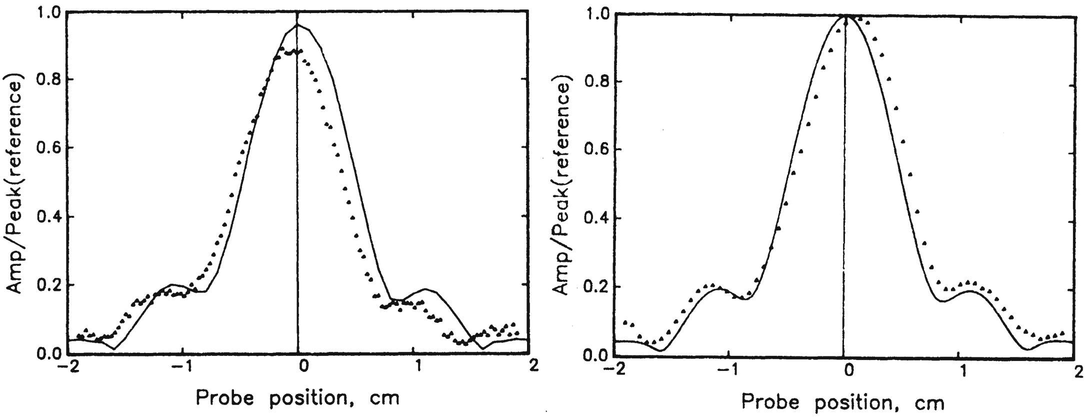


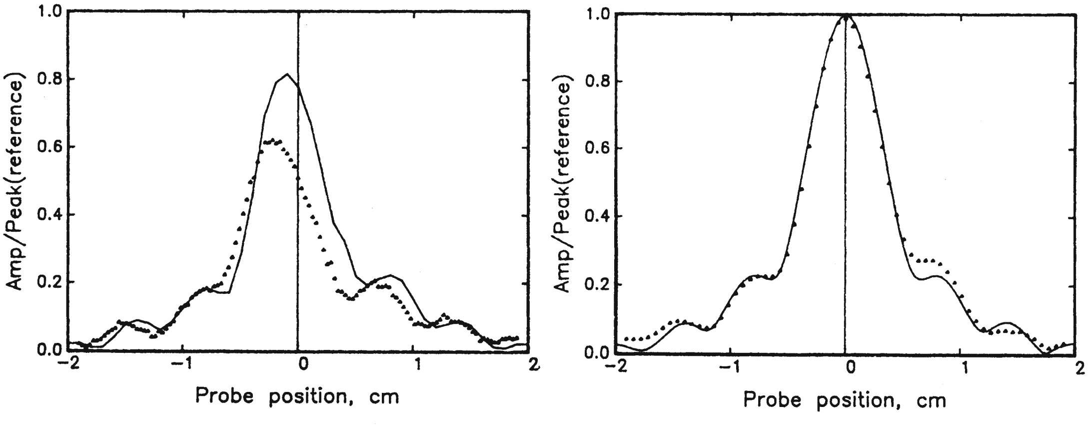
Fig. 4. Beam profile scan at 2 MHz: (a) with step, (b) reference (no step). (Solid line-theory, triangles-exp.)



(a)

(b)

Fig. 5. Beam profile scan at 3 MHz: (a) with step, (b) reference (no step). (Solid line-theory, triangles-exp.)



(a)

(b)

Fig. 6. Beam profile scan at 4 MHz: (a) with step, (b) reference (no step). (Solid line-theory, triangles-exp.)

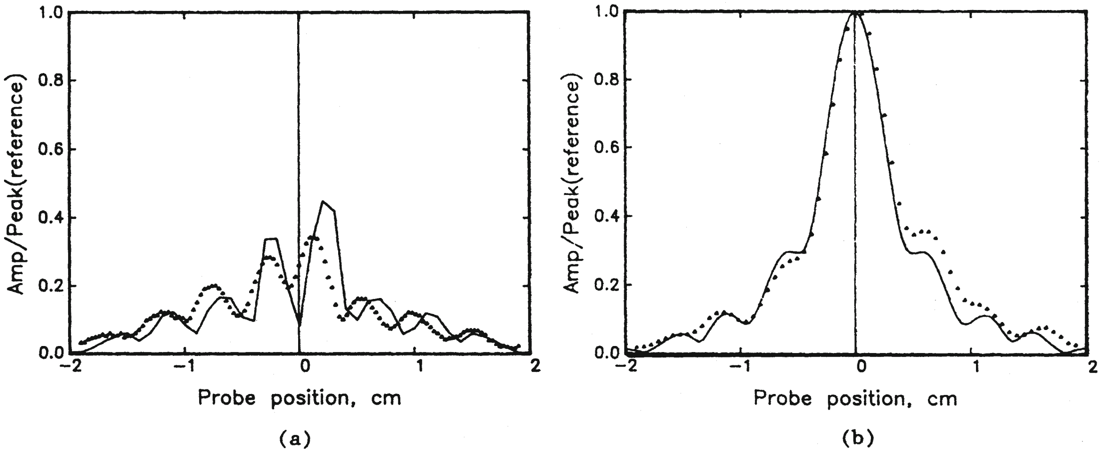


Fig. 7. Beam profile scan at 5 MHz: (a) with step, (b) reference (no step). (Solid line-theory, triangles-exp.)

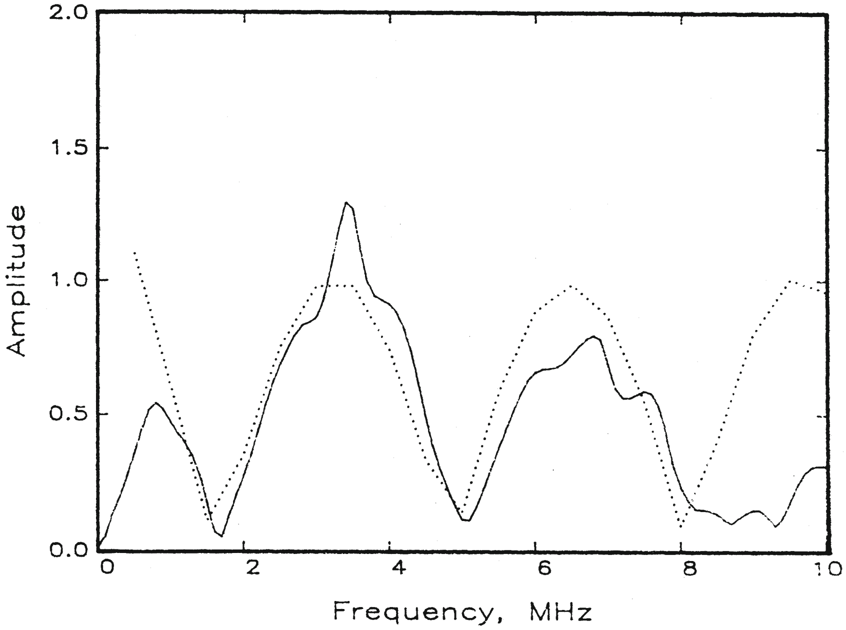


Fig. 8. Through transmitted amplitude vs. frequency in presence of step for coaxial transmitter and receiver. (Solid line-exp., dashed line-theory.)

It can be shown that these nulls occur at frequencies given by

$$f = nV_sV_w/2d(V_s - V_w), \quad n = 1,3,5,... \tag{2}$$

where V_s = velocity in solid, V_w = velocity in water, and d is the step height. These frequencies correspond to the two halves of the beam (on either side of the step) being 180 degrees out of phase. This is the worst case. When n=2, 4, 6, ... the two halves of the beam are in phase and there is no distortion. Referring back to Figs. 4-7, the 2 and 5 MHz cases are close to being out of phase and the 3 and 4 MHz cases are close to being in phase.

CONCLUSIONS

For the simple case examined, the model did an excellent job of predicting distorted beam profiles due to a step discontinuity on the surface of a sample. It was demonstrated that a small discontinuity can produce significant distortions which are highly frequency dependent. If one chooses the maximum beam amplitude obtained at a point in a material during a scan as a simplistic measure of the inspectibility of that point, then it is obvious that the inspectibility is degraded severely at certain frequencies due to the step, for the case shown. It is clear that surface condition plays an important role in ultrasonic examinations. It is hoped that the continuance of this work will help lead to a specification of what surface conditions are acceptable for particular inspections and what conditions are not.

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