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Experiments in the Application of Ultrasound Diffraction Tomography for Nondestructive Testing*

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Experiments in the Application of Ultrasound Diffraction Tomography for Nondestructive Testing

S. G. Azevedo and J. P. Fitch

We have designed computer programs to simulate ultrasound projection scans and to reconstruct the tomographic planar image. We have also used the reconstruction algorithm on actual test data and have obtained a crude but promising image.

Background

Over the last year, we have been exploring new methods of ultrasound imaging through the use of transmission tomography (see Box). Perhaps the best-known example of transmission tomography is the CAT scanner (computerized axial tomography scanner); this is a medical device that uses x-ray illumination projected (straight) through the human body at many angles for reconstructing a planar-section image (or "slice"), popularly known as a "CAT scan." The CAT scanner has been used successfully for several years for noninvasive examination of live tissue.

Our work is specifically concerned with industrial NDE (nondestructive evaluation) applications of ultrasound transmission tomography, which uses ultrasonic compression waves (as opposed to electromagnetic waves or photons) to inspect a wide variety of materials and objects for flaws, such as cracks, voids, inclusions, and anisotropies. The test objects for our studies generally have high indices of refraction and cause significant scattering of the insonifying wave. Because of the dominance of the scattered wavefields, the term "ultrasound *diffraction* tomography" is used to name this particular brand of transmission tomography. We expect ultrasound diffraction tomography to be a valuable new inspection method for the NDE Section at the Laboratory.

Ultrasonic waves can be transmitted and measured at many angles to reconstruct a planar-section image of an object in much the same way that x-rays are used. Ultrasound diffraction tomography has notable features in common with both x-ray transmission tomography and conventional ultrasound imaging methods: It is similar to conventional ultrasound methods in that the received signal is primarily that of scattered waves

that have been reflected, refracted, and diffracted; its relationship to x-ray tomography is briefly outlined in the Box.

Visual images of the object's internal flaws are reconstructed from the received data using a wave-scattering-model reconstruction algorithm. The task of obtaining the actual tomographic data is relatively simple and straightforward (see Box and Fig. 1). However, processing the data for reconstructing a true and clear image requires an algorithm that is especially complex for ultrasound tomography, because it must account for the significant scattering of the propagating wavefield. There are two principal reasons for the scattering: (1) the relatively large wavelengths of ultrasonic pulses,¹ and (2) as mentioned above, the strong bending of the acoustic wavefields caused by typically high indices of refraction of the objects under examination in industrial NDE work. The overall process for reconstructing the tomographic images with the wave-scattering-model algorithm is outlined in the Box and illustrated in Fig. 2(b).

It is the formulation of the reconstruction algorithm to which we are applying our major effort.

Theoretical foundations

Advances have been made recently in applying the principles of tomography to diffracting-wave systems—in particular, ultrasound systems. The theoretical foundations for our ultrasound work come primarily from work done in the medical field. Ultrasound transmission tomography has been previously attempted on biological subjects and is mathematically described in the literature.¹⁻⁴ The theoretical formulations are for

We define here the basic processes, techniques, and terms involved in "transmission tomography." The two basic processes are Data Collection and Image Reconstruction.

Data collection process

In this section, we define the basic features of the data-collection setup (or "test setup") and the energy pulses, and point out the differences between x-ray and ultrasound illumination. We give particular attention to those factors that are relevant to "ultrasound diffraction tomography," which is a hybrid offspring of x-ray transmission tomography and ultrasound methodology. The following paragraph letters (a) through (g) are keyed to Fig. 1.

(a) The test object is assigned an axis of rotation, which is aligned perpendicular to the illuminating ray path (or "propagation direction").

(b) The illuminating energy is aimed at the axis of rotation.

(c) The transmitter (c_1) and receiver (c_2) of the energy are arranged using the "pitch/catch" technique.

(d) For x-ray illumination (d_1), the transmitted energy has such high frequency that it behaves as nondiffracting particles (photons), which project straight through the object and either reach the receiver or are absorbed. X-rays are the principal energy employed in "straight-ray-path" transmission tomography.

For ultrasound illumination (d_2), the transmitted wave is a wide-band, divergent-beam (acoustic) compression pulse with wavelengths on the order of the size of the flaws being imaged. Because of these relatively long wavelengths, the insonifying waves are scattered (reflected, diffracted, and refracted) and thereby attenuated and delayed. (For our work, continuous, parallel-beam illumination is not used because of current limitations in our experimental setup—see main text.)

(e) A data reading (or "scan," or "transmission A-scan") is made by detecting the energy that has been projected through the test object and has emerged on the side opposite the transmitter. This energy is the "projected energy" or the "forward projected energy."

For x-ray illumination (e_1), the readings are essentially a count of emergent (unabsorbed) photons.

For ultrasound illumination (e_2), the readings are of the emergent compression-pulse magnitude over time.

(f) The measured data (or "actual test data," "raw data," "received data," "projection data," or "acquired wavefield") are obtained by holding the test object at one angular position and then taking a reading at each of several locations along a line perpendicular to both the ray path and the axis of rotation. The individual locations for reading the data are the "scan locations." (Numerous readings may be obtained at each scan location to improve the signal quality of the scan.) When, for a given angular position, all scans are sequentially grouped as a set, the composite entity becomes a "projection" (or "projection scan," or "transmission B-scan"). (The general mechanization of receivers for obtaining a projection is a "linear receiving array." This array can be mechanized either by translating a single receiver laterally along a line or by using multiple, fixed receivers.)

For x-ray illumination (f_1), the projection consists of multiple discrete values of x-ray intensity, or photon counts.

For ultrasound illumination (f_2), the projection consists of multiple time-domain waveforms of compression-pulse magnitude.

(g) The reconstructed visual image is of a planar section (or "slice") perpendicular to the axis of rotation.

Image reconstruction process: its validation and implementation

In this section, we outline: (1) the simulation procedures employed both in the design effort and in the final implementation, and (2) the reconstruction-process implementation. The following paragraph letters (h) through (m) are keyed to Fig. 2 as "block" identifiers.

(h) Code 1—Simulation of planar-section profile from model information, which is obtained from physical features of the test object. Purpose is to validate efficacy of model information.

(i) Code 2—Simulation (generation) of forward projections from same model information as used by code 1. Purpose is two-fold: to test reconstruction algorithm early in design effort, and [see paragraph (l)] to provide simulated projection scans to augment actual data for the reconstruction process.

(j) Measured-projection-data input and processing.

(k) Measured reference data obtained from the actual test object (without flaws) are used to remove inherent scattering effects of the flawless object.

(l) Simulated scans are generated to supplant certain projection data that cannot be obtained by our current test setup.

(m) Implementation of filtered-backpropagation technique produces tomographic planar image from the projection data.

weakly scattering objects (i.e., living tissue, which is mostly water) rather than the strongly scattering objects usually found in industrial applications. This means that the existing assumptions and equations are intrinsically inadequate for solving our tomographic problem. We have, therefore, been required to modify and supplement existing theory in order to develop our imaging model; this will be discussed in the following section on "Imaging model formulation."

However, an advantage we have in attempting to apply ultrasound tomography to industrial applications is that we have a set of *a priori* information available to us regarding the object of examination, which is not available in biological applications: We work with duplicated objects of precisely known and relatively simple geometry, and of known refractive indices. The information we have includes: (1) measured projection data obtained from a known flawless object, (2) external dimensions of the known macroscopic structure, and (3) based on the materials used, the expected internal properties for the flawless object. With this information we can generate supplemental diffracted-wave projections and, more importantly, approximations of the expected scattered field, which in theory may be used to remove the inherent scattering effects of the (flawless) object, thereby improving the imaging capability for resolving the details of internal flaws.

Status of work

In this article, we describe work-in-progress on ultrasound diffraction tomography for the NDE Section at the Laboratory. We have designed computer programs to perform the simulation of ultrasound projections and to reconstruct the tomographic planar image. We have also used the reconstruction algorithm on actual test data (from a simple but precisely configured test object) and have obtained a crude but promising image.

To obtain actual test data, we used a cylindrical (elliptical) object with known cylindrical flaws, shown in Figs. 3 and 4. The purpose of the simple test object, or "phantom," is to show feasibility. We used this particular shape because a model of it was easily computer-simulated to test the reconstruction algorithm. Due to minor equipment problems in data collection, the images, although promising, are not yet quantitative. (The test object and setup are discussed under the heading, "Test setup.")

Although we have thus far restricted our efforts to known phantom objects with good ultrasonic properties (i.e., homogeneous and isotropic) and with simple shapes, we intend to continue the work with more interesting and realistic physical structures as we better understand how to formulate and use our model-based algorithm.

Now that the Ultrasonic Test Bed Project has been reinstated at the Laboratory, it will be an

ideal facility for performing experimental tomographic scans.

Imaging model formulation

For very specialized cases, the formulation of an imaging model for diffraction tomography has been shown to be a generalization of straight-ray-path transmission tomography.^{1,5} Embodied in this generalization concept are: (1) several conditional assumptions, (2) a generalized equation for

modeling the interaction of the test object and the acoustical wavefield, and (3) a couple of approximation assumptions to enable the generalized equation to have a more directly solvable form. The generalized equation is, for the most part, directly applicable to our work. However, this is not the case with the assumptions.

We have had to supplement the approximation assumptions with some of our own *ad hoc* remedies; and the conditional assumptions only narrowly apply and nearly breakdown completely for most cases of physical diffraction phenomena.

Fig. 2(a) Validation of critical implementation processes

Fig. 2(b): Overall image reconstruction process

Fig. 2. Implementation diagrams showing: (a) application of simulation codes to validate critical implementation processes, and (b) our overall tomographic image reconstruction process. Our reconstruction algorithm is based on the filtered backpropagation technique developed by Devaney.¹¹ Blocks (h) through (m) are keyed to discussion in Box.

Fig. 3. Plexiglass test phantom (test object) for ultrasound tomography experiments, showing the three emplaced "flaws," which are cylinders filled with materials of three different refractive indices. Bottom half (without flaws) is used as a control to measure inherent scattering of the unflawed object.

The effect of this misalignment of theory is especially severe in NDE work where indices of refraction may differ between surfaces by orders of magnitude. As a result of trying to work within the framework of these assumptions, the effort to develop diffraction tomography for industrial uses has met with only limited success: Few experimental systems have been reported in the literature, and no commercial systems yet exist.¹

The conditional assumptions are listed as follows—with brief explanations. (And comments are included regarding the practical realities of current ultrasound tomographic methodology):

- (1) Scalar plane waves—the incident propagating waves are compression waves with no curvature. (Our incident beam is divergent.)
- (2) Monochromatic wave—a single frequency is insonifying the test object. (Our transmitted pulse covers a broad-band spectrum.)
- (3) Lossless environmental medium—the test object must be immersed in a medium that can be considered lossless (e.g., water). (Water is used in most experimental setups, including ours.)
- (4) Weak scattering—the linearizing approximation to the wave equations assumes that the scattering caused by the (flawless) object is weak; this is equivalent to saying that the refractive index is near unity. (For our applications, the

refractive indices are high and the scattering is strong.)

- (5) No evanescent waves—the effects of evanescent waves at the object's surface are assumed to be negligible; this is a reasonable assumption when the receiver is greater than 10 wavelengths from the object.⁶ (For our setup, using a broad-band pulse centered at 1 MHz, the receiver is greater than 10 wavelengths from the object.)

In our work, we still use assumptions (1), (3), and (5), unmodified. We force assumption (2) by taking a single frequency (for our present work, 1 MHz). Assumption (4) is not valid for the high indices of refraction found in our work. We sidestep this deficiency in two ways: As mentioned previously, we use approximations of the expected scattered field (from measured reference data of the known flawless object) to remove the inherent scattering effects of the (flawless) object, and we supplement the existing approximation assumptions with our own customized add-ons in order to better account for the refraction effects in the generalized equation.

We can model the interaction of the test object with the acoustical field by using the geometry shown in Fig. 5(a) and the following generalized equation (the inhomogeneous Helmholtz

Fig. 4. (a) Ultrasound test setup immersed in water inside ultrasound research tank, used for tomographic data collection. (b) View of rotating stage showing close-up of test phantom, transmitting transducer (right), and point-source receiving transducer (left).

Fig. 5. (a) Experiment geometry used by simulation models and reconstruction algorithm. (a), (b) together diagram the "generalized projection-slice theorem"; the theorem shows that the one-dimensional Fourier transform of a projection equals the values along an arc in the two-dimensional frequency domain. With this knowledge, the algorithm can be formulated for reconstructing the tomographic image from the projection scans.

equation), along with appropriately supplemented approximation assumptions:

$$[\nabla^2 + k_0^2]u(x,y) = -k_0^2 o(x,y)u(x,y) \quad (1)$$

where

∇ is the gradient operator;

k_0 is the wave number of the environmental (or surrounding) medium ($k_0 = 2\pi/\lambda$);

$u(x,y)$ is a scalar field variable at position (x,y) whose magnitude is a measurement of the strength of the acoustical field and is proportional to the square root of the acoustical power; and

$o(x,y)$ is the object function, which for the ultrasound problem is related to the local density and complex compressibility of the object at (x,y) , and can be further expressed in terms of the acoustic index of refraction.

The problem is then an inverse scattering problem: *Given measurements of $u(x,y)$ along a line (the linear receiving array) for many angles, θ , reconstruct the object function, $o(x,y)$.*

In general, Eq. (1) has no closed-form solution, because $o(x,y)$ is nonlinearly and nonlocally (in space) related to $u(x,y)$. However, two different approximating assumptions are commonly used to convert Eq. (1) into a more directly solvable form: They are the Born and Rytov approximations. We have used the Born approximation in our work thus far, but we plan to use the Rytov approximation in future work. The Born approximation is only marginally adequate, because it was derived specifically for the five conditional assumptions; nevertheless, we have been using it because it is the simplest constraint to incorporate into the algorithm.

For plane-wave transmission-tomography problems, Rytov is generally the approximation of choice and is used for most tomographic applications.⁷⁻⁹ Because of our plans for its application and because of its more general efficacy, we choose to discuss the Rytov approximation in the paragraphs immediately following.

Using the Rytov approximation, one can model $u(x,y)$ as consisting of a complex phase term, and then linearizing the nonlinear Riccati equation satisfied by this phase. The principal reason for the superiority of the Rytov approximation appears to be that the linearized approximations of the phase are more accurate than linearized approximations of the field amplitudes (magnitudes) themselves. The Rytov approximation handles (although somewhat crudely) multiple scattering, and it models small differences in refractive index over the object; the Born approximation has nei-

ther of these capabilities. However, a drawback to the Rytov approximation is that knowledge of the fully unwrapped phase component is required in the measured data (i.e., in the acquired wavefield), which means that it is sensitive to phase noise.

With either the Born or Rytov approximation, one can derive the equations of the generalized projection-slice theorem,¹ which is diagrammed schematically in Figs. 5(a) and 5(b), and is simply stated as follows:

The one-dimensional Fourier transform of the forward scattered field, measured on the (straight) line perpendicular to both the propagation direction and the axis of rotation at angle θ , is equal to the values of the two-dimensional Fourier transform of $o(x,y)$ along a circular arc through the origin with radius k_0 and at angle θ .

The significance of this is, of course, that one can use the one-dimensional values to obtain (reconstruct) the two-dimensional result (the image). [An interesting feature of this theorem is that it degenerates to the straight-ray-path (x-ray) projection-slice theorem in the limit as $\lambda \rightarrow 0$ (i.e., as $k_0 \rightarrow \infty$) (Ref. 5).]

We anticipate in our future work that we can forgo the use of *ad hoc* techniques for the removal of effects caused by high indices of refraction. Recently, and subsequent to our work, Devaney¹⁰ has developed a general imaging-model formulation (conforming to the generalized projection-slice theorem) for the types of structures that we are studying—that is, for known structures with large changes in refractive index. We plan to use this model in our future experimental work.

Simulation codes

Simulation codes were written for two basic purposes:

(1) Early in the design effort, to validate critical implementation processes—see Fig. 2(a), blocks (h) and (i); and

(2) In the final mechanization, to provide required auxiliary-data input to the reconstruction process—see Fig. 2(b), block (l).

Two codes were written: Code 1 (ELLIPSE) to generate planar-section profiles of a test object from model information of the test object, and Code 2 (ELLPROP) to generate forward projections expected of a test object from model information of the test object. Both codes use the

same physical description of the test object, either with or without known flaws. Code 1 is used simply to test that our model formulation is correct—purpose (1), above.

Code 2 analytically computes simulated forward projections of the test object (with or without known flaws), for the following purposes:

- *With or without flaws:* Provide simulated input (forward projections) for validation of the reconstruction methods; specifically, to test our reconstruction algorithm—purpose (1), above.

- *Without flaws:* Provide simulated forward projections to append to the left and right extremities of each measured projection scan—purpose (2), above. The simulated data is added to fill in for the data we are unable to obtain because of current equipment limitations. This procedure is our expedient solution to the “truncated-projection problem,” which we will discuss later under, “The reconstruction algorithm.”

Code 1 simulates the planar-section profiles of a test object whose body section and flaw sections are modeled as ellipses (or circles). The known flaws are modeled with different refractive indices. Body and flaw profiles are modeled as ellipses so that their parametric descriptions will be simple and their two-dimensional Fourier transforms will be analytic expressions that are easy to calculate. Shown in Fig. 6(a) is an example image made from code 1 of the so-called “Shepp-Logan head phantom,”¹¹ which contains ten ellipses. The jagged edges result from the fact that it is a 128-by-128-pixel image with no anti-aliasing.

Code 2 simulates the diffracted-wave forward projections analytically through the test object, using the model information of the object (i.e., the same input as for code 1) and the experimental geometry given in Fig. 5(a). The code simulates a phantom (a planar section) of the test object parametrically as an ellipse for which the Fourier transform is known analytically. With this information, it generates the forward projections that would be expected for the object without flaws [see Fig. 2(b), block (l)]. This data is then scaled to the actual part. Code 2 can use either the Born or Rytov approximation to the diffracted field.

We used the code 2 simulated projections in place of actual measured data to test our reconstruction algorithm [see Fig. 2(a), block (i)]. The result of a test reconstruction of the Shepp-Logan phantom from just 32 projections (128 waveforms per projection) is shown in Fig. 6(b), using a wavelength equal to the size of the smallest ellipse; notice how all features are recon-

structed. This simulation used the Born approximation. Use of this code in the actual image reconstruction process is discussed in the following section.

The reconstruction algorithm: implementation and testing

Our image reconstruction code (BACKPROP) is based on the “filtered backpropagation technique” of Devaney.¹¹ It is analogous to the filtered backprojection process for x-ray tomography but with added “depth-dependent” filters to account for diffraction effects. The basic implementation of our reconstruction process is shown in Fig. 2(b), blocks (j) and (m). Blocks (k) and (l) are both temporary expediences (as we have mentioned previously) in which: with block (k) we use approximations of the expected scattered field (i.e., measured reference data) to remove the inherent scattering effects of the (flawless) object, and with block (l) we append simulated forward projections to the measured projections to solve the truncated-projection problem (discussed later in this section). In our early design efforts, we used simulated projections (from simulation code 2) to test and validate our reconstruction algorithm—this is discussed in the previous section. A discussion of several algorithm implementations, with discussions of filtered backpropagation among them, can be found in Ref. 6.

The raw data are average-value, time-domain waveforms (Fig. 7) of the acoustic pulse, which has been transmitted through the object, received, and then digitized at 20 MHz. One waveform corresponds to a single scattered ray measured at a single point along the linear receiving array for one angular orientation of the object.

In order to reduce this waveform data to a single value for the reconstruction algorithm, we first take the one-dimensional Fourier transform (with respect to time) of each waveform. We then choose the frequency (1 MHz) of the highest-magnitude complex Fourier component of the central waveform (the one through the axis of rotation) to be the reconstruction frequency. (Assuming a linear system, this concept of selecting a single frequency for reconstruction is equivalent to having a monochromatic illumination source at that frequency. However, this assumption is not necessarily a good one in all cases.) The complex data gives both the magnitude and phase information required for the Rytov approximation. Use of time-delay information from an electronic

Fig. 6. Diffraction-tomography simulation. (a) Simulated planar-section profile of Shepp-Logan head phantom made up of ten ellipses. (b) Reconstructed image of phantom using 32 simulated projection scans.

Fig. 7. Example output waveforms of transmitter measured by receiver: (a) time-domain plot, and (b) frequency-domain plot. The signal-to-noise ratio for these plots was improved by ensemble-averaging 256 waveforms.

time reference gives an accurate estimate of the unwrapped-phase component values.

Note that any frequency could be used for the reconstruction. In fact, computing the difference between reconstructions generated at different frequency bands may prove to be another means of improving image quality by reducing uncorrelated noise or by enhancing frequency-dependent effects. Also, we have available to us other reconstruction quantities that utilize information from the entire waveform; one such quantity we plan to test is the RMS (root-mean-square) value of the pulse.

The image reconstruction process for our experiments is complicated by the *truncated-projection problem*, mentioned earlier. Since the object is wider than the transmitter (and, hence, wider than the

beam), we are dealing with limited data in that both the left and right extremities of the object are out of the field of illumination, and therefore out of the field of receiver "view."

Standard tomographic reconstruction algorithms produce severe circular artifacts when the data are truncated in this way. We chose to remedy this problem by completing the data set with simulated projection data—Fig. 2(b), block (l). Since the object's structure is known, we can simulate (construct) the expected projections; the simulated data (from code 2) is of the object without flaws. [Alternatively, if the object were one of many identical objects being inspected, the prior projections of a good part (known through other testing methods) could be used for a reference.] The simulated projections are then normalized to the actual projections and appended to them. By completing the background data (with that of the simulated flawless object), internal flaws will be displayed in the final image with more contrast and without as many artifacts. (Note that for smaller objects, where the beam completely surrounds the object, a full data set would be available without the need for augmentation with simulated data.)

Test setup

We assembled an experimental test setup to obtain actual tomographic projection data for verifying our various modeling algorithms. Figure 1 is a schematic diagram of the setup and Fig. 4 shows photographs of the actual setup.

For the experiment, we constructed a simple phantom test object (Fig. 3) that is broadly representative of the production parts we expect to see examined in NDE work at the Laboratory. The object is a 2-in.-diameter plexiglass cylinder. Three holes of different diameters were drilled half-way into the top end and filled with air, water, and epoxy. These holes and their fillings represent known flaws. The holes were drilled only half-way so that the bottom half could be used to represent the same part without flaws.

We chose a cylinder as the test object because (1) it is the shape of actual parts we expect to examine in the future, (2) it has a simple mathematical model for simulation, and (3) for each angular position, there are not excessive reflections from the front (or incident) surface, so that the penetrating energy is high for all projection angles.

Our test setup was adapted with little modification from a standard ultrasound tank normally

used for routine NDE work; the tank belongs to the ultrasonic testing lab at the Sandia National Laboratory, Livermore. The transmitter and receiver were placed on opposite sides of the test object in a pitch/catch arrangement. The transmitter is an unfocused 0.75-in. transducer mounted on a fixed arm. The receiver is a 0.05-in. transducer placed on a movable arm that scans incrementally along a straight line perpendicular to the beam and to the rotation axis; each reading records the scattered wavefield at one small "point" in space. The test object is placed on a rotating stage and centered in the insonifying beam. Movements of both the rotating stage and the receiving transducer are accurately controlled by computer to eliminate operator intervention during the data collection process. The test object, rotating stage, and transducers are immersed in water as the environmental medium.

The transmitting transducer is pulsed with a narrow-band, electronically generated impulse with a center frequency of 1 MHz. Both transducers are tuned to this frequency. Figure 7 shows output waveforms of the transmitter, measured by the receiver. Fig. 7(a) is a plot of wave magnitude vs time, and Fig. 7(b) is a plot of the frequency spectrum; plots are of a single incident wave projected through the center of the test object.

Continuous parallel waves cannot be used because of reflections from the side walls of the tank. Without the continuous parallel wave, we

are without an accurate time origin for phase information. But as we saw in the discussion of "Imaging model formulation," we need an accurate time reference so that relative phases of the scattered waves will be known. This time reference is achieved by synchronizing on the internal pulse generated by the electronics driving the transmitter. All data-collection circuits are triggered from this signal with an appropriate delay.

Test results

Projection data were collected using the test setup shown in Fig. 4. Two sample projections vs time are shown in Fig. 8 as two-dimensional images in continuous gray scale (with black being the minimum value and white the maximum value). The first [Fig. 8(a)] was made without the test object in the beam path in order to obtain the incident-beam profile; it shows that the measurements were made in the near field (i.e., it shows very little lateral spread).

The second [Fig. 8(b)] was made with the unflawed object (the lower half) in the wavefield. Notice that the central part of the waveform arrives first; this is because the acoustic propagation speed through plexiglass is greater than through water (the tank's environmental medium). Also notice that we are dealing with limited data because of the truncated-projection problem, discussed previously.

Fig. 8. Experimental projections shown in continuous tone: (a) without object in beam path and (b) with unflawed object in the wavefield. In figure (b), note that the central part of the wave arrives first because the acoustic propagation speed through plexiglass is greater than through the surrounding water.

An image from actual data was reconstructed using the image reconstruction process shown in Fig. 2(b). With the flawed test object in place, we obtained a projection at each of 180 angular positions (2-deg spacing). The 180 projections were each made up of 32 scans (digitized waveforms), which were themselves obtained from 254 readings that were ensemble-averaged 255 times to improve the signal-to-noise ratio. Because of the truncated-projection problem, simulated scans were appended at the extremities of each measured projection. The data were processed as mentioned in the section, "The reconstruction algorithm."

The frequency used in extracting the frequency-domain information was 1 MHz, which is the center frequency of the insonifying wave.

To obtain estimates of the truncated projections, we simulated projected wavefields from the known object, without knowledge of flaws.

Figure 9 shows the results achieved using the reconstruction algorithm. The three incorporated elliptical flaws are distinguishable but not with the clarity that we desire.

Conclusions

Although ultrasound tomography has met with very little success in the medical field, its potential application to NDE work is encouraging. Usable ultrasound tomography is expected to benefit many Laboratory programs requiring advanced imaging capabilities. The Sandia-Livermore ultrasonic test facility also expects to apply the benefits of these studies to their NDE work. Relatively simple modifications of the existing hardware can provide the means for collecting the projection data needed for tomography.

As yet, there are no indications of the achievable accuracy or resolution. We are currently investigating ways to improve the reconstructions through better data-collection techniques and algorithm enhancements. From initial studies done with the actual data, however, we have reason to believe that the basic algorithm discussed here will be appropriate.

There are many possible areas of study for advancing ultrasound tomography to a state where it would be a practical inspection method. Algorithm improvements are the key to improve-

Fig. 9. Reconstructed planar-section image using actual test data from our (three-flaw) test phantom (Fig. 3) and incorporating information of the unflawed structure.

ments in resolution. Incorporation of *a priori* knowledge of the object's physical features as constraints into the construction process has great potential for improving the images; this is particularly true for NDE problems where accurate object models exist in many cases. Other techniques we would like to investigate include: perturbation modeling; algebraic reconstruction; region-of-interest or limited-view; reflection mode; synthetic-aperture focusing; ray tracing; distorted-wave approximations; and density reconstruction using multiple wavelengths.

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