SINGLE SCAN

S32-39

037270

LAMB WAVE TOMOGRAPHY FOR CORROSION MAPPING

Mark K. Hinders and James C.P. McKeon[1]
Department of Applied Science
The College of William & Mary, Williamsburg, VA 23187-8795
phone: (757) 221-1519, fax: (757) 221-2050, email: hinders@as.wm.edu

ABSTRACT

As the world-wide civil aviation fleet continues to age, methods for accurately predicting the presence of structural flaws–such as hidden corrosion–that compromise airworthiness become increasingly necessary. Ultrasonic guided waves, Lamb waves, allow large sections of aircraft structures to be rapidly inspected. However, extracting quantitative information from Lamb wave data has always involved highly trained personnel with a detailed knowledge of mechanical-waveguide physics. Our work focuses on using a variety of different tomographic reconstruction techniques to graphically represent the Lamb wave data in images that can be easily interpreted by technicians. Because the velocity of Lamb waves depends on thickness, we can convert the travel times of the fundamental Lamb modes into a thickness map of the inspection region. In this paper we show results for the identification of single or multiple back-surface corrosion areas in typical aluminum aircraft skin structures.

INTRODUCTION

After nearly thirty years of clinical use, x-ray computerized tomography has become a routine medical imaging procedure, quickly providing invaluable information to physicians for both diagnosis and treatment planning. By electronically recording the x-rays which pass through the same region of the body in a number of different orientations, convolution-type reconstruction algorithms allow rapid computer reconstructions of internal structures [1]. Seismologists have developed different tomographic techniques to map subsurface structures for development of oil and mineral deposits, which have overcome the inherent geometric limitations not present in medical imaging by employing iterative reconstruction algorithms. We are interested in mapping hidden corrosion in the skins of aging aircraft. Corrosion alters the velocity of Lamb waves as they propagate through the thinned regions, and by monitoring the change in arrival time of Lamb waves traveling between two contact transducers at known separation we are able to detect areas of only a few percent thickness reduction. Although this has allowed us to locate areas of structural deterioration, it does not allow us to quantify the extent of the thinning. Tomographic reconstruction with Lamb waves allows accurate reconstruction of the variation of quantities of interest–such as thickness–throughout the region of interest without the need for highly-trained personnel to interpret Lamb wave signals.

[1]Current address: Sonix, Inc., 8700 Morrissette Drive, Springfield, VA 22152.

Previous tomographic Lamb wave work by Hutchins et al. [2] – [6] Achenbach [7] and Degertekin [8] used a parallel projection technique with the velocity and attenuation of Lamb waves as input for the reconstructions. For comparison to this earlier work, the results of a parallel projection technique for reconstruction using Lamb Wave velocity data on an aluminum plate with a thinned region are presented here. This is followed by a "crosshole" tomographic reconstruction from Lamb wave data shown for the same sample. Although the parallel projection tomographic scans give better reconstructions, the crosshole technique is a much more practical technique for aging aircraft applications. In our laboratory apparatus we are able to compare directly these two Lamb wave tomographic scanning techniques, and have begun to explore the capabilities and limitations of each.

LAMB WAVE TOMOGRAPHIC SCANNING SYSTEM

Our measurements are typically performed at a frequency-thickness of $fd \approx 2$ MHz-mm where only the lowest order symmetric and antisymmetric ($S0$ and $A0$) modes propagate appreciably. We use contact transducers excited by toneburst and then allow the Lamb wave modes to develop as the ultrasonic energy propagates. This is in contrast to other researchers who use angle-block transducers to select particular Lamb wave modes. We find that for automated scanning the careful coupling required to select particular waveguide modes via Snell's law is not practical. Instead we drive the transducers at a high enough frequency that the $S0$ mode has sufficient dispersion to give sensitivity to thickness variations, but low enough that all higher-order modes are cut off or negligible. The $S0$ mode at $fd \approx 2$ MHz-mm is appreciably faster than the $A0$ mode so that in our pitch-catch measurements the $S0$ signal will be distinct from the $A0$ signal. For corrosion detection we find it convenient to monitor changes in arrival time of the $S0$ signals, but depending on the flaws of interest we can monitor any combination of changes in arrival time or amplitude of the $S0$ and $A0$ modes. Although amplitude measurements are often most sensitive to the presence of flaws, the received signals are often more strongly affected by the variations in coupling inherent in automated scanning with contact transducers. Since tomographic reconstructions require many individual measurements to develop the projection data, we have concentrated our efforts on those measurements schemes which have the most promise for being fully automated.

Figure 1A shows schematically the geometry for parallel-projection tomography. The transducers are scanned along parallel lines with the Lamb waves propagating between them. At each position in the scan a measurement of some property of the Lamb waves, which are assumed to propagate along the straight rays shown, is recorded. Once the measurement has been done along each of the rays for that orientation, the sample is rotated by a fixed amount and the measurement is repeated. Projections consisting of seven parallel rays (transducer-pair positions) for four orientations (0, 45, 90 and 135 degrees) are shown. The "ray density" is critical to the quality of reconstruction. Note that the ray density is uniform for parallel projection tomography; this will not be the case for crosshole tomography. Having the rays pass through the region of interest from many orientations is also important to the quality of the reconstruction. The rays for parallel projection tomography cover all angles since projections must be evenly spaced over 180 degrees. This can be a disadvantage for contact scanning because a fairly large ring surrounding the region of interest (shown shaded in A) must be free of obstructions.

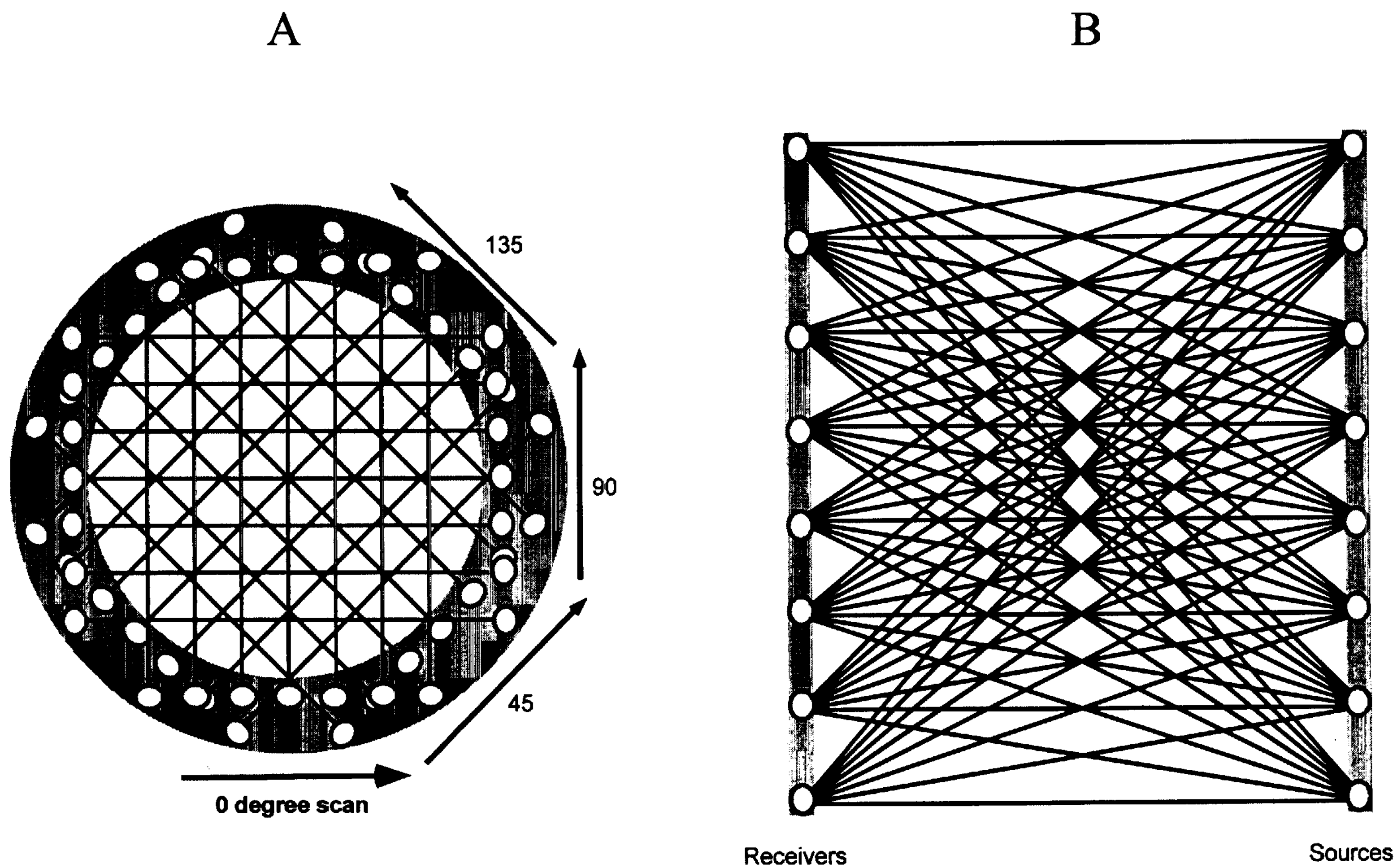


Figure 1: The scanning geometry and ray paths for parallel-projection tomography is shown (A) for the case of seven parallel rays at four orientations. Note that the ray density is uniform, and a fairly large obstruction free ring (shaded area) is necessary for contact scanning. The scanning geometry and raypaths for crosshole tomography are shown (B) for the case of eight sources and eight receivers. Note that the sixty-four raypaths produced do not provide a uniform ray density, but only two narrow obstruction free strips (shaded) are necessary for contact scanning.

Figure 1B shows the scanning geometry and ray paths for crosshole tomography for eight combinations of sources and receivers. Note how the ray density varies and that the rays do not pass through the region of interest from all orientations. These drawbacks in the reconstruction quality are offset by the increased practicality of the measurement. Namely, only two narrow strips (shaded in B) need to be free of obstructions for contact scanning. This can be especially important in aircraft applications where one wants to scan a long line of rivets or a lap joint. Since a complete scan of any large structure will be done via a "composite" of many smaller scans, the rectangular scanning of the crosshole tomography is inherently superior to the circular scanning region of the parallel projection scheme.

In our laboratory we have assembled an ultrasonic system that allows us to perform Lamb wave scans in both parallel projection and crosshole geometries. Schematics of the parallel projection and crosshole scanners are shown in Figures 2A and 2B. Broad banded contact piezoelectric transducers generate and receive the Lamb waves in a pitch-catch arrangement. For the parallel projection configuration, where the two transducers are always in the same relative orientation, shear contact transducers are automatically scanned in the direction perpendicular to the Lamb wave propagation. Two predominant signals, the lowest-order symmetric (S0 mode is first arrival) and antisymmetric (A0 is second arrival) can be observed at a frequency in the range 0.7 to 1.5 MHz. At each location of the transducer pair, the phase shift of the S0 mode is acquired through pulsed-phase-locked-loop (P2L2) circuitry. This instrument compares the phase of its pulsed output signal, which is sent to the transmitting transducer, with that of the amplified and low-pass filtered returned signal from the receiving transducer. A frequency counter is connected to the output of the P2L2, which gives information on the phase difference of the two signals in terms of frequency. The value of this reference frequency can be used to calculate both the time of flight and, because the distance between the two transducers is fixed, the integrated velocity of the Lamb waves. A normalized reference frequency provides the percentage change in these quantities, and allows us to detect changes in material properties. In our setup the sample is rotated by a fixed amount between each scan by a computer-controlled rotary table in order to obtain data from the different orientations necessary for tomographic measurements.

For the cross-borehole method, longitudinal contact transducers are scanned independently so that measurements are recorded at all of the necessary sender/receiver positions. Since the relative orientation of the transducers is constantly changing during the scan, the highly directional shear transducers can not be used even though they give a better signal in contact scanning. Instead, longitudinal contact transducers are used so that signals could be received from any angle. The received signal is sent to a digital oscilloscope, and the digitized waveform is sent to a personal computer and saved for later analysis.

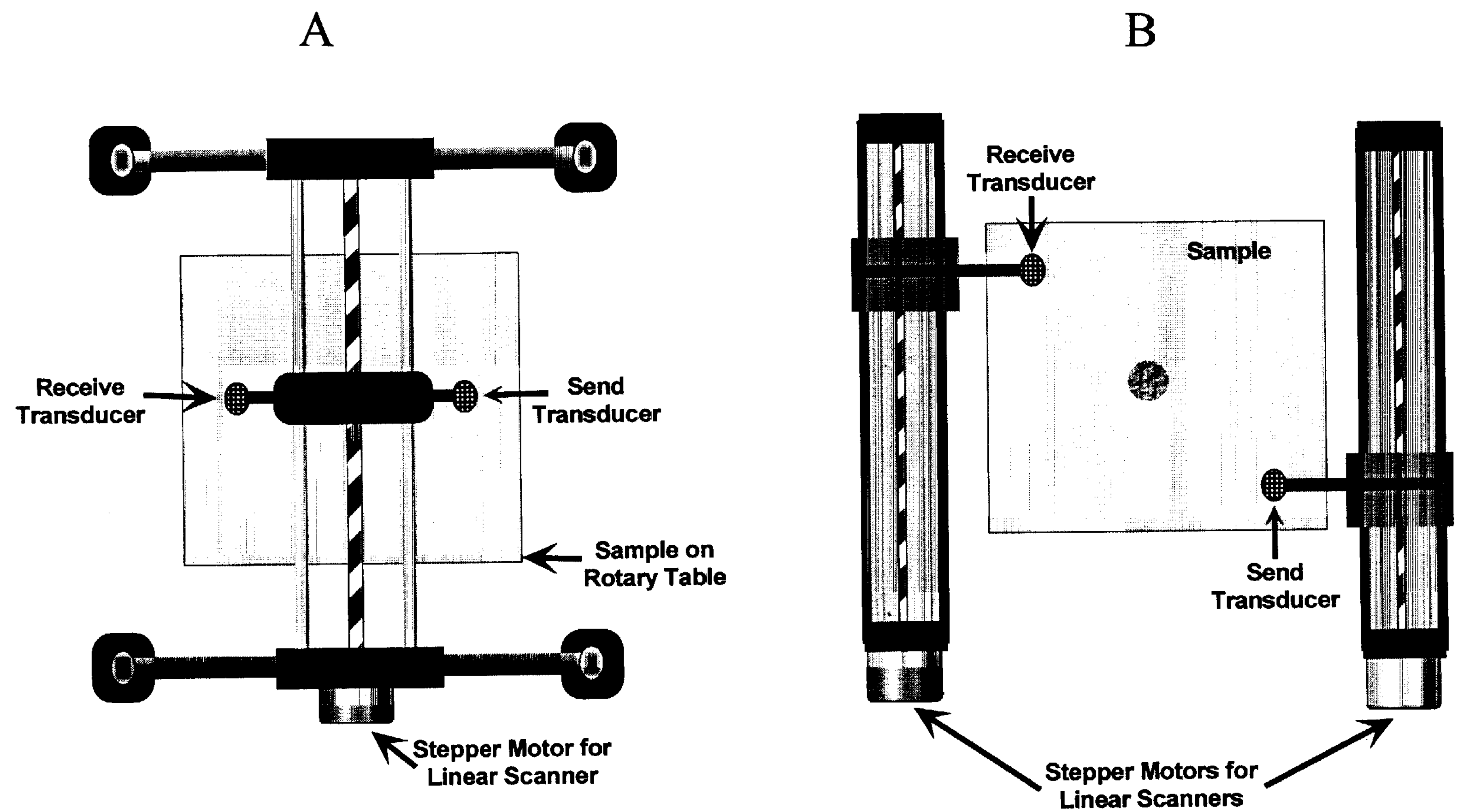


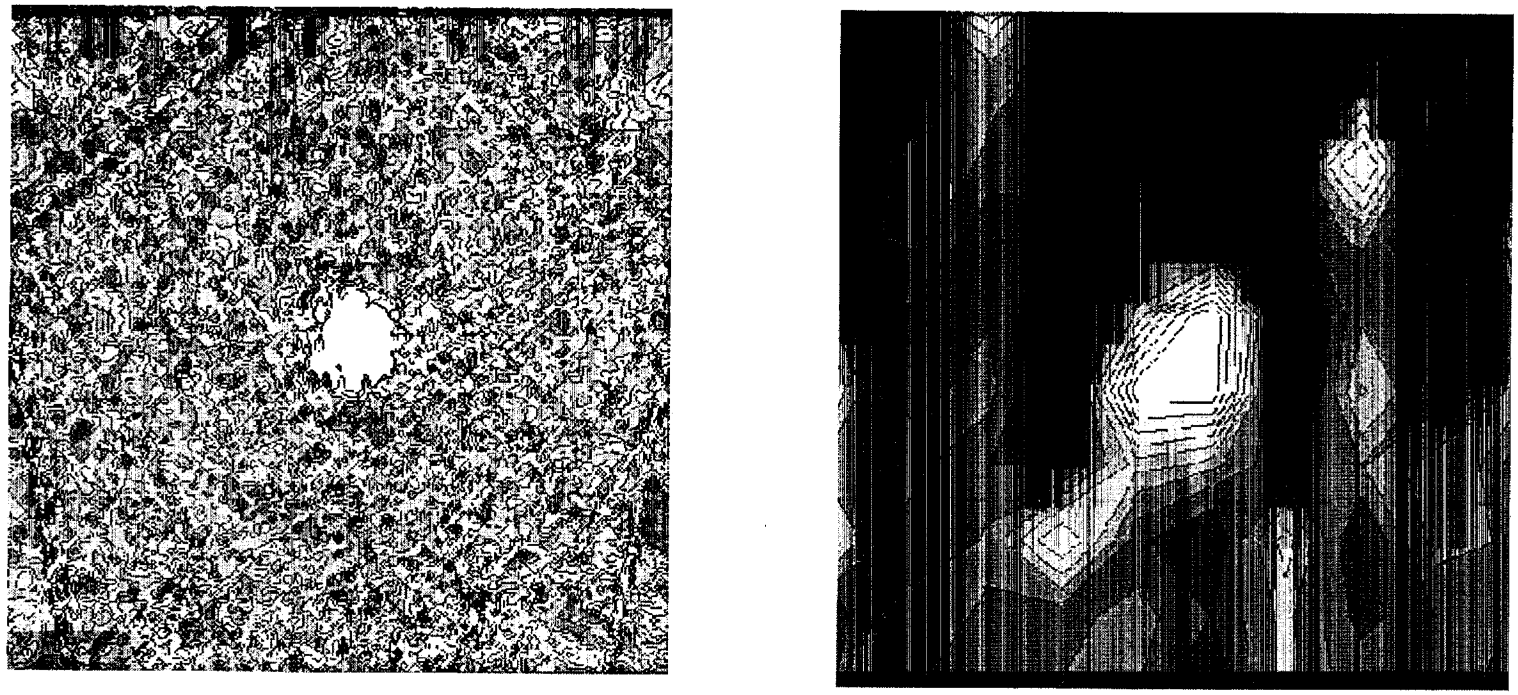
Figure 2: The parallel projection (A) and crosshole (B) scanning systems are shown here schematically. For parallel projection tomography, a pair of shear contact transducers in pitch-catch arrangement are scanned perpendicular to the direction of Lamb wave propagation. Measurements are taken at each point in the scan, and the sample is rotated by a computer controlled rotary table after each scan in order to obtain data from the different orientations. For crosshole tomography, two longitudinal contact transducers are scanned independently to the various sender/receiver positions by two computer controlled linear scanners. At each sender/receiver position, the received waveform is digitized and saved on a personal computer for later analysis.

RESULTS AND DISCUSSION

Figure 3A shows a parallel projection tomographic reconstruction contour plot of Lamb wave contact scanning data taken on a 2.45 mm thick aluminum plate with a 20 cm^2 region of 50% thickness reduction. The image covers 100×100 mm and was reconstructed from 18 projections of 100 rays each. The thinned region is shown clearly as the white region in the center of the image. Figure 3B shows a crosshole tomographic reconstruction of the same 100×100 mm region of the aluminum sample. This image was produced using the ART algorithm and 400 rays. Note that although the much lower ray density in the flaw region decreases the accuracy of the reconstruction, the location and size of the thinned region are accurately reproduced. The crosshole image is inherently lower resolution because the number of pixels corresponds to a much coarser computational grid.

One of the disadvantages of the parallel projection technique is that it requires measurements to be made from all sides of the region of interest. This is clearly impractical in any number of materials testing situations. The crosshole technique requires access to only two sides of the region, although better reconstructions will be possible with transducers scanned along a third (or even fourth) side of the region of interest. This corresponds to having a line of receivers along the surface of the ground in addition to down the two boreholes. It increases the ray density and gives a larger number of ray directions through the region of interest. Both of these increase the accuracy of the reconstruction. In the development of a practical scanning technique we have opted for a two-leg system, but the algorithms and instrumentation developed here can easily be extended. In the parallel projection tomographic scanner the travel distance of the Lamb waves is fixed, so that we can use the P2L2 to detect very small changes in arrival time due to thickness changes. This is not possible for the crosshole tomography because the path length is different for each of the rays. Instead we digitized the entire received waveform for subsequent processing to extract the arrival times of the $S0$ modes needed for input to the ART code. In our initial studies we merely identified the peaks of interest manually, but with hundreds or even thousands of such waveforms required for input to the tomographic reconstruction algorithm this was not practical. To automate this portion of the procedure, we have developed a rudimentary "expert system" which searches through the waveforms for a portion which corresponds to the characteristic $S0$ signal. It then records the time of arrival of that signal for each waveform and passes that to the tomographic code for the corresponding ray. The image shown in Figure 6 used this automated procedure without other signal or image processing.

There are a number of issues yet to be addressed in this work. Many are practical issues associated with developing rapid and operator-independent tomographic Lamb wave images. Scanning with contact transducers is slow and prone to errors from variations in coupling of the ultrasonic energy in and out of the plate. Neither of these are concerns in the laboratory, but are serious drawbacks in service. Both can be overcome by using arrays of transducers which are "electronically" scanned through all the various combinations. A ring of transducers could be used with standard fan-beam reconstructions and two or more linear arrays of transducers could be used with the crosshole algorithms. This would eliminate coupling problems, and would recover the speed inherent in Lamb wave techniques. The reconstruction algorithms run in near real time on modern PCs so there appears to be no inherent limits on implementation of this technique in the field. Although the Lamb wave physics is fairly complicated, an expert system which automatically extracts the tomographic inputs from the received waveforms will make measurements possible by technicians who neither know or care about those subtleties.



A B

Figure 3: Parallel projection (A) and cross-borehole (B) tomographic reconstruction contour plots of Lamb wave contact scanning data taken on a 2.45 mm thick aluminum plate with a 20 cm^2 region of 50% thickness reduction. The left image covers 100 mm $\times$100 mm and was reconstructed from 18 projections of 100 rays each. The thinned region (higher velocity) is shown clearly as the white region in the center of the image. The right image was produced using the ART algorithm and 400 “crosshole” rays. Note that although the much lower ray density in the flaw region decreases the accuracy of the reconstruction, both the location and size of the thinned region are accurately reproduced. The crosshole image is inherently lower resolution because the number of pixels corresponds to a much coarser computational grid.

The most serious limitation in the tomographic reconstruction algorithms that we have used in this work is that we have neglected diffraction effects. We have assumed that the thinning only caused the Lamb wave velocity to change, but that there was no scattering of the Lamb waves. For slight changes in thickness this is a reasonable assumption, but for general flaws there will always be scattering. Figure 4 shows parallel projection reconstructions of aluminum plates with small (A) and large (B) isolated through holes. Note in particular the scalloped edge and star-burst pattern around the large hole. Clearly the assumption of straight rays breaks down in this case. Incorporation of scattering effects into a Lamb wave diffraction tomography theory is the next step in our work. Mindlin's higher-order plate theory and classical scattering theory can be combined for this purpose. This will allow us to accurately map severe corrosion, as well as cracks, disbonds and other flaws which strongly scatter the Lamb waves. We also hope to be able to image subtle flaws in the presence of disruptive features such as lap joints and rivets in aircraft structures.

CONCLUSIONS

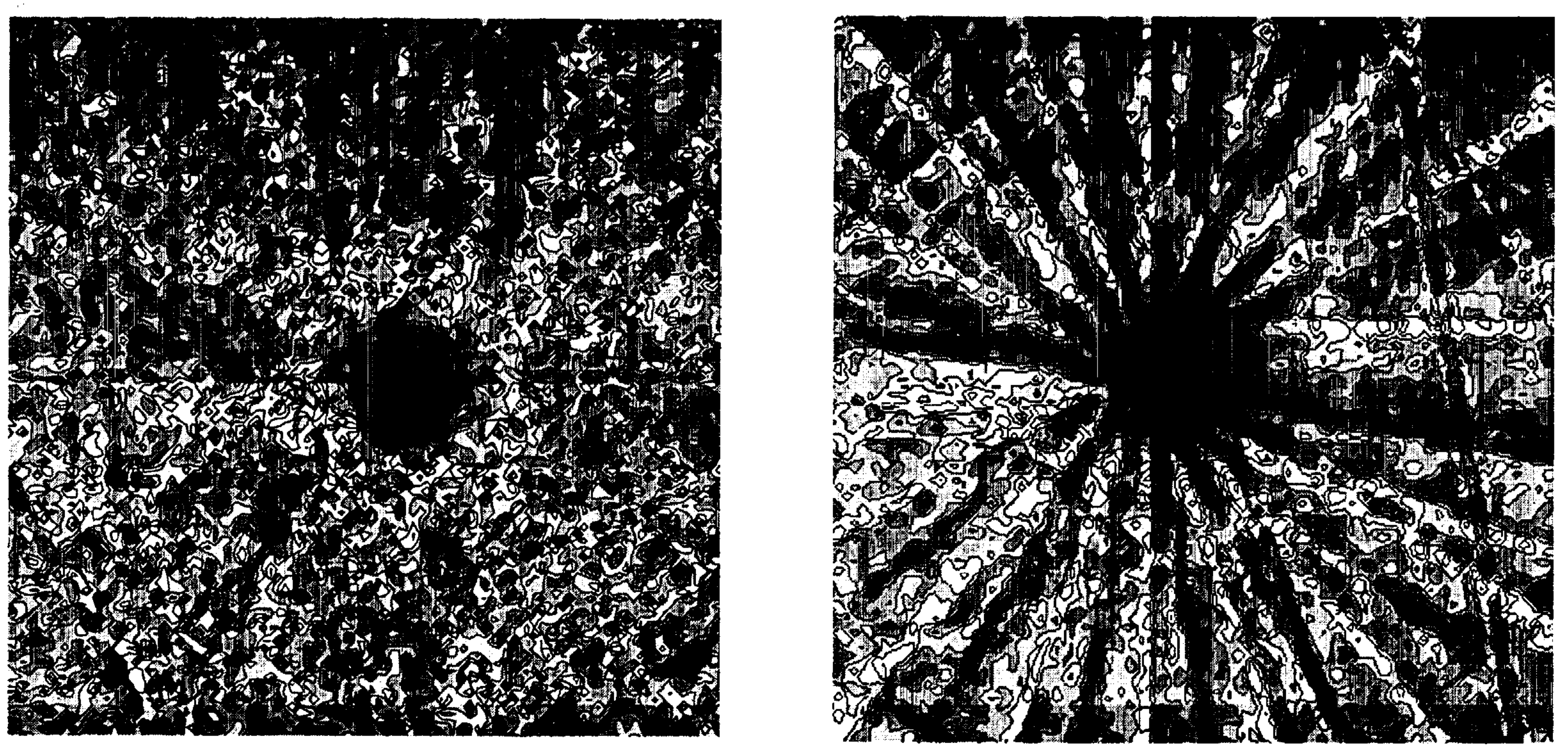
Lamb wave contact scanning is a promising technique for detecting hidden corrosion damage in aging aircraft strutures. Tomographic techniques allow the extent and severity of corrosion to be accurately mapped, without the need for highly trained personnel knowledgeable about waveguide physics. Cross-borehole Lamb wave scans have inherent advantages over parallel-projection methods, when practical implementation for aging aircraft structures is considered.

ACKNOWLEDGMENTS

The authors would like to thank Drs. Pat Johnston and Bill Winfree of NASA Langley NESB for financial and equipment support, as well as many helpful discussions. Additional support has been provided by the Office of Naval Research and by the Virginia Space Grant Consortium.

REFERENCES

1. A.C. Kak and M. Slaney: "Principles of Computerized Tomographic Imaging" (IEEE Press, New York, 1988).
2. W. Wright, D. Hutchins, D. Jansen, D. Schindel "Air- coupled Lamb wave tomography" IEEE Trans. Ultrason., Ferroelect., and Freq. Contr. 44(1) 1997 p. 53.
3. D. P. Jansen, D.A. Hutchins and J.T. Mottram, "Lamb Wave Tomography of Advanced Composite Laminates Containing Damage", Ultrasonics, Vol. 32, No. 2, p.83, (1994).
4. D.A. Hutchins, D.P. Jansen and C. Edwards, "Lamb Wave Tomography Using Non-Contact Transduction", Ultrasonics, Vol. 31, No. 2, p. 97, (1993).
5. D. P. Jansen, D. A. Hutchins "Immersion tomography using Rayleigh and Lamb waves" Ultrasonics 30(4) 1992 p. 245.
6. D. P. Jansen, D. A. Hutchins "Lamb wave tomography" 1990 Ultrasonics Symposium p. 1017.
7. Y. Nagata, J. Huang, J.D. Achenbach and S. Krishnaswamy, "Lamb Wave Tomography Using Laser-Based Ultrasonics", in Review of Progress in QNDE, Vol. 14, Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, p. 561, (1995).
8. F.L. Degertekin, J. Pei, B.T. Khuri-Yakub, K.C. Saraswat "Insitu acoustic temperature tomography of semiconductor wafers" Appl. Phys. Lett. 64 (11) p. 1338 (1994).



A B

Figure 4: Parallel projection tomographic reconstructions of aluminum plate with small (A) and large (B) isolated through holes. Note that the holes are reproduced as dark circles, indicating increased Lamb wave travel time. The image of the large hole has scalloped edges and starburst artifacts due to scattering effects.