Super-Resolution Algorithms for Ultrasonic NDE Imaging

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Generally, one of the major desired results from a nondestructive evaluation (NDE) test of a mechanical part is a segmented image or image cube showing the locations and physical characteristics of cracks, inclusions, voids, delaminations, ablations, and other flaws. A key NDE goal is to obtain images having the best possible spatio-temporal resolution. Unfortunately, the resolution of all ultrasonic measurements is severely limited by the inherent fundamental band-limited spectral transfer function of ultrasonic transducers, the uncertainty principle, and the diffraction limit. In the time domain, the transducer causes severe ringing that can limit resolution.

Previous studies have shown that this ringing can be mitigated by solving an ill-posed and ill-conditioned inverse problem. The solution uses several constraints to regularize the ill-posed problem. The algorithm consists of two steps: 1) Optimal Least Squares System Identification (Wiener) to estimate the impulse response of the material under test, given the available transducer bandwidth; and 2) Bandlimited Spectrum Extrapolation (BSE) using constrained analytic continuation to expand the available bandwidth and improve spatio-temporal resolution.

Project Goals

The goal of this project is to implement BSE in combination with the Wiener algorithm in a user-accessible form to provide an important new ultrasonics super-resolution software tool for NDE. We will 1) implement the super-resolution algorithms for processing signals (A-scans), images (B-scans), and 3-D volumes (multiple

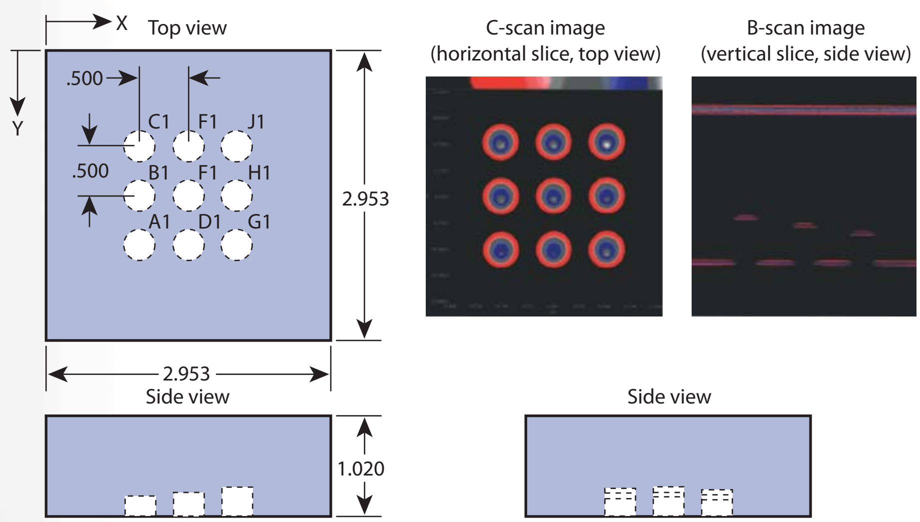

Figure 1. Line drawings (top and side views) and images of an Al block insonified with ultrasound in a water bath. The transducer was raster-scanned across the top surface in multi-monostatic mode. The drilled flat-bottom holes are apparent in the top and side views. Tape was placed over the back of the holes to prevent water from entering. The B-scan represents a vertical slice through the volume. The C-scan represents a horizontal slice through the volume. The B-scan shows the front surface of the Al block at the top, the top surface of the holes in the middle, and the back surface of the block at the bottom. It can be seen from the B-scan that the spatio-temporal resolution (multi-colored lines) is compromised by the transducer ringing.

B-scans); and 2) publish results of validation tests using simulated data and existing programmatic data.

Relevance to LLNL Mission

Resolution enhancement will directly benefit all LLNL programs that require ultrasonic imaging tests. Our project also has been useful in improving the results from time-domain reflectometry for a weapons program.

FY2006 Accomplishments and Results

This is the second year of a two-year project. All of the proposed deliverables have been produced:

1. a MATLAB implementation of the algorithms, complete with a Graphical User Interface (GUI);
2. algorithm validation tests with simulated signals;
3. algorithm validation tests with real programmatic data sets: a) an aluminum block containing known flat-bottom holes; b) a known "phantom" object consisting of concentric cylinders of various materials for sensor fusion studies with ultrasound and x-ray computed tomography; c) ultrasonic multi-monostatic data set for the Stanford Geophysical Exploration Project; d) electromagnetic time-domain reflectometry (TDR) signals for the stockpile stewardship project;
4. a report describing the algorithms, and user information for the software; and
5. technical papers describing the work.

Even greater benefit can be realized in applications in which the raw reflection wavelets are superimposed, as in thickness measurements for very thin layers; *i.e.,* adhesive thickness measurements. Here, the super-resolution algorithms can separate the reflections in time/distance.

An aluminum block (Fig. 1) with flat bottom holes is used to show the improvements obtained using the super-resolution algorithms. With respect to Fig. 2, the original data show low resolution, as the transducer ringing causes the surface edges to appear broad and unclear. The system identification (Wiener) results improve the resolution somewhat, but only within the limits of the transducer bandwidth. The Wiener plus BSE results show that the surface edges have been delineated clearly as sharp impulses. This is the desired resolution enhancement.

Related References

1. Clark, G. A., D. M. Tilly, and W. D. Cook, "Ultrasonic Signal/Image Restoration for Quantitative NDE," *NDT International,* **19**, 3, June 1986.
2. Papoulis, A., and C. Chamzas, "Improvement of Range Resolution by Spectral Extrapolation," *Ultrasonic Imaging* **1**, pp. 121-135, 1979.
3. Clark, G. A., and J. A. Jackson, "Super-Resolution Algorithms for Ultrasonic Nondestructive Evaluation Imagery," *4th Joint Meeting of the Acoustical Society of America and Acoustical Society of Japan*, Honolulu, Hawaii, November 28 – December 2, 2006.

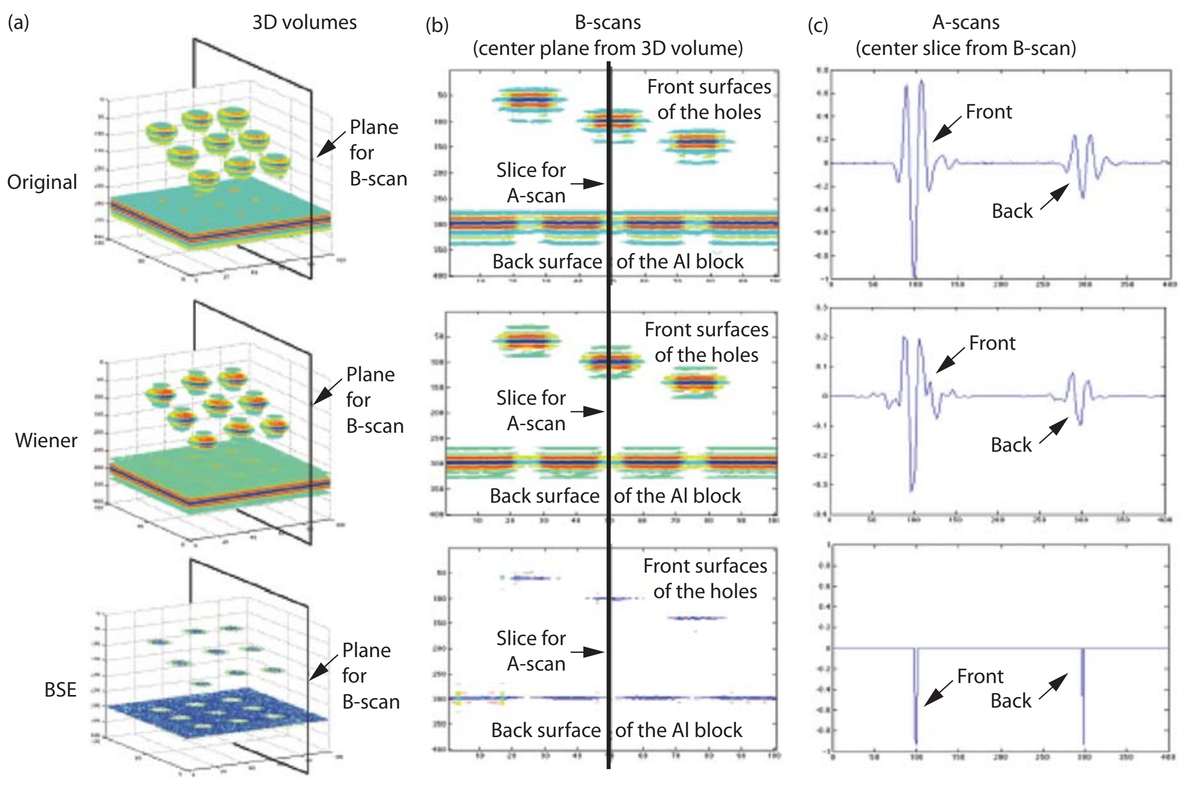

Figure 2. Processing results for experiments with the Al block in Fig. 1. Ultrasonic 3-D volume data are used. (a) Original (raw) 3-D volume, the system identification results (Wiener), and the Wiener plus BSE results. (b) Corresponding results for the B-scan (2-D vertical image (slice) depicted by the planes in (a). (c) Processing results for a single signal (A-scan) selected from the corresponding B-scans (b).