HIGH RESOLUTION LASER ULTRASOUND DETECTION OF METAL DEFECTS

Peter W. Lorraine and Ralph A. Hewes
General Electric Corporate Research and Development Center,
P.O. Box 8,
Schenectady, NY 12301

Denis Drolet
National Research Council Canada, Industrial Materials Institute,
75 de Mortagne
Boucherville, Quebec, Canada J4B 6Y4

INTRODUCTION

The standard for sensitive detection and resolution of defects in metal components is scanned focused immersion inspection to produce C-scans. Laser ultrasound, although successfully applied to composite inspection, has previously not produced comparable results in this arena.

Laser ultrasound offers many advantages over conventional piezoelectric ultrasound including the potential for rapid wide-area scanning, non-contacting (no couplant) generation and sensing, and large bandwidth. Laser ultrasonics, however, suffers from a lack of sensitivity relative to conventional ultrasonics[1]. Overall sensitivity to flaws is given by:

$$Sensitivity = T \times f(\sigma, A) \times R \ , \tag{1}$$

where $T, f(\sigma, A), R$ are terms related to the transmitted sound, the focal or imaging properties of the system determined by the flaw scattering σ and the focal aperture A, and the receiver sensitivity. The generated signal can be improved through the use of tailored surface coatings or by increasing the power in the generating source. However, this approach is limited by the onset of ablation in the target. The receiver sensitivity has been increased with improved speckle-tolerant interferometer designs, notably the confocal Fabry-Perot interferometer[2], and higher energy laser sources[3].

Ultrasonic inspection is critical to safety assurance for aircraft engines. At present, all rotating components are inspected at some stage in manufacture. The highest sensitivity and resolution require focused inspections (maximizing the middle term in Equation 1) and the standard for inspection involves scanning focused immersion transducers to produce C-scan (maximum intensity within a time gate). These transducers have limited depths-of-field that require multiple transducers or multiple scans to produce complete volume coverage. Off-the-shelf, physically focused transducers are designed to image through planar or cylindrical surfaces and are less tolerant of the curved surfaces of billets, forgings, or real parts that defocus the sound. This limits ultrasonic inspection to early in the

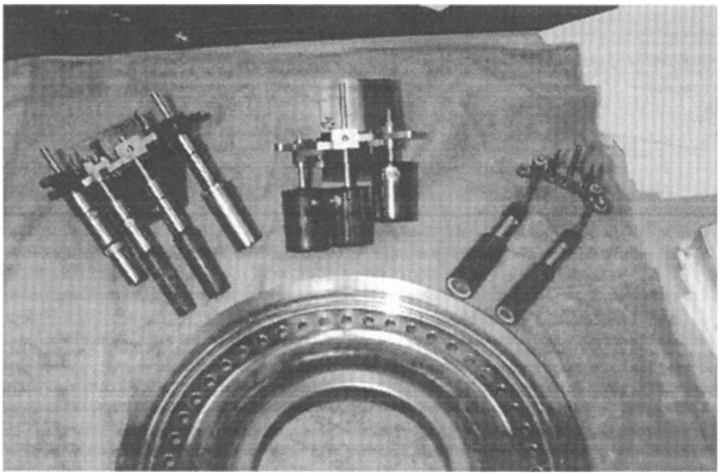


Figure 1. Complex transducer fixtures are used to inspect a curved engine part.

manufacturing process. More recently, "zoned" approaches involving multiple customized surface-tracking transducers have been applied to critical components. The time and cost to design / fabricate / characterize / and conduct these inspections is substantial.

Focusing with piezoelectric transducers may be accomplished directly with shaped transducers or with machined lenses. Because of the tremendous difference between the speed of light and sound, it is difficult to produce analagous devices for laser ultrasound. Laser ultrasound research to improve directivity is being performed by several groups[4-6]. The problem has been approached by creating patterned sources, a direct analog to the medical phased array, typically employing 8 to 16 sources. While an improvement over unfocused imaging, the high energy in the grating lobes (off-axis sound) still produces resolution and sensitivity much worse than focused immersion. On surfaces, progress has been made by focusing the laser to a ring to produce a converging surface wave, resulting in enhanced sensitivity at the direction spot [7-8]. The sensitivity of this technique is still dominated by local surface optical quality at the detection spot.

We have applied receive-aperture synthetic aperture focusing to laser ultrasound inspection to enhance signal to noise ratio (SNR) by 40 dB and produce resolution equivalent to that achieved in focused immersion systems. We have also demonstrated how this technique can be applied to rapidly inspect for surface defects with high area scan rates and sensitivity comparable to eddy current or FPI. In this work we will present experimental results for both volume and surface defect detection. Our results suggest that laser ultrasound may have practical application to several important problems.

SYNTHETIC APERTURE IMAGING AND LASER ULTRASOUND

The benefits of focused imaging are better spatial localization of flaw signals and increased sensitivity to small defects. A physically focused transducer (Figure 2) sums wavefronts arriving across the face of the piezoelectric material. A coherent sum is produced for signals arriving in phase from a localized region (the focus), and an incoherent sum is produced for all other signals. The physical focus can be realized either with a shaped lens with sound velocity different than the propagation medium or with a shaped transducer element. If the single physical transducer is replaced with multiple small

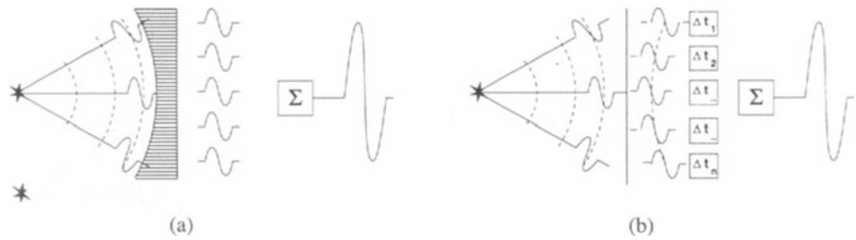


Figure 2. Focusing of sound. (a) physical transducer with shaped lens, (b) synthetic transducer.

elements, a generalized or synthetic transducer can be formed by creating arbitrary delays to move the focal region about. The conventional synthetic aperture focusing technique (SAFT) experiment typically involves a single transmitter with a diverging beam and a single receiver which are scanned to cover the desired aperture. In order to create a correctly focused image, it is necessary to know the transducer location accurately and the appropriate speed of sound[8-9]. The time delay Δt_{ij} from the observation point (x_j, y_j, z_j) to the image point (x_i, y_i, z_i) is given by:

$$\Delta t_{ij} = \left[\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2 + \left(z_i - z_j\right)^2 \right]^{1/2} / v_{material}, \qquad (2)$$

where $v_{material}$ is the speed of sound in the material. The image is formed by summing the detected waveforms $U(x_j, y_j, z_j, t)$ across the reception aperture *j*:

$$I\left(x_i, y_i, z_i\right) = \sum_j U\left(x_j, y_j, z_j, \Delta t_{ij}\right). \qquad (3)$$

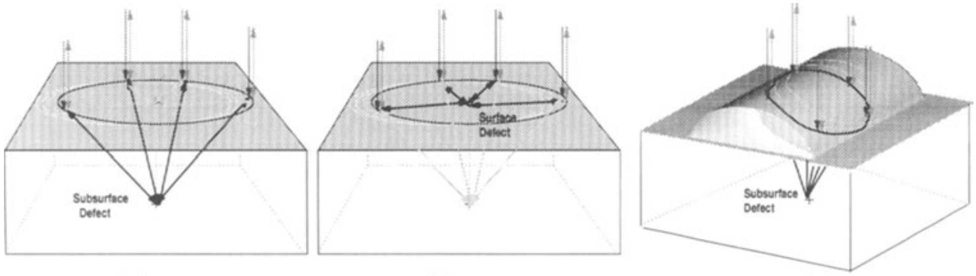
Time delays are calculated for each focal position so SAFT may focus at all depths while a physical transducer focuses only at a single depth.

The ability to handle arbitrary shapes[10] follows if one knows the surface geometry with sufficient accuracy as the algorithm requires only knowledge of the observation position with respect to the image location.

More complex processing schemes are possible. As an example, rectification of the signal prior to summation permits synthesis of phase-insensitive receivers. Adaptive correction of aberrations, while hazardous, is also possible.

The resolution of the SAFT system is determined by the beam divergence angle of the transducer, the sound frequency, the bandwidth, the speed of sound, and the location and number of observation positions. The SNR scales with $N^{1/2}$, where N is the number of aperture points. With this approach, we have been able to form receive apertures with $>10^4$ observation points, as contrasted with other work where transmit apertures have been formed with 16 laser sources.

SAFT with laser ultrasound is the same as SAFT with a very wide bandwidth piezoelectric transducer. The laser source may produce frequency components all the way to DC. The low frequency terms reduce the spatial resolution, however, high pass filtering of the raw data remedies the situation to produce resolution comparable to that obtained with focused immersion transducers. SAFT data acquired by scanning source and detection beams (not necessarily coincident). As we show later, this approach may be applied to produce images of volumetric and surface defects (Figure 3).



(a) (b) (c)

Figure 3. Laser ultrasound and SAFT. (a) volume, (b) surface, and (c) curved part imaging.

The principle implementation difficulty with SAFT has been accurately controlling the phase at the entry surface; with laser ultrasound the entry phase is guaranteed. Producing a small surface spot across curved parts is much easier with a laser than with immersion transducers. The excitation spot may be controlled to adjust the divergence angle of sound away from the source. Small spots may used to create divergent fields suitable for synthesizing very small f/# apertures.

The effect of surface roughness on volumetric inspection is to randomize the phase of the transmitted sound waves thereby preventing coherent image formation at high frequencies. For this reason, high quality ground finishes are frequently applied. A rough estimate of the round trip phase variation introduced by a surface roughness *dx* is for a plane wave traveling from a medium with sound velocity v_1 to a medium with sound velocity v_2 is given by:

$$\Delta\Phi = 4\pi f\left(\frac{v_2 - v_1}{v_2 v_1}\right)dx, \tag{4}$$

where *f* is the frequency. The phase variation for laser ultrasound is roughly $3\times$ less than that for conventional immersion ultrasound suggesting that coarser finishes may be acceptable when laser ultrasound is used for inspection.

VOLUMETRIC DEFECT DETECTION

Using a heterodyne reference-beam interferometer (HRB) as a laser ultrasound receiver, we have measured surface displacement across the surface of a 0.75" thick nickel alloy sample using a fixed ablation source on the back face. Figure 4 shows the resulting displacements as time sequence images with light and dark areas corresponding to displacement away or into the surface. The data shows a compressive (light) longitudinal pulse that spreads out as the spherical propagation shell intersects the surface, followed by a shear wave (dark) at later times. The HRB has very good low frequency response and shows the monophasic nature of the longitudinal pulse.

Figure 5 shows C-Scan images of the source region performed on the raw data, SAFT processed raw data, and SAFT processed filtered data. The raw data shows poor localization and contrast due to the lack of focus. SAFT processing the raw data produces an improved image that resembles an oil-can. Low frequency components in the raw data sum to produce a broad background. This image is equivalent to what a focused phase-insensitive receiver would produce. Filtering the raw data to eliminate low-frequency components permits formation of a high resolution image on a low background, as we would want for subsurface flaw localization. SAFT processing of filtered data in this case improves the SNR from ~6 dB in the raw data to ~40 dB in the focused image.

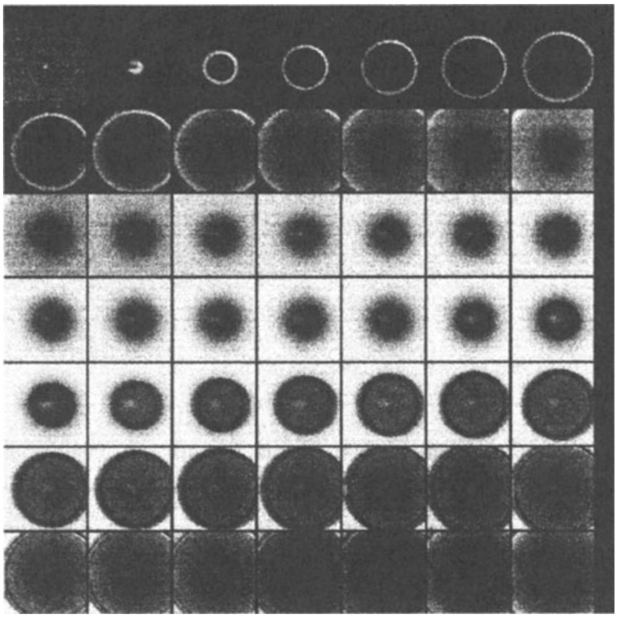
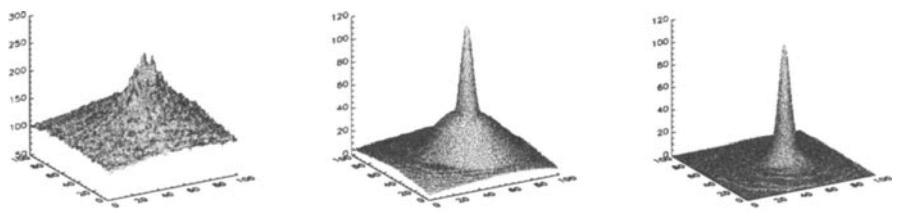


Figure 4. Time sequence surface displacement in nickel alloy sample opposite a laser source. Light is away from surface, dark in toward surface. Each image is autoscaled in intensity.

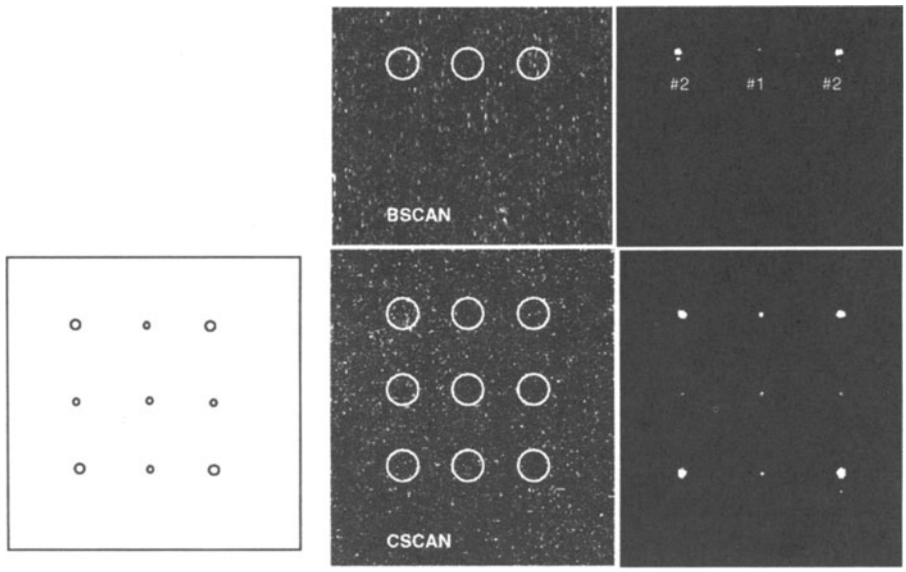


(a) (b) (c)

Figure 5. C-scans of laser ultrasound through-transmission data on RENE 95 sample. (a) raw data, (b) SAFT of raw data, (c) SAFT of filtered data.

A titanium (Ti 6-4) sample block was constructed with an array of reference manufactured defects (flat-bottom holes) 1" below the surface. The surface was scanned at 0.3 mm steps on a dense grid across the surface. At each location, a focused excimer laser pulse (~80 mJ) was used to generate ultrasound and surface-normal velocity was measured using a confocal Fabry-Perot (CFP) interfermometer employing a long-pulse Nd:YAG laser probe beam. Although the laser energy density was above the ablation threshold, we estimate $< 1\ \mu$ of material was removed.

Results are shown in Figure 6. As may be seen, neither the #1 (1/64" or 0.4 mm) nor #2 (1/32" or 0.8 mm) FBH reflectors are visible in the raw data. SAFT focusing of the data accurately focuses both sets of FBH reflectors. In this experiment, the #1 FBH reflector has an SNR of ~12 dB in the focused image. The aperture included approximately



(a) (b) (c)

Figure 6. Laser ultrasound images of subsurface defects in Ti 6-4 sample. (a) experimental sample with 5 #1 and 4 #2 FBH targets, B- and C-Scans for (b) conventional and (c) focused laser ultrasound. Flaw locations are circled.

3500 samples for a predicted SNR gain of 36 dB over the unfocused image. As the synthesized aperture averages across shot-shot variations arising from either the source laser or the local optical quality of the part, drop-out or loss of signal due to poor light return, has a greatly reduced impact on the final image.

SURFACE DEFECT DETECTION

Ultrasonic surface waves may be easily generated by a laser and can travel extended distances when the part is not immersed and loss to a surrounding water bath is eliminated. In addition, the geometric attenuation is significantly less as the sound energy spreads out in a circular annulus rather than in a spherical shell. Focusing permits us to use this information to create images of near-surface defects outside the scan area. A single scan line can be used to image the complete surface of part with high speed, resolution, and sensitivity.

A nickel alloy sample with EDM'd surface breaking holes (manufactured as an eddy current standard) was obtained. A pulsed Nd:YAG source was used to generate surface waves in the thermoelastic regime, and a confocal Fabry-Perot interferometer with a 0.5 W CW probe laser was used to detect surface motion. Data was acquired along a single scan line and reconstructed to provide an image of the flaws. Figure 7 shows a plot through the centers of the flaws showing the relative amplitudes of the signals. The smallest reflector, a hole with diameter and depth of 250 μ is clearly detected. The results shown were acquired with a 25 pulse/sec source laser. Although the effective area scan rate for this system is 1.6 $in^2 s^{-1}$, the physical limit for this technique is determined by reverberant sound considerations and is much higher.

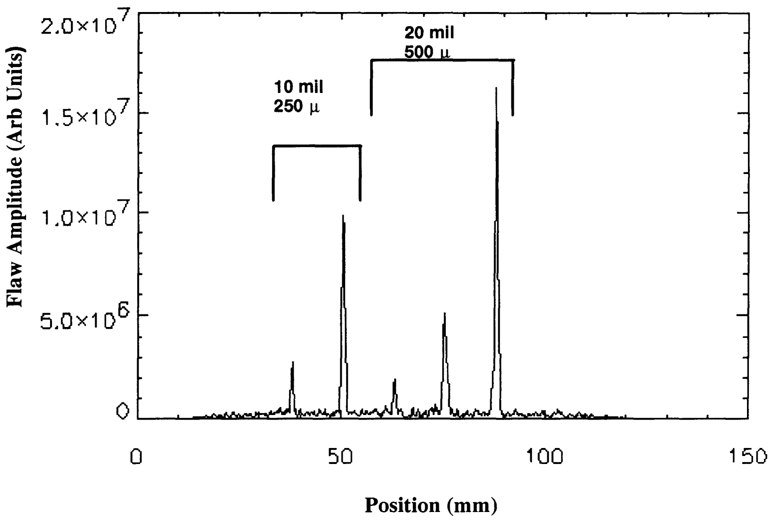


Figure 7. Laser ultrasound detection of surface defects in nickel alloy sample. Defects are EDM'd surface breaking holes with diameters/depth dimensions of 10 / 10 , 10 / 20, 20 / 5, 20 / 10, and 20 / 20 mils.

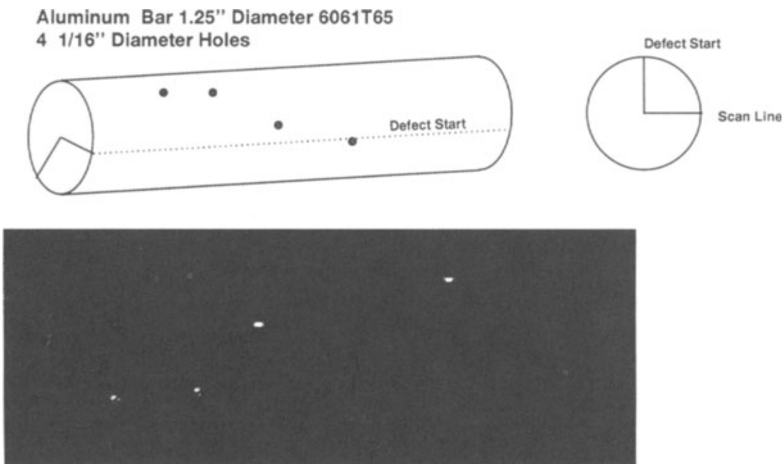


Figure 8. Laser ultrasound detection of surface defects on cylindrical aluminum sample. Defects are breaking holes.

Curved parts may also be handled as shown in Figure 8. An aluminum bar with a series of surface breaking holes was manufactured. Data was acquired along a single scan line, oriented 90 degrees of rotation from the nearest defect. The reconstructed image is shown in Figure 8 and clearly shows all flaws with excellent contrast.

In both cases, the reconstruction was accomplished with a simple time-domain SAFT algorithm with constant f/# (aperture size proportional to range). The computation required for surface reconstruction is significantly less than that for volumes due to the reduction in both the raw data and number of reconstruction points.

SUMMARY

Significant enhancements in laser ultrasound performance for detection of small defects are possible by applying synthetic focusing techniques. We have demonstrated subsurface resolution comparable to that obtained with focused piezoelectric immersion transducers. This approach provides a path for imaging through curved surfaces when geometry knowledge is added to the reconstruction algorithm. In addition, the effect of surface roughness on transmitted and received sound phase is reduced by 3× for most metals. Extended surface areas may also be imaged rapidly from limited numbers of scan lines with resolution and sensitivity comparable to eddy current or FPI inspection.

ACKNOWLEDGMENTS

The authors thank Robert Gilmore of GE CRD for help in preparing the samples and evaluating them with his ultrasonic microscope and Alain Blouin and Christian Neron of CNRC/IMI for valuable help with some of the laser ultrasound experiments. This work was conducted using General Electric Company IR&D funds.

REFERENCES

1. J. W. Wagner, "Optical Detection of Ultrasound", in Physical Acoustics, Vol XIX,), pp 201 (Academic Press, New York, 1990)
2. J-P Monchalin, and R. Heon, "Laser ultrasonic generation and optical detecion with a confocal Fabry-Perot interferometer", Mat Eval, 44 pp1231-1237 (1986)
3. A. D. W. McKie, and R.C. Addison Jr., "A laser-based ultrasound system incorporating a long-pulse probe laser for increased sensitivity", in *Review of Progress in QNDE*, edited by D.O. Thompson and D.E.Chimenti, Vol. 13, pp 517-523 (Plenum, New York, 1993),
4. A. D. W. McKie, J. W. Wagner, J. B. Spicer, and C. M. Penny, Ultrasonics 27, pp 323-330 (1989)
5. M.-H Noroy, D. Royer, and M. Fink, "Improvement in contactless generation of ultrasound with an array of thermoelastic sources", Appl. Phys.Lett. 63 (24), pp 3276-3278 (1993)
6. P. Cielo, C.K.Jen, and X. Maldague, "The converging surface acoustic wave technique", Can. J. Phys. 64, pp 1324 (1986)
7. H. I. Ringermacher, F. A. Reed, and J. R. Strife, "Laser ultrasonics for coating thickness evaluation at 1200 C", in *Review of Progress in Quantitative NDE*, edited by D.O. Thompson and D.E.Chimenti, Vol. 12, pp 549-552, (Plenum, New York, 1993)
8. R. Y. Chiao, Thomas G. Kincaid, and Robert S. Gilmore, "Ultrasonic Synthetic-Aperture Holographic Imaging", in *Review of Progress in QNDE*, edited by. D. O. Thompson and D. E. Chimenti, Vol 11 pp 813-820, (Plenum, New York, 1992).
9. L. J. Busse, H. D. Collins, and S. R. Doctor, "Review and Discussion of the development of synthetic aperture for ultrasonic testing (SAFT-UT)", U.S. D.O.E. Report, no. NUREG/CR-3265, 1984.
10. P. J. Howard and R. Y. Chiao, "Ultrasonic Maximum Aperture SAFT Imaging", in *Review of Progress in QNDE*, edited by D. O. Thompson and D. E. Chimenti, Vol 14 pp 901-908,(Plenum, New York, 1995).