Proceedings of the International Congress on Ultrasonics, Vienna, April 9-13, 2007, Paper ID 1739, Session R29: Ultrasound and lasers
doi:10.3728/ICUltrasonics.2007.Vienna.1739_sharples

Adaptive acoustics: correcting for aberration in materials with microstructure

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Abstract: Ultrasonic wavefronts may be aberrated if the material through which they are propagating has microstructure, such as metals consisting of many grains. This aberration is caused by the grains having different phase velocities for different orientations. The perturbation to the acoustic wavefront affects the accuracy and reliability of measurements and is a fundamental limit to resolution for many materials.

We have designed a closed loop system that can detect the acoustic aberrations experienced by surface acoustic waves, and customize the excitation source in real time to correct them. A light from a pulsed laser is delivered to the material via a spatial light modulator (SLM), which allows any pattern of light to be imaged onto the surface. The surface waves excited by this optical source are aberrated by the material microstructure as they propagate towards their intended focus region. This aberration is detected by an acoustic wavefront sensor, and information from this is used to customize, in real time, the SLM pattern, such that the waves will now successfully propagate to their intended focus.

As well as describing the adaptive acoustic instrument in detail, results are presented that illustrate the improvement in data that can be achieved when using aberration correction.

Key words: Acoustic imaging, aberration, laser ultrasound, wavefront sensor.

A. Introduction

Acoustic waves are sensitive to the properties of the medium through which they travel: this is what makes ultrasound so useful for NDT applications, where we may be trying to find faults (cracks, delamination) or evaluate parameters (residual stress, nonlinear response). Unfortunately, the waves may be sensitive to properties that ruin the measurements.

For example, the orientation of grains in metals affects the velocity of waves passing through them. This has a deleterious effect on the acoustic wavefront. If one tries to focus acoustic waves through this microstructure, the wavefront will tend to be aberrated, and no longer be focused at a diffraction-limited region. This will have an effect on the detected ultrasonic signal, and has implications for the probability of detection (PoD) of faults, and ultimately the resolution of the measurement system.

The greyscale images in Fig.1 illustrate the effects of aberration on focused surface acoustic waves (SAWs), which we can image using our optical scanning acoustic microscope (O-SAM), described previously [1], [2].

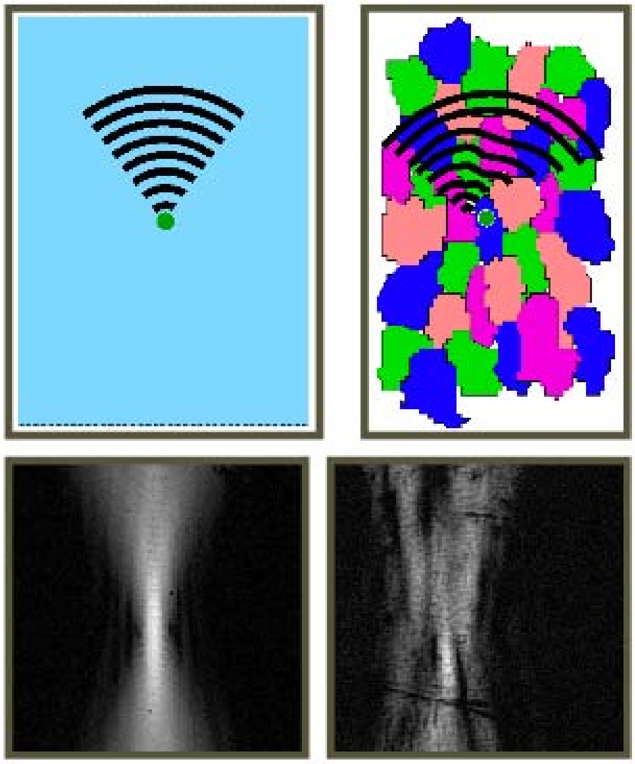

Fig.1. The figure illustrates schematically (top) and experimentally (bottom) the effects of propagating focused surface acoustic waves on the surface of an isotropic material (left), and on a material consisting of grains randomly oriented (right). The experimental images in the lower half of the figure were acquired using the O-SAM instrument, and the grey scale represents relative amplitudes of 82MHz SAWs.

On the left the waves propagate on an isotropic material and a diffraction-limited focus is achieved. On the right, the SAWs are propagating through several grains, randomly oriented. Although very little acoustic energy is absorbed, an acoustic detector at the geometric focus of the arcs would detect only a low signal. In a "normal" system this would be interpreted as a fault with the material (for example a crack) - a "false positive." If your signal is constantly dropping out due to the effects of aberration, it can make your results very difficult to interpret [3].

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B. Aberration correction in theory

We use an analogous technique to adaptive optics, used in Earth-bound astronomy [4]. The technique is illustrated schematically in Fig.2.

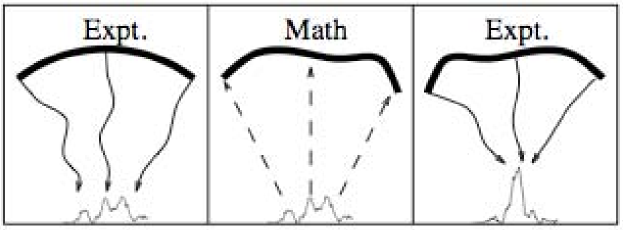

Fig.2. The figure illustrates schematically the process of acoustic aberration correction. An "ideal" source (a set of geometric arcs) is used to propagate surface acoustic waves, which are aberrated by the microstructure of the material. The aberrated wavefront is acquired in the left hand side of the figure. Using mathematics, this is back-propagated through an ideal medium to the excitation region (centre), and the difference between this and the geometrical ideal is then used as the new excitation pattern.

Instead of a "guide star" (a reference by which we can measure the aberration) we use a set of geometric arcs as the ultrasonic excitation source. This "ideal source" represents the pattern we would normally use to achieve a diffraction-limited acoustic focus, as shown on the left of Fig.1. In adaptive optics, an optical wavefront sensor (e.g. Shack-Hartmann) is used to detect the wavefront aberrations introduced by turbulence in the Earth's atmosphere. In the acoustic case, we use an acoustic wavefront sensor (AWFS) [5] across the intended focal plane, to measure the point spread function (PSF).

The information collected by the AWFS is used to calculate what the excitation source would have looked like, if the waves had been propagating on an isotropic material. This is done using back-propagation of the acoustic field by an angular spectrum technique [6]. Comparison of the calculated source with the geometric source that was actually used to excited the SAWs gives a phase error. This is then used to generate a new excitation profile. The ability to change the excitation profile is equivalent to the use of a deformable mirror in the case of optical aberration correction.

It should be noted that, instead of aberration changing with time (in the optical case), acoustic aberration changes with sample position.

C. Aberration correction in practice

Fig.3 shows the experimental system, built around the O-SAM instrument, schematically.

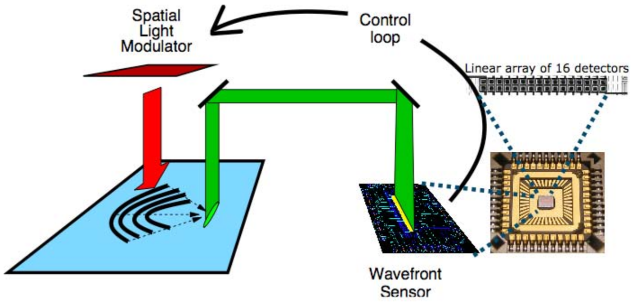

Fig.3. The figure shows schematically the process of aberration correction using the O-SAM.

Of particular note in the system is the spatial light modulator (SLM). This programmable imaging device, in combination with a fixed frequency (82MHz) Q-switched mode locked laser is used as the SAW excitation source. The AWFS is a custom linear array of 16 optical beam deflection detectors, and has been described previously [5].

Fig.4 shows experimentally the process of aberration detection and correction.

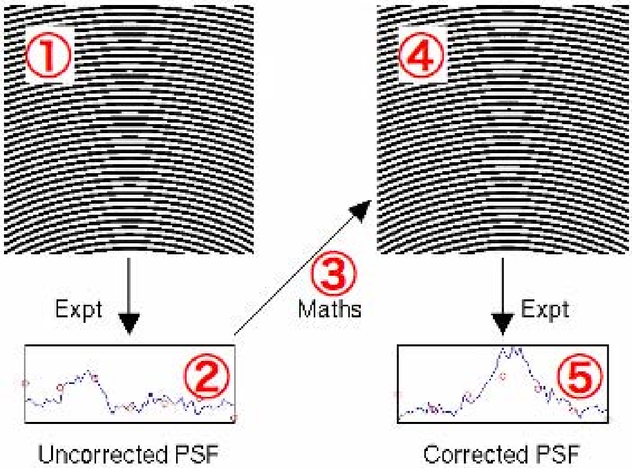

Fig.4. This figure illustrates experimentally the process of aberration detection and correction, which was illustrated schematically in Fig.2. At the top of the figure are the SLM images used to excite the waves: top left is a set of geometric arcs, top right is the corrected set of arcs. The plots in the lower half of the figure show the point spread functions across the intended focal plane. The solid blue lines were acquired by scanning a single detector across the focal plane; the red circles represent the output of the 7 active channels of the acoustic wavefront sensor.

Although the two excitation patterns look very similar, they are subtly different. The data used to generate the corrected pattern on the right was just the seven points of the AWFS that were in use. This small amount of relatively noisy data was sufficient to correct the acoustic wavefront in order to produce the much improved PSF on the right.

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D. Results

Fig.5 shows the effects of two different sorts of aberration correction. The sample used was aluminium.

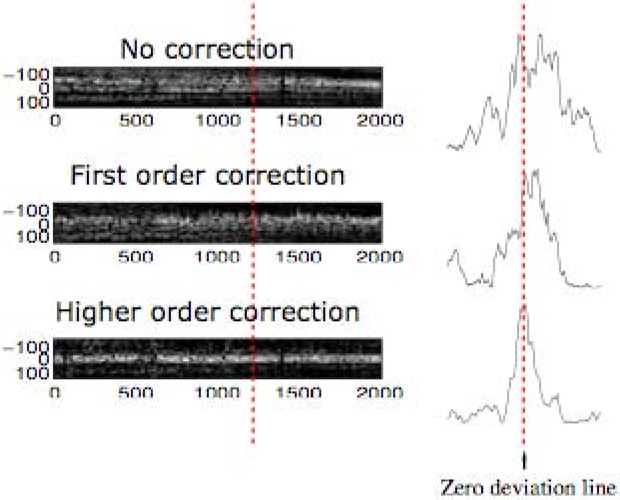

Fig.5. This figure illustrates the relative quality of data as a result of (top) no correction, (middle) first order (tilt) correction, and (bottom) higher order correction. The images on the left are *w*-scans, and represent line scans along a piece of aberrating material, in this case aluminium. The x-axis represents distance along the sample, in microns. The y-axis represents the acoustic field across the focal plane, i.e. the point spread function. The plots on the right take one point on the line and plot the three point spread functions.

At the top of the figure, no correction has been performed. Both the *w*-scan on the left, and the example PSF on the right, show the focus to be of low quality along most of the line. The middle line shows the result of simple "tilt" correction. Here, back-propagation has not been used; rather, the first order moment of the PSF has been measured, and the tilt of the arcs adjusted to attempt to re-centre this. Although the acoustic energy has generally been steered back towards the ideal position, the PSF is still broken and attenuated. The bottom section of Fig.5 shows the result of higher order aberration correction. Not only has the energy been steered back to the zero deviation line, but the amplitude has increased and the width of the PSF has been reduced.

Fig.6 illustrates both the serious effect that aberration has on the quality of acoustic data, and also the beneficial effects of performing aberration correction. The images shown are all of the same 12.5 x 25mm area of a titanium alloy.

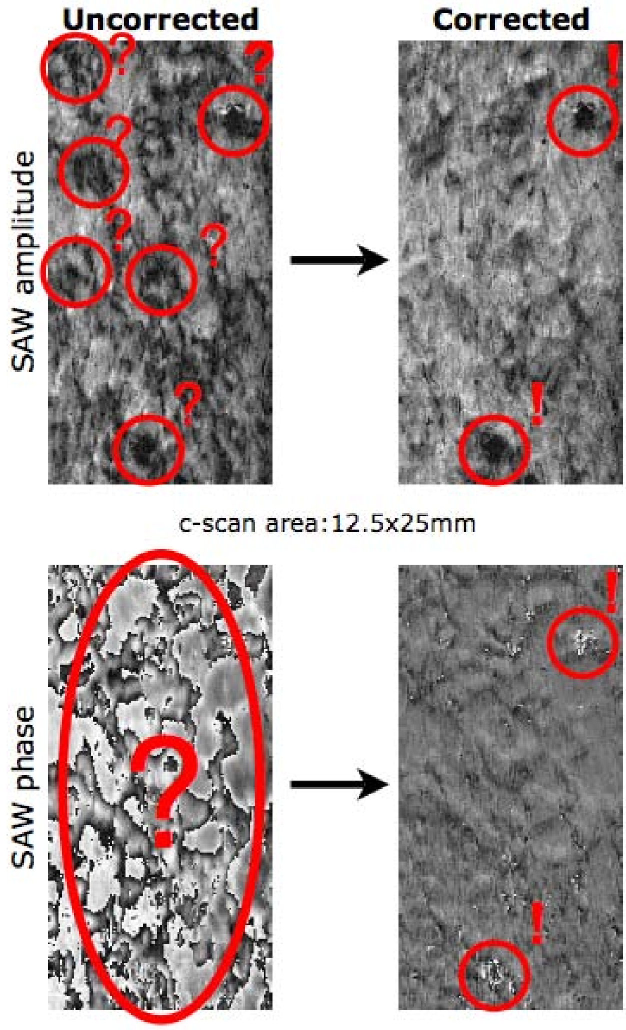

Fig.6. The figure shows 82MHz SAW amplitude (top) and phase (bottom) c-scans on a 12.5 x 25mm area of a titanium alloy. There are two "real" defects on the sample, but these are very difficult to spot in the left hand images which have not been subject to aberration correction. In the right hand images, where aberration correction has been performed, the images are much easier to interpret, and the defects considerably easier to locate.

The uncorrected amplitude (top) and phase (bottom) 82MHz SAW c-scan images are shown on the left. On a "perfect" sample, with no defects, both the amplitude and phase images should be uniform in tone. In the case of this particular sample, there are two "real" defects, which are Vickers indentations. Ideally these would be easy to spot, by reduced SAW amplitude and very obvious changes in phase. As shown on the left of Fig.6 however, the uncorrected amplitude image suffers from severe signal drop-out. There are several areas where reduced amplitude *could* imply a defect, but is actually just the result of the deleterious effects of acoustic aberration. The phase image is particularly difficult to interpret.

On the right, aberration correction has been performed. Not only are the images much easier to interpret (they are more uniform in tone), but also the two defects are now clearly identifiable.

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E. Conclusions

This paper has illustrated the deleterious effects that acoustic aberration can have on the propagation of acoustic waves, and how it can lead to degradation in the quality of recorded data used for nondestructive evaluation. The proposed solution involves the detection of the aberration, using an acoustic wavefront sensor, and a control loop feeding back to the excitation source of the ultrasound. By using a programmable spatial light modulator, the excitation source can be updated with a new pattern very rapidly, and this can correct for the effects of the material microstructure. The result is improvement in the quality of data used to determine whether defects are present in a sample, and this has been graphically illustrated.

Future work in this field will be in the use of better algorithms to determine wavefront distortion, and more efficient methods of constructing the modified excitation source will be developed.

F. Acknowledgements

This work has been supported by the UK Research Centre for Non-Destructive Evaluation (RCNDE).

G. Literature

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