An adaptive technique using measured Green's functions for extending spatial coherence in aberrating materials

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Abstract—Many common engineering materials can aberrate high frequency acoustic waves. The source of the aberrations is spatial velocity variations resulting from the material microstructure. Aberrations can degrade acoustic measurements by distorting the acoustic wavefront and causing acoustic speckle.

A new technique is demonstrated which optimises the spatial distribution of the generation of the ultrasound to compensate for acoustic aberrations. The technique uses a Green's function for the material which is experimentally determined. In aberrating materials the Green's function is a function of source and observation position, $G(R, S)$.

The spatial coherence is optimised in the required measurement region to suppress acoustic speckle. The technique is used to improve the accuracy of velocity measurements in steels with high frequency SAW waves.

The technique was performed using the Adaptive Optical Scanning Acoustic Microscope (AOSAM) at the University of Nottingham, UK.

I. Introduction

Acoustic aberrations or distortions of the acoustic wavefront can arise from acoustic velocity variations in the medium in which the acoustic wave propagates. Acoustic velocity variations can be caused by a range of factors, the most common in metals is the presence of microstructure or grains.

In this paper experimental evidence for the existence of aberrating microstructure in metals is presented using a novel instrument– an optical scanning acoustic microscope (OSAM[1], [2]) at 82MHz with surface acoustic waves (SAWs). The experimental evidence is backed up by simulation results showing that the spatial coherence can be projected away from the source.

The OSAM is used to measure the Green's function response of the sample, and then this Green's function is used to optimise the generation of the SAWs, producing a region of extended spatial coherence which would normally be destroyed by the acoustic aberrations. The spatially coherent region can then be used to perform acoustic measurements with greater certainty than is otherwise possible.

The technique is used to produce an area of high spatial coherence away from the SAW source, this is then used to perform a high quality velocity measurement. While it is possible to produce an estimate of the velocity from the measured Green's functions themselves the main purpose of this paper is to demonstrate that spatial coherence can be restored to the measurement region (and projected away from the source).

Acoustic aberrations

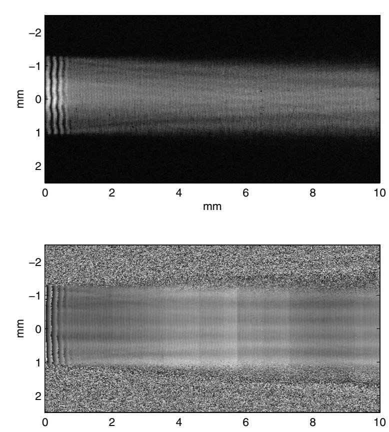

Figure 1. 82MHz SAW propagation on a homogeneous sample (glass) (upper amplitude, lower residual phase). The beam propagates perfectly in this homogeneous sample just diffracting slightly over this distance.

Figure 1 shows SAW propagation on a homogeneous (glass) sample. The image was taken using an OSAM by generating a plane SAW and scanning the detector to build up an image of the propagating wave. The wave propagates from left to right and just diffracts slightly. Figures 2 and 3 show similar experiments on aluminium and steel respectively. In marked contrast to the image on glass (figure 1) they are dominated by acoustic speckle. The speckle in the amplitude distribution is accompanied by large fluctuations in the SAW phase. The speckle can be shown to result from the materials microstructure which causes aberration of the acoustic wavefront, which can be thought of as separate from scattering[3]. The aberration is caused by different parts of the wave experiencing different acoustic velocities resulting in distortion of the wavefront. This distortion builds during propagation

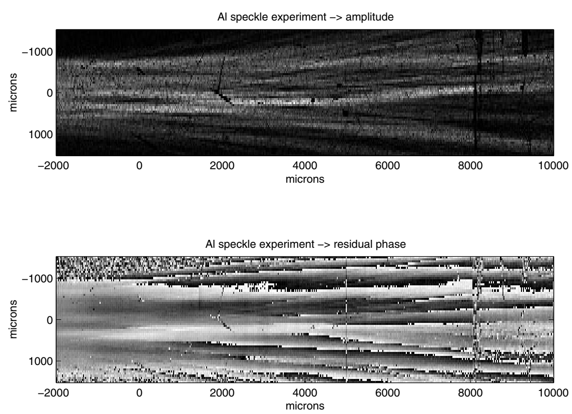

Figure 2. 82MHz SAW propagation on an aluminium sample (upper amplitude, lower residual phase). The amplitude is broken up into acoustic speckles as it propagates from left to right.

to give acoustic speckle which has a detrimental effect on measurement quality. This paper shows how the effect of the aberrations and acoustic speckle on a velocity measurement can be reduced by increasing the spatial coherence. The technique is more general and can be used to improve a wide range of measurements affected by aberrations - especially the detection of defects.

Velocity measurements are usually made by measuring the acoustic phase at two or more points and inferring the phase gradient. It is possible to obtain extremely accurate velocity measurement with this technique in isotropic samples[4] or single crystal anisotropic samples. In aberrating media the speckle can significantly increase the measurement error. There are three main effects: (1) the amplitude

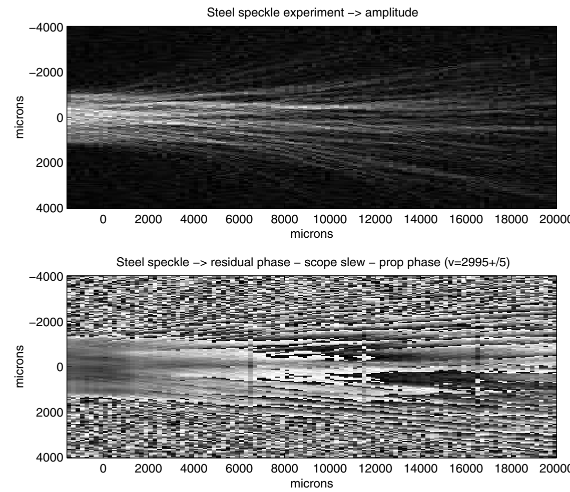

Figure 3. 82MHz SAW propagation on a steel sample (upper amplitude, lower residual phase).

variations can mean that there is not enough signal at one or more of the measurement points, (2) the local phase gradient is distorted and (3) the measurement points occur on different speckles which may have decorrelated phase distributions resulting in large errors and a lack of repeatability.

The signal loss caused by aberrations can far exceed that caused by scattering (or attenuation). Figure 4 shows the acoustic power distribution of the image shown in figure 3. This shows that the variations in amplitude caused by acoustic aberrations can be far more significant than the losses caused by scattering.

Optimisation

We present a technique which is based on improving the spatial coherence of the wave at the measurement zone. This uses measured Green's functions and an optimisation algorithm to improve the spatial coherence where adaption[5] or time reversal would fail[6].

II. Optimisation using measured Green's functions

In this technique we use a direct-search optimisation method[7] to optimise the generation wavefront to compensate for the acoustic aberrations. There are two main differences between [7] and this new technique: (1) the Green's function $G(R, S)$, of the system cannot be determined analytically because of the stochastic nature of the media and therefore must be determined experimentally and (2) the target for the optimisation is applied to the amplitude and phase

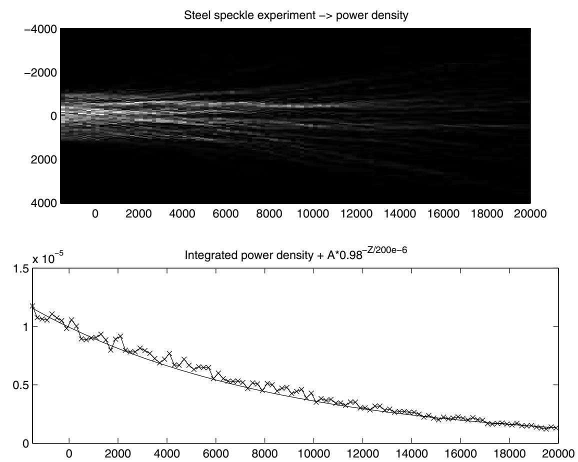

Figure 4. Acoustic power density on steel (upper) and power vs propagation distance (lower).

of the acoustic wave in the measurement zone (rather than the optical intensity) with the aim of increasing the spatial coherence.

Measuring $G(R, S)$

In a stochastic medium the deterministic Green's function, $G(R, S)$, is a function of source, S and receiver, R position. It can be determined by generating a wave with a point source at S and receiving it with a point receiver at R. Experimentally it is measured in the OSAM using a pseudo point source and true point receiver. The source and receiver positions are then scanned to build up $G(R, S)$.

Optimisation

The optimisation of the source is performed as in [7] using $G(R, S)$ and a cost function of the form $C = -a|\bar{U}| + b\sigma|U| + c|\bar{U}|\arg(U)$, where U is the complex amplitude of the wave evaluated over the region of interest as $U(R) = \int G(R, S)e^{-\imath\phi_d} dS$, σ denotes standard deviation, arg the phase, ϕ_d the design phase and a, b and c are cost balancing factors specific to the problem[7]. This function is minimised as the spatial coherence (and signal) in the region is increased.

III. Results

Simulation and spatial coherence

The effect on the spatial coherence of the wave has been investigated using a simulation model. The model is based on a phase screen approximation[8] and uses a simulated medium based on the random growth of grains. We have used the transverse autocorrelation function of the wave as a measure of spatial coherence. Figure 5 shows a typical simulation result. It can be seen that in the case of a plane wavefront the spatial coherence has decayed between the source and detector, and in the case of the optimised wavefront the spatial coherence is initially low and builds to a maximum at the measurement zone.

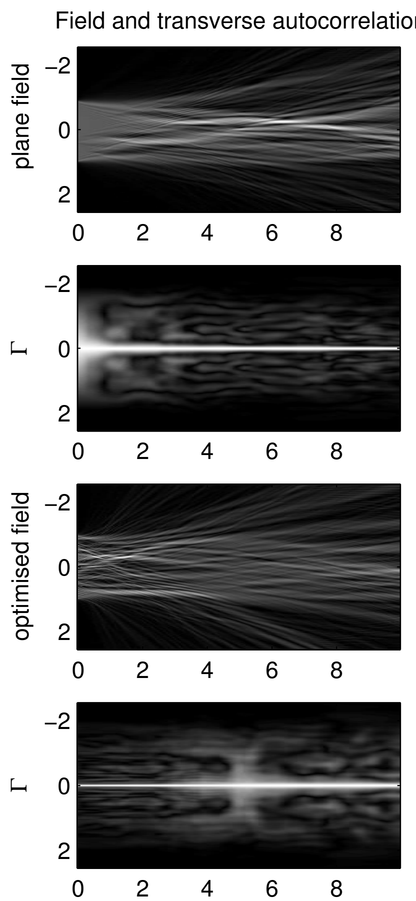

Figure 5. Simulation of experiment showing increased spatial coherence at the measurement zone in the case of optimisation. The target region was an aperture the size of the source located at a distance of 5mm from the source.

Experiment and measurement error

Figure 6 shows the amplitude in the measurement zone taken using a flat (plane) wavefront and with an optimised wavefront. Figure 6 also shows the velocity variation with position (assuming a 2 point velocity measurement technique[4]). Within the optimisation zone the amplitude is high and even and the velocity variation (and hence the apparent velocity error) is lower than with the plane wavefront.

Using this optimised design it is possible to determine the velocity by looking the phase gradient (figure

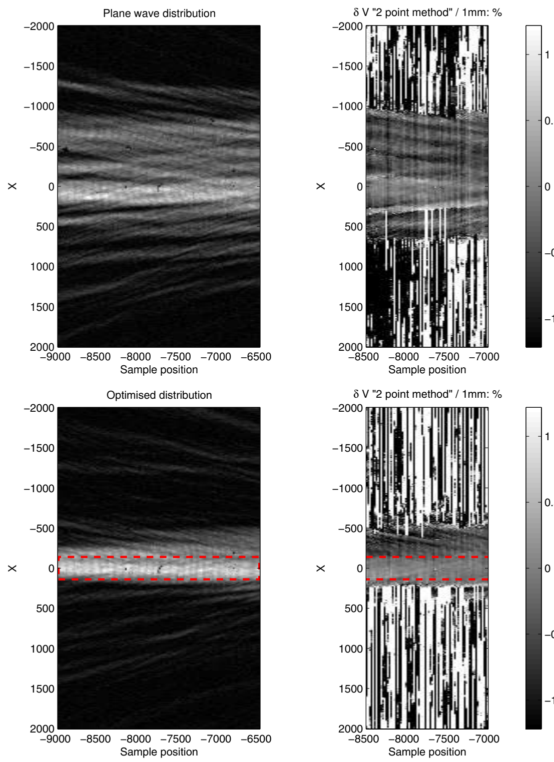

Figure 6. Experimentally measured SAW in measurement region (left) with velocity variation mapped (assuming 2 point measurement over 1mm) (right). Top, using a plane wavefront. Bottom, using an optimised wavefront described in the text. The checked box indicates the optimisation zone.

7). The phase is determined by taking the phase of the 0-order of diffraction of the measurement region to avoid diffraction effects.

The variation of the velocity with distance (figure 7) is greater than the expected experimental error ($< 1/10^4$) and probably results from the varying sample of the microstructure. This error can be estimated from knowledge of the grain size as $\delta c \sim \frac{A\bar{c}}{\sqrt{(N)}} \sim \frac{0.25\times 3000}{\sqrt{2k}} \sim \pm 20\mathrm{ms}^{-1}$. where A is the degree of anisotropy, N is the number of grains sampled.

IV. Conclusion

In this paper we have demonstrated the effect that aberrating materials can have on the acoustic wavefront and therefore on acoustic measurements. This can be severe acoustic speckle with large amplitude and phase fluctuations. We have also shown that the amplitude fluctuations caused by the acoustic speckle

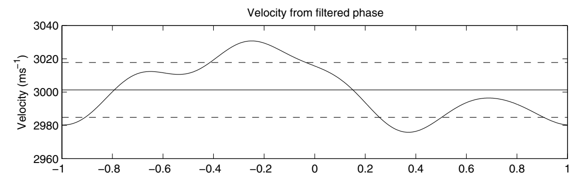

Figure 7. Velocity measured via phase gradient technique using the optimised result in figure 6.

can be more significant than attenuation caused by scattering.

An optimisation technique using measured Green's functions is demonstrated. This was designed to increase the spatial coherence and reduce error in a measurement zone away from the source. The measurement of the Green's function is necessary because it cannot be determined analytically without detailed prior knowledge of the sample microstructure.

Using a simulation environment the technique was shown to increase the spatial coherence *away* from the source as required.

Using an OSAM the technique was shown experimentally to reduce the variation in velocity measurement caused by acoustic aberrations. This is significant because it improves the measurement quality where simple adaption and correction or time reversal would struggle to make any improvement.

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