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All-optical adaptive scanning acoustic microscope ☆

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Abstract

We have constructed a fast laser-based surface acoustic wave (SAW) microscope, which may be thought of as a non-perturbing scanning acoustic microscope. The instrument is capable of rapid high resolution vector contrast imaging at several discrete frequencies, without any damage to the sample. Tailoring the generating optical distribution using computer-generated holograms allows us to both focus the acoustic waves (increasing their amplitude) and to spread the optical power over the sample surface (preventing damage). Accurate quantitative amplitude and phase (velocity) measurements and unique acoustic contrast mechanisms are possible with our instrument based on this technology due to the non-perturbing nature and the instrument geometries.

However, the complexity of the optical generation profile leads to a strong dependence on material properties such as the SAW velocity and material anisotropy. We address these issues in this paper, and demonstrate how a spatial light modulator may be used to adapt the generating optical distribution to compensate for the material properties. This facilitates simpler alignment and velocity matching, and, combined with an acoustic wavefront sensor, will allow real-time adjustment of the generating source to enable imaging on anisotropic materials.

Keywords: Laser ultrasonics; Scanning acoustic microscope; Adaptive acoustics; Spatial light modulator; Vector contrast imaging

1. Introduction

The contact scanning acoustic microscope (SAM) is a powerful tool to investigate the mechanical properties of a material using surface acoustic waves—amongst other things coatings, adhesion, and bonding. The SAM suffers, however, from its dependence on a liquid couplant to couple the acoustic waves from transducer to sample. This couplant can be problematic in several ways: contamination of the sample, perturbation the acoustic waves, it can restrict access to samples of complex geometries, damping can eliminate certain contrast mechanisms, and the non-linearity of the coupling mechanism dominates any material non-linearity, preventing direct measurement of high order elastic constants.

2. Optical techniques

Optical generation and detection of ultrasound has been common practice for many years. For many applications, however, there are inherent difficulties with the technique. A common problem is the lack of detector sensitivity when compared to contact methods [1]—typically of one or two orders of magnitude less. This problem has traditionally been overcome by signal averaging—which is impractical for imaging—or by generating acoustic waves of relatively high amplitude. To do this requires high optical powers and it is easy to damage most materials through ablation or melting. In many cases this is acceptable (or may even be beneficial), however for the purposes of a practical non-contact SAM we will consider any surface damage to be unacceptable.

The problem is difficult to overcome by increasing the optical power of the detection probe, since at some point the probe itself will damage the sample. We note that the signal to noise ratio (SNR) of an all-optical system operating in the thermoelastic regime is proportional to $P_{gen}\sqrt{P_{det}}$ where P_{gen} is the optical power used to generate the ultrasound, and P_{det} is the optical power used to detect the ultrasound [1,2]. There is therefore much

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more to be gained by increasing the generation power, if it can be done without damaging the sample.

3. Tailored generation profiles

One solution to the problem lies in tailoring the profile of the optical distribution used to excite the ultrasound in the material. There are essentially two approaches to this method: (i) to spread the power over the area of the sample such that it adds ultrasonic amplitude to the required acoustic mode; (ii) to focus the acoustic waves to a point, such that the amplitude at this point is greatly increased. Moving gratings have been used previously for the first technique [3], whilst focusing the light from the generating laser through an axicom is an early example of the second technique [4]. The authors have been very active in the use of using computer generated holograms (CGHs) to combine the two techniques [5]. CGHs allow us to produce arbitrary distributions of light on the surface of materials which both focus the acoustic waves, and spread out the distribution of incident optical energy, even over complex three-dimensional geometries.

This technique has increased the SNR of our system by a factor of around 80, compared with a single line source just below the damage threshold limit [6]—this increase in SNR is equivalent to increasing the optical detection power by a factor around 5000. This, combined with real-time capture of signal amplitude and phase using analogue electronic techniques [7], has been instrumental in the enabling of an instrument capable of rapid vector contrast SAW imaging.

An alternative technique we have recently been investigating in order to apply arbitrary light distributions onto sample surfaces is the use of a spatial light modulator (SLM). This type of device consists of a large array of individually addressable pixels, each of which alters some property of any incident light that reflects off the device—examples of such devices can be found in video projectors. The advantage of these devices compared to CGHs is that the generation profile can be adjusted in real time, which is necessary for an instrument that can adapt to the properties of the material. The current state of SLM technology means that there are also disadvantages; they cannot generate three-dimensional distributions and in some circumstances their optical power-handling capabilities are limited.

4. Instrument details

The physical construction of the all-optical scanning acoustic microscope (O-SAM) employing the use of computer generated holograms has been described elsewhere in detail so only brief details and enhancements are described here. The generating laser source is a Q-switched mode-locked Nd-YAG laser emitting 1064 nm radiation. An envelope of approximately thirty sharp pulses with a separation of 12.1 ns (corresponding to a fundamental frequency of 82 MHz) is emitted from the laser every 0.2–1 ms. This pulsed radiation is incident on the spatial light modulator, which is currently a Displaytech model 256 A. This 256×256 pixel liquid crystal device produces a programmed pattern of light onto the surface of the sample. Fig. 1 gives an indication of the type of profile projected onto the sample surface which is typically a set of concentric arcs. It also shows the relationship between the SAW generation, the SAW detection, and the sample under investigation.

The incident pulsed laser light thermoelastically generates surface waves, which converge at the focus of the arcs—in this way the arcs are acting as a surface wave lens. At this point the SAWs are detected using an optical detector. In the simple *c*-scan configuration, the displacement between the generation distribution and the detection point is kept constant, and the sample is scanned on motorised *x*–*y* stages, to build up images similar to those from a standard contact SAM. In addition the detection point may be moved or scanned, either for alignment purposes or to build up a picture of the point spread function of the acoustic waves as they

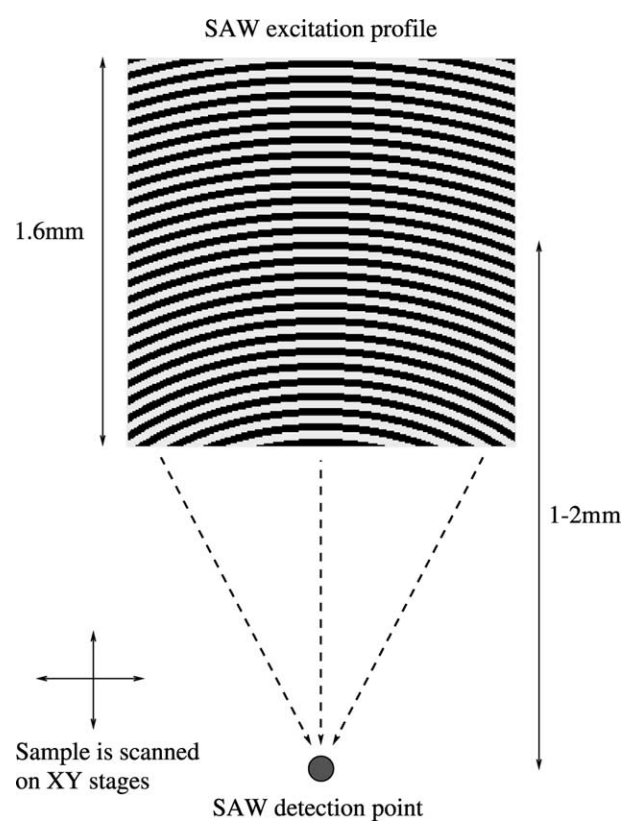

Fig. 1. Indication of the optical excitation profile used to generate focused surface acoustic waves. The SAWs are detected at the acoustic focus using an optical probe. The sample is scanned whilst the separation between excitation and detection regions remains constant.

propagate from the generation region. Typical geometries of the instrument are indicated in Fig. 1. The size of the image of the excitation arcs is determined by the need to resolve half an acoustic wavelength at the highest operation frequency of the instrument, which is in turn determined by the number of pixels on the SLM—currently the image size is 1.6 mm. The arcs are spaced by the acoustic wavelength, for example on aluminium the line spacing for Rayleigh waves at 164 MHz is 18.7 μm. The separation distance between generation and detection regions is determined by a number of factors, including the required numerical aperture of the acoustic lens to obtain signals of a sufficiently high amplitude, and the type of measurements being taken. It can be undesirable for the detection point to be too close to the generation region, since the heating in this region, however small, can perturb sensitive measurements. Typical mean separation distances are 1–2 mm.

The current SLM has severe limitations with regard to light throughput efficiency and power-handling capabilities. The zero-order reflectivity of the device used is only approximately 20% at the wavelength of the generation laser, and half of this light is subsequently discarded by the analyser. At high powers the SLM malfunctions as a result of photon leakage into the electronics. Due to these limitations we operate using an extremely modest 40 mW average power on the surface of the sample.

5. Contrast mechanisms

The O-SAM instrument is capable of rapid (for laser ultrasound) high resolution vector contrast imaging at several different discrete frequencies simultaneously. Some of the imaging capabilities of the instrument (employing the use of computer generated holograms to generate the SAW excitation profiles) have been demonstrated and described elsewhere [5,6]. The lack of couplant means that certain surface wave modes (for example the Lamb a_0 mode) may be observed more readily [6]. The measured velocities of the Lamb modes allows us to determine material thicknesses [7]. Residual surface stress in ceramics can be measured from changes in Rayleigh wave velocity [8], as can coating thickness.

6. Material properties and acoustic aberrations

It has already been stated that the separation of the excitation arcs is dependent on the SAW velocity of the material. This must be controlled precisely, such that the wavefronts generated by all the arcs add up in phase; if this is not so, then destructive interference occurs leading to severe signal loss. Although it is possible to adjust the spacing of arcs produced from CGHs, it is a somewhat involved process involving an optical zoom system. The ease of being able to adjust the arc separation distance using an SLM significantly adds to the usefulness of the O-SAM as a 'real-world' instrument.

A significant benefit in having a method of controlling the SAW excitation profile becomes apparent when attempting to image on aberrating and anisotropic materials. The problem is similar to the problem of optical imaging through a turbulent atmosphere although in the case of SAW imaging on solids the aberration is fixed in time and changes when the sample moves. Fig. 2 shows a heavily degraded SAW amplitude image, where much of the data is lost due to the aberrating nature of the material. Although the image does contain useful information about the defect on the sample (a sub-surface void running left to right approximately half way down the image) it is very difficult to interpret due to the amount of acoustic speckle.

The signal drop-out occurs not because the SAWs are absorbed in the material in the dark regions, but because the acoustic wavefront is being aberrated as it propagates through the randomly orientated grains of the material. Different parts of the wavefront propagate through different grains with different velocities. This results in the wavefront being steered away from the detection point or, in the case of more severe aberration, breaking up altogether.

The O-SAM is an excellent instrument with which to observe this effect, since the amplitude and phase of the surface waves can be imaged as they propagate from the excitation region to the point where the detector would normally be. It should be stressed that this type of effect

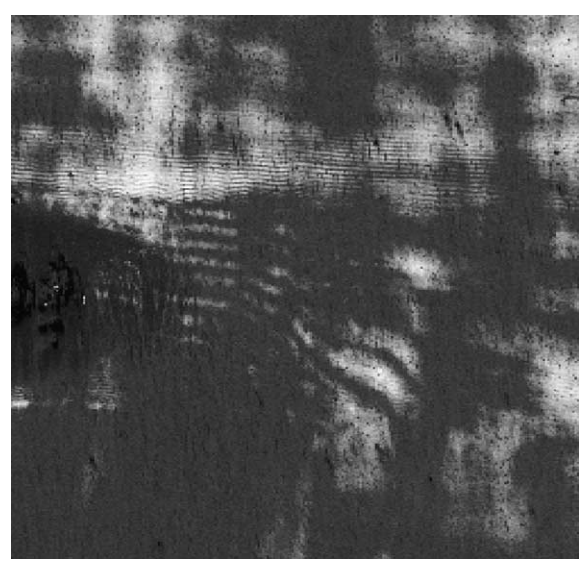

Fig. 2. Badly degraded SAW amplitude image of an area around a defect (a subsurface void running horizontally approximately half way down the image). The image degradation is due to the aberrating nature of the material microstructure, which distorts the acoustic wavefront as it propagates. Image size 5 × 5 mm.

is not limited to the O-SAM instrument or to surface waves. This effect is also important when plane transducers are used in conventional NDE experiments. The higher the frequency, and the longer the propagation distance, the more marked the effect. To correct for the aberration, to recover the signal, we need to be able to detect the wavefront, and to adjust the SAW excitation profile to compensate, in real time as we scan the sample.

7. Real-time control of generation profile

To demonstrate the flexibility of the instrument and the degrees of freedom and control we have over the acoustic distribution, the SLM was programmed with a series of different optical distributions, and an image acquired of the resulting surface waves distributions as they propagate from the excitation region—aerial point spread functions (PSFs) in other words. The images were acquired by scanning the detection probe whilst keeping the sample and excitation positions stationary. The amplitude of the SAW distributions is shown in part (a) of Figs. 3 and 4; the phase is shown in part (b).

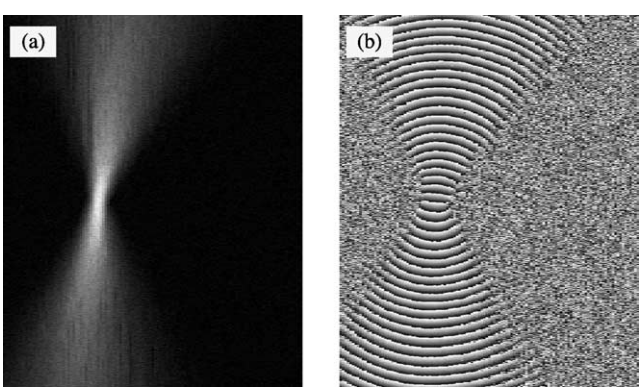

Fig. 3. Amplitude (a) and phase (b) images of laterally displaced 82 MHz SAW PSF. Image size 1.2 × 1.5 mm.

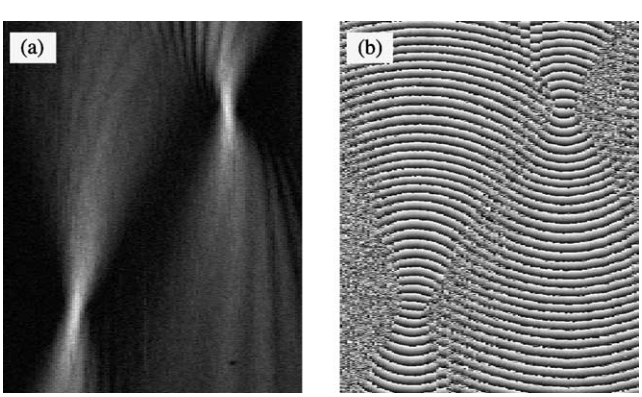

Fig. 4. Amplitude (a) and phase (b) images of two independent 82 MHz SAW foci, displaced both laterally and axially. Image size 1.2 × 1.5 mm.

In Fig. 3, we see a strong diffraction-limited focus similar to that observed when using CGHs, except that the focus is displaced. This is attained by tilting the arcs; this provides an ideal method to achieve tip-tilt correction. Fig. 4 shows two independent foci displaced both laterally and axially. This was attained by programming the SLM to produce a pattern consisting of a thresholded output from two sets of concentric arcs.

8. Aberration correction

To correct for the wavefront distortion introduced by the random grain structure of a material, it is first necessary to acquire information about the acoustic wavefront at the intended detection point.

We can obtain the information required for tilt correction by scanning the detection probe across the PSF for a selection of detection points. These scans show by how much the PSF deviates from the desired detection point, and we refer to these as "wander-scans" or "*w*-scans" since they illustrate how the PSF wanders from its intended central location. In future implementations of the O-SAM instrument, this information will be acquired using an acoustic wavefront sensor.

Fig. 5 shows the *w*-scans for 10 vertical slices within a 5 mm square region of polished aluminium. It is clear that for many of the scan positions, the SAW PSF is still intact, but displaced laterally. This implies that a tilt correction can be obtained by setting the intended focus of the excitation arcs to be an equal-but opposite-distance from the measured displacement. In this way the SAW waves will be subject to substantially the same

Fig. 5. *w*-scans of 10 vertical slices of a 5 × 5 mm area of polished aluminium. The vertical axes represent the vertical axis of Fig. 6 (total distance 5 mm), whilst the horizontal axes represent the amplitude of the SAWs across the PSF (total distance 300 μm). The wavefront is distorted by the material microstructure, and so the focus deviates from the detector position for much of the *c*-scan.

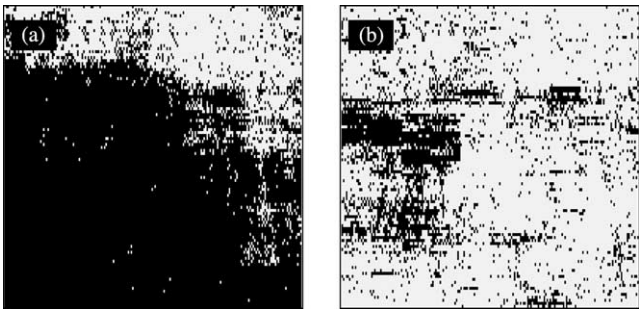

Fig. 6. Thresholded 82 MHz SAW amplitude images taken from the same area as the correction data shown in Fig. 5, (a) before tilt correction, and (b) after tilt correction has been applied. The "valid data" threshold is set at 25% of the maximum amplitude of the uncorrected data. The area of valid data is now visibly much greater.

aberrations that caused the PSF to wander, and should now propagate back to the desired detection point.

Two *c*-scans were performed over the area where the *w*-scans in Fig. 5 were obtained; the first without any tilt correction, the second using the data obtained from the 10 *w*-scans. To illustrate the improvement in the data obtained, Fig. 6a and b shows where the SAW amplitude is greater than 25% of the maximum amplitude for the uncorrected and corrected cases respectively. The area of valid data has now substantially increased, from around 24% for the uncorrected image to approximately 80% for the corrected image. It should be noted also that the correction data was only obtained for 10 discrete slices (due to the time taken to acquire the data by detection probe scanning), and so the further from the measured slice, the less the data is a valid correction. The areas where the signal could not be recovered correspond to areas where the PSF breaks up further (referring to Fig. 5) due to higher order aberrations.

9. Conclusions and further work

We have described a flexible all-optical equivalent to a contact scanning acoustic microscope, which is capable of completely damage-free high resolution vector contrast imaging. Contrast mechanisms not normally available to contact SAMs are possible due to lack of couplant and flexible operating geometries. The key to the successful operation of the instrument is the tailored generation profile, which allows us to spread out the excitation laser energy (preventing damage) and to focus the acoustic waves (increasing their amplitude). We have shown that SLMs can be used to produce flexible distributions of light which, in turn, generate controlled SAW distributions. This flexible real-time control allows us to adapt the generation profile according to the material properties: in terms of matching the velocities of homogeneous samples, and correcting for aberration caused by material microstructure for anisotropic materials. This aberration correction will allow us to extend the range of materials we are able to investigate with the O-SAM, and to extend the frequency range of the surface waves used to probe materials, ultimately increasing resolution. It is worth reiterating that the SAW waves in the images in Figs. 5 and 6 were generated from only 40 mW of average incident optical radiation, which is very small in laser ultrasound terms. This limitation is imposed on us only as a result of the capabilities of the particular SLM used.

The O-SAM is a good contender for the detection and imaging of sample non-linearities, since the lack of a liquid couplant, combined with the flexible generation distributions, allow us to filter and spatially separate generated frequency components.

In the near future we intend to replace the SLM with a more efficient model tailored to our generation laser wavelength, which should lead to a substantial increase in signal levels, and hence the range of materials that we can probe with the instrument. In order to perform real-time aberration correction a real-time acoustic wavefront sensor will be constructed, and higher order correction techniques developed.

Acknowledgements

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