Measurement of elastic nonlinearity using remote laser ultrasonics with CHeap Optical Transducers and dual frequency surface acoustic waves

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Abstract: A new breed of optical transducers has been developed for generation and detection of ultrasound. The CHeap Optical Transducer (CHOT) is an ultrasonic transducer system, optically activated and read by a laser. CHOTs bring the advantages of laser based ultrasound and have already attracted attention from industry for various applications. In this study we have combined the advantages of CHOTs with the potentials offered by nonlinear ultrasound for aerospace applications. Nonlinear ultrasonic techniques comprise a new class of innovative nondestructive methods and provide extreme sensitivity in detecting and imaging early stage damage in the form of microcracks, delaminations etc. The sensitivity is far superior to the traditional linear applied ultrasonic techniques.

We present results measuring changes in ultrasonic velocity corresponding to different stress states of the sample. The nonlinear ultrasonic technique we are using is based on dual frequency parametric interaction and measures the nonlinear elastic properties of materials. We are monitoring the phase modulation of a high frequency (82MHz) surface acoustic wave due to changes in the materials nonlinearity (beta parameter), induced by a low frequency (1MHz) generated surface wave. The high frequency wave is generated by a CHOT whereas the low frequency one is generated by a transducer. This method can be used to investigate the progression of fatigue and stress of components.

Key words: nonlinear ultrasound, optical transducers, parametric interaction, phase modulation.

A. Introduction

The ability to measure the level of stress that is imposed onto a material is of great importance when predicting its point of failure brought on by fatigue. By observing changes in material characteristics well before the initiation of a crack it is possible to identify potential faults within a specimen. It is understood that when a material experiences an applied stress, the velocity with which ultrasound propagates over it is affected [1]. In order to measure the subtle variations in material properties brought on by low level stress, nonlinear techniques have to be implemented, which are of much higher sensitivity than their linear counterparts.

Here, a nonlinear pump-probe (wave mixing) technique is demonstrated using surface acoustic waves (SAWs). Nonlinear experimental techniques have been demonstrated using bulk waves [2] but the use of SAWs is more recent [3]. In a truly linear material, ultrasound velocity would remain constant with applied stress. However, materials such as fused silica and aluminium have shown evidence of nonlinear responses at these stress levels. The stress imposed by the transducer SAW is sufficient to produce measurable phase modulation in the probing pulse. Ultimately, the technique is measuring a velocity change in the high frequency SAW as a direct consequence of this applied stress.

B. Experimental Setup

The pumping 1MHz SAW was generated by a transducer-wedge combination. The high frequency (82MHz) probing wave was generated by means of a g-CHOT (generation-CHeap Optical Transducers). CHOTs are an innovative ultrasonic transducer system which are optically activated both for generation and detection. Lasers are used as actuators providing remote and couplant free operation. One of their many advantages is that they are low profile (minimal weight and size $<1cm^2$) allowing minimal impact to the inspected sample. They can be permanently attached to the sample to provide reliable and repeatable measurements. In addition, they have the potential of becoming very cheap. The detection of the high frequency ultrasonic signal was done either with a knife edge detector or a d-CHOT (detection CHOT). The principle of CHOTs is briefly described below.

B.1. g-CHOT

The g-CHOT is a structure printed, deposited or somehow attached onto the surface of the sample. By changing the geometrical characteristics of the g-CHOT structure one can control the mode and frequency content of the generated wave as well as its directivity. The idea behind the making of the g-CHOT is to create an ultrasonic source with an appropriately high contrast between absorbing and non-absorbing regions of the irradiated sample [4] (figure 1). For example, by depositing lines of aluminium onto a BK7 glass substrate a periodic absorption contrast is setup in which the incident light, is transmitted by the glass, while the areas of the sample coated in aluminium will absorb more of the laser energy thereby causing local thermal expansion in these areas. This difference in local expansion when illuminated with a pulsed laser causes the generation of

an elastic wave. The profile of the lines can be fabricated to form a series of lines or arcs as shown in figure 1 (b) and (c) respectively which in this case would generate a surface acoustic wave. By having a pattern with straight parallel lines, the resulting SAWs will have a plane wavefront. The advantage of using an arc pattern is that the ultrasound will be focused to a single detection point, improving the signal to noise ratio of the detected signal. In this way the g-CHOT controls the directivity (focused or plane waves) and the mode (generation of SAW) of the generated waves.
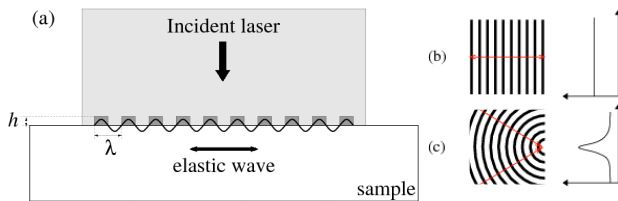

Fig.1. g-CHOT structure (a) in which the incident laser light illuminates a series of aluminium lines, separated by one acoustic wavelength (λ). The line height (h) is 140nm. g-CHOT profiles can be fabricated as a series of lines (b) and arcs (c) generating plane and focused ultrasound respectively.

In order to prevent any damage to the material, the laser energy is kept to the thermo-elastic regime, making the concept completely nondestructive. The desired SAW frequency is selected by choosing the appropriate line spacing using the relation λ=v/f. Where λ is the line spacing, equivalent to the acoustic wavelength of the generated SAW, v is the Rayleigh wave velocity of the material and f is the desired SAW frequency we wish to generate.

In this case, the line separation had to match the frequency of the incident q-switched mode locked laser pulse which is 82MHz. If a non-q-switched laser was used instead which had a broad frequency spectrum, then the g-CHOT could be fabricated to actively select any frequency within the laser's bandwidth [4].

For our experiments we used a g-CHOT fabricated by means of photolithography on a fused silica sample. The g-CHOT pattern was for focused SAWs and was made of aluminium. The outer radius of the co-centred ring was 5mm and the spot size of the illuminating laser was 2.3x2.3mm^2, consequently the pattern was bigger that the laser spot. Figure 2 is a detected 82MHz pulse generated by a focused g-CHOT on fused silica. A modified knife-edge detector was used for detection at the centre of the rings and the distance between the detection point and the laser spot was chosen to be 4mm.
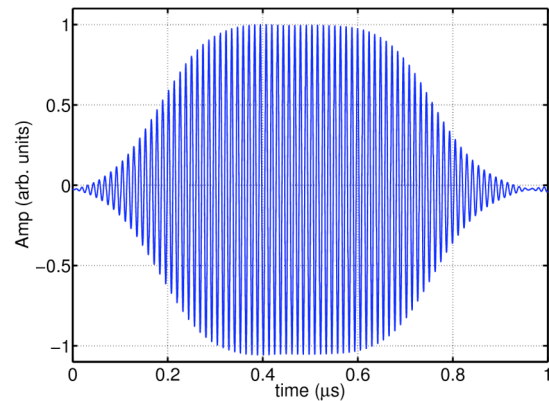

Fig.2. Detected high frequency pulse generated by an 82MHz g-CHOT. This signal was detected by a knife-edge detector.

B.2. d-CHOT

The g-CHOT is based on laser-generated ultrasound and it is preferable for the detection to be based on lasers as well, since this method is also non-contact and couplant free. For this reason we have developed the d-CHOT. As with the g-CHOT, it too consists of a structure placed onto the sample surface. However, in this case it reflects light. It is designed so that its geometrical features will choose the detected mode and frequency and can be coupled with the g-CHOT forming a powerful, robust and sensitive remotely operated ultrasonic system. It may also be used independently to detect ultrasound which has been generated by other means. The d-CHOT is in effect a reflection grating and the steps of the grating have been designed in such a way as to introduce the desired path length difference to the incident light (figure 3).
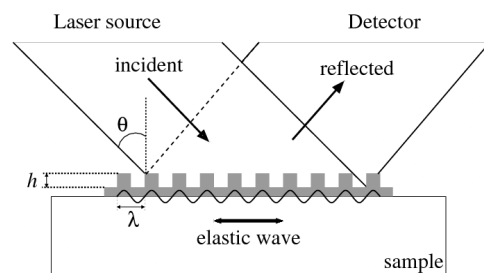

Fig.3. d-CHOT structure with appropriate height (h) and spacing (λ) to detect SAWs. As with the g-CHOT, the lines can be plane or focused.

The height of the steps (*h*) of the d-CHOT for normal incidence corresponds to 1/8th of the optical wavelength. The laser beam illuminating the d-CHOT is reflected and separated into various diffraction orders. One of the orders is then selected and directed onto a photo-detector. When the generated ultrasound travels below the area of the d-CHOT, this height changes, thus modulating the amount of energy within that order. The spacing of the lines of the d-CHOT is tuned to select the ultrasonic frequency to be detected, providing a narrowband detection technique.

B.3. Nonlinear Experiment

The degree of stress experienced by the high frequency SAW is altered by controlling the point in time at which the two waves interact with each other. A computer controlled time delay between the triggering of the pump relative to the probe enables the high frequency to be delayed over a low frequency wave packet, experiencing the range of stresses imposed by the transducer.

Figure 4 shows the overall experimental setup which incorporates the two generation sources, the time control and the detector.
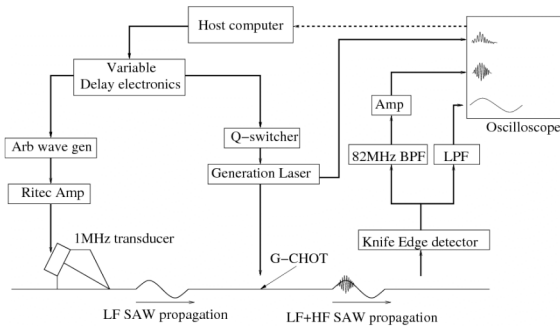

Fig.4. Experimental setup. Mixing pump (1MHz) and probe (82MHz) waves. The delay between trigger times is controlled and determines the point in time at which they interact.

The generation laser is a Q-switched, mode-locked Nd:YAG laser which emits light at a wavelength of 1064nm. The direct output of the laser is detected by a photodiode located near the emission aperture of the laser. The modelocker produces short pulses of light, which have 12ps duration, at a period of 12ns giving rise to the laser's fundamental frequency of 82MHz. Since these pulses are short in time, the output of the laser has a high harmonic content that can be seen to exceed 1GHz.

The Q-switcher pulse repetition rate is 1015Hz which means that the laser delivers an envelope of these pulses ~1ms. A trace of one of these envelopes is shown in figure 5.
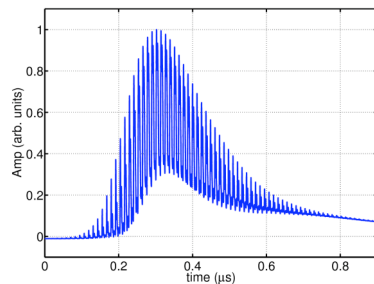

Fig.5. Coherent trigger pulse detected at the output of the laser. The oscilloscope triggers on this signal.

An Agilent arbitrary waveform generator is externally triggered and produces a burst of three 1MHz cycles. Its output is amplified by a Ritec-RPR4000 amplifier, which excites the Panametrics transducer mounted on a wedge, angled appropriately to efficiently generate the high amplitude SAW.

The high frequency pulse is shorter in time duration than the low frequency wave so by changing the point in time at which the two waves interact, the probe effectively experiences different stressed states of the sample. The triggering of the low frequency with respect to the high frequency is controlled by means of the 'variable delay electronics'. The actual delay value is controlled by the host computer which dictates the point in time at which the two SAWs interact. Delay increments of 8ns are possible and the delay range can be up to 0.13ms if required. During an experiment, the delay is adjusted so that the probe pulse interacts with different parts of the pump wave so that at each delay setting, the probe effectively experiences different stressed states of the sample. As a result the phase of the high frequency is modulated accordingly.

Ultrasound detection was carried out by an optical beam deflection technique using a modified knife-edge detector. A doubled Nd:YAG laser is focused onto the sample surface and the reflected beam is focused onto a split photodiode. The incident beam has a typical power level of ~30mW. Any surface displacement caused by a passing SAW deflects the reflected beam which then oscillates between the two photodiodes. Amplification and filtering is then used so that the signal is visible on the oscilloscope. Figure 2 is a typical detected signal. The overall bandwidth of this knife-edge detection system is 300MHz, which allows detection of frequencies corresponding to the laser harmonics.

C. Experimental Results

The experiment was carried out on fused silica and the high frequency SAW is generated using a focused 82MHz g-CHOT. The raw data consisted of a number of detected high frequency pulses which would have undergone varying degrees of phase modulation depending on their point of interaction with the low frequency. Detection of these pulses was performed using a knife edge detector. The phase of the 82MHz component of these pulses was then extracted. Figure 6 shows a plot of high frequency phase modulation against the time delay with respect to the low frequency. Similar results have been obtained by using a d_CHOT for the detection of the high frequency wave instead of the knife edge detector.
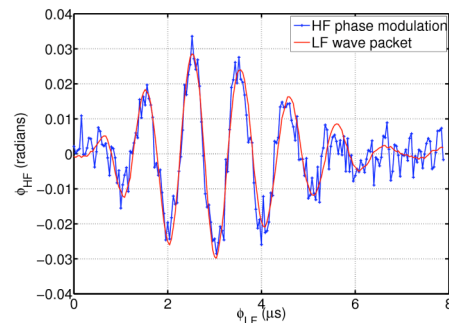

Fig.6. Phase modulation, ϕ_{HF}, observed in the g-CHOT generated probing SAW on a fused silica sample. The solid line shows the transducer wave packet, over which the probe pulse was delayed.

In this experiment, the probing high frequency has been delayed through 8μs which is sufficient to

encapsulate the whole of the low frequency wave packet. The phase modulated results were then be plotted against the normalized surface stress as shown in figure 7.
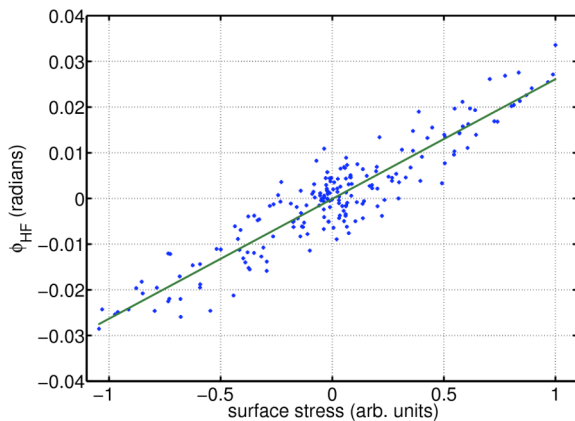

Fig.7. High frequency phase modulation, ϕ_{HF}, against normalized surface stress. The gradient of the line is dependent on the elastic constants of the material.

Figure 7 shows a linear relationship between high frequency phase modulation and applied stress, as indicated by the best-fit line. The gradient of this line is related to the material elastic constants. If the material experiences some level of fatigue, these constants will change and will be observed as a variation in the gradient of this line.

D. Conclusion

A nonlinear experiment based on the parametric interaction between two SAWs has been demonstrated on fused silica. The high frequency SAW was generated by a g-CHOT and both frequency components were detected by a knife edge detector. It was observed that the probing SAW underwent a phase modulation when in the presence of the low frequency pumping SAW. This technique has the potential to be used to study the change in material properties brought on by fatigue.

The implementation of CHOTs in this nonlinear experiment is only one example of their versatility. They provide an extremely powerful, yet cheap method of generating and detecting ultrasound, at any desired frequency and therefore can be used in many NDT applications.

E. Acknowledgements

F. Literature

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