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

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ABSTRACT

A nonlinear ultrasonic technique for evaluating material elastic nonlinearity has been developed. It measures the phase modulation of a high frequency (82 MHz) surface acoustic wave interacting with a low frequency (1 MHz) high amplitude stress inducing surface acoustic wave. A new breed of optical transducers has been developed and used for the generation and detection of the high frequency wave. The CHeap Optical Transducer (CHOT) is an ultrasonic transducer system, optically activated and read by a laser. We show that CHOTs offer advantages over alternative transducers. CHOTs and nonlinear ultrasonics have great potential for aerospace applications. Results measuring changes in ultrasonic velocity corresponding to different stress states of the sample are presented on fused silica and aluminium.

1. Introduction

Ultrasound has proven to be a powerful and effective technique for structural health monitoring. Traditional linear techniques are based on the detection of an ultrasonic signal that contains information about the existence and location of defects. This could be in the form of a reflected signal from the defect itself or the loss of a through-transmitted signal due to the obstruction of a defect.

Very often, defects can be hidden when encountered by probing ultrasonic waves. This is either because they are very small (microcracks) compared to the ultrasonic wavelength or because if a crack is closed, its elastic, acoustic and thermal impedance mismatch is very small and therefore does not cause any disruption to the propagating waves. In order to detect this kind of defect, it is necessary to excite the crack and force it to open and close ('clapping' or 'kissing bond') while they are being probed.

The demand for more sensitive NDT techniques has meant that there have been a growing interest in nonlinear ultrasonic methods which offer a more sensitive solution and have proven to be effective in the detection of microcracks [1–4]. The accumulation of microcracks are caused by the process of fatigue and their presence produces subtle changes in the material elastic constants. These changes can be observed in the nonlinear response of the material. Having the ability to detect changes in material characteristics well before the initiation of a critical crack allows more accurate decisions to be made regarding the condition of aircraft parts for example. This would reduce the danger of disregarding acceptable parts resulting in major cost savings and the potential of continuing the service of a flawed one.

There are various experimental techniques that have been implemented to measure material nonlinearity. A common method is to excite a narrowband wave which propagates either through the material [5] or on the surface of the material [6]. The presence of any nonlinearity causes the energy in the fundamental frequency component of this wave to be transferred to its harmonics. The disadvantage of this technique is that this nonlinearity may have a large contribution from the experimental system itself and separating this experimental nonlinearity from the material nonlinearity is problematic.

A second method, which is immune to the presence of the nonlinearity generated by the experimental apparatus is the use of dual sources of ultrasound and observing the parametric interaction between them as they propagate through or on the surface of the material. This is referred to as a vibro-acoustic technique [7–9]. The presence of material nonlinearity gives rise to sidebands in the frequency spectrum of the detected ultrasound. In a purely linear material there would be no inter-modulation between the two waves.

A variation of this second method is to observe a phase modulation in one of the waves due to the presence of the other [10,11], when the frequency difference between the two waves is relatively high. Previously, this type of nonlinear experiment has been performed with bulk waves and using contact transducers [12], however, this paper will demonstrate its implementation with surface acoustic waves (SAWs) and using optical transducers activated remotely by laser irradiation.

The generation and detection of ultrasound using transducers is a well-established technique and even today the majority of

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ultrasonic testing is performed using such devices. However, contact transducers are associated with several disadvantages. It is a contact method which requires a couplant. This may influence the measurements and result in unreliable or unrepeatable measurements. Transducers may be considered as heavy or too bulky for certain applications especially if there is limited access to the component, a problem frequently encountered during in-service testing. They are also unsuitable for complex geometries.

Laser based ultrasound can overcome these limitations. It is a non-contacting method of generating and detecting ultrasound meaning that it can be used in hostile environments due to its remote and couplant free operation. It is suitable for complex geometries and is capable of broadband frequency generation. However, current laser ultrasound systems are technically complicated, too bulky to be carried in the field, require experienced users and conditions of operation that can only be found in a lab. In addition they all require sophisticated optics which adds a significant cost to the system, making the technique expensive and thus unattractive to end-users. During the last few years, we have been developing a new type of optical transducer, the CHeap Optical transducer (CHOT) [13]. These are structures on the surface of the sample that are optically excited by means of lasers to generate and detect ultrasound.

The implementation of CHOTs allows a narrowband frequency optical system, in which the CHOT has full control of the mode, directivity and frequency of the wave it is sensitive to. Such a device lends itself well to a nonlinear experiment.

In the nonlinear experiment demonstrated in this paper, a low frequency stress inducing pumping surface acoustic wave is generated by a 1 MHz contact/piezo transducer. The second source of ultrasound which is the probing pulse, is generated by a generating-CHOT and is activated by an Nd:YAG laser. Depending on the point in time in which the two SAWs interact, the high frequency pulse will be phase modulated accordingly. Detection of the high frequency wave was performed using two independent laser based methods, for comparison: a knife-edge detector and a detection-CHOT. The advantage of using CHOTs for this experiment is that they can be excited remotely (even a distance of 150 m is within their capabilities), they are robust and reliable, able to operate in industrial environments, they can be permanently mounted onto components and they require minimal optical components without critical adjustments for ease of use.

The nonlinear technique presented measures a velocity change in the high frequency SAW as a direct consequence of the applied stress exerted by the low frequency wave. 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. It is understood that when a material experiences an applied stress, the velocity with which ultrasound propagates over it is affected [14].

2. CHOTs

CHOTs are an innovative ultrasonic transducer system which are optically activated for both generation and detection of ultrasound [13]. The advantage of CHOTs is that they do not require any couplant and their activation is done remotely using lasers. Once attached, they are very discrete (minimal weight and size <1 cm^2) minimising any impact on the inspected area. In addition, they can eventually be produced in large numbers making their cost significantly low. They have the potential of becoming permanently installed, providing reliable and repeatable measurements over time.

2.1. g-CHOT

The generating-CHOT (g-CHOT) is a structure printed, deposited, etched or by some means attached to the surface of the sample. The generated wave mode, direction and wavelength are controlled by its geometrical characteristics. The principle 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. An example of a g-CHOT structure for the generation of SAWs is shown in Fig. 1a.

In this work a fused silica substrate is considered, and the g-CHOT consists of multiple lines of titanium depositing on it by means of photolithography. The layer of titanium deposited was 146 nm thick. Its lines are equally spaced so that there is a periodic absorption contrast between the coated and noncoated areas of the substrate. When an Nd:YAG laser emitting at 1064 nm wavelength is used to activate the g-CHOT, the titanium absorbs its radiation more strongly than the transparent fused silica substrate. We have estimated (based on reflection and transmission coefficients mentioned in [15]) that 76% of the incident laser radiation is reflected, 20% of the radiation is transmitted and 4% of the radiation is absorbed by the thin titanium layer. On the other hand, the fused silica sample transmits 96% of the 1064 nm radiation (according to the manufacturer) through the 6 mm thick sample while 3% of it is reflected. The titanium coated part of the fused silica experiences local thermal expansion whereas the uncoated regions do not. The difference in local expansion when illuminated with a pulsed laser causes the generation of an elastic wave. Even though the absorption contrast between the g-CHOT pattern and the substrate is only 4%, it is still sufficient to generate detectable ultrasound. By increasing the absorption contrast we would improve the efficiency of the g-CHOT. It is within our plans to do so by using materials that absorb more laser energy such as black ink in combination with different manufacturing processes to make the preparation of CHOTs faster and cheaper as well.

The profile of the lines can be altered to control the direction of wave propagation. For example, by having a pattern with straight parallel lines, the resulting SAWs will have a plane wavefront. The advantage of using an arc profile is that the ultrasound is focused to a single point, improving the SNR for point detection. In this way the g-CHOT controls the directivity (focused or plane wave) but also the mode (generation of SAWs) of the generated waves.

An aerial point spread function (PSF) of the generated ultrasonic field from a focused 82 MHz g-CHOT made of deposited aluminium on a fused silica substrate is shown in Fig. 2b. Detection was performed using a knife-edge detector which was scanned over the sample surface in 10 μm steps.

The line spacing of the g-CHOT is selected to match the acoustic wavelength of the ultrasound that one wishes to generate on the inspected material using $\lambda_{SAW} = v/f$. Where λ_{SAW} is the acoustic wavelength (line spacing), v is the Rayleigh wave velocity and f is the frequency of the SAW. In this work, the g-CHOT is activated by a Q-switched and mode-locked Nd:YAG laser emitting at its fundamental (1064 nm) wavelength. The mode-locker produces short pulses of light which have a 12 ns repetition rate giving rise to the laser's fundamental frequency of 82 MHz. However, since these pulses are very short in time (12 ps), the output optical pulse contains a high harmonic content exceeding 1 GHz. The Q-switcher produces a burst of these pulses at a rate of ~1 ms and is detected by a photodiode placed at the aperture of the laser cavity. A trace of one of these coherent trigger pulses, along with a typical output frequency spectrum is shown in Fig. 3.

In this case the line spacing of the g-CHOT had to match the acoustic wavelength at 82 MHz on fused silica. With a Rayleigh wave velocity of 3419 m/s (measured using the Optical Scanning Acoustic Microscope [16]), a line separation of 41.7 μm is required. However, the line separation of the actual g-CHOT manufactured for the experiments presented in this paper was 41 μm corresponding to a frequency of 83.4 MHz. The resulting generated fre-

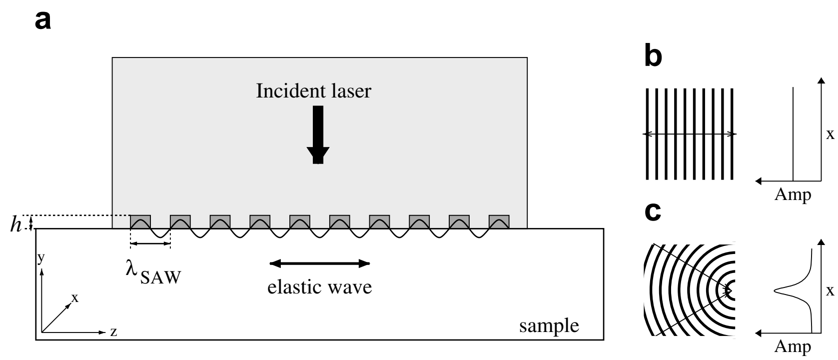

Fig. 1. Basic g-CHOT cross-section showing the structure required for SAW generation (a). Incident laser light illuminates a series of titanium lines, separated by one acoustic wavelength (λ_{SAW}). The height of the titanium (h) is 146 nm. g-CHOT profiles can be fabricated as a series of lines (b) and arcs (c) generating plane and focused ultrasound, respectively.

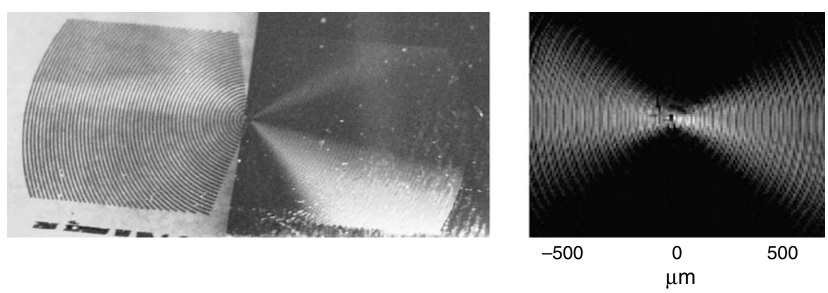

Fig. 2. A photograph of a focused g-CHOT (a) and a PSF of the ultrasound generated by a focused g-CHOT activated by a 1064 nm Nd:YAG laser (b).

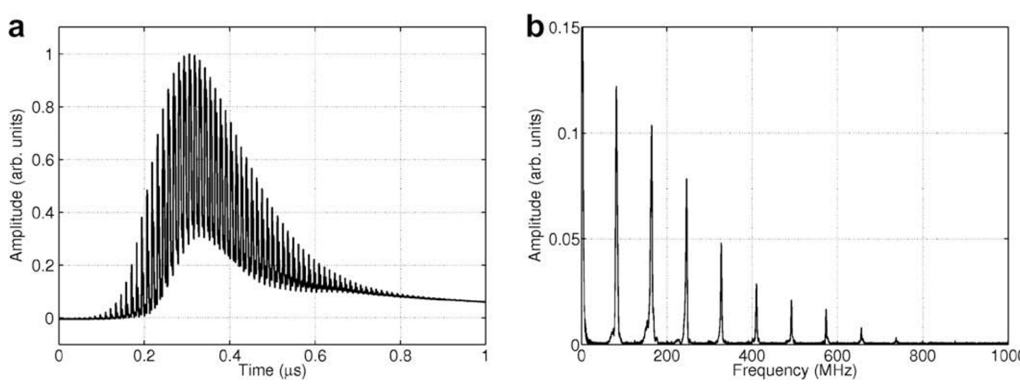

Fig. 3. Coherent trigger pulse detected at the output of the laser (a) with the frequency spectrum of the pulse (b).

quency would be the product of the frequency content of the laser and the frequency response of the g-CHOT i.e. 82.7 MHz, as verified by the experimental results.

In a more general case, where a non-mode-locked laser would be used instead, the output laser energy would contain a much broader frequency spectrum. In this case, the g-CHOT could be fabricated to actively select any frequency within the bandwidth of the laser [13] and the outcome of this is narrowband generated ultrasound.

2.2. d-CHOT

Since the g-CHOT generates narrowband ultrasound it is favourable to have a matching narrowband detection system as well. This has led onto the development of the detection-CHOT (d-CHOT). As with the g-CHOT, the d-CHOT consists of a structure placed onto the sample surface. However, in this case it reflects light and can be considered as a reflective grating. It is designed so that its geometrical features will select the desired mode and frequency. It can be used on its own to detect ultrasound which has been generated through other means or when combined with the g-CHOT, it provides a powerful, robust and sensitive, remotely operated ultrasonic system. A coupled CHOT system is particularly useful for narrowband applications such as in nonlinear experiments where higher harmonics amplitudes need to be detected to provide a measure of the material nonlinearity. The basic d-CHOT structure for the detection of SAWs is shown in Fig. 4.

The d-CHOT is activated by an incident CW laser and the reflected beam is separated into a number of diffraction orders one of which is the zero order (the primary reflection). A single order (preferably the zero order) is selected by an iris and is focused onto a photodetector. As an elastic wave propagates below the area of the d-CHOT, there is a change in the height of the steps, which modulates the light intensity among the orders.

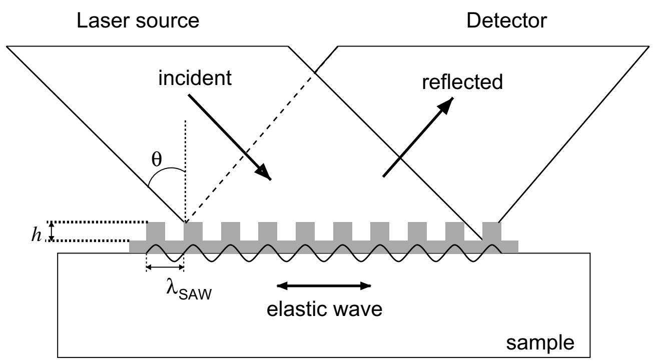

Fig. 4. Cross-section of basic d-CHOT structure with appropriate height (h) and spacing (λ_{SAW}) to detect SAWs. As with the g-CHOT, the lines can be set for the detection of plane or focused waves.

The height of the steps in the grating is designed in such a way as to introduce the desired path length difference in the incident light and is given by $\lambda_{opt}/(8\cos\theta)$. Where h is the step height, λ_{opt} is the optical wavelength of the incident laser and θ is the angle of incidence. Each step of the d-CHOT can be considered to be a miniature common path interferometer as shown in Fig. 4 in which the 'signal' and 'reference' beams are from the top and bottom of the steps. In order for maximum sensitivity, the effective path length difference between the two beams should be 1/4 of the wavelength of the incident laser light. For normally incident light, the path length difference is 2 h which means that h must be 1/8 of the optical wavelength.

For the nonlinear experiment described in this article, a frequency doubled 532 nm CW Nd:YAG laser was used at an incident angle of 45°. The separation of the lines are set to match the g-CHOT (i.e. 41 μm). The d-CHOT was made by evaporating an initial layer of silver (~140 nm) to make the sample surface reflective and then the lines of the pattern were made using photolithography. This second deposited layer of silver created steps of 82 nm height. For optimum operation at 45° incidence angle the steps should be 94 nm in height. Thus we were near the optimal height.

3. Nonlinear experiment

The nonlinear experiment is based on measuring the parametric interaction between a low frequency stress inducing SAW (pump) and a high frequency SAW (probe) on fused silica. An example of each of these is shown in Fig. 5.

This technique was performed using two experimental setups. The first used a plane wave g-CHOT to generate the high frequency and a knife-edge detector system. The second used a coupled plane wave g-CHOT and d-CHOT system. The experimental setup for both cases is shown in Fig. 6.

The degree of stress that the probing pulse experiences is altered by controlling the point in time when it interacts with the low frequency SAW packet. The delay electronics dictates the point in time when the two sources are triggered with respect to each other. During an experiment the delay is adjusted so that the probe pulse effectively experiences different stressed states of the sample, and is phase modulated accordingly.

An Agilent 33250A arbitrary waveform generator is externally triggered by the delay electronics to output a 3 cycle 1 MHz tone-burst. Its output is amplified by a Ritec-RPR4000 pulser/receiver amplifier which excites a Panametrics 1 MHz transducer with a 1400Vpp signal. A wedge is used for the generation of SAWs. The broadband knife-edge detector is able to detect both the pump and the probe waves, for additional adjustment of the delay electronics.

A 3 mm × 3 mm area of the g-CHOT was illuminated by the incident IR laser beam in both experiments generating a plane

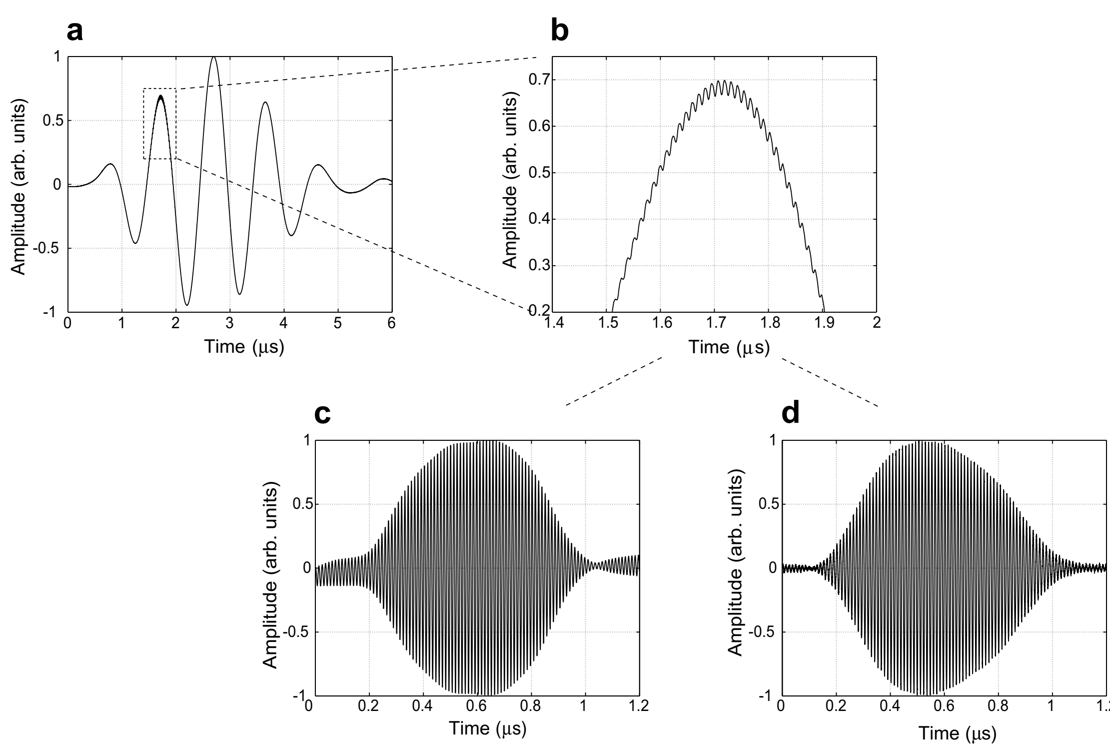

Fig. 5. Knife-edge detection of combined 1 MHz and 82 MHz SAWs (a). An enlargement of the region enclosed by the box is shown in (b), where the high frequency SAW is interacting with a peak of the low frequency SAW. A high frequency SAW pulse detected by a knife-edge detector and a d-CHOT are shown in (c) and (d), respectively.

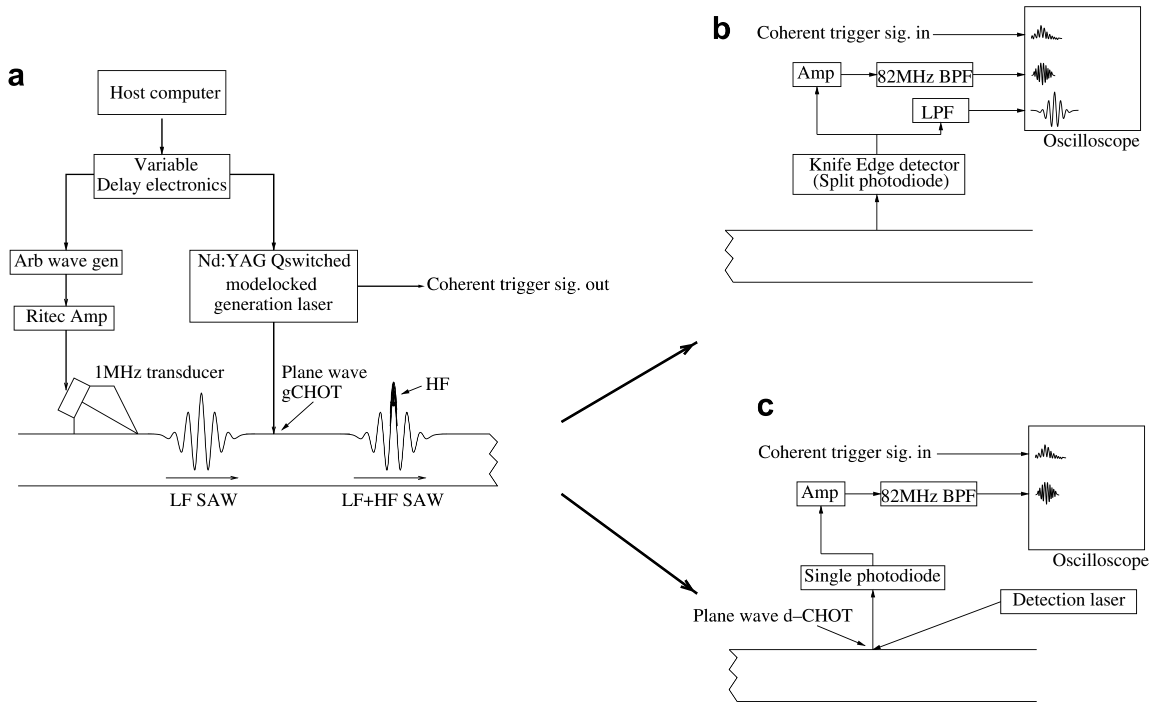

Fig. 6. Experimental setup. The generation of the 82 MHz ultrasound (a) was performed by a plane wave g-CHOT and detected using two different detection systems, a knife-edge (b) and d-CHOT (c). The low frequency ultrasound was generated by a 1 MHz transducer in both cases.

SAW which propagated a distance of 4 mm where it was detected by the knife-edge or d-CHOT. The incident IR laser energy is kept within the thermoelastic regime with ~0.4 mJ/pulse at a repetition rate of 1 ms. The optics required for the d-CHOT system are shown in Fig. 7b. For the activation of the d-CHOT, the 532 nm laser beam was focused to a ~2 mm spot. The energy level incident on the d-CHOT was 30 mW. The reflected beam was split up into several diffractive orders and a simple iris was used to select the zero order beam which was then focused on a single photodiode detector.

The stress induced velocity variations presented here are rather small (of the order of 1 part in 10^5) so a differential measurement technique was employed which measures the phase shift between a reference stress (delay) and a variable target stress (delay). However, the experiment was found to be sensitive to small temperature fluctuations in the laboratory (of the order of 1 °C) over the time scale of a single measurement (~20 s). Despite careful temperature control (of the order of 0.01 °C), the temperature effect could still be observed.

The cause of the temperature induced velocity variation was a combination of geometrical changes to the equipment caused by small expansions and contractions of the apparatus (influencing knife-edge detector only) and the change in sample velocity with temperature (influencing both knife-edge and d-CHOT).

In order to overcome the effect of these temperature variations we interlace the acquisition of the reference and measurement data by switching between them at a relatively high speed (>10 Hz). Using interlaced acquisition the average temperature of the sample during the measurement of reference and target signals is highly correlated and the effect of the temperature variation in the laboratory is effectively suppressed leaving just the effect of the stress.

In order to achieve the interlacing we employed a simple experimental technique whereby the signal from the detector was split and fed through two high speed analogue switches (mini circuits ZSWA-4-30DR) into two channels of an oscilloscope which continuously averaged the input. The switches were driven by the delay

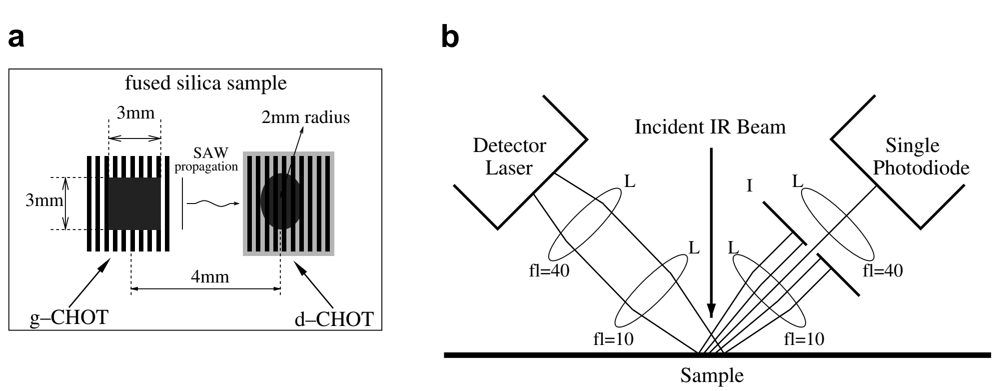

Fig. 7. Schematic representation of sample and CHOTs (a) and optical configuration for activation of CHOTs (b). L = lens, fl = focal length (mm), I = iris.

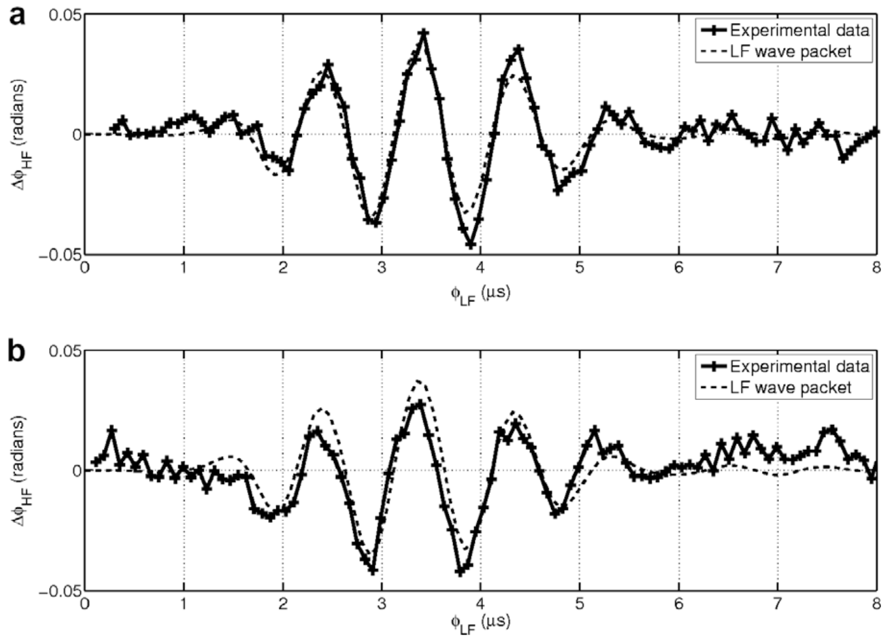

Fig. 8. Phase modulation ($\Delta\phi_{HF}$) experienced by the high frequency pulse at different interaction points with the low frequency (LF) wave packet. A g-CHOT generated the high frequency pulse and was detected by a knife-edge detector (a) and a d-CHOT (b).

electronics so that the reference channel only averaged reference data and the target channel only averaged target data.

4. Experimental results

Results obtained for the knife-edge and d-CHOT detection techniques are shown in Fig. 8a and b, respectively. In both cases, the high frequency was generated by a plane wave g-CHOT and the interaction distance between source and detector was 4 mm.

The low frequency signal shown in both Fig. 8a and b indicates the stress field that the low frequency transducer is exciting on the sample and was detected using the knife-edge detector and appropriate filtering. Different electronic channels are used for detecting the high frequency and low frequency signals. Consequently, the delay differences between the two electronic signal paths has meant that the signals' time of arrival is also different. For this reason an arbitrary phase has been applied to the low frequency so that the high frequency phase modulated results coincide with their respective interaction points on the low frequency wave packet as shown in Fig. 8. In both experiments the high frequency pulse has been scanned in time through 8 μs with steps of 80 ns so that it has experienced various stressed states imposed by the low frequency wave.

Using the technique considered here, typical velocity changes caused by the transducer stress wave are of the order of ±0.1 m/s. Although the precise stress levels are undetermined, the knife-edge detector has been calibrated so that the surface displacement is estimated to be of the order of 20 nm peak-to-peak for a typical transducer generated SAW. It can be seen that both detection techniques, which are completely independent from each other, have measured very similar phase modulated results.

In addition to the experiments previously described, we carried out a series of nonlinear experiments comparing the response on fused silica to an aluminium sample using the Optical Scanning Acoustic Microscope (OSAM) [17] instead of CHOTs. In both cases the experimental procedure was performed as described in section

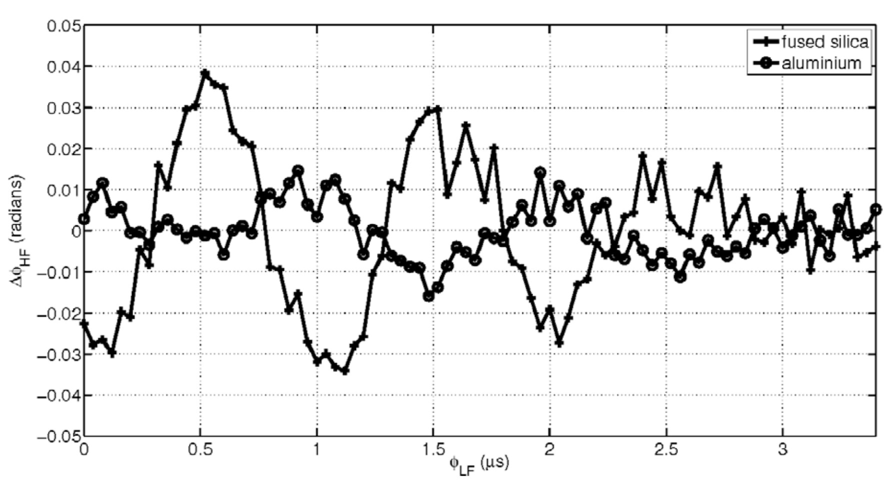

Fig. 9. Nonlinear experiment performed using the OSAM on fused silica (+) and aluminium (○).

3. On both materials the initial point of interaction between the low and high frequency waves (the starting point for the delay scan) was chosen to be the same. The phase modulation results are shown in Fig. 9. It is interesting to observe the opposite polarity in the results. This corresponds to an opposite value of the nonlinearity parameter in fused silica with respect to aluminium, in agreement with the literature [11,18].

5. Conclusions and further work

This paper describes a nonlinear experiment based on the parametric interaction between two SAWs on fused silica. The low frequency wave was generated by a 1 MHz transducer, while the high frequency SAW with a centre frequency of 82 MHz was generated by an optical transducer (g-CHOT). Detection was performed using two independent techniques, a knife-edge detector and a d-CHOT. By controlling the point in time when the two SAWs interacted with each other during the experiment, the high frequency wave experienced different stressed states of the sample imposed by the transducer and was phase modulated accordingly. The phase modulation is directly related to the velocity change caused by the induced surface stress. Both detection techniques provided consistent results.

CHOTs have been used in the experiments presented in this study. Their couplant free narrowband characteristics combined with remote activation and their small size (typical size 1 cm^2) makes them ideal for permanent installation on chosen aerospace components even in hostile environments where they could constantly monitor fatigue and ensure safety. In the present study, a specially modulated laser with a pulse content of 82 MHz was used to excite the g-CHOT. However, a common Q-switched Nd:YAG laser pulse would contain a broader frequency range and the user would be able to actively choose the appropriate frequency by changing the geometrical characteristics of the g-CHOT. A combination of low and high frequency g-CHOTs would have the additional advantage of making the whole technique completely noncontact. The use of 3 dimensional structures as CHOTs for the generation and detection of bulk waves is also under development. Most importantly, the advantage that CHOTs have over other laser based techniques is that they are very simple to use. They require minimal optical components and the laser is simply used to illuminate the CHOT structure avoiding the need for resolving its individual features which would need critical alignment of optics allowing for a long standoff distance. CHOTs are very robust and due to their filtering properties can cope with 'noisy' industrial environments. The implementation of CHOTs in this nonlinear experiment is only one example of their versatility. They provide an extremely powerful, yet cheap and reliable method of generating and detecting narrowband ultrasound at any desired frequency and therefore can be used in many NDT applications.

It has been observed that fatigue causes a change in material elastic constants [19]. The nonlinear technique presented in this study has the potential to be used to assess and monitor fatigue damage over time. The degree of phase modulation would depend on the extent to which the material has been fatigued and therefore can be used as an accurate measure of changes in material characteristics well before the initiation of a critical crack. In this way, the technique can contribute to major cost savings, decreasing components wastage and insuring safety.

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