Investigation of the fatigue process using nonlinear ultrasound

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Abstract. During normal usage components are subject to stresses that while not sufficient to cause fracture cause fatigue, which gradually weakens the component. Linear ultrasonic methods have been shown to be poor at detecting fatigue. However, there is evidence that the accumulation of damage gives the material a nonlinear elastic response that can be probed by ultrasound. By measuring the change in a material’s nonlinear properties a measure of the fatigue can be obtained. Several methods of detecting material nonlinearity using acoustic waves have been proposed. The collinear mixing technique is used here. By measuring the velocity change of a probe wave due to the induced stress from a second pump wave, a measure of the nonlinearity is obtained. By generating the probe wave and detecting both waves using laser ultrasound techniques we gain the benefits of high spatial and temporal resolution. This is important when investigating the nonlinear response of a material as there is evidence that the microstructure affects the nonlinear response of a material. The change in nonlinearity over a region of a specimen (aluminium) has been monitored over several fatigue levels to investigate any relation. Early stage results are given with a discussion on the development of the technique.

1. Introduction
Linear ultrasound techniques are good at detecting large scale damage like gross cracks, however they are relatively poor [1][2] at detecting defects and precursors such as micro-cracks and dislocations which are associated with the initial formation of gross cracks. However nonlinear techniques show potential in detecting these damage precursors. A variety of nonlinear techniques have been developed for a range of materials to investigate this possibility. These methods include harmonic generation [3] and three phonon interaction [4]. Another group of nonlinear techniques of interest is that of collinear interaction. This group relies on a propagating wave being altered—by frequency modulation [5] or phase modulation [6]—by another wave or vibration and this method is used here. The majority of the published work in nonlinear ultrasonics is performed with bulk ultrasonics. However there is evidence [7] in some materials that micro-cracks and dislocations associated with fatigue initiate near the surface of a material. Surface acoustic waves (SAWs) are used as these are more sensitive to these defects. Material nonlinear response is not only associated to fatigue damage but also the microstructure of the material [8]. In this paper we first illustrate how this nonlinear response relates to large microstructure, then explore its relationship to fatigue.
2. Experimental configuration
A full description of our instrumentation can be found in a previous paper [9], the salient points are described briefly here. Figure 1 is a functional schematic of the nonlinear system.

A low frequency pump SAW acts to stress the material through which it propagates, this is excited using a standard contact transducer. A high frequency co-propagating probe SAW is affected by the stress state of the material. The probe wave is generated using a pulsed laser as this allows high frequencies and high spatial resolution, which permits greater control over interaction and simpler separation of the two waves. By varying the timing point of interaction between the two waves a different stress state is experienced by the probe wave. This causes the probe wave velocity to change due to the nonlinearity of the material. By comparing the change in phase velocity of the probe wave to the stress experienced as it propagates—see figure 2—a measure of the material nonlinearity can be obtained.

![Figure 1. Nonlinear experiment schematic. The instrumentation is explained in the following sections in the main text: (2.1) pump; (2.2) probe; (2.3) delay control electronics; (2.4) SAW detection.]

![Figure 2. Measured velocity difference $\Delta v$ (blue - - - -) and stress $\sigma$ (green ——); maximum compressive and tensile stresses are indicated (red o).]

2.1. Low frequency pump generation
An NDT-Tech transducer with a central frequency of 1 MHz (A402S-SB) is attached to the sample, via an angle-wedge to excite the pump SAW. An arbitrary waveform generator produces a three cycle sine wave when triggered by the control electronics. This signal is then amplified and drives the transducer. Stresses of approximately 1–3 MPa are achieved.

2.2. High frequency probe wave generation
The probe SAW is generated using an optical method with a Q-switched laser ($\lambda = 1064$ nm) with a 10 ns pulse width. The beam is patterned using an intensity grating mask and imaged onto the sample. A 45 $\mu$m grating is used, producing a SAW pulse packet with a central frequency of around 68 MHz.

2.3. Control electronics
The stress field experienced by the probe wave is determined by where the probe wave sits on the pump wave. The interaction between these two waves is controlled by precisely timing the points at which they are generated. An FPGA (field programmable gate array) controls the triggering of the pump and probe wave by a computer-set variable delay. The velocity changes due to
the imposed stress are very small, of the order of 0.01 ms\(^{-1}\). This requires a large number of averages—taking tens of seconds—to ensure a sufficiently high SNR (signal to noise ratio). The velocity measurement could easily be overwhelmed by gradually changing environmental factors such as temperature, as the coefficient relating SAW velocity to temperature is approximately 1–4 ms\(^{-1}\) K\(^{-1}\). In addition to some basic temperature control, we implemented a differential interleaving process where by the probe wave is switched rapidly (30 Hz) between interacting with a stress state (target state) and a zero stress state (reference state). The reference wave will be subject to the same environmental conditions as it is interleaved with the target wave. By subtracting the velocity change of the reference state from that of the target state it is possible to eliminate environmental factors. With a sufficiently high number of averages (16k), the standard deviation on the measured velocity change is less than 6 mm s\(^{-1}\).

2.4. SAW detection and data processing

The pump wave is detected using a Polytec vibrometer (30 kHz–24 MHz), this provides a calibrated displacement that can be converted to stress. The probe wave is detected using a split knife-edge (beam deflection) detector with a broadband response (400 kHz–450 MHz).

The time shift between the detected target and reference probe waveforms is determined using a full spectrum method: cross correlation is used to determine the approximate delay, then the slope of the phase of all frequencies—weighted by the energy at each discrete frequency—is determined using a least squares fit. This time shift can then be converted into a velocity shift. The probe wave has a significantly smaller wavelength than that of the pump wave, this means that the probe wave energy is confined to the top region of the pump wave where the stress is essentially longitudinal [10]. The probe velocity change \(\Delta v\) and the pump stress \(\sigma\) are combined to give the nonlinearity coefficient \(\Delta v/\sigma\) in mm s\(^{-1}\)/MPa.

3. Experimental results

By reducing the number of interaction points between the pump and probe waves to two—the peak and trough of the pump wave, see figure 2—the measurement time is reduced to 40 seconds per point. This allows imaging of nonlinearity over the material surface within a sensible time frame. The lateral resolution is determined by the pump/probe interaction distance. On the one hand, longer distances mean bigger time shifts for a given change in velocity, improving SNR; on the other, attenuation and acoustic aberration reduce the SNR, especially for higher frequencies. The optimal distance for our setup is 3 mm.

Experiments were conducted on an aluminium 6061 sample with grains 3–4 mm in size. The linear SAW velocity was imaged using spatially resolved acoustic spectroscopy (SRAS) [11], revealing the microstructure of the sample, see figure 3(A). The area of the nonlinear scan is outlined in the dashed box, taking into account the 3 mm interaction distance (the box is offset by 1.5 mm). This scan area was selected because it covers an area containing part of a very large grain. The region on the right of figure 3(B) indicates nonlinearity of approximately −60 mm s\(^{-1}\)/MPa, in the rest of the scanned area the value is closer to −20 mm s\(^{-1}\)/MPa. The boundary between these two areas coincides with the edge of a large grain, indicating that there is a relationship between the measured material nonlinearity and the microstructure.

Preliminary measurements have been taken to determine the effects of fatigue on nonlinearity. A 2×2 mm area of an aluminium 2024-T351 sample was imaged at 0 %, 60 % and 80 % of its fatigue life (figure 4A–C). There was a overall increase in the mean nonlinear value from −56.6 to −61.4 mm s\(^{-1}\)/MPa. The most striking trend is that the standard deviation changed from 4.4 to 2.8 mm s\(^{-1}\)/MPa. To put this in context, the standard deviation measurement is repeatable to < 0.1 mm s\(^{-1}\)/MPa.
4. Discussion and further work

In this paper we demonstrate a method to image the nonlinear response of aluminium based on the collinear mixing technique. Scans of the nonlinear response of an unfatigued large grained sample show a relationship between the nonlinear response of the material and the microstructure. A scan shows wide spatial variation of nonlinearity between $-20$ and $-60$ mm s$^{-1}$/MPa. This implies that either careful registration, or averaging over a large region, is required for experiments monitoring fatigue. Initial results for a fatigued sample have shown a small increase in the mean nonlinear response across the sample microstructure. The reduction in the variability in the material nonlinearity is interesting, and more experimental evidence is required to determine whether this is a viable metric for fatigue life or not, and if so, then what physical mechanism is responsible. Further proposed work includes investigation into the spatial variation of material nonlinearity with fatigue. Samples that have microstructure considerably smaller—and larger—than the co-propagation distance will also be investigated. This work is supported by the UK RCNDE (Research Centre in Nondestructive Evaluation), and the UK TSB (Technology Strategy Board).

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