The use of non-collinear mixing for nonlinear ultrasonic detection of plasticity and fatigue

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Abstract: This letter reports on the application of the non-collinear mixing technique to the ultrasonic measurement of material nonlinearity to assess plasticity and fatigue damage. Non-collinear mixing is potentially more attractive for assessing material state than other nonlinear ultrasonic techniques because system nonlinearities can be both independently measured and largely eliminated. Here, measurements made on a sample after plastic deformation and on a sample subjected to low-cycle fatigue show that the non-collinear technique is indeed capable of measuring changes in both, and is therefore a viable inspection technique for these types of material degradation.

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1. Introduction

Nonlinear ultrasonic measurements enable the detection of the onset of plastic deformation and fatigue damage at an earlier stage than conventional linear non-destructive testing (NDT) techniques, which have insufficient sensitivity to the changes in the microstructure brought on by dislocation movements. Finite-deformation elastic theory introduces three independent constants, referred to as third order elastic constants (TOECs), which describe the nonlinear stress-strain behavior in an isotropic material. Different sets of independent TOECs have been proposed by various authors, including A, B, and C used by Landau and Lifshitz, which are a linear combination of the \( l, m, \) and \( n \) Murnaghan constants.

Of practical interest is the dependence of TOECs on the level of plastic strain or fatigue damage induced dislocation accumulation in a material. Various ultrasonic methods of measuring material nonlinearity have been developed. The first makes use of the so-called acousto-elastic effect. In this case the nonlinear behavior manifests itself through variations in ultrasonic propagation velocity with applied strain. Through the application of different wave types and the measurement of velocity in unstrained and strained states all three TOECs can be measured. One problem with this technique is the difficulty of measuring the small changes in propagation time and distance accurately enough to allow the velocity, and from that the TOECs, to be determined. A second problem is the necessity of loading a specimen to measure the changes in velocity.

The second and perhaps most widely reported method for interrogating material nonlinearity is the harmonic generation technique. If ultrasonic energy at one frequency is injected into a material, harmonics of the input frequency are generated due to nonlinearity as the ultrasound propagates. By measuring the magnitude of the harmonics the degree of material nonlinearity can be quantified. There is a considerable body of experimental evidence that

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shows a strong correlation between the normalized harmonic amplitude and the amount of fatigue damage or plastic deformation in a material. The major measurement difficulty with the harmonic generation method as a NDT technique lies in isolating the causes of nonlinearity. Specifically, amplifiers, transducers, and coupling methods are all contributors to the measured harmonic, often on a scale greater than the material nonlinearity itself. Thus it is practically very difficult to determine if the measured nonlinearity is due to the material or the equipment.

A third technique, which is the main subject of this paper, for TOEC measurement was first proposed by Jones and Kobett, and experimentally observed by Rollins. This approach is based on the fact that material nonlinearities cause interaction between two intersecting ultrasonic waves. Under certain circumstances, this can lead to the generation of a third wave with a frequency and wavevector equal to the sum of the incident wave frequencies and wavevectors, respectively. Theoretically, there are several incident wave combinations that can achieve this; however, practical material constraints to the theory lead to the interaction of two shear waves generating a longitudinal wave as the most useful case.

The non-collinear mixing technique has two important advantages over the conventional nonlinear ultrasonic harmonic generation technique. First, it is much less sensitive to system nonlinearities due to spatial selectivity (the nonlinear interaction is limited to the region where the incident beams intersect), modal selectivity (the nonlinear mixing signal is a different mode to the incident waves), frequency selectivity (the mixing signal frequency can be separated from harmonics of the incident waves if the driving frequencies are chosen to be unequal), and directional selectivity (the mixing signal propagates in a different direction form the mixed ones and their higher harmonics). Second, unlike the harmonic generation techniques, the level of the underlying system nonlinearity can be measured directly by summing the responses to each of the incident waves excited separately, that is, without the interaction present.

It is important to note that the evidence of correlation between material degradation (e.g., fatigue or plasticity) and nonlinear ultrasonic phenomena that has been reported is based mainly on evidence from the harmonic generation technique. In this configuration, only longitudinal waves can be used, and the harmonic amplitude is a function of all three TOECs \( A \), \( B \), and \( C \) or alternatively two of Murnaghan’s three TOECs \( l \) and \( m \). However, the non-collinear technique based on the interaction of two shear waves to produce a longitudinal wave was shown by Jones and Kobett and Taylor and Rollins to lead to a longitudinal wave amplitude that depends only on TOECs \( A \) and \( B \) (or the \( m \) and \( n \) Murnaghan TOECs).

What has not been studied to date is whether the particular combination of the two TOECs probed by the non-collinear technique is sensitive to fatigue and plasticity, and therefore whether the non-collinear technique can be used for NDT of fatigue damage. The purpose of this letter is to demonstrate that the non-collinear mixing technique can indeed detect changes due to plasticity and fatigue damage, and therefore has the potential to be used as a NDT technique.

2. Experimental arrangement

Experimental measurements were performed on an Al2014-T4 aluminum alloy specimen. Figure 1 shows the basic experimental arrangement. Two intersecting shear waves are generated using oblique incidence shear transducers made of longitudinal transducers of 5 MHz nominal center frequency mounted on 60° Perspex wedges. Within the volume of intersection a third longitudinal wave is generated due to nonlinear interaction. Once generated, this wave propagates through the material in a conventional manner and is detected by the receiver. The receiver was a normal-incidence longitudinal transducer of 10 MHz nominal center frequency. The excitation signals were generated using a digital oscilloscope/signal generator and the detected interaction wave (after amplification) was recorded using the same instrument. The excitation signals were amplified using a power amplifier, resulting in signals with amplitude of approximately 60 Vp-p.

The excitation signals to both input transducers were 20-cycle, Hanning-windowed tone bursts with center frequencies of 5.5 MHz. Using the same driving frequency for both incident waves removes one of the advantages of the non-collinear technique (frequency sepa-
although the following results show that ample suppression of system nonlinearities is still achieved. The recorded data were digitally filtered using an 11 MHz center frequency, 2 MHz bandwidth bandpass filter. The use of incident waves of the same frequency significantly simplifies the experimental apparatus as only one common driving signal needs to be generated. It also simplifies the experimental geometry since with both incident waves excited at equal and opposite angles, the resulting interaction wave is generated perpendicular to the specimen surface. The latter point means that the receiver can be placed on either the top or bottom surface of the specimen. For the purpose of this investigation the single sided arrangement was considered more suitable as it reflects the limited access likely to be encountered in practical applications. Note that the vertical position of the interaction zone can be readily moved by altering the separation of the input transducers.

Throughout all stages of experimentation each test comprised three measurements: one with each input transducer excited individually and one with both excited simultaneously. The signals recorded when the input transducers were excited individually were summed and the amplitude of this signal at the expected arrival time of the interaction wave used to estimate the level of remnant system nonlinearity. Figure 2(a) shows an example of time-domain response obtained from an as-manufactured sample when both input transducers are excited simultaneously. The pulse in the window labeled first reflection is the first received interaction wave after it has been reflected off the bottom surface of the sample. The subsequent pulses in the windows labeled second and third reflections correspond to reverberations of the interaction wave between the sample surfaces. In the following, the peak amplitude in the window corresponding to the first reflection is taken as the measure of material nonlinearity. Figure 2(b) shows the equivalent time-domain signal obtained by summing the responses from each of the two input transducers excited separately. The amplitude of the signal in the window labeled first reflection in Fig. 2(b) is due to the combined effect of all nonlinearities in the measurement system (e.g., reflections due to sidelobes of harmonics in the transmitted shear waves). It can be seen that the system nonlinearity is an order of magnitude smaller than the material nonlinearity, yielding a signal-to-noise ratio of 30, even in the as-manufactured sample, which is expected to contain the lowest nonlinearity anyway.

It is worth noting the presence of the signal at $2.5 \times 10^{-5}$ S in Fig. 2(a) resulting from second harmonic generation on a longitudinal wave propagating through the specimen and off of the back wall. If a conventional harmonic generation technique were employed this signal would be impossible to differentiate from any potential equipment nonlinearity, whereas using the non-collinear technique the interaction wave is spatially separated.
The responses of the three transducers used were calibrated to absolute values using a heterodyne laser interferometer. The purpose of this calibration was to enable a theoretical value of interaction wave amplitude for the as-manufactured material to be estimated for comparison with that measured experimentally. Values of $-25.22 \times 10^{10}$, $-32.5 \times 10^{10}$, and $-35.12 \times 10^{10}$ N/m$^2$ for the TOECs for single crystal aluminum were taken from literature. The approximate amplitude of the interaction wave was then estimated using the expression (Table I, case I) provided by Taylor and Rollins, yielding a value of $3.2 \times 10^{-12}$ m. The measured amplitude of the interaction wave for the intact sample was $2 \times 10^{-12}$ m. This is sufficiently close to the estimated value to give confidence to the basic soundness of the non-collinear measurement technique. The difference is believed to be primarily due to the theoretical values being calculated for a single crystal and therefore not taking into account the polycrystalline nature of the real sample. This calibration procedure illustrates the means by which the non-collinear technique could be used for making absolute measurements.

Having confirmed that the measured nonlinear interaction wave was of similar amplitude to that predicted theoretically, experiments were carried out to investigate changes in the magnitude of the interaction wave as the material was subjected to both quasi-static plastic strain and low-cycle fatigue damage. The first sample was used to investigate the effect of plastic deformation. Strain gauges were bonded to opposing faces of the sample directly above the region of interaction and the sample was loaded in a tensile test machine. After removing the load, the residual plastic strain was measured using the strain gauges and the specimen was removed from the test machine for the non-collinear measurements to be performed. Each set of non-collinear measurements corresponded to eight measurement points along the length of the

![Fig. 2. (Color online) Time-domain signals obtained from as-manufactured sample corresponding to (a) the total response when the shear transducers are excited simultaneously and (b) the sum of the responses when the shear transducers are excited separately. The colored lines show the calculated arrival times of the first, second, and third reflections.](image)
The process was repeated using the same specimen subjected to progressively higher loads to obtain non-collinear mixing data at successively higher levels of plastic strain.

In order to measure the material nonlinearity independent of the excitation level the amplitude of the interaction wave $A_3$ was normalized to the product of the two input amplitudes $A_1$ and $A_2$ measured in volts.

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\chi = \frac{A_3}{A_1 A_2}.
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Figure 3 shows the measured values of $\chi$ as a function of residual strain normalized to the intact value in order to make the change clearer. The key point to observe in this graph is the increase in $\chi$ by around 30% with residual strain, indicating that the non-collinear approach is sensitive to plasticity. Each point on the graph represents the mean of the eight individual measurements made for that particular plastic strain level. Between each measurement the transducer fixture was completely removed and the specimen cleaned. The error bars represent one standard deviation of the measurements.

A second specimen was tested under low-cycle fatigue conditions. These correspond to cyclically straining the material to beyond its yield point but significantly below its failure stress. Typical fatigue life under these conditions is less than 100 cycles. In the example presented here the sample was stressed between 0% and 110% of yield (420 MPa) in blocks of 10 cycles. Initially, this stress level led to a residual strain of 2%, significantly below the failure strain, but still high enough to result in a low-cycle fatigue failure. The results of this test are shown in Fig. 4.

It can be seen that $\chi$ initially increases rapidly with the number of cycles. Beyond 20 cycles the rate of increase drops significantly due to work-hardening in the material, and this is in line with published data in literature. In this experiment the error bars get larger with increasing number of cycles indicating a higher degree of variability in the measurements. This can be attributed to taking measurements along the whole of the test section rather than at a single location. End effects near the points of attachment to the tensile test machine may well result in more localized fatigue damage, hence increasing the variability of measurements.

### 3. Conclusions

These results demonstrate that the non-collinear technique is sensitive to both plasticity and fatigue damage in a similar way to collinear harmonic generation. This is despite the non-collinear technique being sensitive to a combination of different TOECs to the harmonic generation technique. Because of its intrinsically better rejection of spurious system nonlinearities,
the non-collinear mixing technique is highly suitable for measurement of weak material non-linearity, which can be exploited in the future for robust NDT of service-related damage in critical components.

References and links