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Detection and Characterisation of Surface Cracking using Scanning Laser Techniques

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Abstract. The use of lasers for generating and detecting ultrasound is becoming more established in non-destructive testing. However, there is still scope in developing the techniques to fully realise the benefits of non-contact measurements. One application is the detection of surface defects in metals; for example, rolling contact fatigue in rails, and surface cracking on billets or plates. We present measurements using a pulsed Nd:YAG laser to generate surface ultrasonic waves and an interferometer to detect the surface displacement on the sample, and investigate the interaction of Rayleigh or Lamb waves with surface defects. Signal enhancement in the near-field is observed for Rayleigh waves when either the generator or detector is close to a defect. For a scanned detector measurement, enhancement is observed due to constructive interference of the incident and reflected waves. For a scanned generator measurement, the change in generation conditions when the laser is over the defect also lead to an enhancement. In measurements of plate samples we observe similar enhancement effects whereby higher order modes are observed when the laser is above a defect. We discuss the implications of signal enhancements for detecting and characterising surface cracking.

Keywords: laser ultrasound, surface waves, non-destructive testing, defect characterisation.

PACS: 43.35.Yb, 43.38.Dv, 43.60.+d, 43.20.Gp, 81.70.Cv

INTRODUCTION

One important aspect of non-destructive testing (NDT) is the detection and characterisation of defects, and in particular surface breaking defects in metals, for example rolling contact fatigue (RCF) in rails [1] and stress corrosion cracking (SCC) in e.g. pipework [2]. If left untreated such cracking could be disastrous. In recent years, research has shown that surface ultrasonic waves are a good probe of the properties of surface cracking [3-8]. Much of this work has considered simple calibration defects, which are typically machined slots into the surface of the metal. We have shown that it is important to consider the geometry of the defects; for example, RCF initially propagates at an angle of around 25° to the rail surface, whereas SCC grows in a branched manner [4,5].

The type of surface wave one can use to probe the properties of surface defects depends on the sample geometry. In railway track samples, the surface is curved and hence a type of guided wave propagates. However, when considering propagation over short distances this guided wave can be approximated as a Rayleigh wave [9]. On plate samples, where the thickness is less than the wavelength of the ultrasonic surface wave, Lamb waves will propagate with the modes present dependent on the frequency \cdot thickness product [10].

We consider here two different sample and crack geometries. Firstly, we present details of the interaction of Rayleigh waves with defects which propagate at an angle to the surface normal in thick samples, to illustrate the need for consideration of the defect geometry. Secondly, we introduce Lamb wave interaction with surface defects, and discuss transmission and near-field effects on scanning plate samples containing V-shaped defects. For both of these sample geometries we use laser generation and detection of ultrasound. This has many benefits in NDT, particularly the lack of need for couplant, and generation does not impede the motion of the sample surface. The laser system can be remote from the sample and work in difficult conditions, for example on samples at high temperature [11]. The laser system presented here is designed to scan a sample and look at interaction of waves with surface-breaking defects, leading to characterisation of the defects.

EXPERIMENTAL DETAILS

Laser generation and detection of ultrasound is detailed elsewhere [5,11], hence we present here only brief details of these experiments. Laser generation typically uses a pulsed laser, which generates high frequency broadband waves. We use a Nd:YAG laser at 1064 nm wavelength, with a 10 ns pulse duration. The laser can be used in two regimes; at high energy density, the laser will create a plasma at the surface consisting of the vaporised sample and/or air breakdown which will hit the sample, creating an ultrasonic pulse [11]. This method is not generally non-destructive. At lower energy densities there is no damage and the laser pulse heats rapidly a small volume of the sample. The resulting expansion / contraction generates the ultrasound pulse. We work in the thermoelastic regime, with the laser focussed into a line source of approximate dimensions 6 mm by 300 μm , as shown in figure 1(b).

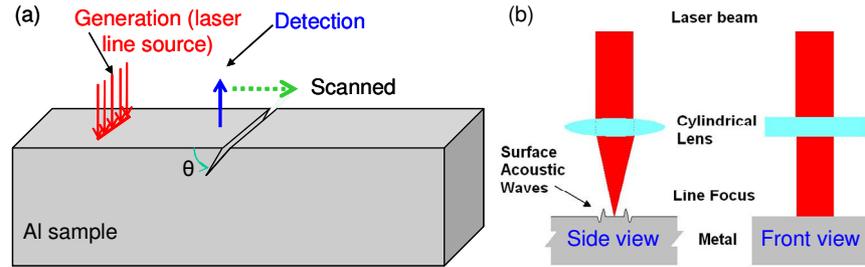


FIGURE 1. (a) Scanning set-up for laser generation and detection of Rayleigh waves on a thick sample. (b) focussing the generation laser into a line source.

Laser detection typically uses interferometric techniques. Here, we report measurements using an IOS two-wave mixer interferometer [12]. This has a 125 MHz bandwidth, allowing measurements over a wide frequency range. The out-of-plane displacement of the sample surface as the wave passes underneath the detection point is measured. The interferometer works on rough surfaces without the need for surface preparation, which brings many benefits to NDT on industrial samples. Figure 1(a) shows the full experimental set-up. The optics for the laser generation and detection are sat on a scanning stage and scanned over the sample. In these measurements, the laser generator or detector are scanned in turn over a surface-breaking defect. Measurements of a defect where the generation laser is in the region of a defect are known as scanning laser line source (SLLS) [7], whereas measurements with the detector in the region of a defect are scanning laser detector (SLD) [4].

LASER SCANNING FOR NDT

We now highlight two applications of this laser scanning system. Firstly we look at the comparison of SLLS and SLD when scanning on thick samples, and consider the interaction of Rayleigh waves with cracks of different orientations relative to the sample surface. Secondly, we consider the near-field interaction of Lamb waves with surface defects and the implications to measurements of detecting out-of-plane signals only.

Rayleigh Waves Incident on Surface Defects

The transmission of Rayleigh waves underneath surface-breaking defects has been shown to be useful for characterisation of surface cracking [3]. Laser generated waves are ideal for this application, due to their broadband nature; an A-scan is shown in figure 2(a), with the frequency content shown in figure 2(b). It is known that a surface crack will act as a filter, allowing the waves with longer wavelengths to pass underneath the defect, while blocking much of the high-frequency waves. One can study changes in transmission as a function of defect depth, or changes in the transmitted frequency content, and use this to characterise the depth of a defect [3]. However, the transmission shows some angle dependence, and hence it is important to know the defect angle before applying a depth calibration [5].

One feature which may be useful for characterisation of the defect angle is the signal enhancement [4,7,13]. This is measured by comparing the peak-to-peak amplitude of the Rayleigh wave when either the generator or detector is close to a defect, with the amplitude for both away from the defect. For a defect which is normal to the sample surface, as a Rayleigh wave is incident on the defect it will be partially transmitted, partially reflected, and partially mode-converted into modes such as a surface-skimming longitudinal wave. When the detector is very close to the

defect (SLD) it will be sensitive to the constructive interference of the incident and reflected Rayleigh waves, plus the mode converted surface-skimming longitudinal wave. As the crack angle changes there is still constructive interference of incident and reflected / mode-converted waves, however, the exact modes present vary depending on crack angle [4]. This leads to an angle dependence of the signal enhancement, as shown in figure 3(a), with enhancements of over 20 times the incident signal observed for shallow crack angles.

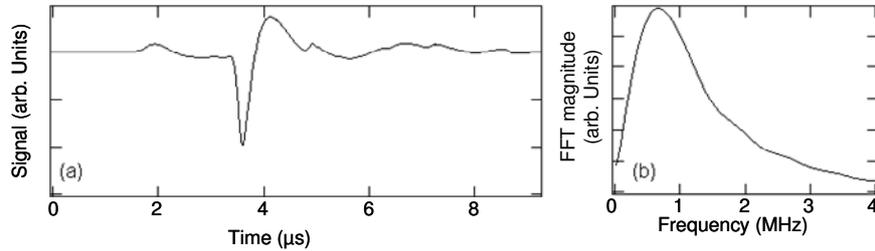


FIGURE 2. (a) Laser generated signal on an aluminium sample. The large feature is the Rayleigh wave. (b) A fast Fourier transform (FFT) of the Rayleigh wave, showing its frequency content.

When the laser generator is close to a defect (SLLS) the generation conditions change; the area over which the laser generates signals will become smaller, altering the generated wave [11]. The boundary conditions also change, which again can lead to a larger signal amplitude. There is also constructive interference of the incident and reflected Rayleigh waves; in this case, the surface-skimming longitudinal wave will be attenuated by the time it reaches the detector and have little effect. For angled defects we observe a small change in the overall enhancement (figure 3(b)) due to the small changes in the reflection coefficient for the Rayleigh wave plus concentration of the laser generation energy into a smaller thickness of sample.

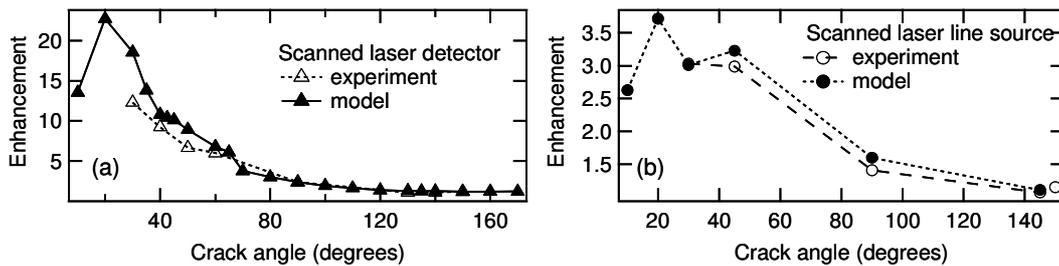


FIGURE 3. Signal enhancements for (a) scanned laser detector, (b) scanned laser generator, as a function of angle.

The scanning detector arrangement shows great promise for detection of angled surface defects, with the large signal enhancements giving an excellent fingerprint of the presence of a defect. The enhancement for shallow angles is due to the mode-conversion of the Rayleigh wave to a Lamb-wave like mode as the local frequency-thickness changes due to the geometry of the defect [4,10].

Lamb Waves and Surface Defects on Plates

In plate samples the propagating surface wavemode is a Lamb wave. It has been shown that when the laser generation is over a defect it will generate higher order modes than are present away from the defect [14]. This, again, is a good indication that a surface defect is present. Here we present SLD measurements, investigating the implications of mode-conversion and interference when the detector is close to a defect. Figure 4(a) shows a typical A-scan generated and detected using laser techniques, while (b) shows the calculated dispersion curve for aluminium [10]. The A-scan shows a very small S0 mode, followed by a distinct dispersive A0 mode. While both modes are generated the IOS interferometer is sensitive to out-of-plane displacements, and for small frequency · thickness the S0 is predominantly in-plane, while the A0 is predominantly out-of-plane. We can see this more clearly in figure 5, showing the time-frequency representation of an A-scan with the calculated arrival times overlaid.

Close to a surface defect the incident wavemodes will again be reflected, with mode conversion from A0 or S0 to other wavemodes possible [15]. As with Rayleigh waves, these modes will interfere leading to an enhancement of the signal. Analysis uses time-frequency representations, measuring changes in the magnitude of e.g. the A0 mode as the detector is scanned across the sample. At the defect enhancement is again observed. Furthermore, in the near-

field we have a mode conversion from S0 to A0, hence this A0 mode will occur at the arrival time of the S0 mode and will be detected by the interferometer in the near-field only.

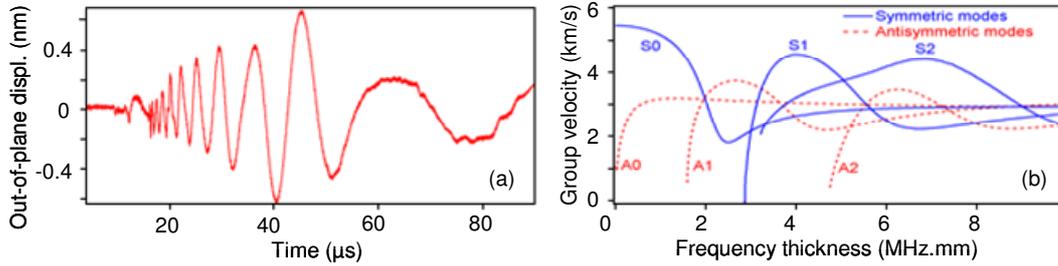


FIGURE 4. (a) A typical laser-generated A-scan. (b) Group velocity as a function of frequency · thickness.

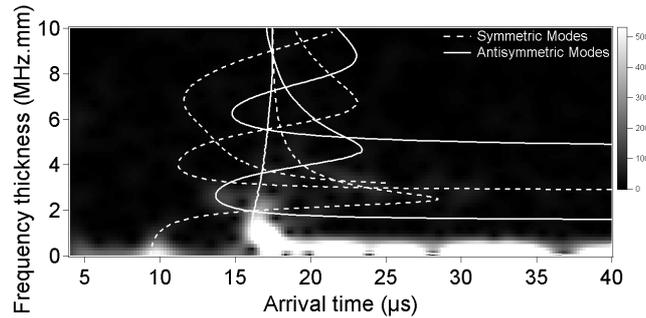


FIGURE 5. Time-frequency analysis of an A-scan measured on an aluminium sample, with calculated arrival times overlaid.

CONCLUSIONS

Scanning laser generation and detection of ultrasonic surface waves can bring many benefits to NDT. For Rayleigh waves on thick samples, the transmitted amplitude and frequency content can be used to characterise the defect depth, which the signal enhancement can be used to position the defect and to gain some idea of its inclination relative to the surface. A similar enhancement effect is observed for Lamb waves incident on defects on plates, and again signal enhancement has been shown to be a suitable fingerprint of the presence of a defect.

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