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Focused Rayleigh wave EMAT for characterisation of surface-breaking defects

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ABSTRACT

Developments towards higher resolution and the ability to detect small defects are bringing a step-change in non-destructive testing. This paper presents a new method for increasing resolution, using a focused electromagnetic acoustic transducer (EMAT) optimised to generate Rayleigh waves at 2 MHz. This high frequency allows detection of mm-depth defects, and the focusing allows sizing of much shorter defects than is possible when using standard EMATs. The focusing behaviour and the aperture angle effect are analysed using laser vibrometry and finite element modelling, showing that a reduced aperture shifts the focal point from the designed value and increases the focal depth. The dual-EMAT has excellent signal to noise ratio (up to 30 dB) and has been used in single shot mode to image a variety of surface-breaking defects, including detecting and positioning a pair of real defects in an aluminium billet sample, and a machined defect of 2 mm length, 0.2 mm width, and 1.5 mm depth, giving an upper limit on the defect length of 2.1 ± 0.5 mm. The results can be used to design an EMAT with optimised focal behaviour for defect detection.

1. Introduction

Non-destructive testing (NDT) and structural health monitoring are essential research areas for industry, with their importance steadily growing as the current infrastructure ages. A 2012 study highlighted required areas of growth, producing a 20-year vision for the field which stressed the importance of increasing sensitivity, with the ability to detect smaller defects and their precursors one of the main requirements of industry [1]. Ultrasonic inspection is one of the fundamental techniques in NDT [2–6]. Non-contact ultrasonic techniques, including laser ultrasonics and electromagnetic acoustic transducers (EMATs), are becoming more widely accepted [4]. These are inefficient when compared to piezoelectric transducers, but this can be mitigated by their lack of requirement for couplant and the ability to operate in harsh environments out of contact with the sample [3,7–9].

Surface-breaking defects such as stress corrosion cracking [10] in pipework and rolling contact fatigue (RCF) [9,11,12] on railway tracks can be characterised using surface acoustic waves [2,3,9,12–15]. Early stage detection of RCF requires sensitivity down to around 0.5 mm depth [16]. Rayleigh waves propagate predominantly within one wavelength of the sample surface [2], hence the sensitivity is dependent on the frequency used for inspection. The lateral resolution is dominated by the lateral extent of the plane waves generated.

Transducers typically used in industry have a large beam profile, limiting the size of defect that can be resolved when using surface-wave techniques. However, if a focused transducer is used, a narrower beam profile and increased signal strength at the focal point is achieved and this can be optimised for defect detection. Rayleigh wave focusing has previously been implemented using shaped piezoelectric elements [18] and with piezoelectric phased arrays [17,19]. The arrays allow for variable focusing, unlike the single shaped element which has a fixed focal point, but the arrays are costly and complex. Piezoelectric focused transducers have been produced with a beam width of 1.2 mm [18], while phased arrays have been used to identify holes drilled through an aluminium sample with diameters of 2 and 1 mm [19].

The use of non-contact ultrasonic methods for generating focused ultrasound beams offers many advantages in terms of implementation of inspection, despite the reduced efficiency of the techniques. The use of optics with laser ultrasound can give a ring shaped beam, which when incident on a sample surface creates an inward traveling wave that becomes focused at the ring centre. This focused point has much higher intensity than is possible with a direct incidence laser beam while staying in the thermoelastic (non-destructive) regime of laser generation [20–22]. A ring focused beam has been used to detect a 1 mm deep, 0.1 mm width, electro-discharge machined (EDM) slot in aluminium, but this measurement required the defect length to be larger than the ring diameter [21]. Sample surface deposits or screens can also be employed to shape the laser footprint on the sample

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surface, changing the frequency bandwidth of the generated ultrasound waves and creating a focus [23–25]. However, lasers are not always viable for regular machine testing in a factory setting due to their high costs and potentially serious safety implications.

EMATs are a robust and inexpensive alternative, free of the safety hazards of the laser generation techniques [4]. They can work without direct physical contact to the samples, with no coupling gel required, allowing them to be utilised in a variety of situations where standard piezoelectric ultrasonics are not viable, such as on moving, hot, rough, or rusted surfaces [3,7–9]. EMATs as generators consist in their simplest form as a coil of wire through which a current is pulsed [4]. This current creates an alternating magnetic field around the coil elements which, when close to a conductive sample, creates a corresponding alternating Lorentz force on the sample's delocalised electrons. These electrons consequently start to oscillate, and the momentum transfer by elastic collision causes their parent ions to move with them. The method can be enhanced by the presence of a permanent magnet above the coil. The configuration of the magnetic field direction and the coil shape alters the wavemodes that are generated. EMAT detection works similarly, however it is more efficient than the generation method [33]. The presence of a permanent magnet is a necessity for detection.

The majority of previous work on focused EMAT techniques have concentrated on shear wave generation [4–6,26,27]. A straight meander line EMAT can generate shear waves which propagate into the sample bulk, and varying the meander spacings causes constructive interference of the beam to form a focal line [4,6]. Curving this design adds a geometric focus for constructive interference at a point location, and this has been employed for detection of slits deeper than 0.05 mm on the opposite surface of a 20 mm thick stainless steel sample [26]. A curved EMAT design for Rayleigh waves has been suggested in EMAT testing standards [28], but this has not been the focus of any concentrated research effort to understand and improve the EMAT behaviour.

This paper details and fully characterises a focused Rayleigh wave dual-EMAT design and demonstrates detection of a variety of machined defects and a pair of real defects, showing high resolution surface breaking defect sizing and detection. The effect of the aperture angle on the focus achieved is explained and steps devised which can be used to design an optimised transducer for a chosen focal point.

2. Method

The focused concentric dual-EMAT coil, shown in Fig. 1, was optimised to generate Rayleigh waves at 2 MHz in aluminium, corresponding to a meander line spacing of 1.5 mm. The wire used was 0.08 mm in diameter and was wound three times through each of the meander line elements. Two separate coils were used, nested together so that they could be used in a pseudo pulse-echo arrangement while allowing for individual impedance matching of the coils. The coils have different aperture angles (11.4° and 20.1°) as they were designed to fit under the same 35 mm diameter NdFeB magnet to facilitate simple scanning and effective alignment with only one transducer. They are individually tuned using capacitors to create an LCR circuit with a resonant frequency of 2 MHz in order to achieve maximum signal strength [4]. This gives a wavelength suitable for detecting defects with depths in the mm range, while still allowing hand-winding of the coils to give a high current density. The generation coil has a designed radius of curvature, and hence focal point, of 50.6 mm when measured from the back edge of the coil.

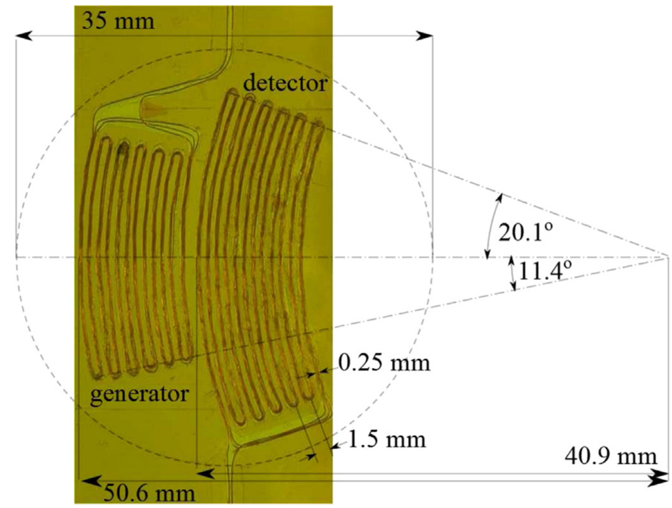

Fig. 1. Annotated photograph of the concentric EMAT coils. Dashed circle indicates magnet placement.

The dual-EMAT was produced to detect surface-breaking defects with high spatial resolution, with this resolution determined by the beam width at the focal point. In order to reliably detect a defect the beam width should be of the order of, or smaller than, the defect length. By analogy with conventional diffraction-limited optics the theoretical focusing resolution is given by the Abbe diffraction limit [29],

$$D = \frac{\lambda}{2\ \sin\ \theta} \tag{1}$$

where D is the minimum width, λ is the wavelength of the ultrasound, and θ is the aperture angle. This predicts $D=3.8$ mm for the generation EMAT.

The generation EMAT coil consists of six meanders. A seven cycle, 2 MHz, sinusoidal tone burst was used to generate a surface wave, using an adapted Ritec RAM-5000 pulser-receiver. Signals reflected from defects return as a seven cycle wave packet, and therefore if no signal processing is used the spatial resolution of the technique is limited. However, simple signal processing techniques can be used to extract the wave packet peak to allow accurate position measurements.

To extract the peak of the wave packet in an automated manner, a synthetic signal G with its real component designed to match the generated signal was created:

$$G = e^{\frac{-(t-t_0)^2}{2a^2}} e^{2i\pi f(t-t_0)} \tag{2}$$

where f is the frequency, t_0 is the time offset, and a is the bandwidth of the signal in the time domain. The values were set to match those contained in the real output signal ($a=1$ μs, $f=2$ MHz, $t_0=20$ μs). This synthetic signal was cross-correlated with the detected waveforms and the absolute value squared returned, giving the signal power of the wave packet (effectively measuring the peak in the wave envelope), making it possible to find the maximum peak position to a good degree of accuracy. The cross-correlation process also takes advantage of data from all seven cycles of the detected wave as it compares the shape of the full signal packet with G, increasing the accuracy of the peak characteristics found, and reducing any noise which has different frequency content.

To illustrate the effect this processing has, Fig. 2 shows an unprocessed and a processed A-scan detected by the dual-EMAT when aligned with the focal point at the centre of the largest defect used in this study (see the 20 mm length angled defect outlined in Table 1 and Fig. 3). The reflection from the defect can