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Enhanced surface defect detection using focused electromagnetic acoustic transducers (EMATs)

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Electromagnetic Acoustic Transducers (EMATs) are non-contact ultrasound transducers which function primarily via Lorentz force induction. Their non-contact nature allows for fast scanning, inspection of challenging surfaces, and performance in harsh environments. To meet industry demand, non-destructive evaluation (NDE) techniques need increasingly high resolution for the detection of smaller defects. For surface acoustic wave inspection of surface-breaking defects, using a higher frequency wave gives better depth resolution. However, the EMAT coil width has to decrease to increase the frequency, leading to a trade off with the signal strength. The use of geometric focusing is showing promise for increasing ultrasound strength and defect imaging precision, overcoming some of the issues associated with the use of higher frequency surface acoustic waves. Understanding and optimising transducer design is essential to obtain optimal signal strength, high frequency operation, and the ability to operate at stand-off from the sample. In this work multiple focused and unfocused EMAT coil configurations are presented. Focusing is seen to give significantly enhanced resolution for defects, with accurate detection of thin cracks, 0.2 wide, 2mm length, 1.5 mm depth. The relationship between coil design and stand-off is investigated. Multiple phased coils are proposed to increase signal strength without lowering the frequency.

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1. INTRODUCTION

Electromagnetic Acoustic Transducers (EMATs) are a non-contact ultrasonic transducer[1] used for non-destructive evaluation of metal components. They function primarily via the Lorentz force, as indicated in figure 1. EMATs have many industrial applications, such as the nuclear industry, they have been shown to function up to 450°C,[2] and the railway industry where they could be used at speeds of 15km/h,[3] potentially higher.

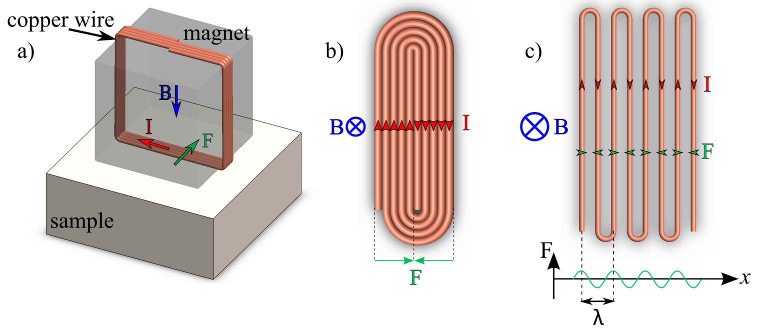

Figure 1: a) Linear EMAT coil schematic. b) Racetrack EMAT coil, which sits between the permanent magnet and the sample. c) Meander-line EMAT schematic. I indicates current direction, B indicates the permanent magnetic field, and F indicates the corresponding Lorentz force induced in the sample.

There is a need for higher resolution for surface breaking defect detection.[4] This work considers a variety of geometrically focused EMAT designs for this purpose, generating and detecting Rayleigh waves. The effect of coil design on lift-off performance is explored for these designs, and also for three unfocused calibration designs.

2. FOCUSED EMATS

Figure 2 gives the schematics of three focused EMAT coil designs. The meander-line (a) and the racetrack (b) have been used for high resolution surface defect detection.[5,6] (a) measures reflections from defects; example data from a micro-machined, 0.2 wide, 2mm length, 1.5 mm depth, crack is shown in figure 3, for single shot data, showing that the small defect is clearly detected. (b) measures transmission in a pitch-catch set up. This work was performed in contact with the samples. Due to the higher noise levels seen at lift-off from the sample, all following data is taken using 64 averages and digital filtering.

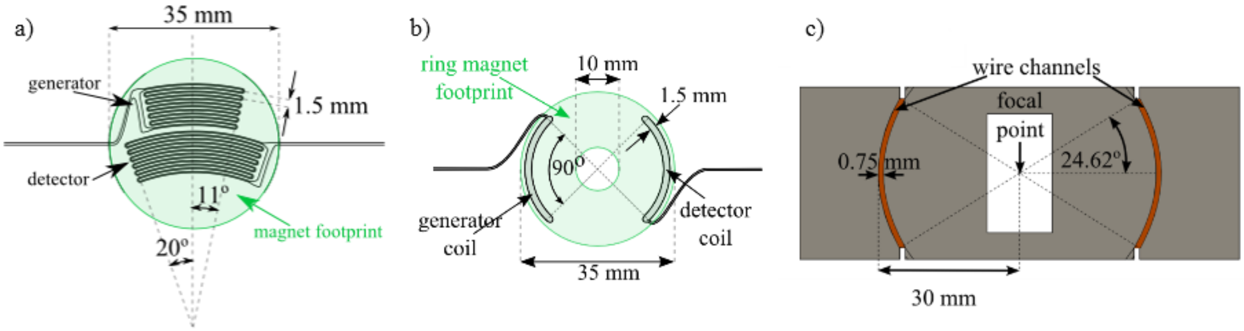

Figure 2: a) Focused meander-line EMAT coil schematic.[5] b) Focused racetrack EMAT coil schematic.[6] c) Focused racetrack EMAT coil schematic, lower segment of coil only shown.

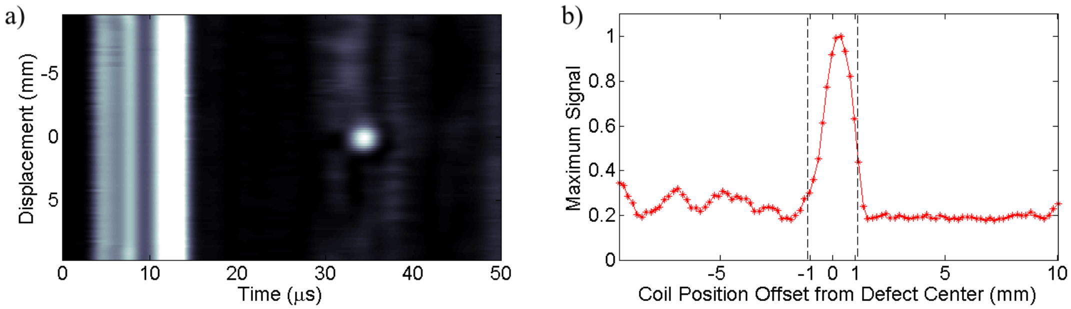

Figure 3: a) Brightness scan of a 0.2×2×1.5 mm laser micro-machined surface defect using the coils shown in figure 2a). b) The maximum peak to peak signal detected at each scan position. Single shot data.

Figure 4 shows the behaviour of the coils as they are moved out of contact with the samples, (increased lift-off). The reflection, meander-line EMAT was aligned with the end of an aluminium sample to give a maximum reflected signal to study. The transmission EMATs were placed in the center of a large aluminium sample away from defects or edges so the maximum transmitted signal is analyzed. The meander-line EMAT clearly shows the worst performance with lift-off, dropping to 0 SNR at 0.3 mm separation from the sample. The linear coils, although they start with a lower SNR when in contact with the sample, show the slowest decrease in their signal with lift-off, with signals above the noise level almost up to 1 mm lift-off. However, this could partly be due to the frequencies of operation. When operating the same linear coil pair at 0.6 MHz and at 1 MHz it can be seen that the lower frequency performs the best at high lift-off. A similar effect is seen in the racetrack coils. Additionally, the coils do not all produce the same frequency signal that they are driven with. For example, the 1.5 mm racetrack coil when driven with a 2 MHz driving signal actually produces a peak signal at 1.8 MHz.

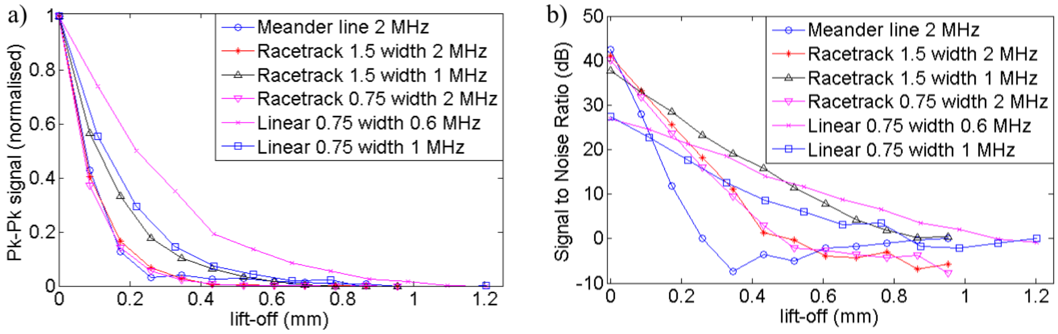

Figure 4: a) Maximum signal detected by the focused EMAT designs(figure 2) as the separation between the EMAT and the sample is increased. b) The signal shown in a) is converted to a signal to noise ratio (SNR), estimating noise as the maximum signal where no Rayleigh wave is present.

3. UNFOCUSED EMAT CALIBRATION

Three unfocused, pitch-catch (transmission mode) EMATs were created to separate the effect of frequency on lift-off from the effect of coil design; one pair of 1.5 mm width racetrack coils, one pair of 1.5 mm width linear coils, and one pair of 0.75 mm width linear coils. Their signals are weaker than the focused designs due to the use of smaller magnets and the lack of geometric focusing. Example lift-off behaviour at different frequencies is shown in figure 5. It can be consistently seen that higher frequencies have worse performance at lift-off than lower frequencies.

All coils are found to produce a detectable signal at 1 MHz when a 1 MHz excitation signal is used, and so this data is plotted as an SNR for comparison in figure 5c). Some linear fits have been added to the data to aid the visual comparison of the different data plots. The linear coil data rapidly becomes very noisy and so it is difficult to differentiate at what point the data should be neglected as noise. However, regardless of the possible fits chosen, the linear coil data is found to have a slower decline in signal strength that the racetrack coil data. It can be concluded that the linear coil designs have the most potential for performing at high lift-offs. However, linear coils produce lower frequencies than the racetrack design for the same size coil, which reduces their ability to detect small defects. Their design needs optimizing for higher frequency signals.

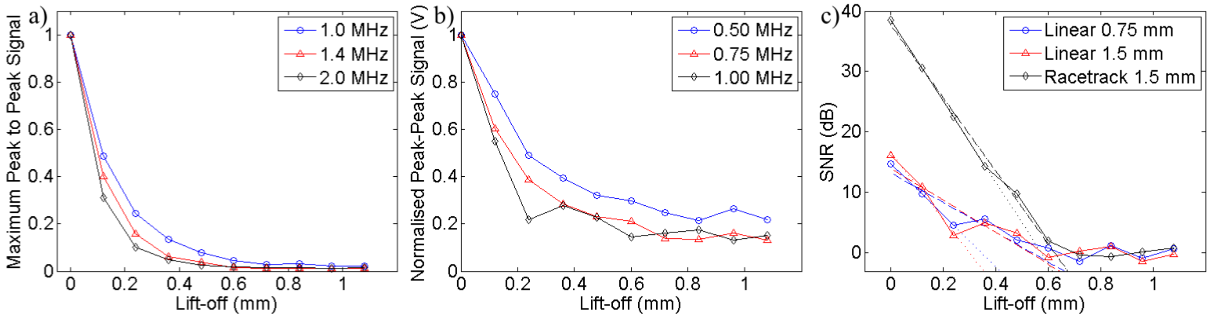

Figure 5: a) 1.5 mm unfocused racetrack coils, b) 1.5 mm unfocused linear coils, maximum detected signal reponse as the coils are lifted from the sample. d) a comparison of the SNR from a), b), and a similar 0.75 mm width linear coil pair for a 1 MHz driving signal. Some proposed linear fits have been added to the data to aid visualisation.

4. PHASED LINEAR COILS

Figure 6 shows a proposed phased EMAT design. The coils are linear in nature and so should have the best lift-off capability out of the different surface wave designs tested. However, the reason the meander-line behaves so poorly with lift-off is because it contains wire with current flow in opposing directions in close proximity. These opposing current directions create opposing magnetic dipoles, required to force the ultrasound wave to the desired wavelength. However, at lift-off these magnetic dipoles cancel out, rapidly reducing the applied force in the sample. To circumvent this, this design is proposed to space the individual coils by $^{3\lambda}/_{2}$, and then to excite them with the corresponding time delay, so the opposing currents will not be active at the same time. A further improvement would be to include geometric focusing for higher signal strengths. A prototype design has been produced and is undergoing testing.

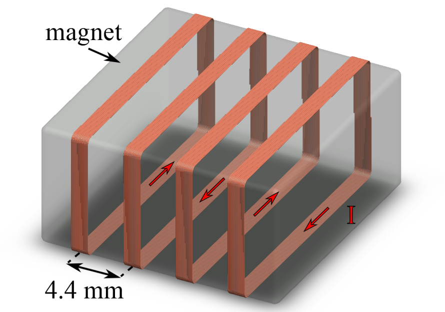

***Figure 6:** A proposed linear coil design to improve the high frequency capabilities. Coils are spaced by $^{3\lambda}/_{2}$ and will be fired with a time delay so the opposing forces from the opposing current directions are not active at the same time.*

5. CONCLUSION

Focusing using EMATs can improve surface wave signal strength and defect resolution. Meander-line designs improve the high frequency content but at the expense of lift-off capabilities, partially because higher frequencies intrinsically suffer more for the lift-off, and partly due to the occurrence of opposing magnetic dipoles in the meander-line design. Linear designs are shown to have the best lift-off capabilities but the weakest overall signals. A phased design is proposed to retain the high frequency nature of the meander-line designs, but with improved lift-off capability as the phasing eliminates the opposing magnetic dipoles.

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