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Experimental development of electromagnetic acoustic transducers for measuring ultrasonic guided waves

Philip W. Loveday[a], Kahesh Dhuness[a], Craig S. Long[a,*]

[a]*CSIR Materials Science and Manufacturing, P.O. Box 395, Pretoria, 0001, South Africa*

email address : clong@csir.co.za[*]

Abstract

Guided wave ultrasound offers the potential to monitor long sections of structures such as pipes and rails from a single transducer location and is used in a system for monitoring continuously welded rail track which was developed in South Africa. The design of such systems is complicated by the fact that numerous modes of propagation exist and that these modes are generally dispersive. Future developments of the system require the use of an array of transducers to be able to distinguish the different modes which propagate and reflect from defects in the rail. Piezoelectric transducers bonded to the rail have been found to interfere with the propagation of ultrasound and this scattering makes the array processing ineffective. Electromagnetic acoustic transducers (EMATs) have been developed by other researchers for transmitting and receiving Lamb waves in plates and surface waves in the head of a rail. These transducers are generally optimized to transmit guided waves as EMATs produce very small excitation forces. In this paper we describe the initial development of EMATs for the purpose of receiving guided wave ultrasound in rail in the low frequency range up to 100 kHz.

The EMAT is comprised of a coil placed on a soft layer on the rail surface with a magnet placed on top of the coil. The magnet produces a magnetic field in the rail and when an ultrasonic wave causes a surface velocity an eddy current is established in the skin. The eddy current induces an opposite current in the coil and this current is amplified electronically and detected as a measure of the velocity of the rail surface. EMATs and pre-amplifiers were designed and constructed. Calibration against a laser vibrometer was performed in the laboratory. The devices were shown to measure only the velocity normal to the surface and had excellent linearity and repeatability. Measurements with an array of eight EMATs on an operational heavy haul rail line were performed. Significant electromagnetic noise was encountered in the field measurements, which was not present in the laboratory. The source of this noise should be investigated in future but the effect of the noise was reduced by performing 1000 averages. Guided waves transmitted from a piezoelectric transducer located 70m away could be easily measured and reflections from two aluminothermic welds were observed. The EMATs had significantly poorer signal to noise ratio than piezoelectric transducers but did demonstrate other advantages including no scattering of ultrasound, ease of attachment and excellent linearity and bandwidth.

Keywords: Electromagnetic acoustic transducer, guided wave ultrasound, rail monitoring

1. Introduction

Guided wave ultrasound offers the potential for inspecting or monitoring a large portion of a structure from a single transducer location. Systems for inspection and recently monitoring pipelines in the oil and gas industry are commercially available while a system for detecting broken rails has been developed in South Africa [1]. Research and development is being conducted to upgrade the broken rail detection system from a system that detects breaks to a system that detects defects prior to rail break and therefore prevents broken rails. The development of such a system is significantly more challenging as cracks in different parts of the rail profile have to be detected and this has to be achieved at reasonable detection distances. At the frequencies used in rails there are numerous modes of guided wave propagation and these modes can be dispersive meaning that energy at different frequencies propagates at different velocities. In order to achieve long ranges piezoelectric transducers have been developed which are optimized to excite selected modes and frequencies with high power [2]. In order to transfer power to the rail the transducers are bonded to the rail. This good coupling is required to transfer power but also presents the drawback that these transducers reflect ultrasonic guided waves. When multiple transducers are attached close together to form a transducer array it has been found that scattering of the waves by the transducers limits the effectiveness of the phased array processing which is commonly used to distinguish different modes of propagation and the direction of wave propagation [3]. When performing field measurements of different modes of propagation and measuring reflections an alternate receive transducer was required. Other techniques of measurement such as strain gauges or small piezoelectric elements bonded to the rail were considered. Measurements have previously been performed using a scanning laser vibrometer but these are time consuming and difficult to perform on operational rail lines [4]. Instead it was decided to investigate the use of electromagnet acoustic transducers (EMATs). These transducers have been used by others for both transmitting and receiving ultrasound although the sensitivity of these devices is low. It was thought that if transmission was performed with a powerful piezoelectric transducer then reception with EMATs may be acceptable. Other advantages of EMATs include that they can be non-contact or can contact the structure via a soft layer thereby preventing scattering the ultrasonic waves. Therefore little of no surface preparation is required. EMATs can be designed to detect specific types of waves or to measure the motion in only one direction and are inherently broad bandwidth devices. They can also be relatively inexpensive to make. This paper describes our first attempt to develop an EMAT array for measuring ultrasonic guided waves in rails.

The operating principle of these devices is described in section 2 which reviews some of the recent literature. The design and construction of our first sensors is described in section 3 while measurements performed in the laboratory and in the field are presented in section 4.

2. EMAT operating principles and concepts

An EMAT generally comprises a magnet, a wire coil, an air gap and a metal surface. The main transduction mechanisms are the Lorentz force, magnetisation force and magnetostriction [5]. Magnetostriction is a non-linear phenomenon but fortunately is only small in low carbon steels and only the Lorentz force needs to be considered in rail applications [6]. The Lorentz force describes the force acting on moving charges in a magnetic field. It also works in reverse causing a current to flow in a conductor moving in a magnetic field. This is illustrated in figure 1. In the figure the current (I) flowing in the conductor in the presence of the magnetic field (B_0) causes an eddy current (J_e) to flow in the skin of the plate. This eddy current flowing in the magnetic field causes the force (F) in the plate material and this force is orientated normal to the current and magnetic field directions. In reception the ultrasonic wave has velocity (v) and this motion in the magnetic field causes current (J_e) to flow in the skin depth layer of the plate which in turn attempts to induce a current in the conductor resulting in a measureable voltage (V).

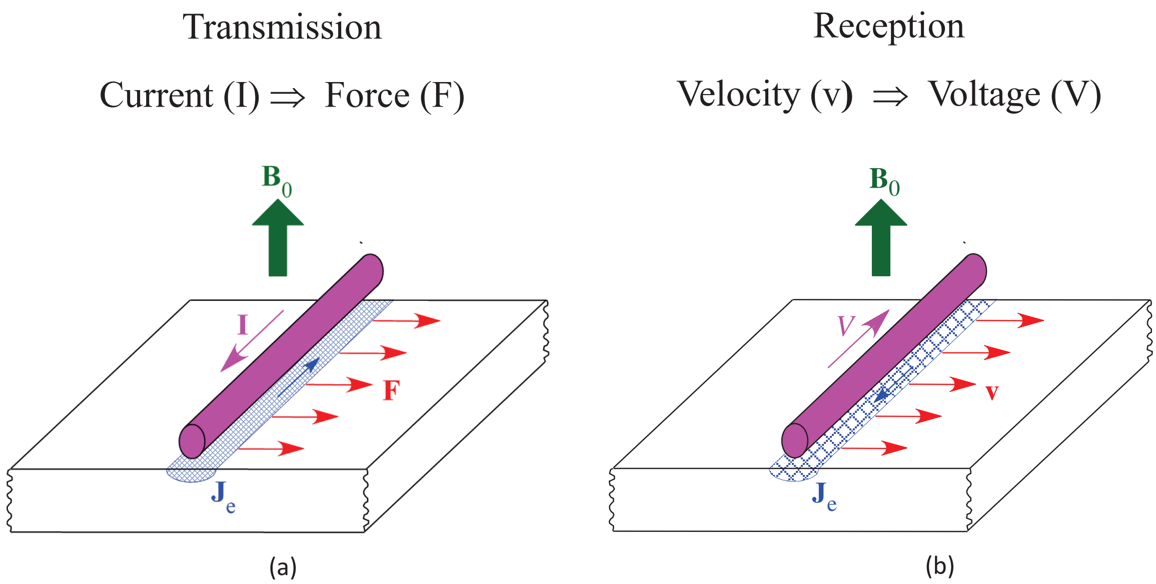


Fig. 1. Lorentz force as used in EMAT design, (a) for transmitting ultrasound and (b) for receiving ultrasound. (Adapted from [7]).

The principle described in figure 1 may be utilised to excite different types of ultrasonic waves by designing the magnetic field and the conductor. Various combinations of magnet design and coil design for exciting different bulk waves are illustrated in figure 2.

Devices for transmitting guided waves in plates, pipes and rails have also been presented in the literature. The magnetic fields shown in figure 2 are simplistic. A computed magnetic field for a cylindrical magnet above a steel plate is shown in figure 3a [8]. It is clear that the magnetic field is not constant in the coil region and that there are radial components that are significant near the outer diameter of the magnet. A device optimised to maximise the ratio of the excited a_0 Lamb wave to the s_0 Lamb wave is shown in figure 3b. When used as a transmitter the current and the axial component of the magnetic field would cause radial traction stresses on the surface of the structure and this would result in omnidirectional transmission. If the device is used to receive a Lamb wave it is expected that the wave would be a plane wave and due to symmetry the axial component of the magnetic field would not cause currents in the coil. Instead, the radial component of the magnetic field should make this device sensitive to vertical velocity of the plate when a Lamb wave is received. Due to the axisymmetric design this device should not be sensitive to motion in other directions. It was decided to design and construct an EMAT based on this simple concept for the purpose of receiving ultrasound by measuring the vertical velocity of the surface under the EMAT.

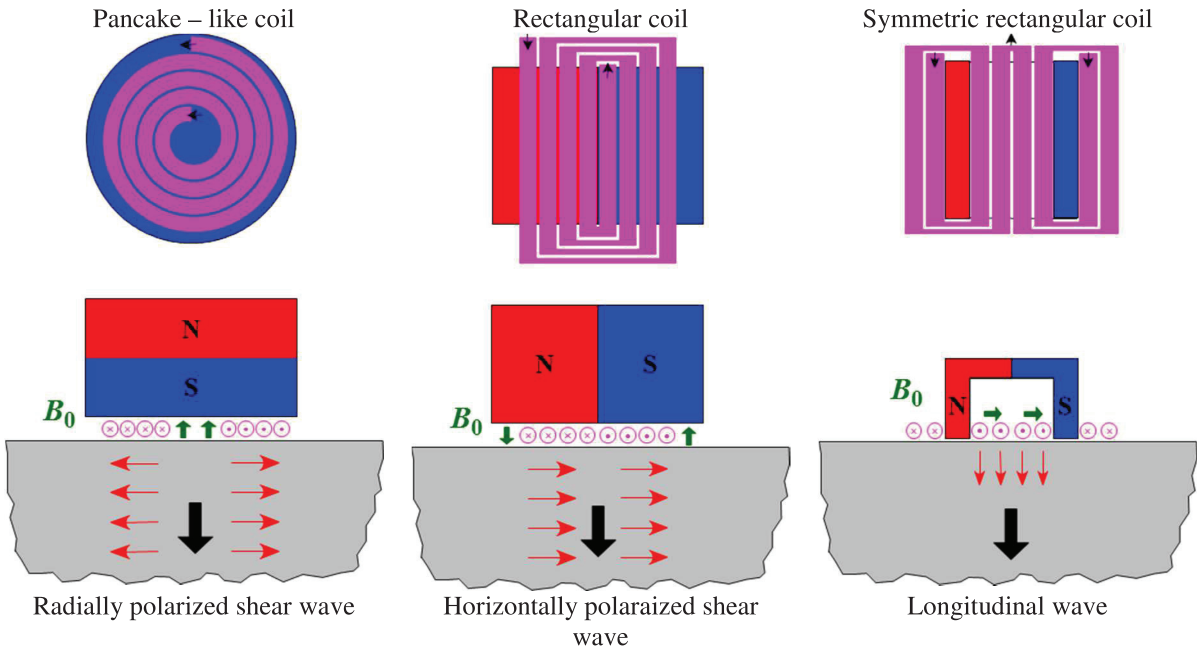
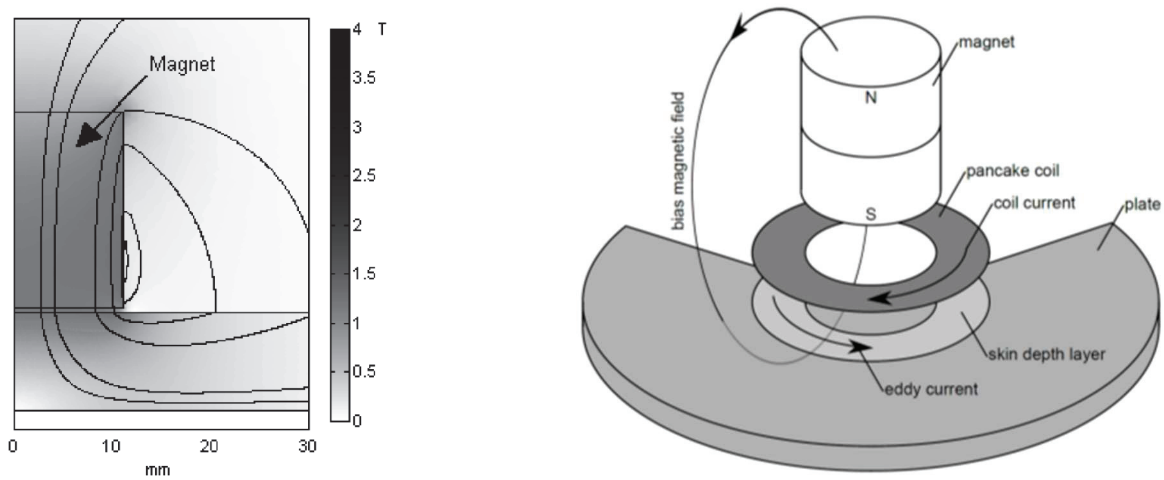


Fig. 2. EMAT configurations for transmitting different ultrasonic bulk waves. (Adapted from [7])



(a) (b)

Fig. 3 a) Magnetic field computed for a cylindrical magnet above a steel plate (from [8]), b) conceptual design of an EMAT for transmitting the a_0 mode in a plate (from [5]).

3. EMAT design and assembly

3.1. Initial experimental investigations

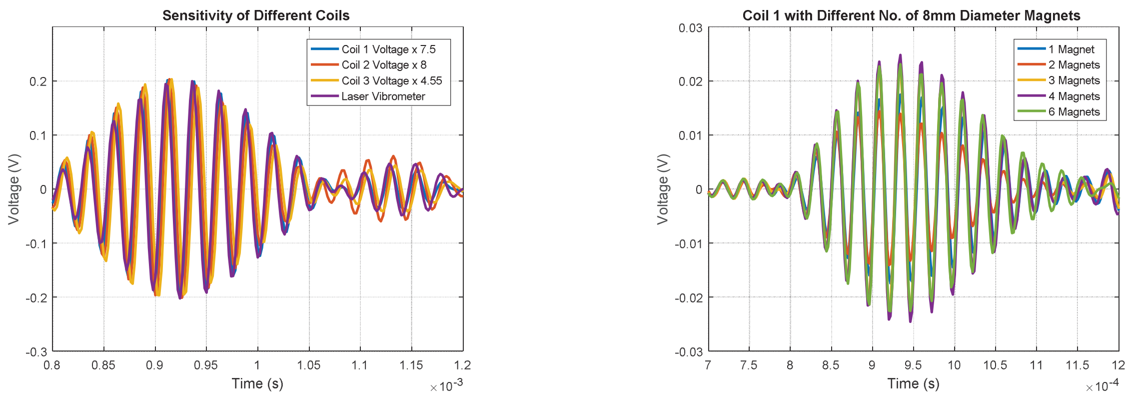
Coils may be printed as flexible PC boards but it was decided to hand wind some coils to investigate the influence of the number of turns on the sensitivity of the EMAT. Plastic bobbins were made by cutting circles out of plastic sheets and sticking these together. The inside diameter of the coils were 6 mm and the outer diameter approximately 11 mm. Three configurations listed in table 1 were made and tested. Four magnets of 8 mm diameter and each 4 mm thick were used in the first tests. The signal from the EMAT was amplified 100 times (40dB gain) by a pre-amplifier before it was acquired using a data acquisition card. The ultrasonic signal was excited in the rail by a piezoelectric transducer glued to the rail approximately 2 m away.

Table 1. Sensitivity of EMAT with different coils.

	Coil 1	Coil 2	Coil 3
Coil thickness	0.3 mm	1.2 mm	0.3 mm
Wire diameter	0.18 mm	0.18 mm	0.08 mm
No. of turns	~ 20	~ 100	~ 120
Sensitivity (mm/s/V)	1.33	1.25	2.20

Figure 4a shows the signals measured using the three coils and a measurement using a laser vibrometer for comparison. The laser vibrometer is only sensitive to velocities along the laser beam, which was orientated to be normal to the rail surface. This is the same component of velocity that the EMATs were designed to detect. The voltage signals were scaled to make the peak amplitude of these signals equal to that measured by the laser vibrometer. The laser vibrometer sensitivity was set at 10mm/s/V and the sensitivity of the EMAT with the different coils was calculated and listed in table 1. The sensitivities listed in the table include the 60 dB gain of the pre-amplifier. It was observed that the EMATs accurately measure the vertical velocity of the rail. There appears to be a phase difference but this is believed to be due to the time and temperature change that occurred between taking the various measurements. Making the coil thicker (by adding more turns of the same thickness wire) did not increase sensitivity. Using a thinner wire (and therefore more turns) did increase the sensitivity by about 60 %. It was felt that this increase in sensitivity did not warrant the extra difficulty involved in constructing the EMAT when the thinner transformer wire was used.

Measurements were then performed using the first coil and varying the number and size of magnets. When the 8mm diameter magnets were used it was found that using one magnet produced greater sensitivity than using two 8 mm magnets stacked on top of each other. Using 3, 4 or 6 stacked magnets produced increased but similar sensitivities. These results are shown in figure 4b. When 6 mm diameter magnets were used three magnets produced the best sensitivity. It was expected that increasing the number of magnets would increase the magnetic field and therefore increase the sensitivity and it is not understood why this did not always occur.



(a) (b)

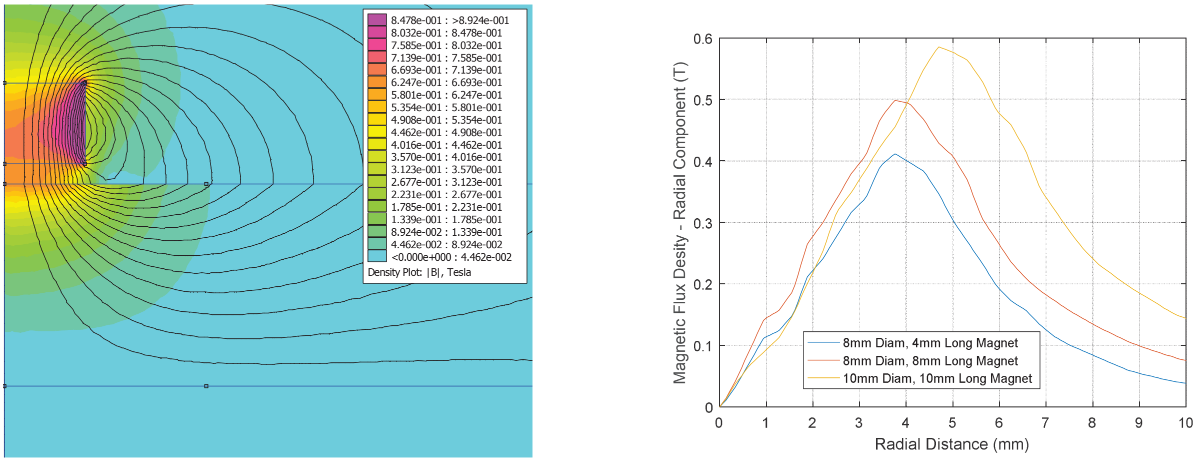
Fig. 4. Influence of (a) coil design and (b) number of magnets on EMAT sensitivity.

3.2. Modelling the magnetic field

The magnetic field shown in figure 3a (from [8]) was computed using Comsol and it was thought that such modelling may explain why the EMAT sensitivity did not always increase with increased number of magnets. Free software for modelling magnetics problems (FEMM V4.2) was used to model the magnetic field produced by a cylindrical permanent magnet above a steel plate using an axisymmetric model. In these models the magnetic material was represented by a remnant magnetic flux density of 1.2 T (neodymium N35 material) while the steel plate had a relative permeability of 120. A plot of the magnetic flux density is shown in figure 5a while the radial components of magnetic flux density on the surface of the plate are plotted for the three cases in figure 5b.

A magnet with diameter of 8 mm and length of 4 mm was modelled (see figure 5a) and compared to two of these magnets represented by a magnet of 8 mm diameter and 8 mm length. The magnetic field appears qualitatively similar to that shown in figure 3a. The magnetic flux density in the radial direction on the surface of the plate was extracted and plotted in figure 5b. This result shows that the magnetic flux increased when the second magnet was added and therefore the sensitivity of the EMAT should increase. This is in contrast to the results plotted in figure 4b and further investigation is required to explain this difference.

The increase in magnetic flux to be expected by using larger magnets was investigated. Two 10 mm diameter magnets of 5 mm length were modelled as a magnet of 10 mm diameter and 10 mm length. It is seen from figure 5b that the larger magnet produced a larger magnetic flux as would be expected. It all cases the maximum of the radial component of the magnetic flux density was near the outer edge of the magnet and this would be the optimal location for placing a coil.



(a) (b)

Fig. 5. (a) Magnetic Flux Density for 8 mm Diameter 4 mm long Magnet. (b) Comparison of radial component for three sizes of magnet.

3.3. Selected design and assembly

It was decided to base the design on two 10 mm diameter magnets each 5 mm thick. Coils were wound and glued to the magnets. A stainless steel housing was added and the volume around the magnets and coil was filled with silicone rubber. The silicone rubber was also used to produce a soft layer between the coil and the rail of about 1 mm thickness. Photographs of one device during construction and when complete are shown in figure 6.

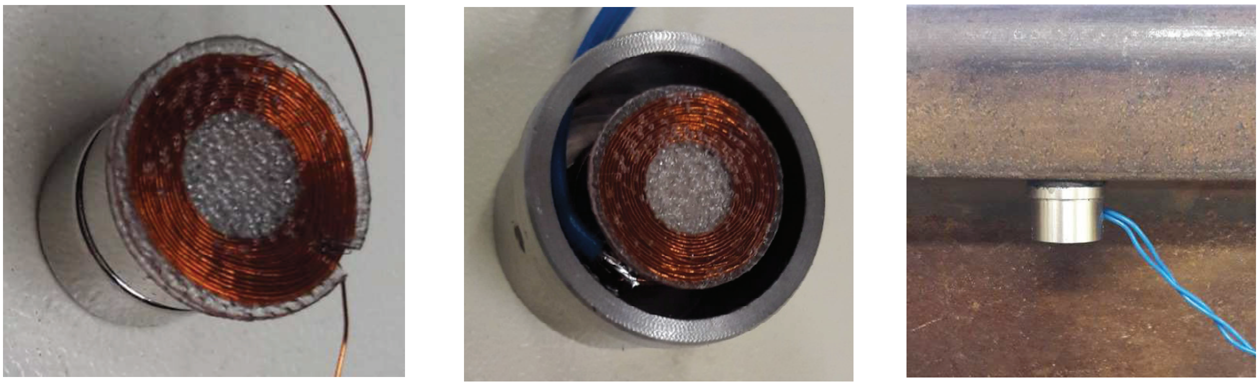


Fig. 6. Photographs of EMAT at different stages of construction.

3.4. Pre-amplifier design

The small signals received by EMATs require pre-amplifiers with high gain and low noise. The intention was to use an array of eight EMATs therefore eight pre-amplifiers were required. No suitable low cost commercial amplifier was found and it was decided to develop a pre-amplifier. The schematic of the circuit is shown in figure 7. The amplifier was required to operate (with low noise) in the 10 kHz – 100 kHz region with 60 dB gain (1000 x amplification), as these were the expected operational ranges of the EMAT. Initially a signal entering the amplifier was passed through a passive low-pass filter with a cut-off of 100 kHz, this was used to limit the back ground noise entering the amplifier circuity. The signal thereafter passed through a three stage, inverting operational amplifier configuration, with a gain of 20 dB per stage. This resulted in a total gain of 60 dB. The operational amplifier chosen was an OP27GPZ. The choice of this operational amplifier was based on its low noise and good gain bandwidth product characteristics. The OP27GPZ, three stage amplifier achieved the 60 dB gain with a minimal constant phase shift (13^o). This amplification circuitry for eight pre-amplifiers was placed in a shielded box, with common grounds, to further eliminate external noise effects.

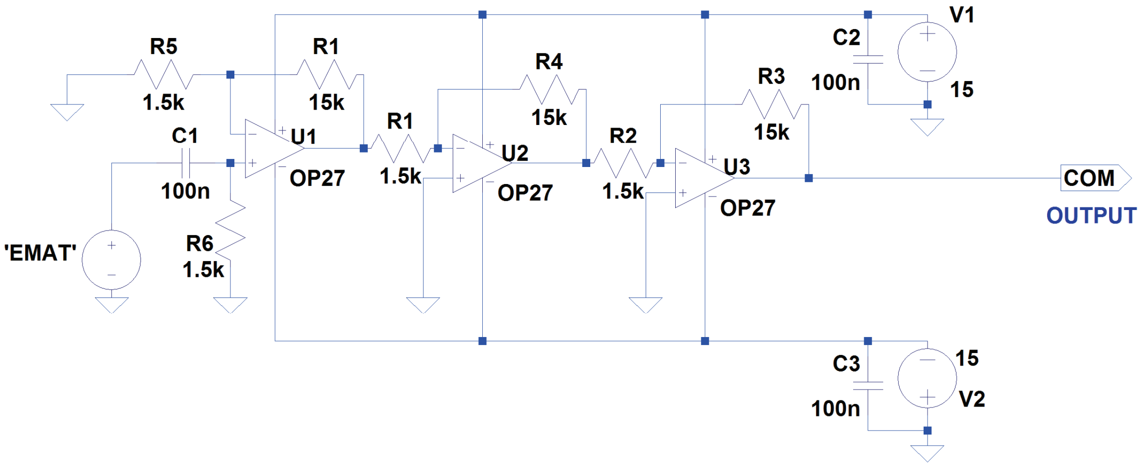


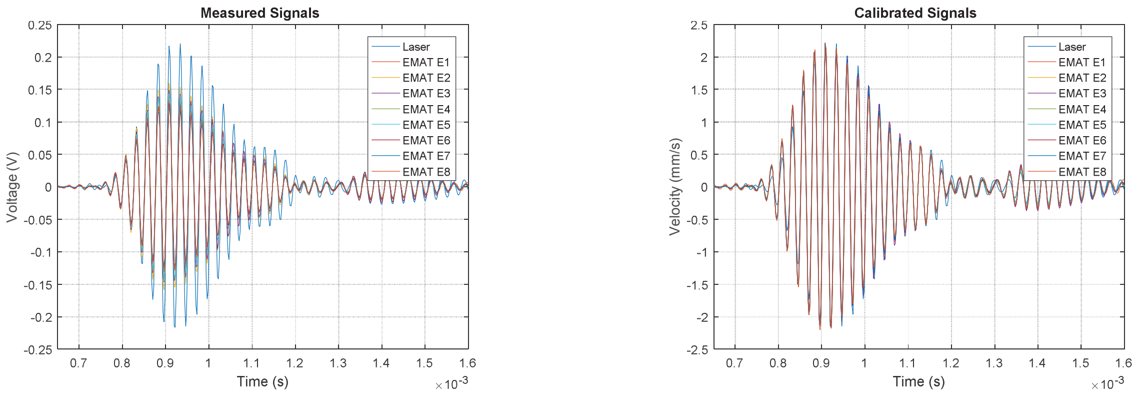
Fig. 7 Pre-amplifier circuit schematic.

4. Measurement results

4.1. Laboratory measurements

A measurement was performed using a piezoelectric transducer to excite guided waves in a rail in the laboratory. Firstly a laser vibrometer was used to measure the vertical velocity at a point on the foot of the rail. Each of the eight

EMATs, connected to a pre-amplifier, were then positioned on this point and the measurement repeated. Figure 8a shows the voltage time signals recorded. These signals were obtained by taking ten averages and filtering. It is seen that the EMATs accurately measure the phase of the velocity but there is some variation in the amplitude measured. The laser vibrometer, which had a sensitivity of 10mm/s/V was used as the reference for calibrating the EMATs. The calibrations factors for the eight EMATs were: 16.6496, 13.8408, 14.8798, 15.5148, 15.2145, 17.0405, 17.8604 and 16.9425 mm/s/V. The measured voltages were converted to velocities and are plotted in figure 8b. It is observed that the EMAT measurements are very similar to the laser vibrometer measurements although there is a small different in the wave packet which may be due to the fact that the vibrometer measures a very small spot whereas the EMATs measure velocity integrated over an area. It should also be noted that the EMATs measure only the velocity normal to the surface.

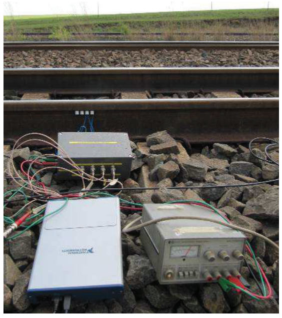


(a) (b)

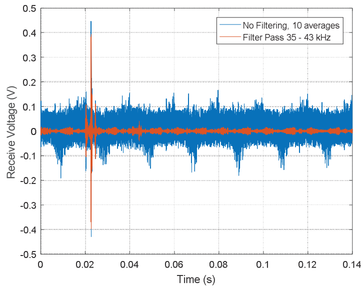
Fig. 8. Calibration of EMATs, (a) voltage signals, (b) calibrated velocity signals.

4.2. Field measurements

Measurements on an operational heavy haul rail line were performed as shown in figure 9a. A piezoelectric transducer was again used to transmit ultrasonic guided waves. The EMAT transducers were placed at a distance of 70m from the transmit transducer and were used to measure the ultrasonic waves. The signals acquired contained significant noise as shown in figure 9. The blue time trace in figure 9b is the result of ten averages, which is sufficient when using piezoelectric receivers, and the noise is very large. The spectrum of this signal, shown in figure 9c, contains regular noise peaks. Unfortunately there is a noise peak within our frequency range of interest. If frequencies outside of our band of interest are filtered out the signal is better but still contains significant noise. To reduce the influence of this noise a measurement with 1000 averages was performed. The eight EMATs were positioned under the head of the rail, four on either side. These measurements are shown in figure 10. The time signals in figure 10a show the incident waves arriving between 0.02 and 0.03s followed by a reflection from an artificial reflector between 0.04 and 0.046 s. A zoomed in view of the peak signals is shown in figure 10b. This corresponds to the arrival of a symmetric mode of propagation. There are phase differences in the signals due to the spacing of the EMATs along the propagation direction. Figure 10c shows the wave packet envelopes of the incident waves showing the arrival of different modes of propagation. Here the signals group into two sets depending on which side of the head the EMAT is located. The differences are due to the superposition of symmetric and anti-symmetric modes being different on each side of the rail. Finally, figure 10d shows the arrival of reflections. The reflections of different modes by a small mass glued under the head of the rail arrive between 0.04 and 0.046s while aluminothermic welds produce the reflections between 0.059 and 0.68s and between 0.078 and 0.088s respectively.



(a)



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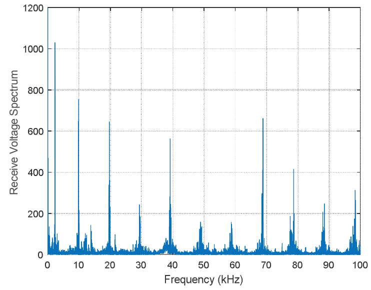
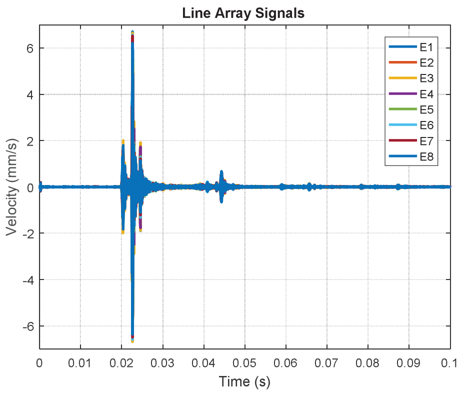
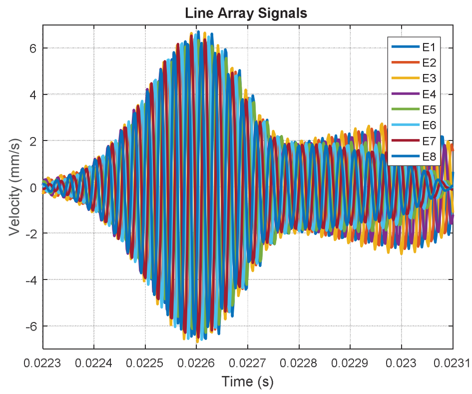


(c)

Fig. 9. EMAT measurement (a) in field, (b) averaged signals and (c) noise spectrum.



(a)



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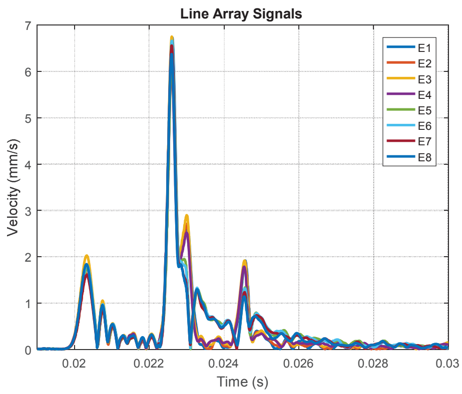
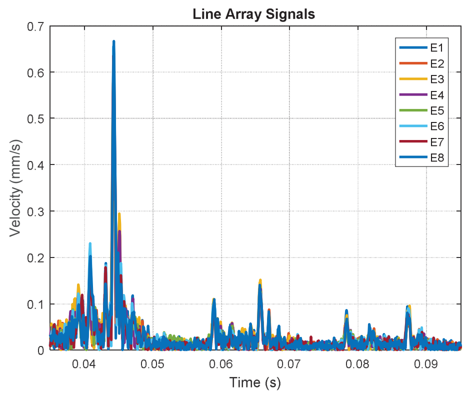


(c)



(d)

Fig. 10. Measurements performed with four EMATs under each side of the rail head, (a) time signals, (b) zoomed view of peak signal, (c) wave packet envelope of incident waves and (d) wave packet envelope of reflected waves.

5. Conclusions and recommendations

A simple EMAT was developed and tested. Calibration of these devices against a laser vibrometer showed that they measured one component of velocity with very good phase accuracy. The amplitude sensitivity of eight devices was calibrated against the laser vibrometer and then the eight EMATs produced very similar velocity measurements. The EMATs performed very well in the laboratory where the guided wave surface velocities are relatively large and there is little electromagnetic noise. Field measurements were performed on a rail line and significant electromagnetic noise was encountered. The source of this noise needs to be determined and steps taken to reduce the noise. Alternatively, an EMAT design with greater sensitivity and the same noise sensitivity would be useful. If measurement time allows, the use of a large number of averages can reduce the electromagnetic noise. Measurements performed with 1000 averages produced reasonable measurements of the velocity under the head of the rail when guided waves were transmitted from a piezoelectric transducer. It was possible to detect reflections from aluminothermic welds at relatively close range. The EMATs developed showed some of the advantages of this technology including ease of manufacture, ease of mounting/attachment and moving, excellent bandwidth and linearity.

Acknowledgements

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