



EMAT phased array: A feasibility study of surface crack detection



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ABSTRACT

Electromagnetic-acoustic transducers (EMATs) consist of a magnet and a coil. They are advantageous in some non-destructive evaluation (NDE) applications because no direct contact with the specimen is needed to send and receive ultrasonic waves. However, EMATs commonly require excitation peak powers greater than 1 kW and therefore the driving electronics and the EMAT coils have to be bulky. This has hindered the development of EMAT phased arrays with characteristics similar to those of conventional piezoelectric phased arrays. Phased arrays are widely used in NDE because they offer superior defect characterization in comparison to single-element transducers. In this paper, we report a series of novel techniques and design elements that make it possible to construct an EMAT phased array that performs similarly to conventional piezoelectric arrays used in NDE. One of the key enabling features is the use of coded excitation to reduce the excitation peak power to less than 4.8 W (24 Vpp and 200 mA) so that racetrack coils with dimensions $3.2 \times 18 \text{ mm}^2$ can be employed. Moreover, these racetrack coils are laid out along their shortest dimension so that 1/3 of their area is overlapped. This helps to reduce the cross-talk between the coils, i.e., the array elements, to less than -15 dB . We show that an 8-element EMAT phased array operating at a central frequency of 1 MHz can be used to detect defects which have a width and a depth of 0.2 and 0.8 mm respectively and are located on the surface opposite to the array.

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1. Introduction

Electromagnetic-acoustic transducers (EMATs) consist of a magnet and coil and do not require mechanical contact with the specimen under test [1–3]. EMATs are widely used in non-destructive evaluation (NDE) to speed up the inspection process because ultrasonic couplant is not required and coatings thinner than a couple of millimetres do not need to be removed [4–7]. However, EMATs produce less intense signals in comparison to piezoelectric elements and therefore more attention to their design optimization is required [8–10] as well as the use of signal processing techniques, such as pulse-compression, to increase the signal-to-noise ratio (SNR) [11].

EMAT phased arrays would be advantageous in general over standard monolithic transducers because, as any ultrasonic phased array, they can generate different electrically-controlled ultrasonic fields and rapidly visualise the internal structure of the specimen through focused images [12]. However, the fact that EMATs are inherently poor transmitters and receivers and therefore have to be excited using powers in excess of 1 kW [3] has hindered the

development of bulk-wave phased arrays. This is mainly because the array elements have to be smaller than a wavelength at the central frequency, typically less than 5 mm in the frequency range from 0.5 to 2 MHz, in order for the array to perform satisfactorily [12,13], and these smaller elements cannot withstand driving powers in excess of 1 kW.

Because of the above reason, there is virtually no literature on bulk-wave EMAT phased arrays, albeit for an 8-element system reported in [14,15], whose performance in detecting defects is unclear. The majority of EMAT designs which have been reported so far where the ultrasonic beam can be electrically steered or deflected consist of a magnet on top of a meander coil [16–19]. These designs are very convenient for their simplicity since only one active element or coil is required. However, the central beam of the ultrasonic radiation pattern is steered by changing the central frequency; this limits the resolution (i.e. the capacity of the system to resolve defects) and the steering capabilities.

In this paper, we make use of two recent developments in EMAT technology, namely a methodology for increasing the bias magnetic field of shear wave EMATs [20] and a new type of coded excitation for pulse-echo mode operation [21–23] to design the first pulse-echo EMAT array, which can be used to image defects. The coded excitation consists of a long chain of bursts (e.g., 10^3), where the polarity of the bursts is alternated according to a binary

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sequence. It is used to reduce the excitation power to less than 4.8 W (24 Vpp and 200 mA) so that racetrack coils with dimensions $3.2 \times 18 \text{ mm}^2$ can be employed. The dimensions of these coils can be considered narrow for conventional, reported EMATs. It is important to highlight that the main focus of [21,23] is to present the general, pulse-echo, coded excitation, and that an example employing an EMAT transducer (intended for thickness measurements [20]) driven with 4.5 Vpp and 150 mA was just shown to demonstrate the capabilities of the sequences.

A novel contribution of this paper is the detailed study of the radiation pattern of racetrack coils as the array elements and the coil layout. Coils are laid out so that they are offset along their shortest dimension and overlap by 1/3 of their area. This helps to reduce the crosstalk between the coils, i.e., the array elements, to less than -15 dB and creates a periodic pattern where the separation between the array elements, i.e., the array pitch is 2.1 mm. Considering a centre frequency of 1 MHz and shear-wave generation in aluminium or steel, this pitch is close to half a wavelength ($\approx 1.6 \text{ mm}$), as required to avoid grating lobes [24]. We will show that these racetrack coils generate shear waves similarly to many conventional piezoelectric arrays which are mounted on a wedge to convert the wave mode from longitudinal to shear [12,25], see Fig. 1. Such configurations can be used to detect small surface cracks (e.g., width and a depth of 0.2 and 0.8 mm respectively) that can be produced by material fatigue [4,26–28] and to inspect welds [29,30].

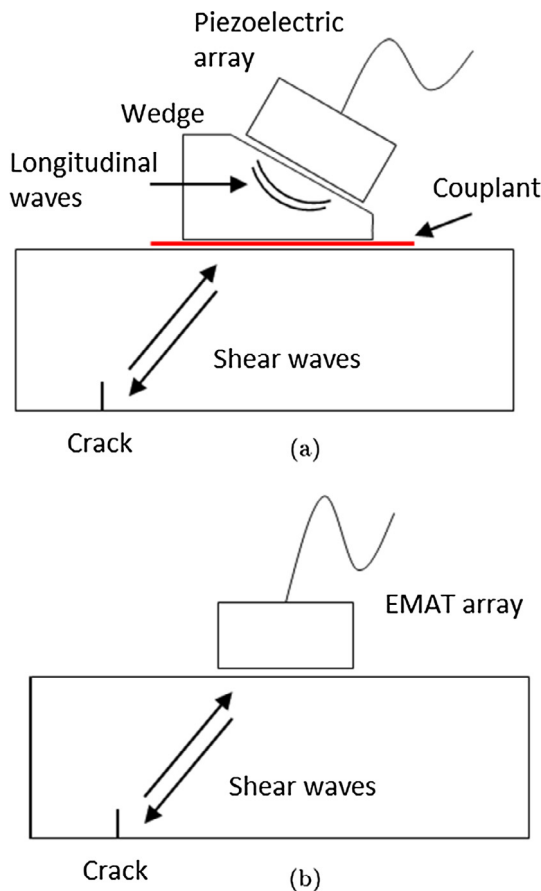


Fig. 1. Alternative configurations of angled shear wave phased arrays that can be used to detect surface cracks. (a) A piezoelectric array mounted on a wedge. (b) A shear-wave EMAT array. The piezoelectric version has the disadvantages of requiring couplant and retaining longitudinal and shear wave reverberations in the wedge, which increases the background noise.

The outline of this paper is as follows. First, the design elements of the proposed EMAT array are discussed in detail, namely the ferromagnetic core-magnet arrangement and the layout of the coils. The source of the bias magnetic field and the radiation pattern of the racetrack coils are simulated using finite elements (FE) whereas the crosstalk between adjacent coils is measured. In Section 3, the synthetic focusing algorithm is recalled as well as the coded excitation with receive intervals for pulse-echo mode. Then, the performance of a 1-MHz, 8-channel EMAT array in detecting a surface crack is simulated using FE. This is followed by an experiment to corroborate the results. Finally, the conclusions are drawn.

2. Array design

In this paper, we assume that the Lorentz force is the dominant transduction mechanism; however, other transduction mechanisms exist, such as magnetostriction in ferromagnetic materials. This is a reasonable and frequently made assumption, which has been shown to be valid in [20,31–34].

EMATs based on the Lorentz force consist of a permanent magnet and a coil. When alternating current passes through the coil, eddy currents are induced in the specimen beneath the coil. The eddy currents interact with the bias magnetic field from the EMAT magnet and generate Lorentz force components normal to the eddy currents and the bias magnetic field. These force components generate shear waves in the specimen. On reception, the incoming shear waves interact with the bias magnetic field and generate currents in the specimen, which induce a voltage across the coil terminals.

A sketch of the proposed array is shown in Fig. 2. The coils of the array are laid out in an overlapping pattern under a ferromagnetic core. Each coil constitutes an element of the array so that the array equivalent pitch, i.e., the separation between adjacent coils, is 2/3 of the coil width. The real prototype is shown in Fig. 3. The

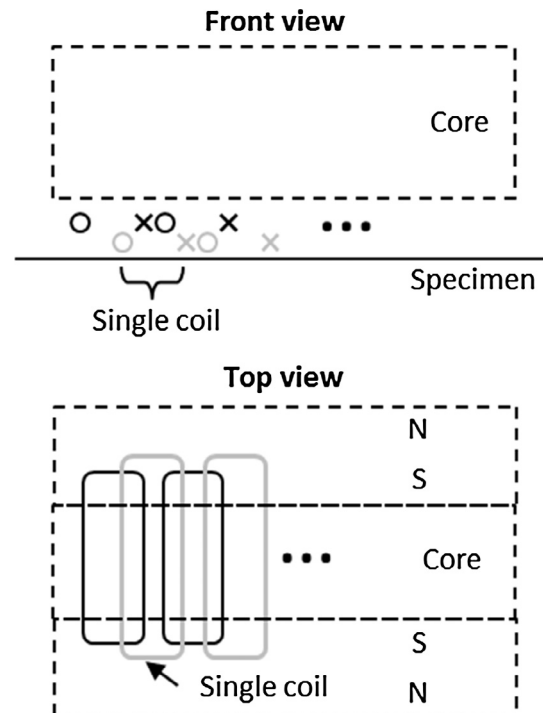


Fig. 2. Sketch of proposed EMAT array showing the overlapping pattern of the coils and the ferromagnetic core abutted by magnets with like poles facing the core. The circles and crosses in the top view indicate that the currents in the coils leave and enter the plane of the figure respectively.

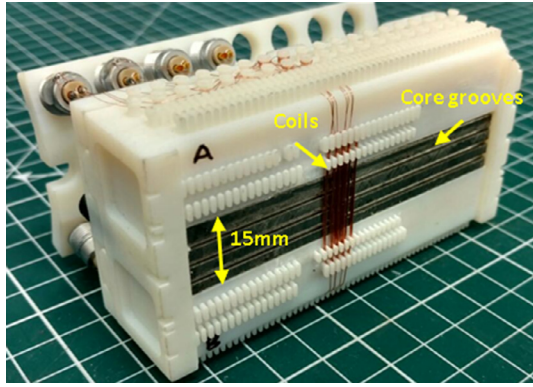


Fig. 3. Photo of the EMAT array prototype that was built.

ferromagnetic core is abutted by magnets with like poles facing the core to increase the magnetic flux density; the advantages of this configuration were discussed in [20].

2.1. Bias magnetic field

The bias magnetic field of the EMAT array is produced by a ferromagnetic core abutted by two magnets with like poles facing the core. This configuration exploits two basic mechanisms to increase the bias magnetic field under the core: repulsion between magnets and low reluctance paths [20].

The width of the core defines the active regions of the coils, and also the focusing capabilities in the passive dimension, i.e., the dimension where there is no electronic beam steering; the width of the passive dimension is commonly referred to as elevation. A 15-mm core width was selected to match the common elevations encountered in commercial arrays, which are normally between 10 and 20 mm for 1 MHz probes (e.g., see array probe models 2L8-DGS1 or 1.5L16-A4 from Olympus Scientific Solutions Americas Inc., MA, USA). The height of the core (21 mm) and the dimensions of the magnets (cross section $20 \times 10 \text{ mm}^2$) were chosen by the authors as a good compromise between the intensity of the bias magnetic field and the overall volume of the array. A study of such a compromise was presented in [20] for axisymmetric configurations.

The core-magnet arrangement was simulated in COMSOL Multiphysics 5.2 (COMSOL Inc., Massachusetts, USA) using the Magnetic Field (No Current) interface of the AC/DC module model library. A symmetric (two-dimensional) model was employed as shown in Fig. 4; the axis of symmetry is on the left-hand side of the figure. In our case, a two-dimensional model is a good approximation because the core-magnet arrangement is larger in the active direction of the array, i.e., the direction on which the coils are laid out, with respect to the other direction.

The dimensions of the cross-section of the core in the model of Fig. 4 are $7.5 \times 21 \text{ mm}^2$ ($15 \times 21 \text{ mm}^2$ in the real core). The dimensions of the magnet cross-section are $10 \times 20 \text{ mm}^2$. Aluminium (a) and mild (b) steel samples that have dimensions $20 \times 60 \text{ mm}^2$ are simulated beneath the magnet and the core. The lift-off between the magnets and the sample is 3 mm, whereas the lift-off between the core and the sample is 2 mm. These lift-offs correspond to the thickness of the housing of the array, the coils and a non-conductive coating layer over the sample surface. Finally, the model is enclosed in a domain modelled as air which has dimensions $100 \times 120 \text{ mm}^2$ and is surrounded by magnetic insulation boundaries.

The mesh elements of the model had a quadrilateral shape and a maximum length (distance between the furthest nodes) of less

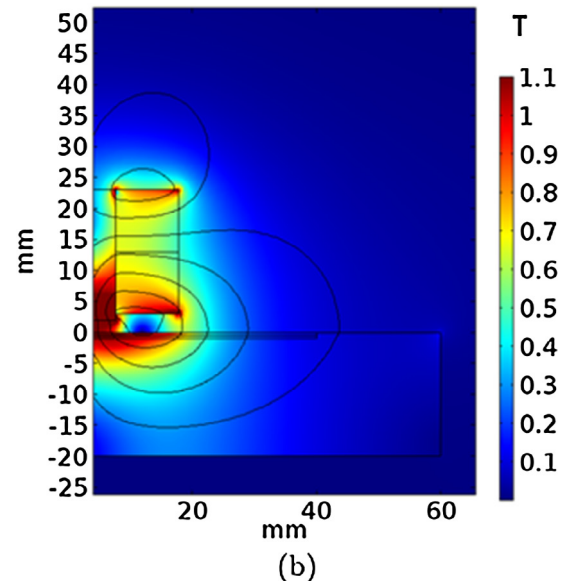
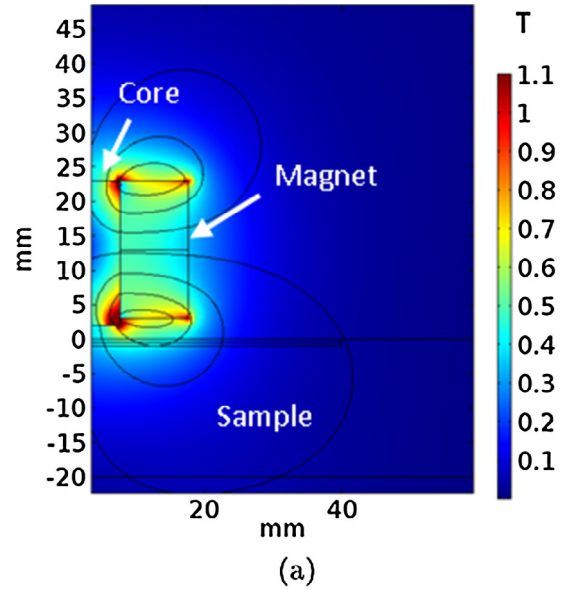


Fig. 4. 2D simulations of the distribution of the magnetic flux density in the ferromagnetic core, magnet (Neodymium N42, $B_r = 1.32 \text{ T}$), and sample. (a) Aluminium sample. (b) Mild steel sample. The colour scale corresponds to the absolute value of the flux density in Tesla (T), whereas black curves represent flux lines.

than 0.1 mm under the core. The length of the elements was increased progressively until the elements furthest from the core and the magnets reached a maximum length of 2 mm. A convergence test was conducted to confirm that the results did not change by more than 1% when using a denser mesh; this value was selected by the authors as a good compromise between accuracy and run length of the simulation. The remanence of the magnet was set to $B_r = 1.32 \text{ T}$, equivalent to Neodymium N42 (Hitachi Metals America, Ltd., “Permanent Magnets”, 2015) and oriented towards the core in the centre of the model.

Given that the permeability of steel changes with the intensity of the magnetic field H , a curve that relates B and H was used in the simulations; this curve was obtained from the COMSOL library. Other B vs. H curves, e.g., for mild steel, were also used finding no significant differences in the results under the core; this is because the strength of the field in that region is such that the different materials saturated easily [20].

The simulation results are shown in Fig. 4a and b for aluminium and steel respectively. The colour scale corresponds to the absolute value of the flux density in Tesla (T), whereas black curves represent flux lines. The distribution of the field is similar to that observed in [20] for the axisymmetric case. The field is concentrated beneath the core, where the field lines are perpendicular to the surface of the sample. The main difference between Fig. 4a and b is the increase in the flux density in the presence of the steel sample due to the existence of a lower reluctance path between the core and the ferromagnetic sample.

A detailed distribution of the normal components of the field at the surface of the samples is given in Fig. 5. The dashed and continuous black curves correspond to the core-magnet arrangement over the aluminium and steel samples respectively. The distribution of the flux components is similar in both cases with the maximum values appearing under the core and then decaying rapidly. The flux density is twice as large in the steel sample under the core compared to the aluminium sample; in pulse-echo mode, this corresponds to a 12-dB signal increase because the signals double on both transmission and reception.

To offer a quick, fair comparison point, a single magnet which has a cross-section area equal to that of the core and magnet combined ($35 \times 20 \text{ mm}^2$) was simulated. The lift-off of the magnet relative to the sample was 2 mm, $B_r = 1.32 \text{ T}$ and the magnetic field was oriented towards the sample. The dashed and continuous red curves in Fig. 5 correspond to the single magnet over aluminium and steel samples, respectively. There is no significant difference in the maximum flux density between the core-magnet arrangement and the single magnet when placed over the aluminium sample. However, over the steel sample, the core-magnet arrangement produces roughly double the flux density compared to the single magnet.

Finally, to validate the simulations, a Gaussmeter (GM08, Hirst Magnetic, UK) that has a transverse Hall probe (TP002, Hirst Magnetic, UK) was used to measure the flux density under the core-magnet arrangement in air, which is equivalent to the case where the core-magnet arrangement is placed over an aluminium sample. The ferromagnetic core of the real prototype shown in Fig. 3, was made out of mild steel and has dimensions $15 \times 23 \times 86 \text{ mm}^3$. The core is abutted by 4 magnets that have dimensions $10 \times 20 \times 20 \text{ mm}^3$ such that like poles face the core. The core height is slightly larger than in the 2D model for ease of construction. The core-magnet arrangement was simulated in a 3D model to take into account the changes in the design with respect to

the 2D model. For example, there is a 2-mm gap between the magnets, a 0.5-mm gap between the magnets and the core that was filled with glue, and $1 \times 1 \text{ mm}^2$ grooves on the surface of the core.

The results are given in Fig. 6, where the circle and square markers correspond to measurements taken on the edge and centre of the core, respectively. The continuous red curve corresponds to 3D simulations and the dashed black curve to 2D simulations. There is almost no difference between the measurements taken at the end and centre of the array, which implies that fringe effects are negligible. In general, the 3D simulation fits the experimental measurements better than the 2D.

Experiments were not conducted over a steel sample because the probe housing was fabricated using a fragile polymer that could easily be broken if exposed to the magnetic forces between the ferromagnetic sample and the probe; however, these simulations are expected to be accurate according to [20].

2.2. Radiation pattern of single coils

The radiation pattern of an array is determined by its elements, in our case the racetrack coils, or more precisely the path of the eddy currents induced by them. The radiation pattern of the individual coils was simulated in COMSOL Multiphysics 5.2 (COMSOL Inc., Massachusetts, USA) using the Solid Mechanics module. The eddy currents induced by the coils were approximated as two line sources of opposite phase; a two-dimensional simulation suffices because the racetrack shape of the coil is long and narrow.

The two-dimensional model consists of a semi-circular region, see Fig. 7, simulated as steel, which has a density of 7850 kg/m^3 , a Young's modulus of 205 GPa and a Poisson's ratio of 0.28. The radius of the semi-circular region is 60 mm. The mesh consisted of quadrilateral elements that had a maximum length (distance from the furthest nodes) of 0.53 mm; this is roughly 1/6 of the shear wavelength in steel at 1 MHz, where the shear velocity is 3.2 mm/s.

The excitation signal consisted of a 3-cycle Hann tone-burst centred at 1 MHz. The sampling frequency was 16 MHz. This excitation was applied as prescribed displacements of opposite phase tangential to the surface at two points symmetrically located around the centre of the semicircle (marked by the red circles in Fig. 7) to simulate the shear line sources. The distance between the two sources was set to 1/4, 1/2 and 1 shear wavelength (3.2 mm). A convergence test was conducted to confirm that neither a denser mesh nor a higher sampling frequency improved

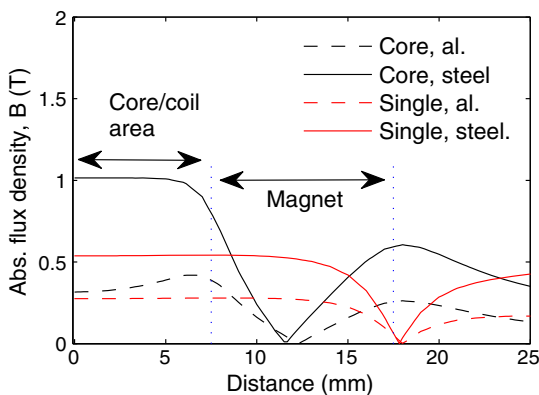


Fig. 5. 2D simulations of the normal components of the flux density over aluminium and steel samples. The lift off is 2 mm. The dotted vertical lines correspond to the ends of the core and magnet in the core-magnet arrangement, whereas the single magnet extends from the origin to the dotted vertical line on the right.

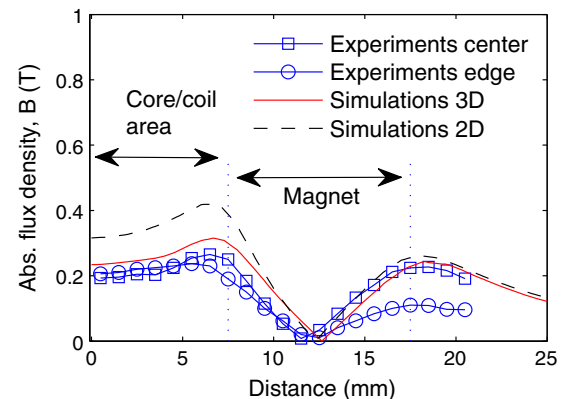


Fig. 6. Distribution of the normal components of the magnetic flux density over the surface of an aluminium sample (simulations and experiments). The dotted vertical lines correspond to the ends of the core and magnet in the core-magnet arrangement.

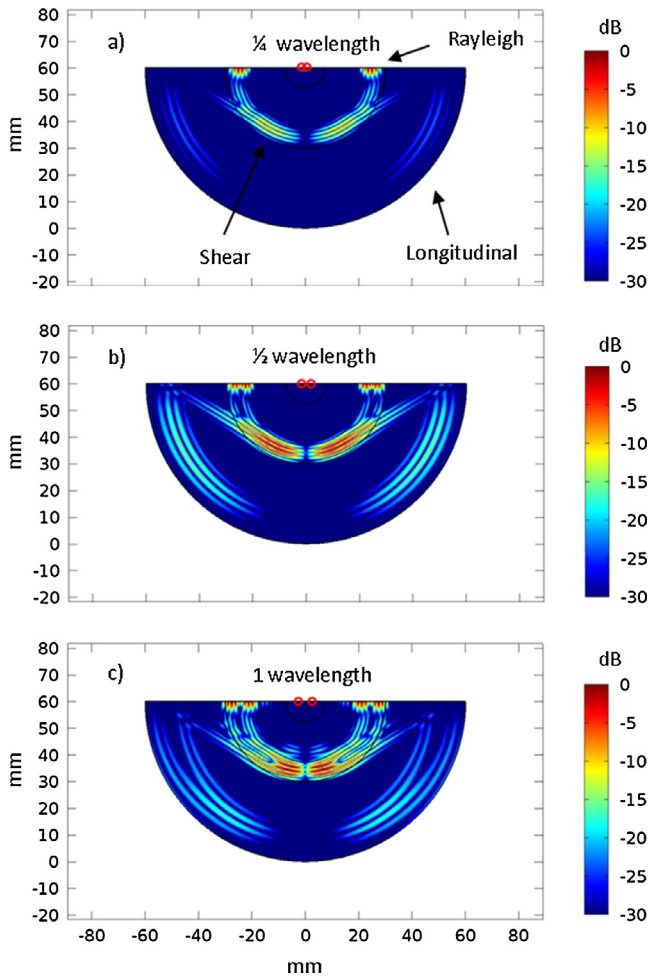


Fig. 7. 2D simulation of two shear line sources of opposite phase in steel 10 μ s after the burst excitation. The distance between the sources (red circles) is (a) 1/4, (b) 1/2 and (c) 1 shear wavelength. The absolute total displacement is normalised with respect of the maximum of the plots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the results by more than 2%; the authors consider that this value is an acceptable compromise between the overall run length of the simulation and its accuracy.

Fig. 7 shows the absolute value of the displacements 10 μ s after the burst excitation. The distance between the line sources in Fig. 7a–c is 1/4, 1/2 and 1 shear wavelength, respectively. In general, four types of waves can be observed, Rayleigh waves on the surface, longitudinal waves travelling at an angle of roughly 30° with respect to the plane defined by the surface, shear waves at roughly 60°, and head waves for angles greater than the critical angle (roughly 33°), see [35].

When the distance between the sources exceeds half a wavelength, the wave packets split in two; having more than one wave packet is not desirable because it deteriorates the resolution of the system and can lead to artifacts in the resulting focused image. In general, the distance between the line sources, i.e., the width of the coil, poses a trade-off between ease of construction and the distortion of the wave packet. In practice, an adequate separation of the sources is between 1/2 and 1 wavelength; at 1 MHz this corresponds to 1.6 and 3.2 mm respectively. All these results also apply to aluminium samples, because aluminium and steel have similar wave velocities.

2.3. Crosstalk between array elements

To evaluate the crosstalk between the array elements, two pairs of racetrack coils were built such that the wire bundles were as compact as possible; these have mean dimensions $3.2 \times 18 \text{ mm}^2$. The coils were built by winding 12 and 15 turns of magnet (enamelled) 52-AWG wire, which has a diameter of approximately 20 μm , so as to create a tight bundle with a diameter of less than 0.3 mm. One of the coils was connected to a custom made driver that is able to produce a maximum output of 24 Vpp and 250 mA. The other coil was connected to the input of an oscilloscope (LeCroy WaveRunner 44Xi). The coils were initially laid out on top of each other and then carefully slid in the direction perpendicular to their straight section while recording the amplitude of the signal. The recorded values are given in Fig. 8, where the vertical axis shows the relative amplitude of the signals (attenuation) and the horizontal axis indicates the distance between the centres of the coils normalised by the width of the coil (3.2 mm). The measurements were recorded using two different pairs of coils in order to assess the impact of the design tolerances on the results.

It can be observed in Fig. 8 that the difference between the two pairs of coils can be as high as 5 dB. This can be due to errors in the alignment of the coils or a different coil mean width. When the distance between the coils is roughly 2/3 of the coil width, the crosstalk reaches a local minimum of approximately –27 dB. This is because the coils are balanced, i.e., the magnetic flux within the area shared by the coils has opposite direction but equal magnitude to the flux outside this area.

The existence of a local minimum at roughly 2/3 of the coil width is convenient to create a regular overlapping pattern. Following such a pattern, the third coil would be located at 4/3 of the coil width, where the crosstalk is roughly –15 dB. From the fourth coil onwards, the crosstalk is below –25 dB as can be extrapolated from Fig. 8. Although piezoelectric probes may achieve smaller crosstalk values, this level of isolation is enough to produce a good degree of independence between the elements – a necessary to obtain focused images of adequate quality.

3. Digital processing techniques

3.1. Synthetic focusing

Synthetic focusing is a faster alternative to physical (electronic) focusing [36,13]. To implement it, the signal from each transmit-receive path has to be acquired first. This process is shown in Fig. 9, where, for example, h_{21} is the path from transmit element 1 to receive element 2.

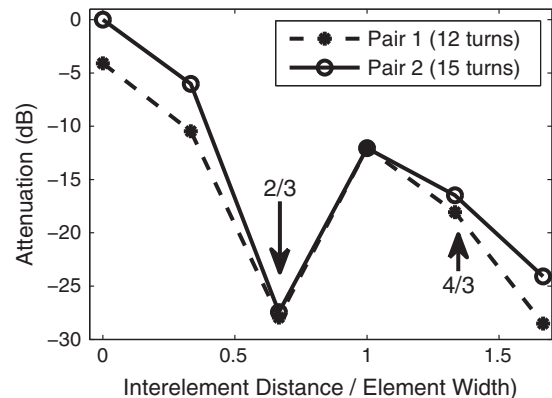


Fig. 8. Measured crosstalk between two pairs of coils.

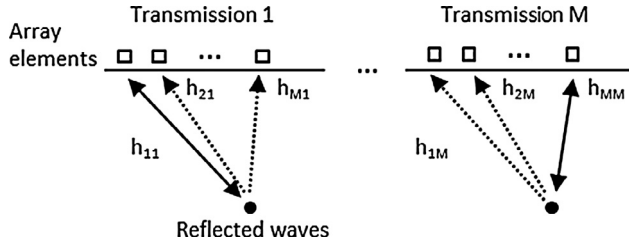


Fig. 9. Acquisition of every transmit-receive path. Each array element acts as a transmitter at a time and the signals are recorded at every receive element simultaneously.

In the two-dimensional case, the goal is to form an image I_{xy} , where x and y are the coordinates of the image. To do so, each path is delayed following a focal law so that they add up coherently at the coordinate of interest. Assuming the elements are point-like sources

$$I_{xy} = \sum_a \sum_b h_{ab}(t) \cdot d_{abxy}(t), \quad (1)$$

$$d_{abxy}(t) = \delta \left[t - \frac{\sqrt{(x_a - x)^2 + y^2} + \sqrt{(x_b - x)^2 + y^2}}{c} \right] \quad (2)$$

where $h_{ab}(t)$ is the recorded waveform that corresponds to the waves travelling from element a to b , c is the speed of the wave, and δ is a delta function. For large images and dense arrays, the computational effort increases significantly and the Fourier transform can be employed to speed up computation [36–38].

3.2. Coded excitation

Coded excitation has been in use for many decades to increase the SNR. It works by transmitting a long chain of bursts, where the polarity of the bursts is alternated according to a binary sequence. Then, the received signal is cross-correlated with the transmitted sequence. The result of the cross-correlation is a compressed version of the transmitted sequence that has a greater SNR [39–41]. Longer sequences produce greater SNRs; however, in pulse-echo mode, long sequences cannot be used because the incoming waves from close reflectors are masked by the transmitted sequence.

Recently, the authors proposed a technique whereby long sequences can be used in pulse-echo mode [21–23]. It consists in introducing receive intervals within a sequence. When the SNR at the input of the receiver is low (e.g., below 0 dB), these sequences can be an order of magnitude faster than averaging.

For very long sequences, e.g., greater than 1000 intervals, the synthesis and reception steps are given in Algorithm (1). The expected SNR increase, with respect to the input signal, can be estimated as $L/4$, where L is the number of transmit and receive intervals, which have equal length.

Algorithm 1. Sequence synthesis and cross-correlation of sequences that have receive intervals.

1. Input sequence length, L , and burst, b , which has Q samples.
2. Synthesise the sequence
 - (a) Generate a binary random vector, s , of size L that takes on values 1 and -1 .
 - (b) Generate binary random vector, v , of length L that takes on values 0 and 1.
 - (c) Multiply each element of s by the corresponding elements of v .

- (d) Up-sample the result by Q samples.
- (e) Convolve the result with the burst b .
3. Transmit the resulting sequence
4. Record the received signal using the complement of vector v (up-sampled by Q) to activate the receiver.
5. Cross-correlate the received signal with the transmitted sequence.

4. Results

4.1. Simulations

In this section an 8-element EMAT array is simulated using the Solid Mechanics (transient) module of COMSOL Multiphysics 5.2 (COMSOL Inc., Massachusetts, USA). Fig. 10 shows a two-dimensional finite element model of an aluminium block, which have a density of 2700 kg/m^3 , a Young's modulus of 70 GPa and a Poisson's ratio of 0.33. The block has a $0.2 \times 0.8 \text{ mm}^2$ slot as shown in Fig. 10.

Absorbing layers are placed at the side boundaries of the model to attenuate any incoming wave by more than 40 dB. The absorbing layers were simulated as in [42]. 16 absorbing layers are employed. The innermost layer has a width equivalent to a quarter of a wavelength and this is increased following a quadratic law so that the width of the outer layer is half a wavelength. In each absorbing layer the mass damping parameter is increased following a cubic law so that the value of the outer region is $2 \cdot 10^7 \text{ s}^{-1}$.

Free-triangular elements are used in the mesh of the FE model. The maximum size of the elements corresponds to $1/6$ of the wavelength. When using a finer mesh, the results only changed by less than 2%; this was deemed to be a good compromise between overall run length and accuracy.

Each element (coil) of the EMAT array is simulated as two point loads separated by 3.2 mm (roughly the wavelength of the shear waves at 1 MHz in aluminium) which exert tangential forces of opposite phase on the surface of the aluminium block as in Fig. 7. Each element overlaps adjacent ones such that the array pitch is $2/3$ of the element width.

Each element is excited individually by a 3-cycle burst centred at 1 MHz and apodized using a Hanning window; the sampling frequency was 16 MHz. For each excited element, the signals received on all of the array elements are recorded, which results in a total of 64 signals. The received signals are obtained by subtracting the tangential displacements at the loading points of each element.

Eq. (1) is employed to produce a focused image using a regular spatial grid equivalent to $1/16$ of the wavelength at 1 MHz and a wave velocity of 3.1 mm/s. Results are shown in Fig. 11a, where the back wall of the aluminium block is marked using a white hor-

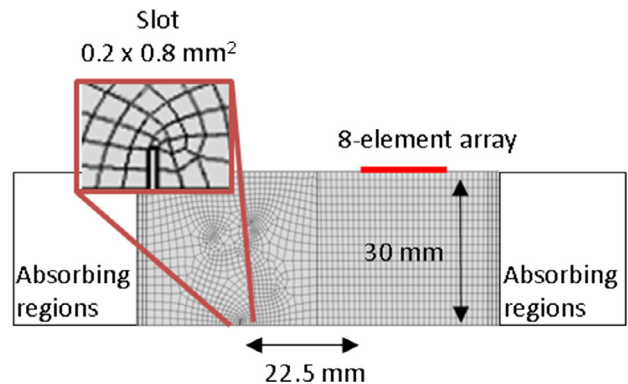


Fig. 10. 2D model of an aluminium block that has a slot.

horizontal line. Both the back wall and the slot in the back wall can be clearly identified. Focusing artifacts also appear at the right-hand side of Fig. 11a. The authors confirmed that the focusing artifacts disappear when the distance between the two point loads of the elements or the frequency is reduced; this can be attributed to the effect of the side/grating lobes.

Reflections from the back wall are only recovered beneath the array by those elements close to the edge. This is a result of the radiation pattern of the array elements, which have their main lobes oriented at roughly 60° from the surface of the array, see Fig. 7c.

Moreover, the centre of the focal region that corresponds to the defect in Fig. 11a lies slightly below the original location of the defect. This is because in Eq. (1) the array elements are assumed to radiate cylindrical shear waves; however, head waves (see Fig. 7c) predominate in this region with respect to the shear waves due the orientation of the array elements with respect to the defect. These head waves travel faster, which causes the downward shift effect of the focal point. This aberration could be fixed using a more sophisticated focusing algorithm since the radiation pattern of the individual elements is known, but that is out of the scope of this paper.

4.2. Experiments

The EMAT array prototype that was built is shown in Fig. 3; details of the core and magnet dimensions are given in Section 2.1. As in previous simulations, only 8 channels are used to simplify the instrumentation. The coils are wound such that the mean distance between the wire bundles is 3.2 mm, which roughly corresponds to a wavelength (3.1 mm) at 1 MHz in aluminium. The distance

between the coils, i.e., the array pitch is $2/3$ of the coil width. The effective elevation of this array is 15 mm (Fig. 3); this is determined by the core width. Each coil comprises 12 turns of magnet (enamelled) 52-AWG wire, which has a diameter of approximately $20\mu\text{m}$.

Each coil is connected to a custom made transmit-receive electronics board, comprising a driver which can deliver 24 Vpp and 200 mA, a transmit-receive switch to protect the receive amplifier and an ultra-low-noise, 60-dB-gain receive amplifier. The input of the driver and the output of the receive amplifier are connected to a digital-to-analog converter (DAC) and to an analog-to-digital converter (ADC) respectively. The DAC and the ADC are embedded in a programmable acquisition system (Handyscope-HS5, TiePie, Netherlands) and both use a sampling frequency of 20 MHz. This acquisition system is set to transmit a binary sequence that was obtained using Algorithm (1) [21–23]. The sequence consists of $L = 2^{14}$ transmit and receive intervals randomly distributed, where each interval has $Q = 480$ samples. Each transmit interval consists of a 3-cycle, Hann-tapered bursts centred at 1 MHz, whose polarity is randomly chosen. This produces an SNR increase of more than 36 dB. Each interval has a length of $24\mu\text{s}$, which yields a sequence with an overall length of roughly 100 ms. The intervals of the sequence are 8 times longer than the bursts to allow the electronics to recover from excitation before receiving starts.

The EMAT array is placed over a 30-mm-thick aluminium block that has a slot on the back wall as shown in Fig. 12; the slot cross-section is 0.2-mm wide and 0.8-mm high. The horizontal distance from the closest coil of the array to the defect is 22.5 mm. The signals from all of the 64 transmit-receive coil pairs are recorded after transmitting the coded sequence one element at the time. The amplitude of the received echoes is in the order of 0.5 mV and the root-mean-square value of the noise is 2 mV (both after a 60-dB amplification); this corresponds to an SNR of roughly -12 and 24 dB at the receiver input and after cross-correlating the digitised signals with the transmitted sequence respectively. The superposition of the different channels when using Eq. (1) to produce the focused image also has an averaging effect equivalent to a 9-dB-SNR increase for 8 channels. As a result, the overall image SNR is greater than 33 dB.

All of the recorded signals were visually inspected and 12 out of 64 were found to be highly distorted. Most of the distorted signals correspond to the cases where the same transmit and receive element are used; this is due to poor performance of the instrumentation, mainly caused by a slow recovery from saturation, which subsequently affects the performance of the sequences. The distorted signals were discarded and the rest used in Eq. (1) to obtain the focused image.

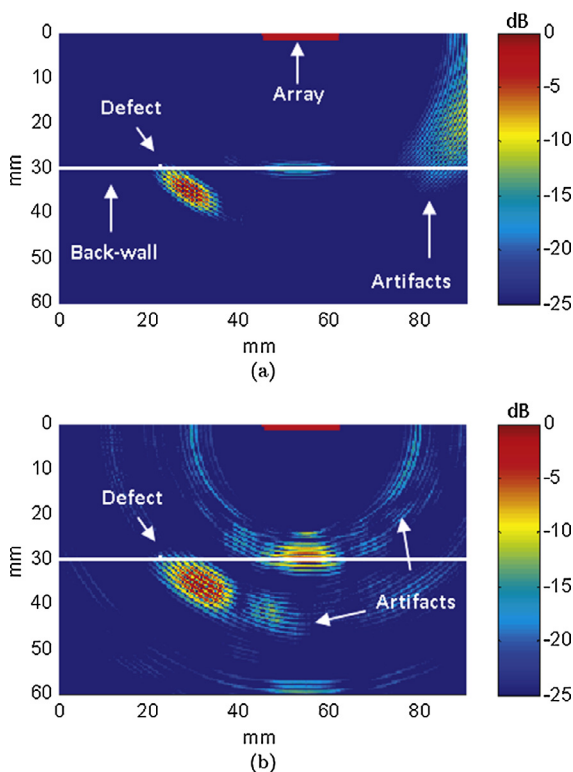


Fig. 11. Focused image that corresponds to a 30-mm aluminium block that has a slot (defect). The array consists of 8 elements, which have a width of 3.2 mm and a pitch of 2.1 mm. The central frequency of the excitation is 1 MHz. The white and red horizontal lines correspond to the back wall of the aluminium block and the location of the array respectively. (a) 2D simulation. (b) Experimental results.

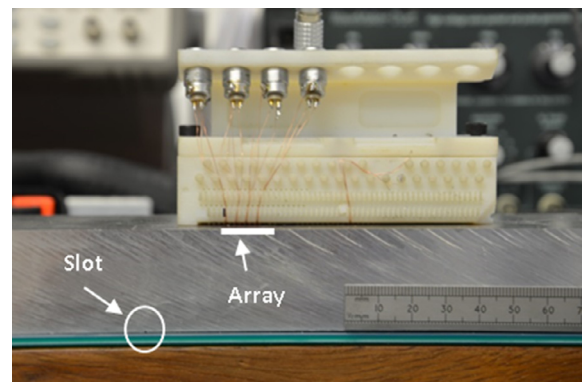


Fig. 12. Experimental setup: an 8-channel EMAT array is placed over an aluminium block that has a slot on the back wall; the slot cross-section is 0.2-mm wide and 0.8-mm high. Only 4 connectors can be seen from the front; the other 4 are at the back.

The focused image is shown in Fig. 11b. Overall, the focal regions of interest, namely the defect and the back wall, match well with the simulations in Fig. 11a despite the fact that signals from some transmit-receive pairs were discarded; this also indicates that crosstalk is sufficiently low, as expected from the results of Fig. 8. The focal regions are slightly larger in Fig. 11b, which could be due to a narrower bandwidth or ringing of the transducer.

Several artifacts can be seen in Fig. 11b, for example, the semicircle-like artifact that is closer to the array, which is suspected to have been produced by the generation of longitudinal modes inside the ferromagnetic core of the array. According to [20], shear transducers, as the racetrack coils of the EMAT array, can generate/receive longitudinal modes due to the discontinuity of the traction forces on the surface of the specimen, and since the displacements that correspond to the longitudinal mode are aligned with the bias magnetic field, the longitudinal mode can propagate unaffected. The use of a ferrite core could reduce the eddy currents and attenuated the waves in the core further. The rest of the artifacts in Fig. 11b are believed to be associated with the transmit-receive switching functionality of the electronics and its low recovery from saturation, which affect the performance of the sequences.

5. Conclusions

We have reported, to our knowledge, the first fully-steerable, pulse-echo EMAT array, which can be used to image defects. This was experimentally confirmed and a surface breaking defect with cross-section area of $0.2 \times 0.8 \text{ mm}^2$ was imaged using the array and excitations signals of only 24 Vpp and 200 mA per channel.

By using coded sequences with receive intervals, it was possible to sufficiently enhance the SNR so that ultrasonic waves could be generated and received from the small and weak EMAT coils, while keeping the injected power low enough so that the delicate coils were not damaged. To enhance the signal further, a core-magnet arrangement is used to increase the bias magnetic field over the eddy currents; compared with a single magnet, the core-magnet arrangement can produce signals whose amplitudes are 10-dB greater.

The array elements consist of racetrack coils that mainly generate shear waves at roughly 60° from the surface of the array. This radiation pattern is similar to that of conventional piezoelectric arrays mounted on a wedge. The layout of the coils yields a compact design which has a sub-wavelength pitch of approximately 2 mm and reduces the crosstalk between the array elements to less than -15 dB . A comparison of experimental and simulated data showed that these crosstalk levels are acceptable.

The authors speculate that a low-power EMAT phased array as described in this paper might enable new types of inspection in hazardous environments where conventional high power equipment cannot be used because of the risk of explosion and non-contact measurements are required.

Data accessibility

Readers who are interested in accessing data associated with this paper are referred to www.imperial.ac.uk/non-destructiveevaluation where either the data or details of how to obtain the data can be found.

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