Characterization of Electromagnetic Acoustic Transducers using Finite Elements

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Abstract

In this paper a comprehensive finite element analysis of Electromagnetic Acoustic Transducer (EMAT) is presented. EMAT is an emerging technology that provides a non-contact process of testing materials compared to Ultrasonic Testing (UT) technique that requires a coupling medium. The EMAT phenomenon can be particularly useful in rail, pipeline and Aerospace industry for thickness measurements and defect detection in conductive materials. The Lorentz force and the effect of varying the EMAT parameters such as lift off was investigated to show the effects it has on the performance of EMAT. The accuracy of the numerical method was further investigated by firstly decreasing the triangular mesh and varying the time steps to determine the convergence of the displacement, which will ensure the convergence of all other physical quantities. Additionally, the wave propagation in a conductive material is investigated, which involves the coupling of several physical parameters, which includes mechanical and electromagnetic properties. This leads to the investigation of defect detection in an Aluminium material. Results obtained shows the model is capable of detecting the depth, width and location of the surface defect using the mechanical displacement amplitude.

1. INTRODUCTION

Non-Destructive testing of materials is a method used for the inspection of materials to produce information leading to decisions to be taking on the serviceability of the material. It is the most common method of testing materials, NDT does not require the disabling or tampering of the system of interest, it is a highly-valuable technique that saves both money and time in product evaluation and troubleshooting. Depending on the type of material and defect, there are various types of NDT testing procedures available for any kind of testing requirements, such NDT techniques include; Radiography, Eddy current, Magnetic particle inspection, visual method, Ultrasonic Testing and electromagnetic Acoustic Transducer. The disadvantage of Ultrasonic testing is that a coupling medium is needed to transmit
ultrasonic waves into the material, but sometimes the material surface may not be accessible due to rust, the temperature of the material, location or positioning of the material. Sometimes the coupling medium might absorb the transmitting signal not allowing the propagation of ultrasonic wave into the material. This is where an EMAT comes in. It combines the advantages of Ultrasonic testing but doesn’t need a coupling medium, it uses the electromagnetic properties of the EMAT coils and mechanical properties of the material to create a force known as Lorentz force to launch ultrasonic waves into the material. Electromagnetic Acoustic Transducer (EMAT) consists of a permanent magnet or electromagnet, meander coils and a conductive material as shown in Figure 1. The magnet introduces a static magnetic field, while the meander coils are excited with an alternating current source. The meander coils are placed underneath the magnet near the surface of the conducting materials, and excited by an external current at a desired ultrasonic frequency, leading to induced current at the skin depth surface of the electrical conducting material\(^1\).

![Figure 1. 2D structure of an EMAT which includes a Permanent or Electro Magnet\(^1\)](image)

The interaction between the induced current and static magnetic fields creates a force known as the Lorentz force, which excites the material to generate propagating acoustic waves. The wave source is created in the material under test compared to other UT testing like the piezoelectric transducer where the material is excited and the energy is transferred through the coupling medium, which can lead to losses of ultrasonic energy to be transferred into the material\(^1\). There is a wide range of numerical techniques used to evaluate EMAT, such as method of moments, Boundary Elements, Finite Difference, Finite element and many more. Finite element and Finite difference methods are the most common numerical methods used to solve EMAT problems. There have been work published on various numerical models of EMAT, which includes Ludwig el al.\(^2\) and Kaltenbacher et al.\(^3,4\), which is based on finite element and finite difference methods for testing non ferromagnetic material. The emphasis in Kaltenbacher work was based on guided wave generation and reception in thin plate. Mirkhani et al\(^5\) work was based on experimental and numerical methods of analysing an EMAT transmitter, where the EMAT model gives several important improvements over previous published work. In this work
spatial inhomogeneities in the magnetic flux density are calculated and used to determine the force. Xjian et al.\(^6\) worked on Rayleigh wave and the effect on ultrasonic generation of a back plate in EMATs. A permanent magnet is included behind the EMAT coils and an electrically conducting backplate is placed between the coil and the magnet to prevent ultrasonic generation in the magnet by the current generated in the EMAT coil. Shapooradadi \(^7,8\) also presented finite element analysis of EMATs operating in transmitting mode, where two different definitions of source current density are compared to highlight the importance of skin and proximity effects. Ludwig et al.\(^9\) developed a multi-stage numerical model of an EMAT system, particularly focusing on the EMAT receiver. The model is capable of accounting for static magnetic field, pulsed eddy current, Lorentz force distribution, acoustic wave generation and propagation and acoustic wave detection. The presented finite element model has been developed in the spirit of work conducted in Ludwig and Thomas \(^8,9,10\), to accurately account for induced current distribution, the Lorentz force and the effects of varying the EMAT design parameters such as the “lift off”. This work was further investigated by rigorous convergence tests for the stability of the finite element model to stabilise the material to allow accurate propagation of surface waves in the material \(^11\). In addition to the comprehensive analysis of the EMAT, the model is also accountable for the detection of surface defects in conductive material; it is able to detect different types of defect like depth, width and defects inside the material, compared to other literature \(^12\), where this analysis wasn’t presented.

2. Analysis

The governing equation involved in transient magnetic field for the transmitting EMAT, where the schematic is represented in Fig 1, is expressed in terms of magnetic vector potential (MVP) \(A\), and source current density (SCD). The current density \(J_{sk}\) and MVP have only longitudinal direction, \(Z\)-component \(A_z\):

\[
- \text{div} \left( \frac{1}{\mu} \nabla A_z \right) + \sigma \frac{\partial A_z}{\partial t} = J_{sk}
\]

(1)

where \(\sigma\) is the conductivity, \(A_z\) is the \(Z\)-component of the MVP, and \(\mu\) is the permeability, \(J_{sk}\) is the SCD of the \(K\)-th source conductor.

For the geometry of the system shown in Fig 1, there are two different expressions for the source current density \(J_{sk}\). For the incomplete equation the simple expression for \(J_{sk}\) is

\[
J_{sk} = \frac{i_k(t)}{S_k}
\]

(2)

where \(i_k(t)\) is the total current flowing in the \(K\)-th source coil conductor, and \(S_k\) is the cross section area of the coil conductor. Substituting Equation (2) in (1), the governing equation for the transient magnetic field of the transmitting EMAT becomes
However, it should be noted that in Equation (2) the effects of the magnetic field generated in the coils is not taken into account and this can affect the accuracy to when modelling the real phenomenon by (3). For a more accurate equation, the integral form of Maxwell equations is used, where it is possible to insert the effect of the magnetic field generated in the coils in the expression of $J_{sk}$, which leads to:

$$J_{sk} = \frac{i_{k}(t)}{S_{k}} + \frac{\sigma \partial}{\partial t} \int_{S_{k}} A_{k} ds$$

$$................................. (4)$$

$J_{sk}$ is not only a function of total current but it is also a function of the time derivatives of the surface integral of the magnetic vector potential ($A_{z}$) (7) where $R_{k}$ represents the cross-section region of the $K$-th conductor. By substituting (4) into (1), the following differential equation is obtained

$$-\frac{1}{\mu} \text{div} \left( \frac{1}{\mu} A_{z} \right) + \sigma \frac{\partial A_{z}}{\partial t} - \frac{\sigma \partial}{\partial t} \int_{S_{k}} A_{k} ds = \frac{i_{k}(t)}{S_{k}}$$

$$................................. (5)$$

For the accurate equation the magnetic fields produced by the coils are taken into account, which gives an accurate equation for modelling the scenario under consideration. The incomplete equation is a simple calculation of the total current divided by the cross section of the coil in (2), while the accurate equation takes into account the magnetic field provided by the coil, by taking the surface integral of the magnetic vector potential, which enhances the accuracy of the results as will be shown later.

$$\sigma T \frac{dA}{dt} + \frac{1}{\mu} S A = T J$$

$$................................. (6)$$

Equation.(6) is then discretized using a Finite element procedure in the whole computation domain obtaining (7). $A$ and matrices $S_{n \times n}$ and $T_{n \times n}$ are FE coefficient matrices (8). Same procedure if followed for (5), obtaining

$$\sigma(T - QP^{-1}Q^{T}) \frac{dA}{dt} + \frac{1}{\mu} S A = QP^{-1}I(t)$$

$$................................. (7)$$

To solve the ordinary differential equation (7), a pure implicit scheme is applied (4)

$$\left[ R + \frac{1}{\mu} S \right] A_{n+1} = R A_{n} + QP^{-1}I(t_{n})$$

$$................................. (8)$$

Where the matrix $R_{n \times n}$ is giving by
and $R$ is symmetric\(^{(4)}\).

The Lorentz force in the material is calculated as the aluminium material has no magnetisation properties. The Lorentz force is a result of the interaction between the induced current $J_z$ and the magnetic flux density $B_0$. The calculation of the interaction between these fields is conducted, leading to the force component being calculated.\(^{(1)}\)

$$f_z = J_z \times B_0$$ \hspace{1cm} (10)

The direction of the force is also determined by (10). Due to the set up of the 2D EMAT model, $B_0$ has $x$ and $y$ components, while induced current $J_z$ has only one component in $z$ direction. The Lorentz force calculated above is coupled with the mechanical analysis to vibrate the material which launches the acoustic wave in the material. The acoustic field equation is stated in terms of a particle displacement vector $\mu$ and the Lorentz force as follows

$$\mu \nabla \times \nabla \times \mu - (\lambda + 2\mu)\nabla \cdot \mu + \rho \frac{\partial^2 \mu}{\partial t^2} = f_z$$ \hspace{1cm} (11)

Where $\rho$ is mass volume density and $\lambda$ and $\mu$ are lame constants\(^{(8)}\).

3. Results

The structure of the EMAT considered in this paper is shown in Fig 1. It consists of six rectangular meander coils with identical cross section of height $a$ and width $b$. $d$ is the distance between coils and $h$ denotes the lift off distance between the meander source coils and the conductive material.

The transient excitation current in the coils is the given as\(^{(8)}\)

$$i(t) = \begin{cases} (-1)^t I_0 \left[1 - \cos((a_0 t)/n)\right] \cos(a_0 t) & \text{for } 0 \leq t \leq (2n\pi)/a_0 \\ 0 & \text{for } t \geq (2n\pi)/a_0 \end{cases}$$ \hspace{1cm} (12)

where $I_0$ is the current amplitude, $\omega_0=2\pi f_0$ is the angular centre frequency and $n$ is the number of cycles. The parameters used are $f_0= 500$kHz, $n=2$, $I_0=100$A, $B_0= 1$T, $a=0.1$mm, $b= 0.5$mm, $d = 0.5$mm and $h=1$mm. The Mesh based on Second order quadratic triangular elements as shown in Fig 2. The mesh elements were refined around the skin depth surface of 0.1mm depth into the material, the time steps, relative tolerance and the absolute tolerance were adjusted for a more accurate calculation.
A Detector was placed underneath the fourth coil from the left of the EMAT structure to record the time variation of all the extracted data from the simulations. Taking into account the external source current applied to the coils and the static magnetic field across the material, the complete equation is solved to calculate the induced current in the material. The result shown in Fig 3 indicates the presence of induced eddy current at the skin depth surface (0.119mm) of the material. The Lorentz force is observed at the same point as the induced current shown in Fig 4. The result also shows that the Lorentz force is related to the induced current, both having the same waveform, this is an expected result because the Lorentz force depends on the induced current as expressed in equation (10). Further work was carried out to investigate the performance of EMAT varying the lift off distance $h$. Results shown in Fig 5 indicate that the force in the material is a non linear function of lift off. When the lift off distance is reduced from 1mm to 0.1mm, the force present at the surface of the material is 16 times stronger. Which is in good agreement with earlier published work\(^8\). For 1mm of lift off the force obtained was approximately 120M N/m\(^3\), while at 0.1 mm the force obtained was approximately 2000M N/m\(^3\)\(^{(10)}\)
The accuracy of the numerical method was further investigated by firstly decreasing the triangular mesh element size to determine the convergence of the displacement, which will ensure the convergence of all other physical quantities. A detector was placed at the surface of the material underneath the coils. The Mesh consists of second order quadratic triangular elements which are refined from 1110 to 10072 elements with $\Delta t$ of 0.01$\mu$s. Results shown in Fig 6 illustrate how the displacement reaches its convergence from 3000 elements. Furthermore, the accuracy of the numerical method was tested by reducing the size of the time step. A fine mesh consisting of 7519 elements was used although results show that any amount of mesh over 3000 elements is sufficient to obtain accurate results. The detector was also placed in the same point at the surface of the material underneath the coils. By observing the result shown in Fig 7 illustrates the time step larger than 0.1$\mu$s is inaccurate, which is also confirmed by Nyquist law. In this case the largest amount of the time step to be used in this scenario is 0.1$\mu$s. By reducing $dt$ further to 0.01$\mu$s increased the computation running time significantly and the amplitude was further improved by 0.5nm to the value of 4.12nm. The time steps were further varied between 0.01$\mu$s and 0.05$\mu$s to verify the size of the time step between this range results to the convergence of all physical quantities. Based on the results obtained from the analysis of the convergence of the model for all simulations a mesh of 7519 elements with time step size of 0.01$\mu$s has been used for all coupled analysis.\(^{(10)}\)

![Figure 5. Variation of Lift off in the material at 500Khz\(^{(10)}\)](image)

![Figure 6. Varied triangular mesh elements from coarse mesh to fine mesh](image)
Following the analysis of the numerical EMAT model, a surface defect is introduced into the model 7mm away from the centre of the transmitting coils. The defect dimension is 1mm by 1mm, the depth of the defect will be varied from 1mm to 3mm as the thickness of the aluminium material is 4mm and extended by length to 15mm. The analysis will be conducted to investigate if the EMAT model can detect the depth of a defect in the material. Fig 8 shows the introduction of the defect in the material, with refined mesh around the defect. The results shown in Fig 9 are of different defect depths, the contour plot show that the displacement is less where the defect is deeper. The results are highlighted in Fig 10 to show that the deeper the depth of the defect inside the aluminium material, the amplitude of the displacement at the surface of the material decreases. The results show for a defect of 1mm the amplitude recorded was 1.2µM and at defect of 3mm the amplitude is reduced to 0.06µm. This proves that the model is able to detect changes in the defect depths. This also confirms the results shown in Figure 9 where we notice the surface displacement reduced with the depth of the defect. This is due to the reflection caused by the depth of the defect, which prevents the waves from being transmitted to receiver freely.
The Surface defect was further investigated to examine if the EMAT model would be able to detect if there is a change in the defect size. The defect width size was varied from 1mm to 3.5mm. Fig 11 shows the varied width at the surface of the material, the length and thickness of the Aluminium material stays the same as the previous analysis but the excitation was changed from the initial excitation of a 2 cycle turn burst to a 7 cycle turn burst. The detector is placed 10mm away from the transmitting coil where the surface displacement amplitude is detected and recorded.

Results of the recorded displacement are shown in Fig 12, which illustrates that the wider the defect size leads to an increase of the displacement at the surface of the material. The result obtained is a reverse of the results obtained in depth detection shown in Fig 10. The depth of the defect has less vibration at the surface of the material, however with the width the vibration increases, which proves the fact that by decreased the surface geometry of the material we observe more vibration at the surface of the material. Results shown in figure 12 illustrate with a 1mm defect a peak displacement amplitude of 0.36µM was observed, while with a defect width of 3.5mm a displacement amplitude of 0.47µM was observed, which proves the point that the wider the defect the stronger the vibration experienced at the surface of the material.
The EMAT model was further investigated to analyze the capability of the Model in locating the position of the defect inside the Aluminium material. A defect size of 1mm by 1mm was introduced inside the material at a depth of 1mm in the material as shown in Fig 13. Three defects were introduced at different locations, one was placed directly under the transmitting coil while the second was placed few millimeters after the transmitting coil. The third was placed underneath the detector, 10mm away from the transmitting coil as shown in Fig 14.

Results shown in figure 14a prove that the Model is capable of detecting the location of the defect in the material. From the Plots we can see that when the defect is underneath the transmitting coil we observe the highest mechanical displacement compared to when its further away from the transmitting coil. Further investigation was carried out to investigate the size of the defect inside the material directly underneath the transmitting coil. The size of the defect was varied from 1mm by 1mm to 1mm by 2mm. Figure 14.b shows that the larger the defect the amplitude of mechanical displacement increases which correlates with results of the width of defect obtained in figure 13. Displacement amplitude of 2.4 mm was observed with a defect of 1 x 2 mm, by reducing the size of the defect the amplitude
reduces to 2.1mm and by removing the defecting completely from the model, the displacement amplitude observed was at its lowest unit of 1.4mm.

![Figure 14a](image1.png)

**Figure 14a** plot of displacement amplitude of defect inside the material at different position

![Figure 14b](image2.png)

**Figure 14b** Plot of displacement amplitude of different size of defect inside the material

4. **Conclusion**

In this paper the numerical modelling of Electromagnetic Acoustic Transducer has been investigated. A comprehensive analysis on the coupling of the Electromagnetic and Mechanical analysis of an EMAT was conducted, which includes the investigation on the effect of lift of on the Lorentz force. The coupled EMAT model was further developed to investigate the mechanical displacement in a conductive material. The study includes convergence test for the variation of second order quadratic triangular elements, which are already known to be very accurate for finite element method. The time step size was rigorously investigated for the accuracy of the numerical model. Furthermore the EMAT model was extended to analyse the effect a defect has on the surface mechanical displacement, the analysis included the varied depth, width and location. Results proved the EMAT model was capable of detecting and characterizing the size and location of the
defect. The peak amplitude increases when a defect is introduced inside the material. A change in the displacement is also noticed when the defect size is increased and when its location is moved away from the transmitting coil. This model can be further developed into a 3D model to give a more realistic defect detection model.

References


