# Electromagnetic Acoustic Transducers for In and Out of plane Ultrasonic Wave Detection

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## Abstract

A model has been developed for the detection of ultrasonic waves using electromagnetic acoustic transducers (EMATs). EMATs are particle velocity sensors, which can be designed to have sensitivity to in-plane and/or out-of-plane ultrasonic displacements, by suitably arranging the magnetic field in the receiving EMATs relative to the orientation of the coil. Good agreement between the results from the modeling undertaken and experimental measurements has been demonstrated.

**Keywords**: EMAT, particle velocity sensor, in-plane velocity, out-of-plane velocity, lift-off

## 1. Introduction

Ultrasonic field measurements are of great interest in transducer development, material evaluation and non-destructive testing (NDT)[1-7]. The in-plane and out-of-plane components of the particle velocity of bulk waves (longitudinal and shear) are always in phase. However, the in-plane and out-of-plane particle velocities of guided waves such as Rayleigh waves or Lamb waves are not in phase[7, 8]. The ratio of the amplitude of the in-plane particle velocity to that of the out-of-plane particle velocity is dependent on the material elastic properties (and particular wave mode for the Lamb wave). It has been reported that the responses from defects for in-plane and out of-plane ultrasonic wave displacements are different[7]. Thus it is reasonable to speculate that a particular particle velocity component may have an optimal sensitivity for specific defect inspection and sizing applications.

EMATs generate and detect ultrasonic waves via electromagnetic coupling between the EMAT and the metal samples. They operate via the Lorentz force or magnetostriction mechanisms or the use of both simultaneously[9-12]. EMATs are non-contact devices, and therefore ultrasonic waves can be measured with minimal disturbance to the ultrasonic wave itself or to the material. However, the relationship between an EMAT and a metal sample does have an influence on the wave generation or detection characteristics. EMATs are inexpensive, inherently safe and highly portable, but are fairly insensitive when compared to piezoelectric based devices.

It has been reported that the EMAT generation efficiency can be enhanced by arranging the magnetic field correctly[2] or by means of a ferrite back-plate[1]. The ultrasonic field generated by a circular coil EMAT can be modeled to analyze the influence of the various parameters of the EMAT design upon the ultrasonic generation mechanism[9-10].

## 2. Theory

A model for the calculation of the ultrasonic signal induced in an EMAT detection coil is presented, which is useful for both general EMAT design for tailoring an EMATs to a specific NDT application.

### 2.1 Large EMATs

Generally, the thickness of the test specimen and the magnet in the EMAT is much larger than the electromagnetic skin depth at the corresponding frequency of the detected ultrasonic waves. Figure 2 shows schematic diagraph for analysis of a receiving EMAT, where zone 0 is the air gap between the magnet and the test specimen, and is the region where the receiving coil of the EMAT is located. Zone 1 corresponds to the magnet, which is usually an electrical conductor and zone 2 is the electrically conductive test specimen. The magnetic permeability and electrical conductivity of the magnet (zone 1) are defined as $\mu_1$ and $\sigma_1$ respectively. The magnetic permeability and electrical permittivity of air (zone 0) are defined as $\mu_0$ and $\varepsilon_0$ respectively. The magnetic permeability and electrical conductivity in the test specimen (zone 2) are defined as $\mu_2$ and $\sigma_2$ respectively.

Ultrasonic waves induce particle vibration in the test specimen as they propagate through it. Eddy current is induced in the test specimen in the presence of a static magnetic field, produce time-varying magnetic fluxes though the receiving coil and generate a voltage across the coil. The induced eddy current sheet at a depth $z_0$ in the test specimen, which is due to the particle vibration, is given by

$$\boldsymbol{J}_{\text{ed}}(z_0) = \sigma_2 \boldsymbol{v}(z_0) \times \boldsymbol{B}_0(z_0) \tag{1}$$

Where $\boldsymbol{v}(z_0)$ and $\boldsymbol{B}_0(z_0)$ are the vectors of the particle velocity and magnetic field at depth $z_0$ in the test specimen respectively. Here and elsewhere in this paper, variables in bold denote a vector.

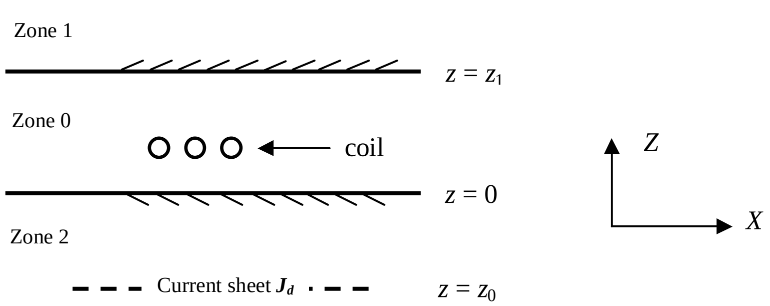


Figure 1 Current sheets in an electrically conductive test specimen, generate magnetic vector potentials in the air above the conductor.

From Maxwell's equations, the magnetic vector potential differential equations in zones 1, 0 and 2 are $\boldsymbol{A}_1$, $\boldsymbol{A}_0$ and $\boldsymbol{A}_2$, and are given respectively by,

$$\nabla^2 \boldsymbol{A}_1 = j\omega\mu_1\sigma_1\boldsymbol{A}_1 \tag{2}$$

$$\nabla^2 \boldsymbol{A}_0 = -\omega^2\mu_0\varepsilon_0\boldsymbol{A}_0 \tag{3}$$

$$\nabla^2 \mathbf{A}_2 = j\omega\mu_2\sigma_2\mathbf{A}_2 \tag{4}$$

where $\omega$ is the frequency of the changing magnetic field, and $j$ is $\sqrt{-1}$.

Taking the boundary conditions into account, the following solutions are obtained. The magnetic vector potential in zone 0, due to a sheet current at a depth, $z_0$, is given by,

$$\boldsymbol{A}_0 = \mu_2 e^{\frac{1+j}{\delta_2}z_0}\frac{\delta_2}{1+j}\boldsymbol{J}_{ed}(z_0)(e^{jk_0z} + e^{-jk_0z}e^{j2k_0z_1}) \tag{5}$$

where $\delta_2$ and $k_0$ are the skin depth and the wave number of the electromagnetic wave of frequency, $\omega$, in the test specimen respectively.

Integrating over the thickness of the test specimen, the total magnetic vector potential in zone 0, due to the eddy current sheet in the entire test specimen is obtained as,

$$\boldsymbol{A}_{0t} = 4\frac{1}{j\omega(1 - jk_0{}^2\delta_2{}^2/2)}\boldsymbol{v}_0 \times \boldsymbol{B}_0 \tag{6}$$

The total voltage induced in a linear coil of $N$ turns and length $l_0$ in the receiving EMAT is given by

$$V = -4N\frac{1}{1 - jk_0{}^2\delta_2{}^2/2}\boldsymbol{l}_0 \cdot (\boldsymbol{v}_0 \times \boldsymbol{B}_0) \tag{7}$$

The voltage signal detected by the EMAT receiver is proportional to the cross product of the vector of particle velocity, $v_0$, and the vector of the magnetic field, $B_0$, and is not dependent on the lift-off between the coil and the test specimen. This is therefore a particle velocity sensor. It is noted that the detected ultrasonic signal by a practical EMAT is dependent on the lift-off between the receiving EMAT and the test specimen.

In the case that the eddy current induced in the magnet is ignored, the detected voltage signal is given by [3]

$$V = -2N\frac{1}{1 - jk_0{}^2\delta_2{}^2/2}\boldsymbol{l}_0 \cdot (\boldsymbol{v}_0 \times \boldsymbol{B}_0) \tag{8}$$

**2.2 EMATs of finite size**

Only particle vibrations within the skin depth of the electromagnetic wave can produce an effective contribution to the induced voltage signal [3, 9-10]. An equivalent current $\boldsymbol{J}_{\mathrm{eq}}$ in air that generates an identical magnetic field in the coil of the receiving EMAT to what is generated by the current sheet, $\boldsymbol{J}_{\mathrm{ed}}$, at depth $z_0$, is assumed and is given by,

$$\boldsymbol{J}_{\mathrm{eq}} \propto \mu_2 e^{\frac{1+j}{\delta_2}z_0}\frac{\delta_2}{1+j}\boldsymbol{J}_{\mathrm{ed}} \tag{9}$$

Considering the magnetic source of size of $w_0$ wide and $l_0$ long with its centre at the origin of the coordinate system, the static magnetic field $\boldsymbol{B}_0$ is mainly limited to this area. The magnetic field, $\boldsymbol{B}$, at point ($x$, $y$, $z$) produced by the current sheet element due to the particle vibration within the area between $-w_0/2$ to $+w_0/2$ in $x$-axis and $-l_0/2$ to $+l_0/2$ in $y$-axis, where $\boldsymbol{B}_0$ has significant amplitude, is given by

$$\boldsymbol{B} = \mu_2 e^{\frac{1+j}{\delta_2} z_0} \frac{\delta_2}{1+j} \int_{-\frac{l_0}{2}}^{\frac{l_0}{2}} dy \int_{-\frac{w_0}{2}}^{\frac{w_0}{2}} \frac{\mu_0}{4\pi} \frac{\boldsymbol{J}_{\mathrm{ed}} \times \boldsymbol{r}}{r^2} \cdot dx \tag{10}$$

where $r$ is the distance between the eddy current element and the field point .

Considering that the particle velocity, $\boldsymbol{v}_{0,}$ is in the $x$-axis direction, and the magnetic field $\boldsymbol{B}_0$ is in the $z$-axis direction, the eddy current sheet, $\boldsymbol{J}_{\mathrm{ed},}$ therefore is in the $y$-axis direction. Assuming that the coil is arranged in the middle of the magnet in the $x$-axis direction, the magnetic field $\boldsymbol{B}$ that is induced by $\boldsymbol{J}_{\mathrm{ed}}$, the eddy current sheet in the test specimen, is in the $x$-axis direction due to the symmetry and this is given by,

$$B_x = e^{\frac{1+j}{\delta_2} z_0} \frac{\delta_2}{1+j} \frac{\mu_2 \mu_0}{4\pi} \int_{-\frac{w_0}{2}}^{\frac{w_0}{2}} dx_0 \int_{-\frac{l_0}{2}}^{\frac{l_0}{2}} \frac{J_{\mathrm{ed}} B_0 (z - z_0)}{r^3} dy_0 \tag{11}$$

After some manipulations, the voltage of the detected ultrasonic signal may be given by,

$$V = j \frac{\mu_0}{4\pi} N l_0^{\ 2} w_0 B_0^{\ 2} \frac{v}{z^2} \tag{12}$$

### 2.3 In-plane and out-of-plane ultrasonic waves

The in-plane and out-of-plane particle velocity components of the Rayleigh waves can be given by[8]

$$v_x(z) = A_R k_R (e^{-q_R z} - \frac{2 q_R s_R}{k_R^{\ 2} + s_R^{\ 2}} e^{-s_R z}) e^{j(k_R x - \pi/2)} \tag{13}$$

$$v_z(z) = A_R q_R (e^{-q_R z} - \frac{2 k_R^{\ 2}}{k_R^{\ 2} + s_R^{\ 2}} e^{-s_R z}) e^{j k_R x} \tag{14}$$

The out-of-plane particle velocity of the Rayleigh waves within the skin depth is of phase $\pi/2$ ahead of the in-plane particle velocity. The amplitude ratio of the out-of-plane particle velocity to in-plane particle velocity is dependent on the material of the test specimen. For a test specimen of Aluminum, the former quantity has amplitude which is larger than the latter.

## 3. Experimental measurements

### 3.1 Measurement set up

Two generations of EMATs are considered in this paper. The linear generation EMAT has a linear coil of 16 turns, 20 mm wide and 5 mm wide, and is used for the generation of Rayleigh waves. The spiral generation EMAT has a spiral pancake coil of diameter of 30 mm, and is used for the generation of Rayleigh waves.

Three linear receiving EMATs are further considered in this work. The first has a coil of 5 mm in width and 20 mm in length and contains a circular magnet of diameter of 25 mm. The second is used for the measurement of in-plane ultrasonic waves and the third for the measurement of the out-of-plane ultrasonic waves. Both the second and the third receiving EMATs contain a rectangular magnet and a coil that is 3 mm wide and 25 mm in length. The orientations of the magnet in the second and the third receiving EMATs are different. The perpendicular component of the magnetic field of the magnet used in the first receiving EMAT is 0.25 Tesla whereas the perpendicular component of the magnetic field of the magnet used in the second receiving EMAT is 0.35 Tesla. The parallel component of the magnetic field of the magnet used in the third receiving EMAT is 0.25 Tesla.

Two aluminum test specimens are used in his work, all of which have propagation velocities of the longitudinal and shear waves of 6310 and 3100 m/s and a propagation velocity of the Rayleigh wave of 2920 m/s. The first test specimen is a large aluminum test block for the measurement of both longitudinal and Rayleigh waves whereas the second test specimen is an aluminum sheet of thickness 0.125 mm.

### 3.2 Influence of Liftoff

Figure 2 shows the ultrasonic wave response against liftoff measured in the aluminum block. The line “LLR” represents the Rayleigh waves generated using the linear generation EMAT with a fixed liftoff and received using the first receiving EMAT with varied liftoff. The line “LLG” is the Rayleigh waves generated by the linear generation with varied liftoff and received using the first receiving EMAT with a fixed liftoff. The separation between the generation EMAT and the receiving EMAT for both lines “LLR” and “LLG” is 250 mm. The line “SLR” represents longitudinal waves generated by the spiral generation EMAT with varied liftoff and received by the first receiving EMAT with fixed liftoff. The separation between the generation EMAT and the receiving EMAT is 250 mm and the measured longitudinal and Rayleigh wave amplitudes decrease with the liftoff.

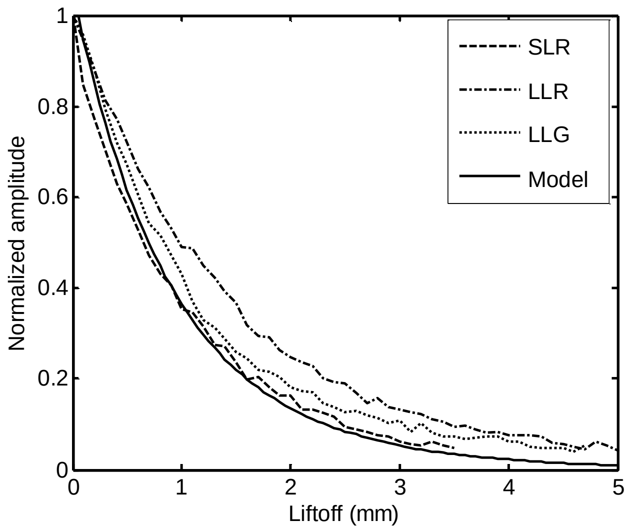


Figure 2 Measured ultrasonic wave amplitude on axis against lift-off.

The line “Model” is the result of the calculated based on equation 12. The calculated amplitude of the signal also decreases with liftoff but, however, it is found that the “Model” is more sensitive to liftoff than is the measurement because the magnetic field is also a function of liftoff.

### 3.3 Measurement of in-plane and out-of-plane velocities

Figure 3 shows the structure of the receiving EMATs for out-of-plane ultrasonic wave detection (top) and for in-plane ultrasonic wave detection (bottom) based on equation 12. Rayleigh waves in the aluminum test block are measured and shown in Figure 4. The lines

“In” and “Out” denote in-plane and out-of-plane ultrasonic waves. The line “Out” is about 1.7 times larger in amplitude than that of the line “In”, and it has phase of $\pi/2$ ahead of the latter.

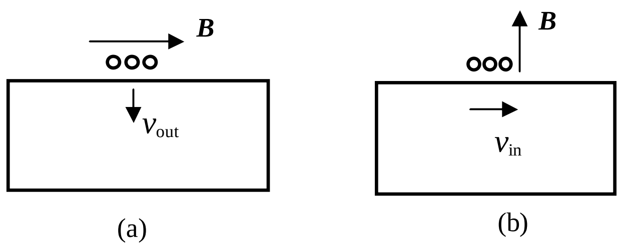


Figure 3 Schematic structure of EMAT receivers for out-of-plane (a) and in-plane (b) particle velocity detection, where the applied static magnetic fields in the specimen supplied by the magnet in the EMATs are in-plane and out-of-plane respectively.

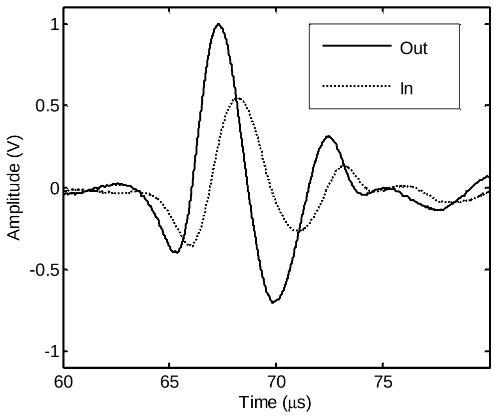


Figure 4 Measured in-plane and out-of-plane particle velocity of Rayleigh waves. The out-of-plane particle velocity is of $\pi/2$ phase ahead of the in-plane particle velocity.

## 4. Conclusion and discussion

A model has been developed which allows for the calculation the ultrasonic signal picked up using EMATs. Receiving EMATs are seen as particle velocity sensors, detecting mainly the ultrasonic waves with the skin depth of the electromagnetic wave in the test specimen at the frequency interested. The influence of liftoff on the detection of the ultrasonic plane wave is dependent on the size of the coil and a large receiving EMAT is less subject to the issue of liftoff.

By arranging the static magnetic field of the magnet in the EMATs perpendicular to the surface of the test specimen, the EMATs pick up the in-plane particle velocity of incident ultrasonic waves. By arranging the static magnetic field parallel to the surface of the test specimen, the EMATs pick up the out-of-plane particle velocity of incident ultrasonic waves.

The defect response of an in-plane particle is different from the out-of-plane particle velocity where one may carry more information on the defect than the other for a specific inspection. The capability of selective detection of the in-plane or out-of-plane particle velocity is sometimes very useful for defect evaluation using guided waves such as Rayleigh waves or Lamb waves[7-8]. However, for more general applications, receiving EMATs are designed to pick up both in-plane and out-of-plane particle velocities to enhance the detection sensitiveness of the receiving EMATs.

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