Validation of FEM simulation of EMATs for versatile EMAT configurations

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ABSTRACT

An electromagnetic acoustic transducer (EMAT) generates ultrasonic waves using the electromagnetic interaction and does not require a coupling medium. The final goal of this study is to provide a method to optimize the configuration of an EMAT for obtaining a higher signal-to-noise ratio (SNR). As the first step, this paper shows the results of numerical simulations performed to seek an EMAT configuration that makes shear waves or longitudinal waves dominant.

1. INTRODUCTION

An electromagnetic acoustic transducer (EMAT) consists of a coil and magnets to generate ultrasonic waves at the surface of a conductive material by the electromagnetic interaction. Thanks to its mechanism of generation of ultrasonic waves, it does not require a coupling medium between the transducer and the surface of the material. This becomes a great advantage especially for some specific applications such as inspection in a high-temperature environment and inspection of a porous material. On the other hand, an EMAT provides a much lower signal-to-noise ratio (SNR) compared with generally-used piezoelectric transducers because of its low transfer efficiency. To compensate for the low transfer efficiency of an EMAT, an EMAT configuration is expected to be optimized by utilizing its configuration flexibility. The purpose of this study is to establish a simulation procedure to support the optimization of an EMAT configuration.

2. INSTRUMENTAL VISUALIZATION

In our past study, numerical simulations were performed to reproduce propagation of ultrasonic waves generated by an EMAT in austenitic stainless steel, and these simulation results were validated by comparing them with actual measurement results. The actual measurement results were given as wave propagation images created by an instrumental visualization method. Similarly, this paper provides wave propagation images obtained with a slightly improved instrumental setup to validate the simulation results.

Figure 1 shows the configuration of the measurement system for the instrumental visualization that was first introduced in 3). A transmitting probe that generates the ultrasonic waves to be examined is placed near the edge on the top surface of a test block so as to make the central axis of the ultrasound beam closer to the side surface of the test block. To observe the propagation of the ultrasonic waves, a two-dimensional scan is performed with a receiving probe on the side surface.

For the instrumental visualization performed for this study, the transmitting probe was an EMAT. According to the preceding study 4), this EMAT consists of a coil of coated copper wire and two samarium-cobalt magnets merged together with their polarization directions made vertically opposite. To unify the vibration direction of the generated shear waves, a racetrack coil was selected as the coil of the EMAT, and only the straight-line segment of the racetrack coil was used to produce the Lorentz forces for the wave generation. Figure 2 shows the configuration of the EMAT.

The receiving probe was a piezoelectric transducer for longitudinal waves. Actually, a piezoelectric transducer for either longitudinal or shear waves can sense both wave modes, though the sensitivity to the intended wave mode is superior. Thus, both longitudinal and shear waves can be observed with this setup. Whereas the contact area of the piezoelectric transducer is a 14 mm square,
the size of its oscillator is a 1 mm square. While the two-dimensional scan is performed with the receiving probe on the side surface of the test block, the received signals are recorded. By reorganizing the transient changes of the signal voltage data obtained at each sampling point of the scanned area, two-dimensional images can be created to represent the distribution of the signal voltage on the side surface at each moment. Since the signal voltage corresponds to the wave intensity at each observation point, displaying these images one after another results in a moving image that depicts the propagation of the waves on the side surface. The size of the test block is 200 mm×50 mm×30 mm as shown in Fig. 1. The material of the test block is 316 austenitic stainless steel (JIS G 4305 SUS316).

![Figure 1 – Measurement system for instrumental visualization](image)

Driving pulses were applied to the coil of the EMAT by the pulser-receiver RITEC RPR-4000. Each pulse was a three-cycle sinusoidal pulse with a center frequency of 2 MHz, and its peak-to-peak voltage was approximately 500 V. To match the center frequency of the driving pulses, the piezoelectric transducer with a nominal frequency of 2 MHz was used as the receiving probe. While the receiving probe was moved on the side surface, the received signals were recorded at 0.2 mm pitch.

Because this EMAT is not axisymmetric, different propagation behaviors are observed from Side A and Side B of the EMAT as illustrated in Fig. 3. The two magnets of the EMAT create an arc-shaped magnetic field directed from the north pole toward the south pole under the magnets. In addition, the eddy currents induced by the coil in the surface of the test block flow along the straight-line segment of the coil under the EMAT. According to Fleming’s left hand rule, the Lorentz forces produced in the test block are perpendicular to the arc-shaped magnetic field and therefore radially oriented in each cross-section parallel to Side A. Thus, these Lorentz forces generate longitudinal waves having a cylinder-formed wave front. While these longitudinal waves are observed as circular waves from Side A, these waves are observed as plane waves from Side B. The measurement for the instrumental visualization was performed in both cases.

The results of the instrumental visualization are later shown in the next section to validate simulation results.
3. SIMULATION PROCEDURE

To simulate the propagation of the ultrasonic waves generated by an EMAT, two commercial finite element method (FEM) simulation software packages (EMSolution and ComWAVE) were used. EMSolution was used to compute the Lorentz forces produced by an EMAT, and ComWAVE was used to compute the propagation of the ultrasonic waves caused by the Lorentz forces.

Figure 4 shows the shape model for EMSolution to compute the Lorentz forces produced by the EMAT described in Fig. 2. Symmetric boundary conditions were imposed on the central plane of the EMAT to reduce the shape model to half. The entire coil is displayed in Fig. 4 because the coil was defined independently from the other FEM meshes, and the magnetic field created by the coil was calculated based on the Biot-Savart law. The size of the metal region is 50 mm in X, 100 mm in Y, and 20 mm in Z. The air region extends 30 mm in the direction of each horizontal axis, 50 mm toward the top, and 10 mm toward the bottom from the metal region. Since the material of the test block is 316 austenitic stainless steel, the conductivity and the relative permeability of the metal region were set to 1.35×10^6 S/m and 1.0, respectively. The dimensions of the EMAT were made the same as shown in Fig. 2. The thicknesses of the coil and the gaps above and under the coil were set to 0.5 mm. Because the number of turns in the coil is 40, the cross-sectional current of the coil was given by multiplying the input current by 40. The input pulse was a three-cycle sinusoidal pulse with a center frequency of 2 MHz and given by

\[ w(t) = \sin(2\pi ft) \left[ 1 - \cos \left( \frac{2\pi f}{3} t \right) \right], \]

where \( t \) is time in seconds and \( f \) is the center frequency in Hz (2×10^6). The magnetization vectors of the two magnets were respectively set to 1 and −1 T in the Z-direction. To simplify the problem, the magnets were treated as nonconductive and nonmagnetic objects. In reality, an EMAT sometimes generates ultrasonic waves in the magnets as well. This may cause noise on the received signals. To suppress the generation of ultrasound in the magnets, the bottom of the magnets was wrapped with aluminum foil, which prevents the penetration of eddy currents into the magnets. Therefore, it was assumed that the influence of the magnets as a conductor could be ignored.

Figure 4 – Shape model for EMSolution
ComWAVE was used to simulate the propagation of the ultrasonic waves caused by the Lorentz forces based on the results obtained with EMSolution. In the instrumental visualization, the measurement was performed in the two cases where the scanned surface is parallel to either Side A or Side B of the EMAT. Therefore, the wave propagation was computed for both cases. This can be realized by exchanging the horizontal axes of the distribution of the Lorentz force. The simulation was performed in the computational domain that represents part of the test block where its length is reduced to 80 mm and the other dimensions remain the same in comparison to the size of the test block. In this domain, the sound velocities of the longitudinal waves and the shear waves were set to 5790 m/s and 3100 m/s, respectively. The Lorentz forces computed with EMSolution were extracted only in the 0.5 mm deep area under the EMAT. The extracted Lorentz forces were applied near the front edge on the top surface of the domain as external forces in the simulations with ComWAVE.

The simulation results are visualized as the distribution of the magnitude of displacement. Figure 5 provides some examples of the results. In the early stage of the wave propagation, large displacement is observed under the location where the EMAT is assumed to be placed as shown in Fig. 5 (a). In the following discussion, cross-sectional views taken out from the three-dimensional distributions are used for comparison and analysis. Figure 5 (b) and (c) show how the two-dimensional distributions are extracted on the front side of the domain and on the central plane of the EMAT, respectively.

![Displacement caused by external forces](image)

(a) Early stage of wave propagation

(b) Observation on side surface

(c) Observation on central plane of EMAT

Figure 5 – Examples of the results obtained with ComWAVE

Figures 6 and 7 provide comparisons of the instrumental and computational visualization results. The instrumental visualization results are shown as the distribution of the received signal voltage obtained with the receiving probe at each point on the scanned surface of the test block. The color in the distributions changes from black to white as the signed voltage value increases. The computational visualization results are shown as the distribution of the magnitude of displacement at each point on the front side of the computational domain, which corresponds to the scanned surface. The color in the distributions changes from blue to red as the magnitude value increases. The origin of the coordinates is located at the intersection between the top surface of the test block and the center axis of the EMAT.
Figure 6 – Comparisons between the instrumental and computational visualization results (Side A)

Figure 7 – Comparisons between the instrumental and computational visualization results (Side B)
Figure 6 shows the results when the scanned surface is parallel to Side A of the EMAT, while Figure 7 shows the results when the scanned surface is parallel to Side B of the EMAT. In these figures, the distributions at the same elapsed time after the emission of the ultrasonic waves for both visualization methods are horizontally aligned in each row. It is recognized that the longitudinal waves precede the shear waves in these images. When the longitudinal waves are reflected by the bottom surface, another group of shear waves occurs due to mode conversion. The propagation of the wave fronts of these longitudinal and shear waves can be observed in the images obtained by both visualization methods, though the images obtained by the instrumental visualization method include superfluous waves. As mentioned in Section 2, in the images for both visualization methods, the longitudinal waves are observed as circular waves from Side A, while these waves are observed as plane waves from Side B.

The comparisons of these results show that the shapes of the wave fronts of the principal longitudinal and shear waves observed in the instrumental visualization results were well reproduced in the computational visualization results.

4. DIFFERENT EMAT CONFIGURATIONS

As an example of the application of the simulation procedure described in Section 3 for optimizing the configuration of an EMAT, this section shows the results of numerical simulations performed to seek an EMAT configuration that makes shear or longitudinal waves dominant. In Figs. 6 and 7, both longitudinal and shear waves can be clearly recognized. When only either one of the longitudinal and shear wave modes is utilized for inspection application, the other wave mode becomes noise and may deteriorate the SNR. Thus, eliminating unwanted waves is important to improve the SNR. In this section, the magnetic field and the distribution of the Lorentz force obtained in the numerical simulations are investigated to confirm how the configuration of an EMAT affects the generated ultrasonic waves.

Figure 8 shows the magnetic field and the distribution of the Lorentz force obtained in the simulation with the EMAT configuration depicted in Fig. 2. The area displayed in these images is part of the central plane of the metal region that is parallel to Side A of the EMAT, while the EMAT is placed at the center of the top surface of the metal region. The origin of the coordinates is located at the intersection between the top surface of the metal region and the center axis of the EMAT. The vectors indicate the direction of the magnetic field or the Lorentz force at each point, and the colors represent their magnitude at that place. These images capture the moment that 0.6 μs elapse after the input pulse is triggered. The magnetic field remains almost unchanged throughout the time because the static magnetic field prevails. Although the magnitude of the Lorentz forces varies with time, the direction of the Lorentz forces does not change appreciably except a change in the opposite direction. Figure 8 illustrates that the two permanent magnets create an arc-shaped static magnetic field beneath the EMAT, the magnetic field has a dominant component in the horizontal direction around the center, and thus the Lorentz forces have a dominant component in the vertical direction around the center as shown in Fig. 3. This causes longitudinal waves as well as shear waves.

Figure 9 shows the shape model of another EMAT configuration (Shape model 2). Instead of a combination of two permanent magnets, a single permanent magnet is used to create a vertical magnetic field under the EMAT. This is confirmed in Fig. 10 (a), which shows the magnetic field due to the EMAT of a racetrack coil and a single permanent magnet. The magnetization vector of the magnet was set to 1 T in the vertical direction. Thus, the Lorentz forces have a dominant component in the horizontal direction as shown in Fig. 10 (b). Figure 11 shows the propagation of the ultrasonic waves generated by this EMAT at 5.5 μs after the emission of the ultrasonic waves. It is recognized that longitudinal waves are suppressed but still observed to some extent.

Because the directions of the current flows are opposite between both sides of the loop of the coil, the directions of the eddy current flows are also opposite between the left-hand and right-hand sides in Fig. 10. Thus, the directions of the Lorentz forces become opposite between the left-hand and right-hand sides. This is thought to give rise to repeated compressive and tensile stresses at the center, which causes longitudinal waves.
Figure 8 – The simulation results with the EMAT configuration depicted in Fig. 2

Figure 9 – Shape model 2 for EMSolution

Figure 10 – The simulation results with Shape model 2
Figure 12 shows the shape model of an EMAT using a one-way current flow (Shape model 3). To avoid the Lorentz forces being reversed at the center, one-way currents are used for generation of ultrasonic waves. This is realized by using the straight-segment in only half part of a big racetrack coil. Because the cross-sectional area of the current path of this coil is doubled compared with the racetrack coil used in the former configurations, the number of turns in this coil was set to 80. The magnetic field created by this EMAT is almost the same as Fig. 10 (a). Figure 13 shows the distribution of the Lorentz force obtained with this EMAT. As intended, the Lorentz forces have a dominant component in the horizontal direction, and their directions are uniform at both sides. Figure 14 shows that this configuration makes shear waves dominant. However, longitudinal waves are still observed. Since the Lorentz force abruptly decreases away from under the utilized straight-segment of the coil, the region where the strong Lorentz force is exerted ends suddenly under both edges of the utilized straight-segment of the coil. This gives rise to repeated compressive and tensile stresses under these edges, which causes longitudinal waves, similarly to the EMAT shown in Fig. 9. This is supported by the fact that the longitudinal waves originate under these edges.

By a similar notion, the horizontal magnetic field is supposed to make longitudinal waves dominant. Figure 15 shows the shape model of an EMAT using only half part of a big racetrack coil and a partial Halbach array of magnets (Shape model 4). A 20 mm-cubed magnet is inserted between the pair of the magnets used in the first EMAT configuration to form a partial Halbach array. The magnetization vector of the center magnet was set to $-1 \text{T}$ in the vertical direction. This array of magnets creates a relatively strong magnetic field along the bottom of the magnets as shown in Figs. 16 and 17 (a). Thus, the Lorentz forces have a dominant component in the vertical direction as shown in Fig. 17 (b). Figure 18 shows that this configuration makes longitudinal waves dominant.
Figure 14 – Propagation of ultrasonic waves generated with Shape model 3

Figure 15 – Shape model 4 for EMSolution

Figure 16 – Magnet arrangement of Shape model 4

Figure 17 – The simulation results with Shape model 4
5. SUMMARY

Numerical simulations were performed to reproduce propagation of ultrasonic waves generated by several configurations of EMATs. The magnetic fields and the distributions of the Lorentz force obtained by the simulations were analyzed to seek an EMAT configuration that makes shear waves or longitudinal waves dominant and suppresses unnecessary components of the ultrasonic waves to be generated.

The simulation results confirmed that the horizontal Lorentz forces generate shear waves, and the vertical Lorentz forces generate longitudinal waves. Because the Lorentz forces should be perpendicular to the magnetic field, the vertical or horizontal magnetic field makes shear waves or longitudinal waves dominant, respectively. In this manner, the distribution of the Lorentz force determines the wave mode of the ultrasonic waves to be generated, and analyzing the distribution of the Lorentz force provides help to design an EMAT configuration.

Because the received signals are ultimately formed by the receiving process of an EMAT, suppressing the generation of unnecessary ultrasonic waves is only one aspect of the optimization of an EMAT configuration to improve the SNR of the received signals. To establish a complete optimization method, analysis of the receiving process of an EMAT is also required.

REFERENCES