Easy-to-operate thickness measurement method for steel plate using bulk-wave EMAT

Ye Zhiling 1, Han Zandong 1*, Du Dong 1

1 State Key Laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing, China
email: ye-zl16@mails.tsinghua.edu.cn; hanzd@tsinghua.edu.cn; dudong@tsinghua.edu.cn

KEYWORDS: bulk-wave EMAT; Thickness measurement; Signal processing; Wavelet denoising;

ABSTRACT

The electromagnetic acoustic transducer (EMAT) method, due to its couplant-free feature, is crucial to defects detection during the in-line inspection of steel pipelines. However, different EMAT approaches require particular analysis under specific testing situation. To solve this problem, an easy-to-operate bulk-wave EMAT is adopted to measure the thickness of the steel plate in this paper. The EMAT set-up basically contains a single permanent magnet and a spiral coil. Experiments are conducted on manual defects with depth and width differences. The EMAT signal processing and analysis on different testing conditions is described, where a denoising algorithm is applied to the original inspection data. The results of the method proposed show that it has great potential to precisely measure thickness on steel pipelines.

1. Introduction

Nondestructive testing (NDT) methods have been widely used in industry for material inspection and evaluation without altering the tested article. The most frequently used NDT methods include radiation testing, magnetic particle testing, liquid penetration testing, ultrasonic testing, electromagnetic testing (ET) and visual testing. Especially for pipeline inner inspection, NDT methods such as magnetic flux leakage (MFL), ET methods including eddy current (EC) and remote field (RF), and electromagnetic acoustic transducer (EMAT) are currently used and studied.

Different from conventional piezoelectric transducers, EMAT requires no couplant and contact[1], can easily generate various types of ultrasounds and is able to operate in harsh environment[2], which makes it very attractive for continuous testing tasks. Among all available EMATs, bulk-wave EMAT is especially suitable for pipeline inner inspection task, for its plain and compact structure, broad bandwidth, flexible wave generation and relatively high transfer efficiency[3].

Previous studies have revealed the EMAT’s coupling mechanism of energy transfer between the electromagnetic and the sound fields on ferromagnetic material[4–6]. Specifically for bulk-wave EMAT, earlier research has provided analytical and numerical solutions[7]. Based on the theoretical foundation, several optimized bulk-wave EMATs are proposed[2, 8, 9]. However, there’s hardly research about the bulk-wave EMAT simulation on different surface conditions, and signal processing of thickness measurement is usually neglected.

* Corresponding author.
This paper mainly focuses on steel thickness measurement using a plain spiral-coil EMAT. The EMAT configuration and analysis is stated and carried out in Section 2. In Section 3, experiments on steel plate are conducted to verify the simulation results. Section 4 presents the results and discussion on the experiments, where the influence of different surface conditions is discussed. Section 5 concludes the applicability of the bulk-wave EMAT proposed, its high thickness measurement accuracy and possible future improvement.

2. Configuration and Analysis

This section describes the detailed configuration of the bulk-wave EMAT, which contains a spiral-coil and a single permanent magnet. The dominant transduction mechanism is discussed. A two-dimensional finite element model is also established to verify the results and provide a clear view of influence of surface conditions to the magnetic flux and eddy current density distribution.

2.1 EMAT Configuration

2.1.1 Basic Setup

There’re two basic configurations of bulk-wave EMAT, one that consists two magnets while the other only has a single magnet\(^3\). The one with a spiral coil and a single biased magnet is adopted, because of its easy setup and ability to provide larger static fields in material. Figure 1 (left) shows a vertical section view of the EMAT. For spiral coil, printed circuit board is used, as shown in Figure 1 (right).

![Figure 1. Bulk-wave EMAT with a single magnet and a spiral coil (left); Spiral coil on PCB (right)](image)

2.1.2 Parameter Design Principles

On the one hand, the bulk-wave EMAT proposed is aimed at long-distance testing task, especially in the gas industries. Therefore, the high voltage should be avoided, leading a relatively low current density in coil. On the other hand, for the EMAT size design, there’s tradeoff between high transduction efficiency and high testing accuracy. The details will be discussed in the EMAT simulation.

2.1.3 Transduction Mechanism

The permanent magnet produces a static magnetic field in the material, which interacts the eddy currents inducted by the current pulse, forming the Lorentz forces in the normal (z-axis) and radial (x-axis) directions\(^3\). Due to its low current design, the dynamic magnetic field contribution can be neglected. Therefore, the Lorentz forces can be given by Equation 1.

\[
f_x^{(L)} = B_{n} \frac{\partial H^N}{\partial x}
\]
\[ f_z^{(L)} = -B_{0x} \frac{\partial H^M_x}{\partial z} \]  

Here, \( f_x^{(L)} \) and \( f_z^{(L)} \) (N/m^3) denote Lorentz forces per unit volume along the x-axis and z-axis, respectively, \( B_{0x} \) and \( B_{0z} \) (T) the magnetic flux density, \( H_x^M \) (A/m) the magnetic field in the material.

As steel is a ferromagnetic material, there’s magnetostriction force when applied with magnetic field. However, it is found that Lorentz force is actually the larger transduction effect in this situation\(^{[10]}\).

In conclusion, the major transduction mechanism in this bulk-wave EMAT is Lorentz forces, which means it’s important to focus on the static magnetic field and the eddy current distribution in the steel.

2.2 EMAT simulation

2.2.1 Model Details
A two-dimensional finite element model is established to study the magnetic fields and the eddy currents in the steel plate, shown in Figure 2.

![Figure 2. 2D finite element model of the bulk-wave EMAT using COMSOL](image)

For geometric parameters, the steel plate is 180 mm wide and 10 mm thick. The magnet is 20 mm in width, and the lift-off distance is set to 1 mm. A 4-turn spiral is placed between the magnet and plate, whose wire radius is 0.2 mm. All the objects are surrounded by air to better simulate in the real situation. For electromagnetic parameters, the residual magnetic flux density of the permanent magnet \( B_r = 0.6 \, T \), the current intensity \( I_{\text{coil}} = 10 \, A \), the current frequency \( f = 4 \, \text{MHz} \).

In order to simulate the skin effect in the plate, the upper surface is meshed as boundary layer. Free quad mesh is used on the magnet and coil. The air is defined as infinite element domain with free triangular mesh.

2.2.2 Results and Discussion

The z-axis component of static magnetic flux density is shown in Figure 3, which induces \( f_x^{(L)} \).

It can be seen that the z-axis component distribute relatively even (around 0.35 T) on the upper surface right below the magnet, which covers the eddy currents area. This Lorentz force component produces shear wave that proves to be the major mechanism.
Figure 3. Z-axis component of static magnetic flux density in steel plate

Figure 4 shows the x-axis component, which concentrates around the magnet boundary (x = -0.01 m and 0.01 m). As a result, the longitudinal wave produced is not prominent compared with the shear wave.

Figure 5 shows that the eddy currents are induced right below the coil, and the penetration depth is rather thin (around 0.2 mm) because of the skin effect. And the force load in the steel exists nearly the same location of the eddy currents.
In conclusion, the bulk-wave EMAT proposed mainly produces shear wave in steel plate and the major transduction area is near the plate surface. As the propagation velocity $v$ of sound in steel is known, the plate thickness $d$ can be measured by Equation 2.

$$d = v \cdot \frac{t}{2}$$  \hspace{1cm} (2)

Here, $t$ denotes the time difference between two echoes.

It can be inferred from the results that this kind of EMAT is good at detecting continuous thickness change. As the essential part of the transduction is the induction of the eddy currents, the EMAT might not be sensitive to small cracks on surface. However, when larger metal loss comparable to the EMAT size occurs, it causes change in echo amplitude or produces different echoes, which make it possible and also difficult to recognize.

3. Experiments

Steel plate with artificial defects testing experiments are conducted to demonstrate the performance of the bulk-wave EMAT, and figure out the influence of the defects to the measurement when they’re on the same or different side of the EMAT.

3.1 Experiments Setup

3.1.1 EMAT and the Test Plate Design

A PCB coil (Figure 1) and a bar magnet are used to form the bulk-wave EMAT. The spiral coil has 10 turns and its outer diameter is 20 mm. The bottom size of the magnet is 27*27 mm.

Otherwise, a steel plate with artificial defects is designed to study their influence to the thickness measurement. One side of the plate is flat with no surface defects, the other side is shown in Figure 6, which contains long metal loss (30 mm in length) with various depth and width. Experiments are conducted on both sides.
3.1.2 Pulsed Current
The pulsed current is set to 4 MHz with 3 cycles, as shown in Figure 7.

![Pulsed Current Input](image)

Figure 7. Pulsed current input

3.1.3 Testing Surface
Thickness measure tests are conducted on the side with defects and the side without.

3.2 Signal Processing
The signal acquired contains high-frequency noises that make it inconvenient to locate the time of arrival of the echoes. Figure 8 shows the original signal in time and frequency domain.
One simple way to remove such noises is to use a Fourier filter. Figure 9 shows the results of passing a band-pass Butterworth filter.

But the Fourier-based methods have the same problem, they’re trying to separate the signal from the frequency domain. As a result, the noises still exist between the actual echo signals in Figure 9. This is where wavelet denoising comes handy. The basic idea of wavelet denoising is to shrink the small
coefficients, which are usually noise, in the wavelet domain. Therefore, the important signal can be preserved after the denoising. Figure 10 shows the results of using a Daubechies 5 wavelet (db5) and soft threshold. The noises between echoes are nearly removed.

4. Results and Discussion

4.1 Experiment Results

4.1.1 Test from the same side
When the EMAT is right on the top of the defects, it’s observed that the amplitude of the signal decreases as the defect gets wider. Figure 11 shows the received signal from the 2 mm and 6 mm wide defects.

It can be easily explained by the simulation that the defects cancels a part of the eddy currents, leading to the decrease of the Lorentz forces and the shear wave intensity.

4.1.2 Test from the different side
When the EMAT is placed on the side without surface defects, apart from the amplitude decrease, a new echo is produced by the reflection of the defects, as shown in Figure 12.
4.2 Thickness Measurement and Discussion

The thickness calculation step is quite straightforward when processing a denoised signal. As shown in Figure 12, the time of the two peaks are used to calculate the travel time respectively. The shear wave velocity in steel is approximately 3250 m/s. In such cases, the measured thickness is 8.75 mm, which is very close to the actual one, around 8.8 mm.

The results are not that surprising because the main advantage of this kind of EMAT is its accuracy. But the challenge is to distinguish the target signal when two echoes overlap in time domain. For example, in Figure 10, the signals with low amplitude are from 4.8 mm-deep surface, and the two kinds of echoes overlap slightly at the beginning. However, this issue doesn’t exist when the thickness changes gradually.

5. Conclusions

This paper presents a bulk-wave EMAT to perform thickness measurement for steel plate. The EMAT configuration consists of a single magnet and a PCB coil. This paper mainly address the application circumstances and the measurement accuracy of the EMAT.

Based on the analysis of the magnetic fields and the eddy currents density, Lorenz force induced by the static magnetic field is the main transduction mechanism of this configuration, which is confirmed by the numerical simulation. The simulations results also suggest that the EMAT mainly generates shear waves, whose intensity depends on the eddy currents density.

The simulation results show that the shear wave generation relies on the eddy currents distribution. When part of the eddy currents is cancelled by the surface defects, the amplitude of the signal may decrease significantly. The experiments on a steel plate with artificial defects are conducted to verify this idea. It is found that the signal is attenuated as the defects broaden. The quantitative relationship could be a meaningful topic for future study.

Furthermore, the paper presents a wavelet denoising method for the signal acquired, which removes the high-frequency noises while keeping the target signal. Finally, the thickness is measured by using the denoised signal. The EMAT shows a great advantage in accurate measurement on plate with gradual change in thickness.

Acknowledgement
I’d like to express my gratitude to my adviser, Prof. Han Zandong, for his informative guidance on this project, as well as my colleagues in lab, for their kindness help.

References and Footnotes