Journal of Sensor Technology, 2017, 7, 25-38
http://www.scirp.org/journal/jst
ISSN Online: 2161-1238
ISSN Print: 2161-122X

Study of an Omnidirectional Guide Wave Sensor Using an EMAT

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How to cite this paper: Murayama, R. and Iwaya, K. (2017) Study of an Omnidirectional Guide Wave Sensor Using an EMAT. *Journal of Sensor Technology*, **7**, 25-38.
https://doi.org/10.4236/jst.2017.72002

Received: May 20, 2017
Accepted: June 27, 2017
Published: June 30, 2017

Abstract

Nondestructive inspection of structures is important for ensuring the safety of the social infrastructure. Among them, the ultrasonic inspection method plays a role as a major technology. However, when examining a huge structure, the inspection time tends to be very long. Therefore, a system for transmitting and receiving ultrasonic waves in all directions from the ultrasonic sensor has been constructed. Several types of ultrasonic sensors using this concept have already been devised, but since the ultrasonic energy is dispersed in all directions, there is a problem that a sufficient detection performance cannot be ensured, especially when the thickness of the material to be inspected becomes thick. Therefore, we developed a highly sensitive omnidirectional ultrasonic sensor utilizing the resonance phenomenon of the ultrasonic wave propagating in the thickness direction. The omnidirectional ultrasonic system also consists of an electromagnetic ultrasonic transducer (EMAT) using a circular magnet. It is possible to inspect the plate thickness from 0.3 mm to 10 mm and the inspection range of the diameter of 300 mm around the sensor by the developed system. It is indicated that the developed system allows the high-speed inspection of huge structures.

Keywords

EMAT, Surface Wave, Omnidirectional Detection, Inspection

1. Introduction

Periodic inspections are being conducted every 1 to 2 years to ensure the safety of giant structures such as gas tanks and power plants. Depending on the type of the structure, the periodic inspection ranges from 1 to 6 months. This means that it is very important to make the periodic inspection short. For example, in case of an ultrasonic method, an inspector uses an ultrasonic probe with an effective range of about 10 mm^2 to inspect on earea at a time. Therefore, it takes more than one month to inspect a gas tank. In addition, the ultrasonic sensor using the piezoelectric vibrator requires a medium, such as oil and water, to transmit and receive the ultrasonic wave in the material being inspected [1] [2]. In addition, it is very difficult to uniformly paste them on the surface of the material. If the uniformity cannot be maintained, the reliability of the inspection cannot be assured.

One of the answers to solve this problem is a guide wave because its distance attenuation is rather low. This means that a guide wave can inspect alarge area [3]. For example, inspecting a pipe [4], rail [5], and cold rolled steel [6] using a guide wave has been tried. Furthermore, the inspection of an aircraft has also been reported [7]. However, the success is not sufficient for a large structure and there is still the problem of the couplant. There is a guide wave inspection system using an air-coupled ultrasonic transducer as a more convenient method because an air-coupled ultrasonic transducer does not need to use a couplant thus why the system can easily move the transducer over the structure [8] [9]. However, the performance can be easily affected by the local environment surrounding the probe. As another approach, an array system using a PZT-transducer has been studied by many researchers [10] [11] [12]. However, there is still the problem that the system needs to use a couplant. As an omnidirectional ultrasonic inspection system that does not require a couplant, an omnidirectional EMAT for transmission using circular array magnets has been reported [13]. Thus a system that combines the omnidirectional transmitter-EMAT for S0, A0, SH0 plate waves, and the receiver-EMATs concentrically placed around the transmitter-EMAT has been developed [14] [15] [16]. An EMAT array system has been also studied [17]. An omnidirectional array system using a magnetostrictive material patch instead of an EMAT has been reported [18] [19]. An inspection system has been proposed using an EMAT consisting of the same shaped circular magnet and an electromagnetic induction coil for the transmitter and receiver-EMAT, and using the transmitter-EMAT and receiver-EMAT at distance of a few hundred mm [13]. An omnidirectional EMAT for an SH-plate wave has also been developed [20] [21].

These reports basically revealed an omnidirectional EMAT for transmission using a circular magnet, but the receiver-EMAT is a system that scans the effective range of the ultrasonic wave transmitted from the transmitter-EMAT around the transmitter-EMAT.

It was not a truly omnidirectional inspection system that used a plate wave or a surface wave. Furthermore, when transmitting or receiving plate waves or surface waves by the EMAT, the sensitivity rapidly decreases when the plate thickness increases. However, the solution to this problem could not be clearly presented.

Therefore, an omnidirectional EMAT combined with a transmitting and receiving part has been proposed and the concurrent use of a resonance method

[22] as a measure to minimize the thickness concern of the material are proposed in this paper.

2. Driving Principle of Integrated Transmitter and Receiver Omnidirectional Electromagnetic Acoustic Transducer (Electromagnetic Acoustic Transducer = EMAT) [23] [24] [25]

The basic principle is the same as the surface wave EMAT using the magnetostrictive effect as shown in Figure 1. A biased magnetic field is created in the propagation direction of a surface wave or a plate wave, and a high-frequency induction magnetic field in the same direction is generated by an electromagnetic induction coil. The magnetostrictive vibration generated by this complex induction magnetic field induces a surface wave or a plate wave oscillating in the traveling direction [26] [27]. In order to apply this principle to the omnidirectional EMAT, a ring-shaped permanent magnet is used. The circular electromagnetic induction coil is installed inside the magnet. The concentric high-frequency electromagnetic wave then generates a concentric vibration by them agnetostrictive effect and transforms into an omnidirectional surface wave or a plate wave as shown in Figure 2.

3. Optimization of the Omnidirectional Transmitter-EMAT

In order to optimize the omnidirectional transmitter-EMAT, it has been investigated as how to combine the magnet and the electromagnetic induction coil, in which the inner magnetic flux density becomes an appropriate value using manybar magnets and ring magnetsas shown in Table 1. The optimum electromagnetic induction coil to be used has also been studied by changing the diameter of the wire and the number of turns.

3.1. Experimental Conditions

As the first experiment, a steel plate with a thickness of 0.6 mm, a length of 1000 mm, and a width of 1000 was used. The omnidirectional transmitter-EMAT was

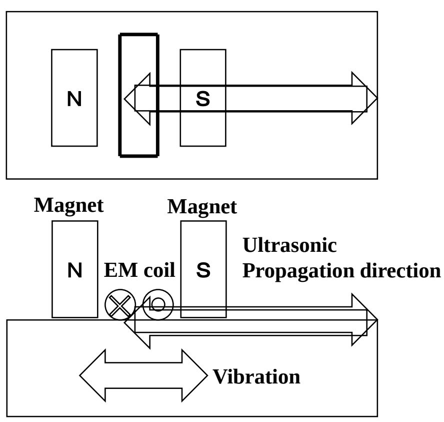

Figure 1. Drive principle of a conventional EMAT for a surface wave.

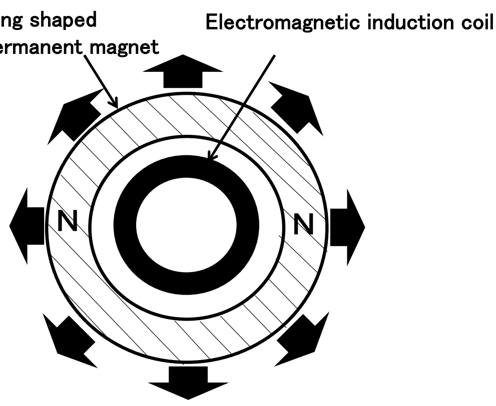

Figure 2. Drive principle of an omnidirectional E-MAT for a surface wave.

Table 1. Specifications of the scale of the magnetsused to obtain the optimum magnetic flux density.

	Ring shaped magent		Cylindrical shaped magent
	Outer Diameter	Inner diameter	Diameter
Size (mm)	55 - 65	10 - 46	20 - 40
Magnetic Flux Density on the surface (T)	0.096 - 0.4423		0.155 - 0.345

placed at the center of the steel plate. The receiver-EMAT for the surface wave was placed at the distance of 300 mm as shown in **Figure 3**. In order to determine the influence of the plate thickness, steel plates with a size of 1000 mm × 1000 mm and a thickness of 0.6 mm to 10 mm were also prepared.

Figure 4 shows a diagram of the experimental equipment system. The pulser injects a burst pulse-type high-frequency electrical current of ±50 V_{pp} to the omnidirectional transmitter EMAT. On the receiving side, the electrical signal injected from the receiver-EMAT was first amplified by the preamplifier with a frequency band of 1 kHz to 1 MHz and the amplification degree of 40 dB. It is then amplified by the degree of 30 dB with the frequency band of 100 kHz to ∞ by the main amplifier. The driving frequency was initially fixed at 800 kHz. The specification of the magnet size used to obtain the optimum magnetic flux density is also shown.

3.2. Experimental Results about How to Combine Both Permanent Magnets

As shown in **Figure 5(a)**, a single ring magnet was first used and a circular electromagnetic induction coil was installed at the inner peripheral edge of the ring magnet. However, as shown in **Figure 6(a)**, a sufficient magnetic flux density could not be obtained, and the received signals having an insufficient S/N ratio were obtained. Therefore, as shown in **Figure 5(b)**, the magnetic flux density

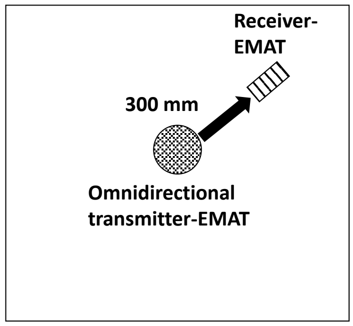

Figure 3. Experimental setup for testing the omnidirectional EMAT using a conventional EMAT as a receiver for a surface wave.

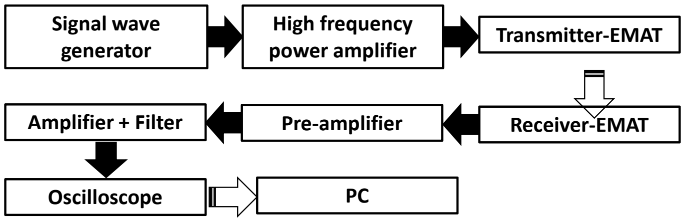

Figure 4. Diagram of the experimental equipment system.

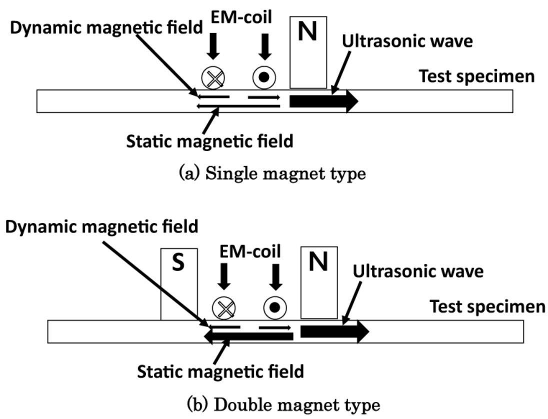

Figure 5. Structure of the omnidirectional transmitter-EMAT.

between the ring magnet and cylindrical magnet was used. The results are shown in Figure 6(b). It was confirmed that it is possible to obtain a magnetic flux density of over 200 mT at the edge position between both magnets. Therefore, the received signal was significantly improved as shown in Figure 6(b) by installing the circular electromagnetic induction coil. Finally, the combination of both magnets was reconsidered so that the most suitable magnetic flux density could be obtained at a position where the electromagnetic induction coil is actually installed between both magnets. As a result, it was possible to obtain a received signal with a sufficient S/N as shown in Figure 6(c).

As a result, the best received signal has been obtained by the combination of a ring-type neodymium magnet with a 40 mm outer diameter × 30 mm inner

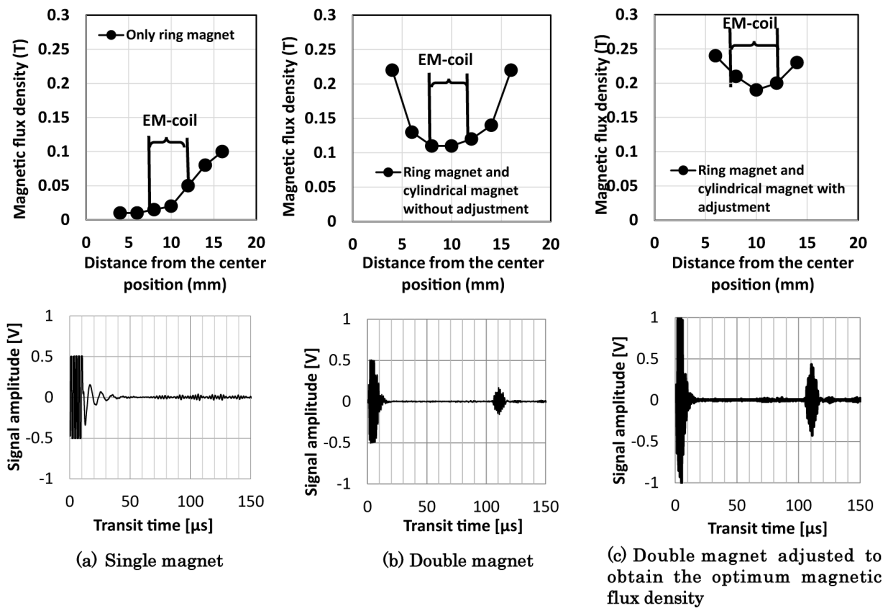

Figure 6. Measurement results of the magnetic flux density and the received signal.

diameter × 10 mm height and a cylindrical magnet of 8 mm diameter × 10 mm height. The magnetic flux density at the position of the electromagnetic induction coil was 0.122 T to 0.193 T. The received signal amplitude was 0.856 V and the S/N ratio was 30.57.

Next, in order to check whether the omnidirectional transmitter-EMAT is transmitting a surface wave in all directions on the sample plate, the received-EMAT was circularly scanned around the omnidirectional transmitter-EMAT as shown in Figure 7 and the received signal was confirmed. It has been confirmed that the surface wave could be transmitted in all directions although there was a variation of about 10% as shown in Figure 8.

4. Omni-Directional Receiver-EMAT

The omnidirectional receiver-EMAT has been developed in order to detect the reflectedultrasonic wave from all directions and the status of the area around the omnidirectional transmitter-EMAT was evaluated.

Experimental Results

First, as shown in Figure 9(a), we set up the omnidirectional transmitter-EMAT, and the omnidirectional receiver-EMAT was installed outside the omnidirectional transmitter-EMAT. The omnidirectional receiver-EMAT consists of a circular permanent magnet with a diameter larger than that of the omnidirectional transmitter-EMAT. The electromagnetic induction coil was placed under the permanent magnet for the omnidirectional receiver-EMAT. However, as shown in Figure 9(b), it was found that the reflection signal from the same position was received twice. That is, although the ultrasonic signal should appear at the transit time of about 60 μs because the traveling distance is about 100 mm

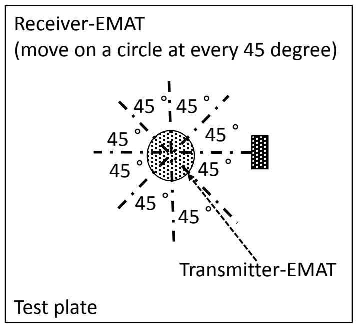

Figure 7. Method to obtain the orientation distribution of the injected surface wave intensity.

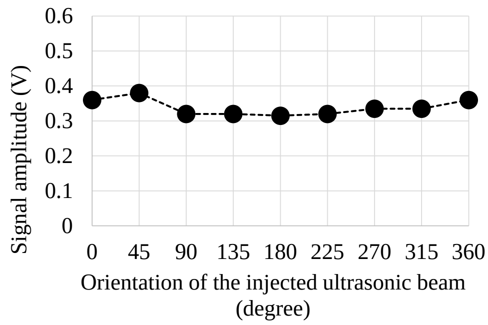

Figure 8. Experimental result of the received signal amplitude distribution in the propagation direction.

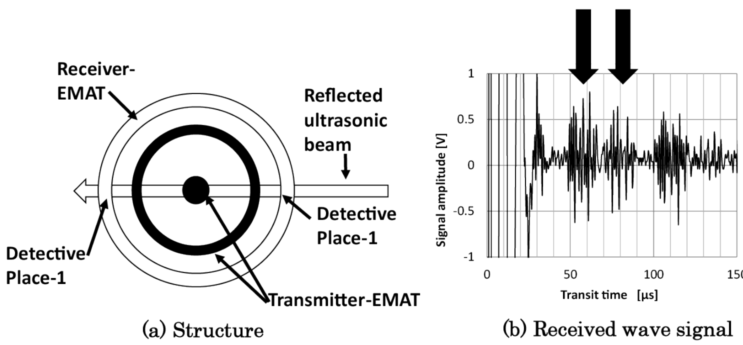

Figure 9. Omnidirectional receiver-EMAT using a larger magnet than that of the omni-directional transmitter-EMAT.

and the group velocity is about 3200 m/s, the signal appeared to be divided into two independent signals. It was confirmed that the time for the shift of the two split signals coincided with the time for propagating between the diameters of the magnetic induction coil for the receiver. That is, as shown in **Figure 9(a)**, when the diameter of the magnetic induction coil for the receiver is large, it is possible to detect the reflected ultrasonic wave at two different positions. Therefore, as shown in **Figure 10(a)**, it is considered that the signal does not split into two parts if the diameter of the electromagnetic induction coil for the receiver is as small as possible with respect to the omnidirectional transmitter-EMAT. The circular electromagnetic induction coil for the receiver has been installed under

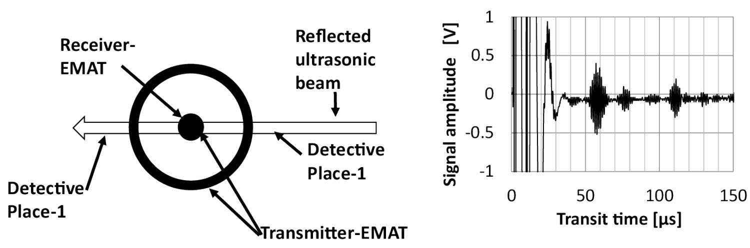

Figure 10. Omnidirectional receiver-EMAT using a cylindrical magnet installed at the center of the omnidirectional transmitter-EMAT.

the cylindrical magnet for the transmitter-EMAT to solve this problem. As a result, as shown in Figure 10(b), it was possible to clearly detect the reflected signal from the end the test piece with a sufficient S/N ratio.

Figure 11 shows the detection performance by making a through hole of from 1 mm to 10 mm diameter at positions of 100, 200, 300, and 400 mm from the center of the omnidirectional transmitter and receiver-EMAT. Although the signal intensity sharply decreases as the traveling distance increases, it was confirmed that a through hole with a diameter of 3 mm can be detected up to a distance of 300 mm.

5. Resonance Experiment Result

Figure 12 shows the relationship between the plate thickness and the received signal amplitude when the driving frequency is 800 kHz. When the plate thickness exceeds 2 mm, the signal amplitude rapidly decreases. In addition, the signal cannot be detected for a thickness over 6 mm. Therefore, the resonance method was used as shown in Figure 13. A transverse wave is also generated in the thickness direction by the transverse-EMAT. If the driving frequency is selected at the frequency value corresponding to the reciprocal of the time that the transverse wave propagates in the plate thickness direction, the transverse wave intensity will drastically increase and lead to making the strong guide wave being transformed from the transverse wave as a result.

An example of the experimental results when changing the drive frequency using a 6 mm thick-plate is shown in Figure 14. It is clear that the signal intensity is increasing at a specific drive frequency. **However, there were a contradictions between the experimental results and calculation results**. The relationship between the drive frequency and the received signal amplitude for each test thickness is shown in Figure 15(a). Figure 15(b) also shows the relationship between the thickness and the optimum frequency. As the thickness decreases, the optimum frequency tends to increase. However, the optimum frequency seems to be too low compared to the calculated value of the resonance frequency. Furthermore, the difference between the experimental and calculated values becomes greater as the thickness of the plate becomes thinner. To understand this phenomenon, a simulation computation was done the ultrasonic propagating

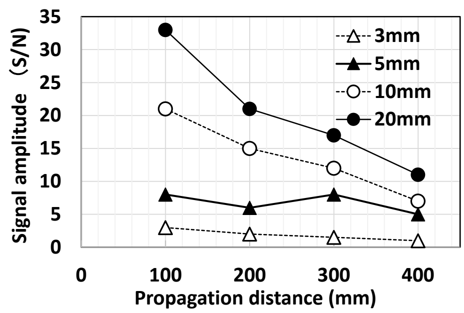

Figure 11. Relationship between the received signal amplitude and propagation distance.

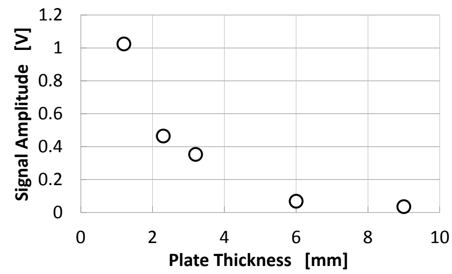

Figure 12. Relationship between the received signal amplitude and plate thickness.

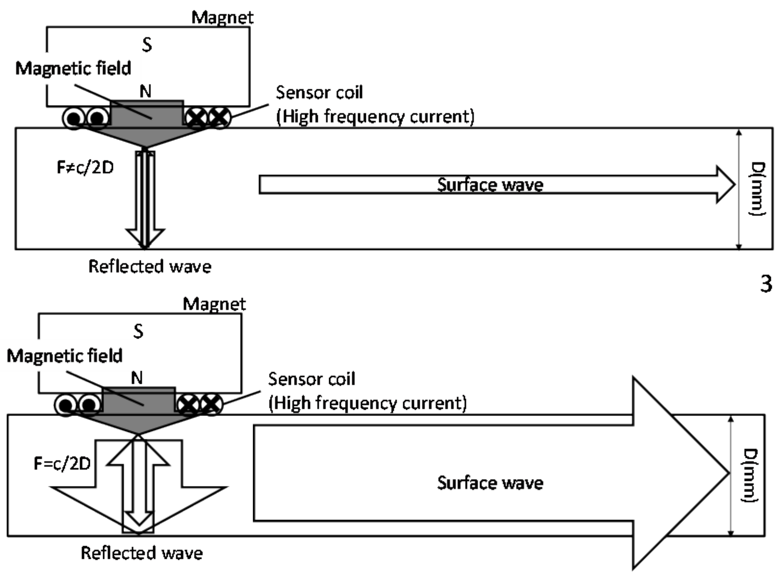

Figure 13. Concept of the resonance method for the surface wave.

simulator-SWAN21 [28]. The results are shown in Figure 16. The optimum frequency for the 6 mm and 9 mm plates seems to be observed at around a 200 kHz-drive frequency. However, it is unclear for the 2.3 mm thick plate. Figure 17 shows the drive frequency when the A_0 mode group velocity is almost converging at the same velocity. The frequency is almost the same as the optimum drive frequency determined by the experiment and the calculated resonance

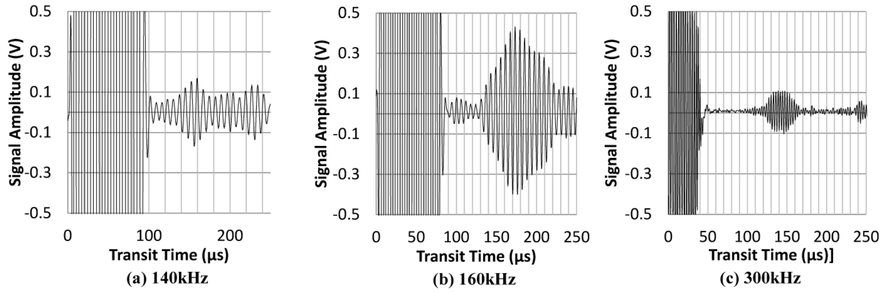

Figure 14. Received signal reflected by the sheet edge (Distance = 200 mm plate thickness = 9 mm).

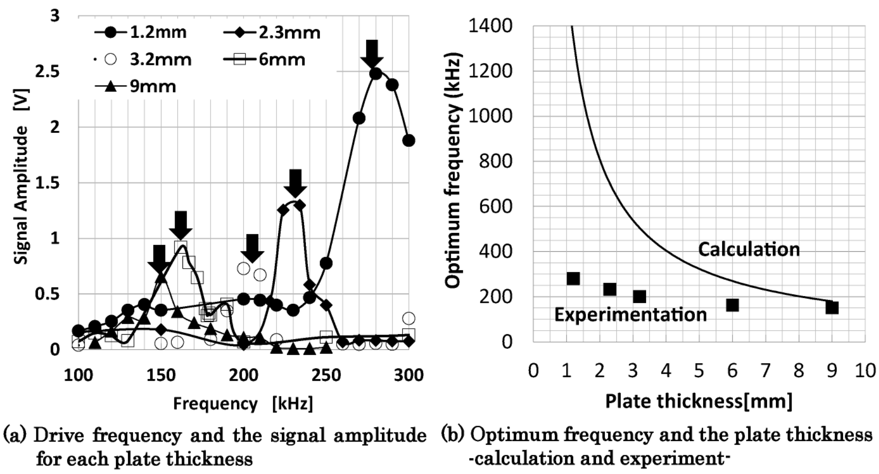

Figure 15. Experimental result of the resonance method.

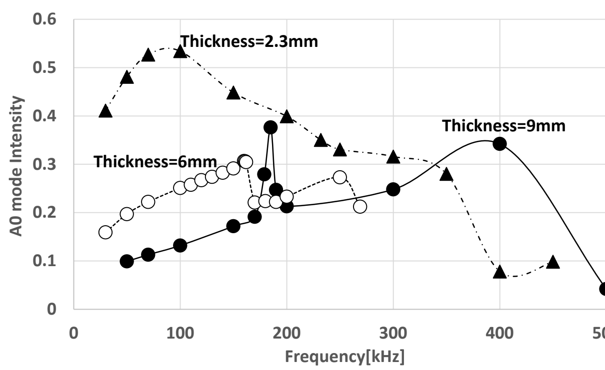

Figure 16. Generated guide wave intensity using SWAN21.

frequency. For under 6 mm thick plates, at first, the drive frequency when the A_0 mode group velocity is almost converging at the same velocity and the calculated resonance frequency is rather different. Next, the EMAT uses an electromagnetic wave to generate and detect an ultrasonic wave. An electromagnetic wave generally decreases in proportion to the square of the frequency. This means that the effect of the resonance phenomenon has been cancelled out. This is why the optimum drive frequency has not increased as the thickness decreases. In any case, as shown in **Figure 18**, the received signal with a sufficient strength up to

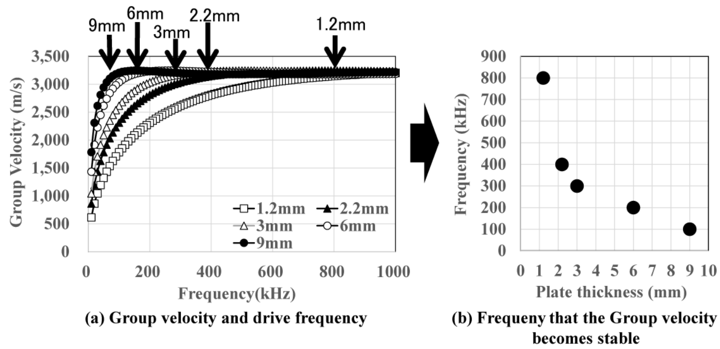

Figure 17. Drive frequency when the group velocity (A_0) becomes stable.

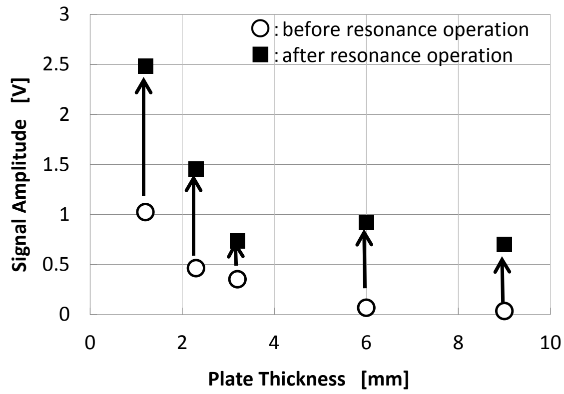

Figure 18. Signal amplitude before and after the resonance method.

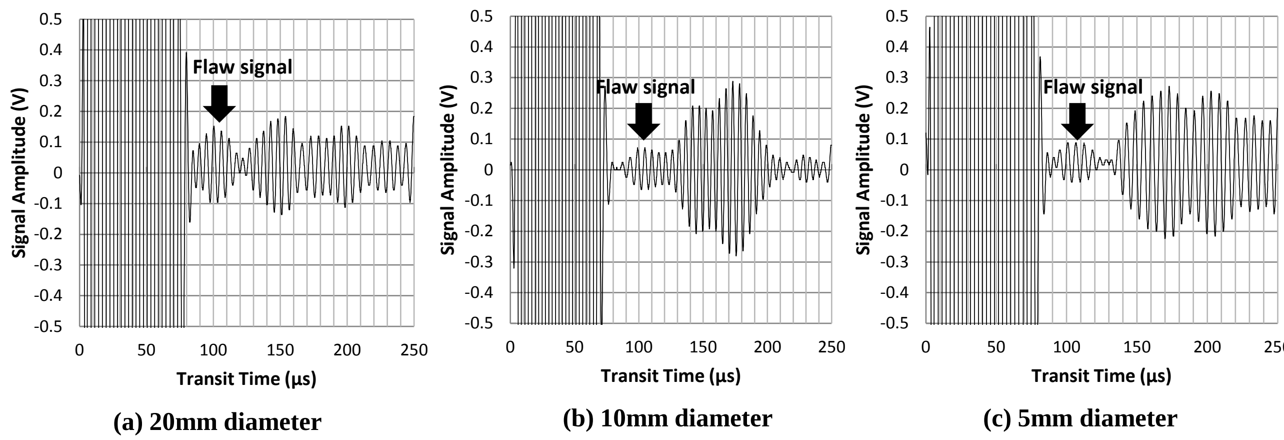

Figure 19. Reflected signal from any drilled hole.

a thickness of 9 mm was obtained. Figure 19 shows the reflected signal from one of drilled holes. Although it is not a sufficient signal, it was confirmed that the system can detect any defects even if the thickness is 9 mm.

6. Conclusions

An omnidirectional ultrasonic inspection system capable of transmitting and receiving ultrasonic waves in all directions to reduce the inspection time of large area structures has been developed.

By combining rod-type and cylindrical-type magnets, it was possible to fabricate a prototype transmitter and receiver-EMAT which can inspect in all directions. Especially, the cylindrical inner magnet was also used for the receiver-EMAT. The developed EMAT is very simple and small. However, the detection ability dramatically decreased as the thickness of the test specimen increased. The resonance method was then applied to the developed omnidirectional EMAT. Although the optimum drive frequency determined by the experiment was different from the calculated results, the detection ability was dramatically improved even if the plate thickness became thicker.

Of course, it was insufficient for practical use in its detection capability, the scope of inspection, etc. Advanced studies aimed at improving the performance of the receiving ultrasonic probe are continuing.

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