PPM-EMAT Design Configurations for Ultrasonic Communication through Metallic Channel

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***Abstract*— Electromagnetic acoustic transducers (EMATs) are a preferable non-contact alternative to PZT transducers. EMATs use the electromagnetic method to transform electrical energy into ultrasonic energy. Ultrasonic waves are generated in the material regardless of the contact condition with the channel surface, which overcomes signal uncertainty faced by the coupling conditions of PZT transducers. We have investigated the feasibility of using periodic-permanent-magnet electromagnetic acoustic transducers (PPM-EMATs) as transmitters and receivers for ultrasonic communication. By configuring the winding structure of coils, the periodicity of the permanent magnet array, and directions of polarizations, the PPM-EMATs are designed to generate shear horizontal (SH) waves through the plate channels and torsional waves through the pipe channels. Furthermore, the ultrasonic wave reflections are proved to be the main reverberations causing the multipath effect. Experimental tests of signal transmission with PPM-EMAT on a 160cm-long stainless-steel plate determine the optimal frequency for communication to be 700KHz. Information transmission experimental results confirm the validity of PPM-EMAT for communication with a bitrate of 10 kbps.**

Keywords—Ultrasonic Communication, Metallic Channel, PPM-EMAT

I. Introduction

In an ultrasonic communication system, the conventional ultrasonic wave generation method utilizes the piezoelectric lead zirconate titanate (PZT) transducer as the transmitter and receiver [1][2][3]. Though it can provide good performance in a laboratory environment. The trustworthiness of transferring information is highly dependent on the coupling condition between the PZT transducer and the surface of the communication channel over long-term reliability. Electromagnetic acoustic transducers (EMATs) are a preferable non-contact alternative to PZT transducers. EMATs use the electromagnetic method to transform electrical energy into ultrasonic energy [4][5][6]. Ultrasonic waves are generated in the material regardless of the contact condition with the channel surface, which overcomes signal uncertainty faced by the coupling conditions of PZT transducers. Thus, EMAT transmitters and receivers can be flexible nodes on the communication channel and can particularly be applied in hot, cold, sealed, or contaminated environments [7][8][9][10]. In addition, since EMATs are mainly made up of magnets and coils, many geometrical fittings can be designed to fit EMATs with different shapes of the communication channel by configuring the winding structure of coils, periodicity of magnet arrays, and directions of polarizations. In contrast, EMAT has become a promising choice for transmitters and receivers in ultrasonic communication. However, using EMAT in ultrasonic communication has many technical challenges [11]:

1. EMAT has poor transduction efficiency due to the deficiency of design theories, and it needs substantial excitation power to transform electromagnetic energy into ultrasonic energy.

2. The generated ultrasonic signal suffers from significant attenuation and distortion caused by wave distortion and limited bandwidth across the metal channels. This undesirable effect is more pronounced, particularly in irregular-shaped channels like an elbow pipe.

3. The ultrasonic wave multipath propagation due to the boundary reflections causes intersymbol interference (ISI), which highly degrades the SNR.

In this paper, a PPM-EMAT is designed to be the transmitter and receiver to create SH wave and torsional wave in the plate channel and pipe channel in the 200 kHz to 1 MHz frequency range. An experimental reverberation analysis is presented to discuss the solutions for using PPM-EMAT as the transmitter and receiver.

This paper is organized as follows. Section II presents the configuration of PPM-EMAT for plate and pipe channels. Section III presents the ultrasonic wave propagation in the metallic channel. Section IV presents experimental results using PPM-EMAT as transmitter and receiver. Section V summarizes the key design issues for PPM-EMAT ultrasonic communications.

II. PPM-EMAT Configuration

EMATs have been developed for bulk wave and guided wave generation by the Lorentz forces. EMAT consists of a permanent magnet and a flat coil. When the alternating current is applied to the coil, the eddy current is induced in the material within the skin depth surface. The eddy current interacts with the static magnetic field from the magnets, producing Lorentz force. The ultrasonic waves are generated in the material by periodic vibration caused by the Lorentz force [12].

In this study, a PPM-EMAT transmitter and receiver are designed for ultrasonic communication through a metallic plate or pipe channel [13][14][15]. Fig. 1a demonstrates the PPM-EMAT two-dimensional model on a plate channel in x and z directions. Two magnets array and one racetrack coil are considered as one element. We can see that those three elements of EMAT are perpendicular to the material surface. The current direction interacts only with the axial static magnetic field in the z-direction. Thus, a Lorentz force in the x-direction is generated. Fig. 1b illustrates the PPM-EMAT in the y-z directions. The backward direction of Lorentz force is generated in the adverse polarization of PPM elements. The forward and backward directions are arranged next to each other. As a result, the shear horizontal (SH) waves are launched parallel to the material surface on both sides.

Though a large air gap exists between the extremities of flat EMAT and pipe surface, the contoured PPM-EMAT [6] is introduced in Fig. 1c. The curvature of the 3D printed holder is presented to match that of the pipe, thus placing the magnets in the arrangement for optimal energy coupling. Both the magnets and coils of the contoured PPM-EMAT can conform to the curvature of the pipe. The directions of the three elements are perpendicular to the pipe surface. When the alternating current induces an adverse axial eddy current below the pipe surface, a circumferential Lorentz force in a clockwise direction is generated in the radial static magnetic field, which is shown in Fig. 1d.

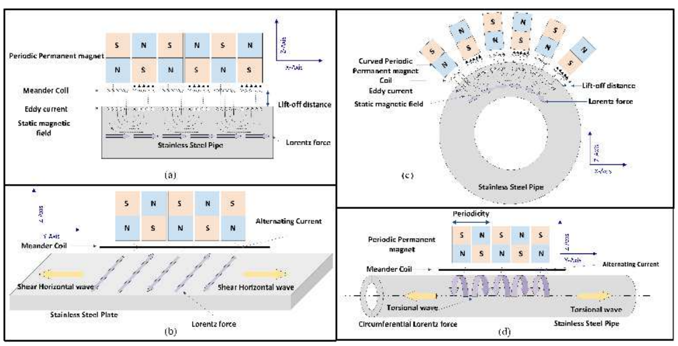

Fig 1. Lorentz force generation on the plate and pipe channel of PPM-EMAT. (a) Lorentz force generation on the plate channel, (b) SH wave generation of PPM-EMAT on the plate channel, (c) Lorentz force generation on the pipe channel, and (d) Torsional wave generation on the pipe channel.

III. Ultrasonic Wave Propagating in the Metallic Channel

The beam steering characteristics of PPM-EMAT [16] are illustrated in Fig. 2. The oblique angle α is determined by Eq. (1).

$$\sin(\alpha) = \frac{\lambda_s}{d} \tag{1}$$

Here, λ_s is the wavelength of the shear-horizontal (SH) wave, and d is the period of the magnets. Based on the SH wave dispersion behavior and periodicity of the magnet array, we can expect that the incident angle of ultrasonic waves generated by PPM-EMAT can be tuned by the excitation frequency and periodicity of the magnet array. The incident angle can vary from 0° to 90° when frequencies are selected between 230 kHz and 720 kHz.

For h = 9.5 mm and c_{T1} = 3180 m/s, the frequencies of 227 kHz, 279 kHz, 396 kHz, 537 kHz, and 688 kHz correspond to SH0, SH1, SH2, SH3, and SH4. This indicates that we can selectively generate SH waves by different excitation frequencies using PPM-EMAT.

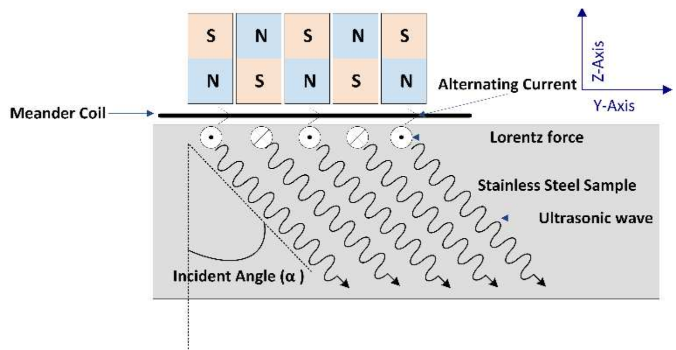

Fig. 2. The incident angle of the SH wave generated by PPM-EMAT.

SH waves propagating in the metallic channel tests are implemented by fixing the position of the transmitter and receiver. The transmitter is 40 cm from the left edge, and the receiver is 20 cm from the right edge. In this study, 230 kHz, 279 kHz, 395 kHz, 555 kHz, and 700 kHz are used as the excitation carrier frequency. The excited pulse with a 200 µs duration is transmitted. The received pulse response is shown in Fig. 3.

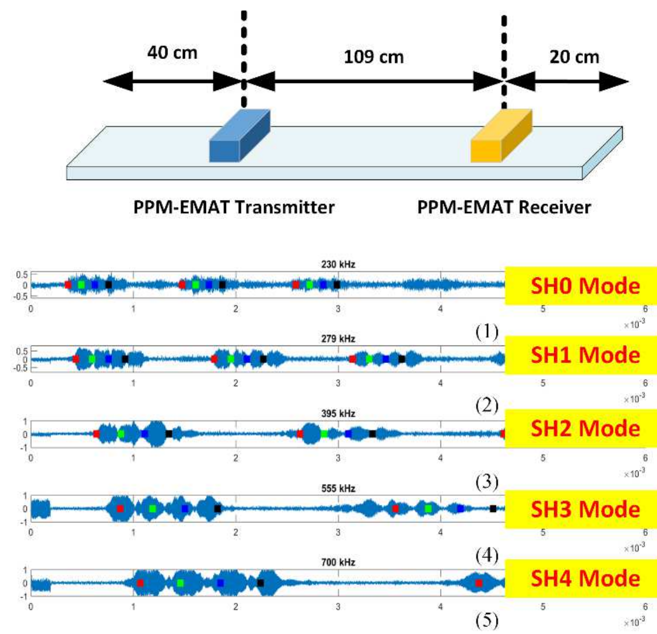

Fig. 3. A 200 µs pulse response of different carrier frequencies under fixed positions of transmitter and receiver, and excitation frequency varies with (1) 230 kHz, (2) 279 kHz, (3) 395 kHz, (4) 555 kHz, and (5) 700 kHz.

Based on the results in Fig 2, we can retrieve the actual velocity of different modes of SH waves by the arrival time of each pulse. By comparing the SH waves dispersion curve, which matches reasonably well with the experimental measurements. Also, we can find the travel distance of each pulse. Therefore, the received pulses with significant magnitude are all reflections from the edges of the plate. These results confirm our assumption. The reflections are the main reverberations causing the ISI effect and degrading communication performance.

IV. Experimental Test Results

The random binary message is transmitted and received in the PPM-EMAT communication platform for the steel plate channel. PSK modulation methods are used. The distance between the transmitter and receiver is 160 cm. Results from testing on the plate channel are displayed in Fig. 4. The upper plot is the received signal, and the bottom field is the demodulated signal compared with the transmitted signal. The carrier frequency is 700 kHz, and the bitrate is 10 kbps.

The received signal displays the whole binary message. The binary message can be fully recovered without any error when a proper threshold value is set to the received signal. We, therefore, conclude that the plat and contoured PPM-EMAT can be used as a transmitter and receiver for ultrasonic communication through a plate channel.

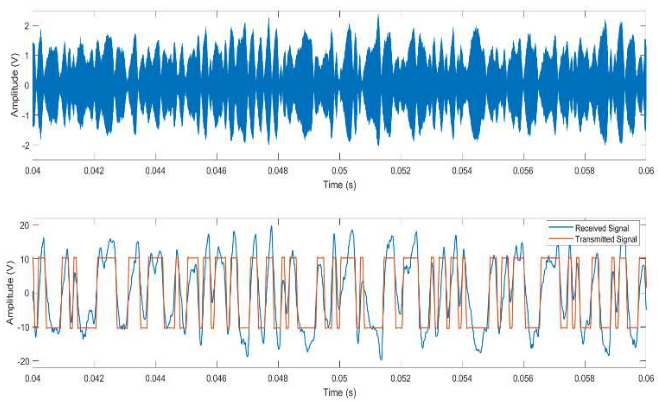

Fig. 4. Communication test on the plate channel using PSK modulation.

V. Conclusion

The paper discusses the feasibility of using PPM-EMAT for ultrasonic communication through the steel plate and pipe channel. An innovative PPM-EMAT is designed to generate SH waves by a selected frequency range. A communication test platform using PPM-EMAT as transmitter and receiver is described. Reverberation analysis demonstrates the characteristics of SH wave propagating in the solids. The final communication test reveals that a 10-kbps bitrate through the plate channel can be achieved for stable ultrasonic communication without any error. PPM-EMATs are proven to be as efficient and robust as the non-contact transducer in an ultrasonic communication system.

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