Ultrasonic Communication System Design using Electromagnetic Acoustic Transducer

Xin Huang and Jafar Saniie
Embedded Computing and Signal Processing Laboratory
Department of Electrical and Computer Engineering,
Illinois Institute of Technology, Chicago, Illinois

Sasan Bakhtiari and Alexander Heifetz
Nuclear Engineering Division
Argonne National Laboratory
Lemont, Illinois, United States

***Abstract*—Ultrasonic communication is a technique of transmitting a message through solids such as steel plates or pipes. Electromagnetic acoustic transducers (EMATs) are non-contact sensors able to generate and receive ultrasonic waves. In this study, periodic-permanent-magnet (PPM) EMATs are used to produce shear-horizontal (SH) waves. We present experimental results to show channel characterization of SH waves carrying information over the frequency range of 200 kHz to 800 kHz. An experimental ultrasonic communication platform was built for assessing the SH wave propagation through stainless steel plate channels. An arbitrary function generator (AFG) and a power amplifier with 50 dB gain excite PPM-EMAT resulting different SH modes. The transmitted ultrasonic signal is detected by the SH-wave EMAT receiver. The received signal is conditioned, amplified and sampled by a digital oscilloscope. The AFG and the digital oscilloscope can be configured by the computer. In addition, the receiver is connected to an impedance matching network for signal conditioning which minimizes the signal interference and reflections. A random binary message is modulated with amplitude shift keying (ASK) also known as on-off keying (OOK), and the received message is processed to recover the binary code to examine bit error rate (BER). The proposed method can transmit digital data through a 165 cm distance in the presence of undesirable multipath effect with the bit rates of 2.5 kbps under 0.48% BER.**

Keywords: SH-EMAT, ultrasonic communication system, EMAT transmitter and receiver

I. Introduction

Ultrasonic communication creates a wireless connection between two remote communication nodes using elastic waves [1] [2]. The communication channels such as steel plates or pipes are susceptible to a variety of transmission impediments such as multipath, path loss, interference, and blockage [1] [3]. The channel characterization varies according to the properties of ultrasonic waves and the geometry of the channel. There are two main waves that can be utilized as the carrier of the information for the plate: one is the Rayleigh surface wave [4], and the other one is the plate wave [4] [5].

The Rayleigh surface wave is a specific type of waves propagating along the solid surface. It consists of a linear combination of longitudinal and transversal vibrations. The amplitudes of surface waves depend on their depth under the surface. Surface waves can propagate over a large distance, but the waves selectively respond to the defects based on the defect orientation relative to the direction of the wave. Depending on the depth and the defect on the surface, the waves produce the reflections on the surface, which would bring more interference to the communication.

Waves in a strip plate can propagate along a plate. The SH wave is one kind of plate wave which can suffice for ultrasonic communication. The SH wave can't be attenuated by water in contact with the plate surface and is less attenuated by the coating on the plate. There is also little energy loss when propagating in the plate. In addition, the SH wave has a predictable dispersion curve [6]. As a result, when using the SH-wave, the multipath effect of the channel can predictably be analyzed. SH waves are generated by an angle beam piezoelectric transducer which suffers from the uncertainty in signal quality due to coupling conditions. However, a PPM-EMAT can selectively excite different modes of SH waves requiring no direct contact with the samples [7] [8]. Moreover, EMAT holds promise for the ultrasonic signal generation in a harsh environment (cold, hot, sealed or contaminated).

In this paper, we will present the SH wave propagation in the solids. An ultrasonic communication system using PPM-EMAT as transmitter and receiver will be explained. The performance of PPM-EMAT will be discussed. The system will improve the signal-to-noise ratio (SNR) of EMAT, while it minimizes the RF interference coupling between transmitter and receiver. The PPM-EMAT structure is introduced in Section 2. In Section 3, communication noise caused by interference and reflections is analyzed. In Section 4, system configuration and measurement results are presented which support the feasibility of applying PPM-EMAT in the ultrasonic communication system. By analyzing the experimental results, some practical methods are proposed to minimize the interference and reflections and to enhance the performance of the ultrasonic communication.

II. PPM-EMAT Theory

EMATs can transform the electromagnetic energy into ultrasonic energy [7] [9]. SH waves can be generated by using PPM-EMAT. The PPM-EMAT transmitter and receiver consist of a matrix periodic permanent magnet with alternating north and south (N/S) poles and a meander coil. The layout of the magnets, meander coils and input current connector are shown in Figure 1.

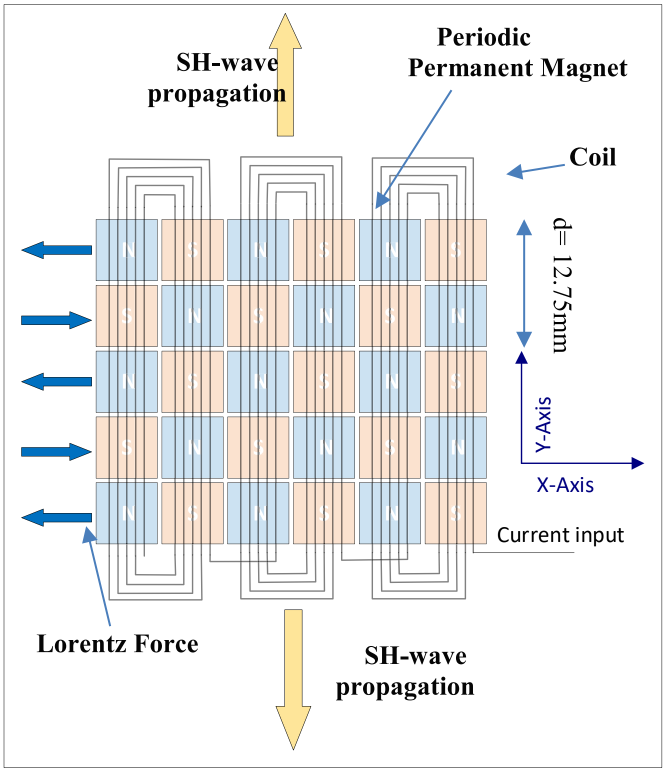


Figure 1. Layout of the PPM-EMAT

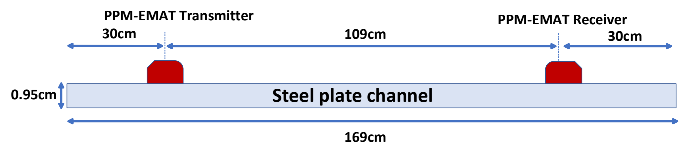
When an alternating current is applied to the meander coil element placed near the metallic material, the magnetic field penetrates through the material. Eddy current will be induced in the test material. The eddy current interacts with the permanent magnetic field, causing Lorenz force and generate elastic waves. The SH wave generated by EMAT have larger incident angle range compared with an angle beam wedge used by ultrasonic PZT. The incident angle [10] is determined by the wavelength of the SH wave in the sample and the geometrical period of the permanent magnets. Based on the structure of the PPM-EMAT, the incident angle can change from 90^o to 20^o, when the excitation frequency varies between 230 kHz to 700 kHz.

III. PPM-EMAT Interference Analysis

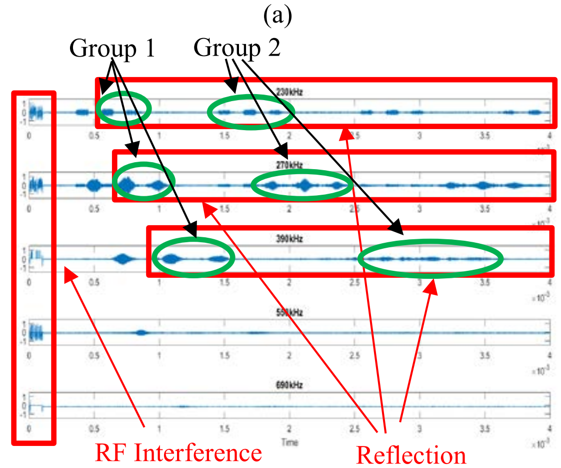
In a communication system, the ideal situation is that the transmitter sends a pulse and the receiver picks up the same signal. However, this is not the case for PPM-EMAT used as transmitter and receiver where the noise from the SH wave reflections and RF interference occur. In this section, we will explain the source of these noises.

When sound travels through a channel, it gradually decays as it travels farther. In ideal materials, acoustic pressure (signal amplitude) is reduced linearly proportional to the distance. Furthermore, in solid materials, the acoustic amplitude decays even faster due to scattering and absorption [6]. Scattering is the reflection of the acoustic signal in directions other than the intended direction of propagation. Absorption is the energy conversion from acoustic wave to other forms of energy. The signal amplitude decay takes place according to the law: $A = A_o e^{-\delta x}$, where x is the distance that the wave travels through a medium; δ is the attenuation coefficient, which may be proportional to f^2. To further confirm, we implemented basic measurements to observe the effect of signal attenuation.

Multipath propagation in the steel plate channel causes inter-symbol interference (ISI), which means that the subsequent signal is distorted by the reflection of the current signal [3]. Since the communication channel has a finite length and the EMAT transducer generates (or receives) signals in both forward direction and backward direction, more reflections can be seen in the receiver side compared with the PZT transducer. An experiment is designed to show the interference and reflection. To see reflections better, the transmitter and receiver are placed 30 cm from both ends of a strip plate. An excitation pulse with 100 µs duration is generated by the PPM-EMAT transmitter. Five tests were performed using different carrier frequencies 230 kHz, 270 kHz, 390 kHz, 550 kHz, and 690 kHz. Figure 2 shows the measured signal, where the attenuation of signals depends on the frequency (higher frequency results in higher signal attenuation). The Group 1 echoes are directly reflected from both edges of steel plate and Group 2 echoes are from the reverberation of the Group 1 echoes traveling through the length of the plate. The detection timing of all these reflections depends on the excitation frequency and can affect communication efficiency and BER.



(a)



(b)

Figure 2. (a) Position of the transmitter and receiver on the strip plate (b) EMAT signals displaying reflections and interference

The attenuation means that the lower frequency ultrasonic signal, in this case 230 kHz, can propagate longer and have more reflection echoes. Similarly, high carrier frequency pulses attenuate more, and consequently, have fewer reverberation echoes. During the experiments, we positioned the transmitter and receiver next to either end of the plate and set a longer bit duration to make the reflections overlap. By this arrangement, the Group 1 reflections overlap to a single echo. In this study, we chose excitation frequencies in the range of 290 kHz to 400 kHz to obtain the stronger received signal through a stainless-steel channel.

The EMAT transmitter needs a large excitation power to generate the ultrasonic signal. Any imbalance in the communication system caused by the cable, power cord and system interconnection results in poor SNR and undesirable RF interference [11]. The interference can be seen in Figure 2 which is at least five times larger than the desirable information bearing ultrasonic echoes. If the interference is not removed properly, the system fails to communicate using the ultrasonic signal. To alleviate RF interference, an impedance matching network is applied on the receiver side to improve the quality of the received signal.

The transfer efficiency between electric energy and ultrasonic energy with an EMAT is much lower than PZT. The impedance of the EMAT transmitter is comparable to the output impedance of the power amplifier. While on the receiver side, there is a large impedance mismatch between the EMAT receiver (140 Ω resistive) and low-noise amplifier (100MΩ resistive). This will cause inefficiency in transforming the acoustic wave into the electrical energy. A signal conditioning box (SCB) is necessary for the impedance matching. The impedance matching unit improves the quality of received signal significantly.

IV. Experimental Results and Data Analysis

The communication platform developed for this study consists of EMATs transmitter and receiver, a binary message generator, a power amplifier for EMAT excitation, a low noise pre-amplifier, impedance match network attached to the receiver and a data acquisition unit. We developed two application programs for testing and analysis: the frequency sweep program and the communication test program.

A. System Configuration

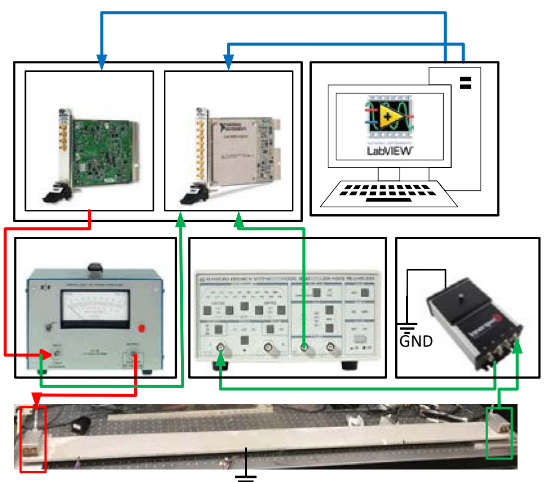


Figure 3. Communication Test Platform

As mentioned earlier, the EMAT used in the system is composed of periodic-permanent-magnet and RF- racetrack coils from INNERSPEC. The operating frequency is from 200 kHz to 800 kHz. As explained above, the SCB is added to improve quality of the signal and to suppress the RF interference. The plate communication channel is used to propagate the ultrasonic signal for performance evaluation. This plate is stainless-steel, 169 cm long, 10 cm wide and 0.95 cm thick. The system configuration is shown in Figure 3. The digital information (binary code) is modulated using the ASK method for transmission through the plate channel.

B. Experimental Results

The SH wave velocity is estimated by studying the main reflections of the received signal. An experiment is implemented by fixing the position of the receiver and moving the transmitter close to the receiver while collecting the data. The transmission distances vary from 145 cm, 120 cm, 95 cm, 70 cm to 35 cm. In Figure 4, the orange arrows represent the transmitted signal and green arrows represent the received signal. Edge 1 is the distance from the transmitter to its closer edge and Edge 2 is the distance from the receiver to its closer edge.

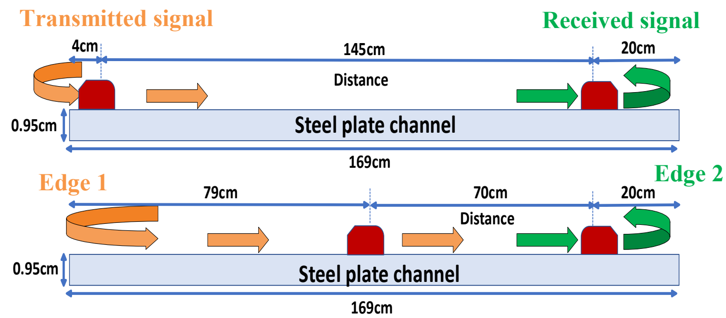


Figure 4. Ultrasonic Signal Velocity Measurement in Steel Plate

Figure 5 shows experimental results for a 100 µs pulse with the 291 kHz carrier frequency for different channel length.

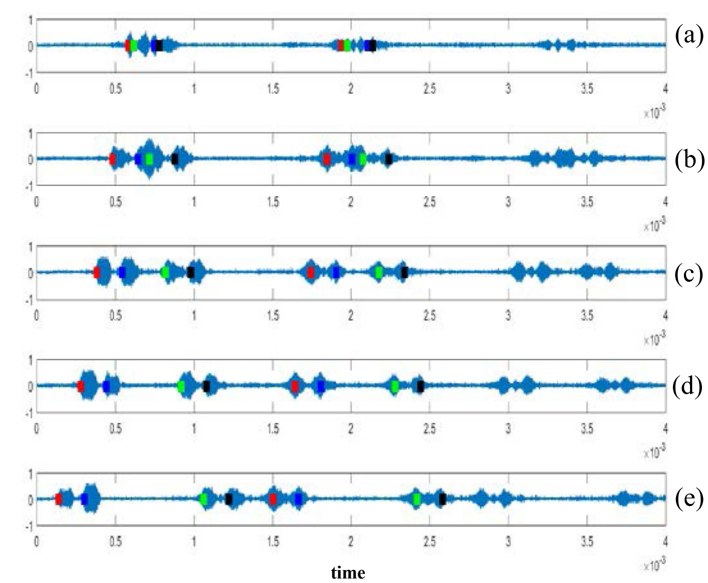


Figure 5. Test Results using the Steel Plate (a) received signal when receiver is 145 cm away from transmitter; (b) received signal when receiver is 120 cm away from transmitter; (c) received signal when receiver is 95 cm away from transmitter; (d) received signal when receiver is 70 cm away from transmitter; (e) received signal when receiver is 35 cm away from transmitter

The squares of different colors are used for the arrival time estimation of echoes. The equations to calculate the arrival times are shown below in Table I.

TABLE I. ARRIVAL TIME ESTIMATION EQUATIONS

Square	Arrival Time Estimation
red1	$t_{red1} = \frac{distance}{c_g}$
blue1	$t_{blue1} = \frac{distance + edge2}{c_g}$
green1	$t_{green1} = \frac{distance + edge1}{c_g}$
black1	$t_{black1} = \frac{distance + edge1 + edge2}{c_g}$
echoes	$t_{echoes} = \frac{travel\ path + 2 * channel\ length}{c_g}$

Here c_g is the group velocity of the SH wave with the 291 kHz carrier frequency. As shown in Figure 5, red_1 squares are the primary received signal and $blue_1$, $green_1$ and $black_1$ squares are the first group of reflections. red_2, $blue_2$, $green_2$, and $black_2$ squares are the second group of reflection echoes. The group velocity from the dispersion curve is 2443 m/s and the calculated velocity using results in Figure 5 is 2420 m/s. Calculation results match reasonably well with the experimental measurements

In order to minimize the undesirable reverberant reflections, the communication channel is arranged such that both the transmitter and receiver EMATs are positioned close to the edges of the plate channel. For this experiment, the carrier frequency is selected as 390 kHz. The distance between the EMAT transmitter and receiver is 1.65 meters. A 250-bit random binary code modulated by ASK is transmitted in the steel plate channel. Figure 6 shows the EMAT communication experimental results.

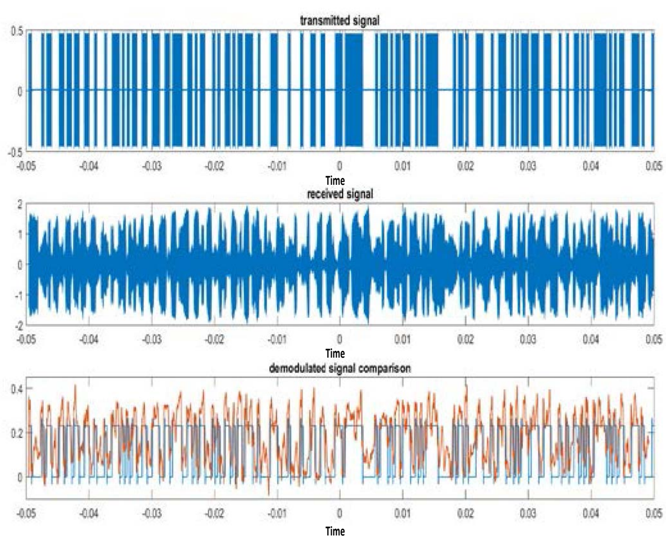


Figure 6. Signal Transmission and Reception using PPM-EMAT

For the result shown in Figure 6, the bit duration is 400µs which means a 2.5 kbps communication rate. The comparison of transmitted signals and received signals can help in transferring the received waveform into a binary code. By setting the appropriate threshold on the received waveform, only 1-bit error was observed among the transmitted 250 bits. We repeated the experiments with different random binary codes. The average bit error was 1.2 error bits among 250 bits transmission. This corresponds to the 0.48%-bit error rate. The multiple reflections and reverberations affect the performance of the ultrasonic communication. However, for a longer communication channel, the communication quality can be highly improved resulting in a higher communication bit rate with lower BER.

V. CONCLUSION

In this paper, we discussed the feasibility of using PPM-EMAT as transmitter and receiver in the ultrasonic communication system. An experimental system is introduced. An impedance matching network is added to the receiver to eliminate the RF interference. With this experimental system, all type of interference in the received signal are examined. The carrier frequency selection and position of the transmitter and receiver affect the quality of the signal propagating in the communication channel. In a 165 cm stainless steel plate channel, a digital communication with a bit rate of 2.5 kbps is achieved. The BER is 0.48% based on the communication test platform. The experimental results prove the potential for applying PPM-EMAT as transmitter and receiver in the ultrasonic communication system.

VI. REFERENCES

[1] X. Huang, J. Saniie, S. Bakhtiari and A. Herfetz, "Applying EMAT for Ultrasonic Communication through Steel Plates and Pipes," in *ELECTRO/INFORMATION TECHNOLOGY (EIT)*, Rochester, Michigan, USA, 2018.

[2] B. Wang, J. Saniie, S. Bakhtiari and A. Heifetz, "Architecture of an Ultrasonic Experimental Platform for information transmission through solid," in *Ultrasonics Symposium (IUS)*, Washington, DC, USA, 2017.

[3] M. Stojanovic, "Recent advances in high-speed underwater acoustic communications," *IEEE Journal of Oceanic Engineering,* vol. 21, no. 2, pp. 125 - 136, 1996.

[4] J. L. Rose, Ultrasonic Waves in Solid Media, Cambridge, United Kingdom: CAMBRIDGE UNIVERSITY PRESS, 1999.

[5] Z. Nazarchuk, V. Skalskyi and O. Serhiyenko, Acoustic Emission Methodology and Application, Springer International Publishing, 2017.

[6] R. A. Kline, "Measurement of attenuation and dispersion using an ultrasonic spectroscopy," *The Journal of the Acoustical Society of America,* vol. 76, no. 2, 1998.

[7] M. Hirao and H. Ogi, Electromagnetic Acoustic Transducers, Japan: Springer Japan, 2017.

[8] S. Choi, H. Cho and C. J. Lissenden, "Selection of Shear Horizontal Wave Transducers for Robotic Nondestructive Inspection in Harsh Environments," *sensors,* vol. 17, 2016.

[9] E.R.Dobbsa and J.D.Llewellyn, "Generation of ultrasonic waves without using a transducer," *Non-destructive Testing,* vol. 4, no. 1, pp. 49-56, 1971.

[10] S. Hilla and S. Dixon, "Localisation of defects with time and frequency measurements using pulsed arrays," *NDT & E International,* vol. 67, pp. 24-30, 2014.

[11] D. Rueter and T. Morgenstern, "Ultrasound generation with high power and coil only EMAT concepts," *Ultrasonics,* vol. 54, no. 8, pp. 2141-2150, 2014.