Contoured PPM-EMAT Design for Ultrasonic Communication On Metallic Pipe Channels

Xin Huang and Jafar Saniie
ECASP Research Laboratory (http://ecasp.ece.iit.edu)
Department of Electrical and Computer Engineering
Illinois Institute of Technology, Chicago IL, U.S.A.

Sasan Bakhtiari and Alexander Heifetz
Nuclear Science and Engineering Division
Argonne National Laboratory
Lemont, IL, U.S.A.

***Abstract*— Ultrasonic guided waves can be used as the carriers of information in ultrasonic communication for pipe or plate channels. Permanent Periodic Magnet (PPM) Electromagnetic Acoustic Transducer (EMAT) can potentially provide unique capabilities for a communication system as a non-contact transmitter and receiver, which can selectively generate different modes of shear-horizontal (SH) waves. The SH wave shows the potentials in achieving high bitrate without error in ultrasonic communication. However, when a steel pipe is used as the communication channel, especially one with a radius comparable to the size of the transducer, no guided wave signal can be excited or detected by existing PPM-EMAT's with flat coupling surface. In this paper, a 3D printed magnet holder is designed which can shape the magnet array. Also, the transmitter/receiver coils are made of flexible printed circuit which can fit over the curvature of the pipe channels. The contoured PPM-EMAT transmitter and receiver can conform to the surface of the steel pipe channel in order to generate and detect torsional waves. Experimental tests of signal transmission with PPM-EMAT on a 160cm-long stainless steel pipe determine the optimal frequency for communication to be 916KHz. Information transmission experimental results confirm the validity of contoured PPM-EMAT for communication with a bitrate of 5kbps.**

I. Introduction

Ultrasonic communication utilizes the ultrasonic guided waves as the carriers of information through a solid channel. A promising option to implement the transmitter and receiver used for generating and sensing SH wave on the steel plate is PPM-EMAT [1] [2]. The application of PPM-EMAT as transducers in ultrasonic communication has shown great potential for reliable information transmission through solid channels in oil or nuclear industrial [3] [4] [5]. Using PPM-EMAT for ultrasonic communications has several advantages. First, EMAT does not require direct contact with the surface of the channel. Compared with the piezoelectric transducer (PZT), EMATs do not suffer from signal uncertainty due to coupling conditions. Additionally, EMAT can be easily re-positioned to a new location along the communication channel. Second, PPM-EMATs have a simple structure which can be tuned for generating a guided wave with desired characteristics. The excitation frequencies and guided wave propagation velocities are determined by the period of magnets array based on the channel requirements. Lastly, materials of PPM-EMAT transmitter and receiver are resilient to a harsh environment, such as high temperature and ionizing radiation. This makes PPM-EMAT attractive candidates for ultrasonic communications in nuclear energy applications. However, the limiting factor to the application of PPM-EMAT in ultrasonic communication on pipes is the transducer design in which the coupling surface is flat. When PPM-EMATs are installed on the steel pipe channel, particularly on a pipe with a radius comparable to transducer size, no ultrasonic signal could be generated and detected. This deficiency is due to the large air gap between the flat of EMAT and the curved pipe surface, which limits energy transfer.

In this paper, we present a new design of contoured PPM-EMAT which is optimized for generating and receiving torsional ultrasonic waves on a steel pipe. A 3D printed case is designed to hold the permanent magnets array into a curved topology arrangement. The bottom arc of the holder is designed to conform to the cylindrical surface of the steel pipe. The inexpensive holder can be rapidly 3D-printed for arbitrary piping geometry. The material of the case can resist the magnetic force and hold the magnets in their periodic place. Moreover, we use a flexible printed circuit method to manufacture the meander coils, which can conform to any radius of steel pipe. The contoured PPM-EMAT removes the air gap and can generate and receive a torsional wave on the steel pipe channel. Torsional wave modes [5] [6] share the same dispersion characteristics with plate wave SH modes, where one can excite different modes by applying different excitation frequencies. Rather than a collar-type circumferential array of transducers, the design in this paper simplifies the torsional wave generation. In addition, for communication on high-temperature pipes, less insulation needs to be removed for a smaller size EMAT. Depending on the Signal-to-Noise Ratio (SNR) of a torsional wave propagating in the pipe channel, we can use amplitude shifting keying (ASK) [7] [8] or time-reversal method [9] to conduct ultrasonic communications. The pulse shaping method [10] is implemented to compensate for the multipath effect.

In Section II, the contoured PPM-EMAT design for steel pipe is described, including the 3D printed holder and flexible printed circuit manufactured coils. In addition, the theory of torsional wave generation is presented. In Section III, we discuss a series of experiments implemented to verify the validity of using contoured PPM-EMAT on a pipe channel. Different distance for signal transmission along the pipe and

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communication carrier frequencies are tested. Finally, a multiple bit test is conducted, which shows that the PPM-EMAT can be used for ultrasonic communication on the pipe channel.

II. CONTOURED PPM-EMAT DESIGN FOR PIPE CHANNEL

In recent prior work, we have shown that PPM-EMAT can selectively generate different modes of SH-waves (SH0, SH1, SH2…) by applying different excitation frequencies [4] on the plate channel. When an alternating current is applied to the coil, eddy current is induced in the material of the channel. The eddy current interacts with the permanent magnetic field, causing Lorenz force and generating elastic waves. The direction and amplitude of the Lorenz force can be determined by the following equation,

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B} \tag{1}$$

where $\boldsymbol{J}$ is the eddy current and $\boldsymbol{B}$ is the static magnetic field.

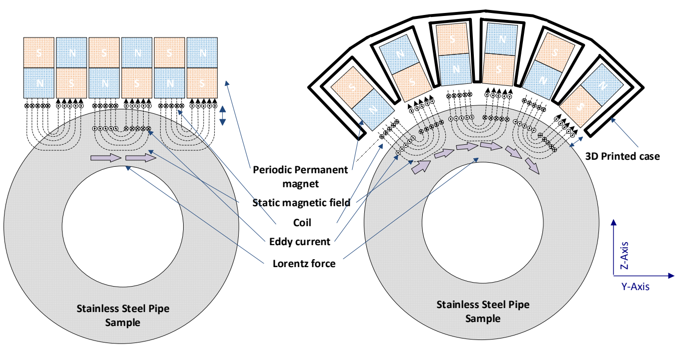

Figure 1. Lorentz force generation. (a) flat PPM-EMAT place on the pipe channel. (b) contoured PPM-EAMT placed on the pipe channel

The Lorentz force generated in the material is the key to the production of ultrasonic waves. As shown in Figure 1(a), two magnet arrays and one racetrack coil are considered as one element. There exists a large air gap between the extremities of conventional flat EMAT and pipe surface due to the curvature of the pipe channel. The extremities of the meander coil are too far away from the pipe to generate an eddy current. In addition, the static magnetic field along the extremities cannot interact with the eddy current. As a result, only the PPM-EMAT element in close contact with the pipe can generate Lorentz force in the horizontal directions. Thus, no signals can be generated and detected on the pipe channel using conventional flat PPM-EMAT.

A 3D printed holder and flexible printed circuit coil have been developed in this work to contour the PPM array and meander coil into an arc shape, as shown in Figure 1(b). 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 is generated in the radial static magnetic field. Depending on the polarization directions of magnets and alternating current, Lorentz force is generated in the same circumferential direction and enhances circumferential vibration, which generates a torsional wave propagating along the pipe channel [11].

The photograph of the 3D-printed plastic holder and meander coil are shown in Figure 2 in the top left and top right panels, respectively. The curvature of the 3D printed holder matches that of the pipe**,** thus placing the magnets in the arrangement for optimal energy coupling. Each slot of the holder is occupied with one magnet in the array. The volume of the slot is determined by the size and periodicity of magnets in the array. The meander coil is made of flexible material and couples with a BNC connector. The size of the coil is matched with that of the magnet array. The PPM with holder is placed on top of meander coils. With a voltage source to drive the coils, the assembly can create a circumferential current in the axial direction. A photograph in the bottom panel of Figure 2 shows the contoured PPM-EMAT installed on stainless steel pipe.

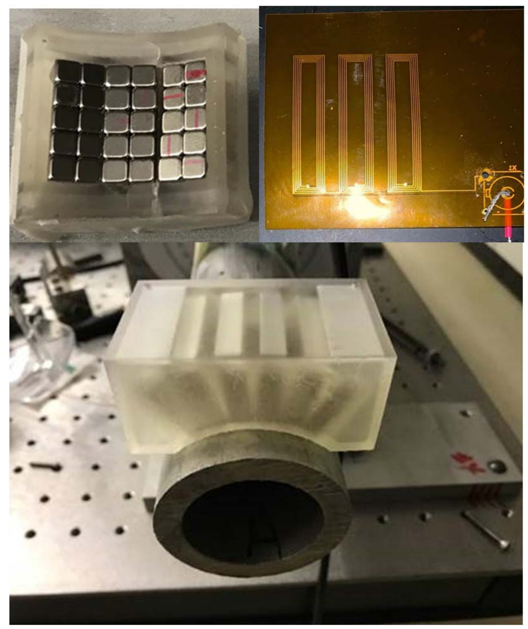

Figure 2. Photographs of the 3D printed case for magnet arrays (top left) and flexible printed meander coils (top right). Contoured PPM-EMAT is installed on a pipe (bottom).

III. EXPERIMENTAL TESTS

Experimental tests have been conducted to evaluate the performance of the contoured PPM-EMAT as a transmitter and receiver for ultrasonic communications. The communication channel used in the test is a 169 cm (5.54 feet) long stainless-steel pipe with an outer radius of 6.1 cm and an inner radius of 4.1 cm. The communication test is conducted using the communication test platform described in our previous research papers [1] [2] [10]. There is usually a large impedance mismatch between the meander coils and the power amplifier, which makes electromagnetic-acoustic energy transfer inefficient. In order to achieve a good SNR for communication, the impedance matching network for transmitter and receiver have been designed and optimized.

Several experiments were designed to transmit ultrasonic signals with the EMAT transmitter and receiver positioned at different distances on the pipe. As shown in Figure 3, the contoured PPM-EMAT receiver is fixed at 50 cm distance from the right end of the pipe. For the first measurement, the transmitter is set 49 cm away from the left end of the pipe, and the distance between the transmitter and receiver is 70 cm.

Then, the transmitter is moved towards the receiver to make the distance to be 60 cm and 30 cm, respectively. A 200 µs excitation pulse modulated with 8 carrier frequencies is fed to the transmitter. The orientation of the transmitter and receiver were adjusted so that they are positioned on top of the pipe channel on a straight line. The excitation frequencies are 260 kHz, 283 kHz, 413 kHz, 432 kHz, 536 kHz, 601 kHz, 795 kHz, and 916 kHz, which correspond to different modes of the torsional wave. The excitation frequencies are listed in Table I.

Figure 4 shows the received signal with a distance of 70 cm between transmitter and receiver. The pulse response with eight excitation frequencies can be observed in eight strip charts of Figure 4. The channel crosstalk in the received signal is significant, which appears as a 200 µs duration pulse without any time delay. Different modes of the torsional wave can be generated with 260 kHz to 916 kHz frequencies, respectively. The received signals contain wave modes with significant amplitudes and show undesirable multipath effects for all excitation frequencies. Both the channel crosstalk and multipath effect are sources of inter symbol interference (ISI) in ultrasonic communication.

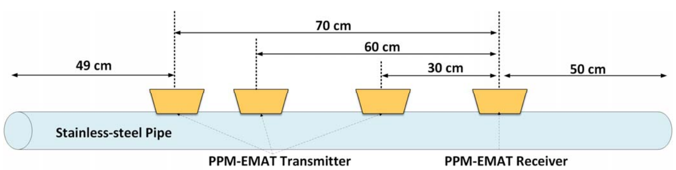

Figure 3. Setup for communication with contoured PPM-EMAT on a pipe channel

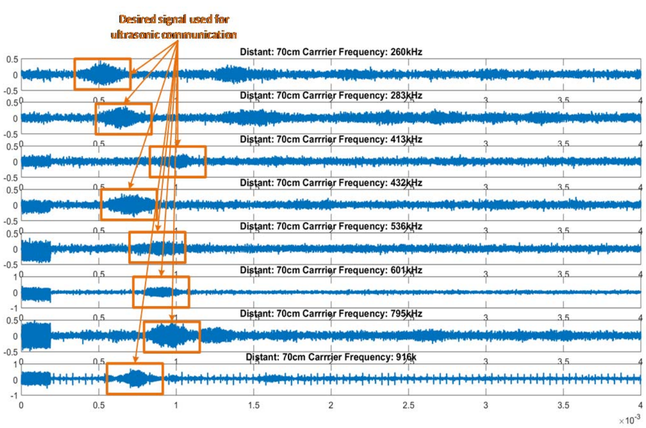

Figure 4. Transmission across 70 cm distance

Compared with the SH waves generated in the plate channel, the received wave components for communication on a pipe are more complex. In particular, it is difficult to distinguish the direct path from other paths (reflections from the pipe end) of a torsional wave propagating on the pipe channel. Nevertheless, the signals with a large amplitude which contains the largest energy of the received signal indicate that there is one bit of information transmitted through the channel, which can be filtered out through amplitude thresholding. The "desired" signals are regarded as the strongest torsional wave propagation path through 70 cm distance of the pipe channel, which are indicated with wire frame boxes in Figure 4.

TABLE I. TORSIONAL WAVE TIME OF FLIGHT VELOCITY ESTIMATION

Excitation Frequency	Time of flight Velocity
260 kHz	1600 m/s
283 kHz	1300 m/s
413 kHz	780 m/s
432 kHz	1200 m/s
536 kHz	820 m/s
601 kHz	860 m/s
795 kHz	810 m/s
916 kHz	1000 m/s

Using information from Figure 4, the time of flight for different modes can be estimated. Velocity for the pulse of each frequency is calculated and listed in Table I. These velocities do not yield the actual torsional wave velocity of different modes. We will trace the strongest path in cases of 60 cm and 30 cm distance. Based on the time of flight velocity in Table I, we use the red square to mark the estimated arrival time of the pulse for the cases of signal transmission across 60 cm and 30 cm. These are shown in Figures 5 and Figure 6, respectively.

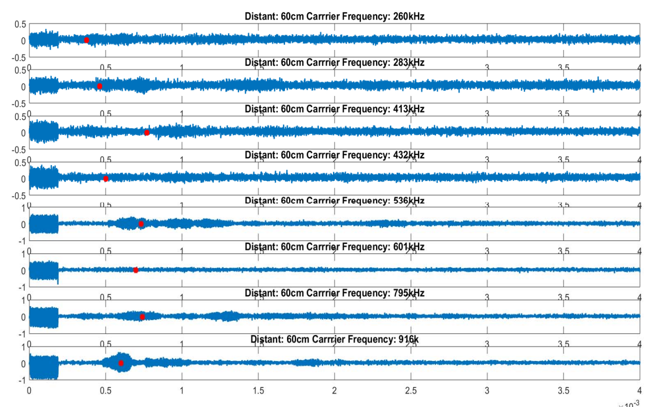

Figure 5. Transmission across 60 cm distance

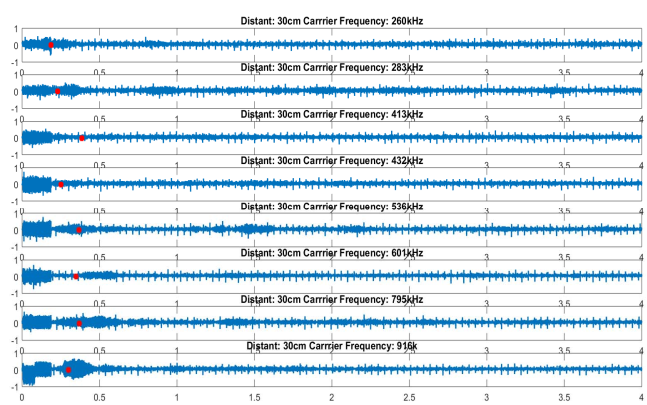

Figure 6. Transmission across 30 cm distance

Figure 5 and Figure 6 displaying ultrasonic transmission across 60 cm and 30 cm distance between transmitter and receiver, respectively, show significant channel crosstalk in the received signals. Comparing the red square and received signal, the 60 cm and 30 cm measurements do not entirely match the arrival time estimation. For example, the results of transmission across 70 cm distance for 260 kHz excitation frequency show a time delayed pulse with significant amplitude. The amplitude of the same frequency signal for transmission across 60 cm and 30 cm distances is smaller. When the excitation frequency is 601 kHz, no valid signal can be seen in the 60 cm distance measurement. When the excitation frequency is 916 kHz, all three received signals show a consistent result for pulse reception.

IV. Communication Test Results and Analysis

This section presents the results of a communication test in which multiple bits were sent and received by transmitter and receiver placed at the opposite ends of the pipe. The distance between the transmitter and receiver is 160 cm. An optimal excitation frequency was selected by analyzing the SNR of a single transmitted pulse. Information was transmitted with a train of pulses of 200 μs duration, which corresponds to 5 kilobits per second (kbps) bitrate. The SNR is calculated based on the three distance measurements with eight carrier frequencies. The results of calculations are shown in Figure 7.

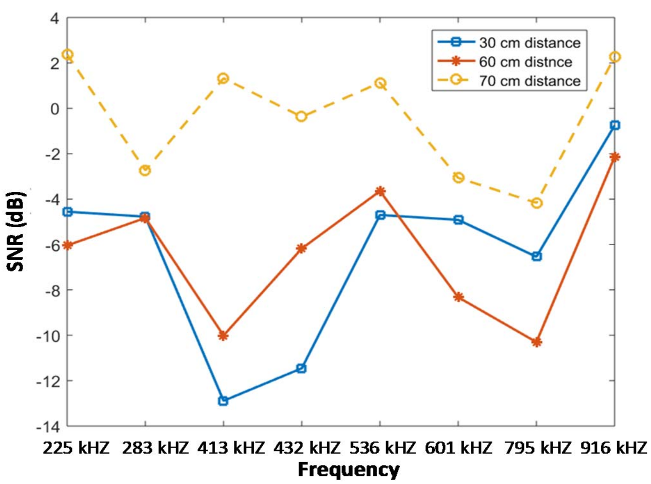

Figure 7. SNR calculation of experimental test

The dependence of SNR on frequency is similar for transmission experiments across 60 cm and 30 cm distances, which are described in Figures 5 and 6, respectively. The SNR for 70 cm is overall larger than 60 cm and 30 cm, which means that the strongest propagation path of 70 cm distant might not be the case of 60 cm or 30 cm under some excitation frequencies. The 916 kHz excitation frequency has the largest SNR for all three curves, which means that using 916 kHz as carrier frequency can achieve a better communication performance, independent of the distance between transmitter and receiver.

For the multibit communication test, 916 kHz frequency was used for information transmission. The binary message consists of the string of bits '11000111001101011101'. Received signals of the communication test are shown in Figure 8(a). The pulse shaping technique is implemented in the demodulation method which can reduce the ISI effect and improve the SNR of the communication system. The demodulated waveform is shown in Figure 8(b), from which can recover the transmitted binary information without any errors. We therefore conclude that the contoured PPM-EMAT can be used as a transmitter and receiver for ultrasonic communication through a pipe channel.

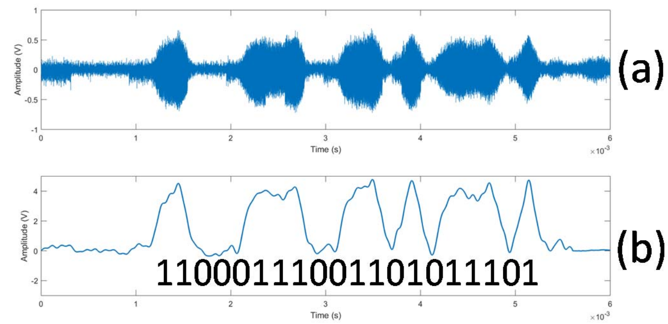

Figure 8. (a) 20 bits communication test received signal; (b) Demodulated signal

V. Conclusion

In this paper, we investigate the feasibility of using PPM-EMAT as the transmitter and receiver in the ultrasonic communication through a steel pipe channel. A 3D printed magnet holder and flexible coils were designed to couple a PPM-EMAT with the pipe channel. A series of experiments are conducted to explore the performance of contoured PPM-EMAT in ultrasonic communications with different carrier frequencies. The received signals in communication tests show complex signals when torsional wave propagates in the pipe channel. The desired signal used for communication is traced by velocity estimation. When using a 169 cm stainless steel pipe channel, a suitable carrier frequency is determined to be 916KHz, and digital communication with a bitrate of 5 kbps can be achieved. These results prove the potential of extending the application of PPM-EMAT to ultrasonic communication on a pipe channel.

VI. Acknowledgment

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