Applying EMAT for Ultrasonic Communication through Steel Plates and Pipes

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***Abstract*— Ultrasonic communication methods have been used for sending data through elastic solids such as steel pipes or plates to overcome physical hurdles that hamper the conventional communication methods (wired and RF wireless). EMAT (Electro Magnetic Acoustic Transducer), an ultrasonic signal generation technique that generates different modes of waveform, is particularly useful for hot, cold, or dry environments, which overcome many of the issues faced by conventional PZT ultrasonic probes. In this paper, EMAT is used as the transmitter for non-contact ultrasonic signal generation and PZT is used as the receiver for the communication system. This system is designed to assess the efficiency of Lamb waves and to examine Bit Error Rate (BER) of digital communication. The communication system was configured using National Instrument arbitrary waveform generator (AWG) and PXI digital oscilloscope. The accuracy of transmitted information is tested on a 5-foot long stainless-steel plate and pipe. The system operates with the frequency of 414 kHz signal and uses Amplitude-Shift Keying (ASK) modulation for transmission. This method can transfer digital data in presence of undesirable multipath effect with bit rates of 20 kbps and 40 kbps without any error.**

Keywords*— *EMAT, ultrasonic communication, Amplitude-Shift Keying

I. INTRODUCTION

In conventional ultrasonic communication systems using solid materials as the communication channel, a piezoelectric (PZT) transducer is used as the transmitter of information and the trustworthiness of the received information is highly dependent on the coupling condition between the PZT transducer and the communication channel [1] [2]. EMAT (Electro Magnetic Acoustic Transducer) as an alternate to PZT was not utilized for communications because EMAT demands high power excitation and offers low transduction efficiency [3]. In addition, with high power excitation, EMAT to EMAT communication may induce large RF coupling interference, which adversely affects the reliability of the acoustic communication [2] [3]. However, in harsh environments (hot, cold, sealed or contaminated), the noncontact EMAT holds promise for the transmission of information by acoustic means in solids. In practice, the conventional ultrasonic communications techniques which employ contact PZT transducers [4] may suffer from the ambiguity in signal quality due to uncertainty in a coupling condition. In contrast, EMAT is non-contact transduction [5] and becomes a promising choice for transmitting information in solids such as pipes and plates. In this paper, we present a practical solution using EMAT as a noncontact transmitter and PZT as a receiver. This system configuration can compensate the disadvantage of EMAT to EMAT RF coupling interference. To keep the quality of the signal that can propagate through a 5-foot stainless steel plate or pipe with less attenuation [6], we select the central frequency of the signal to be 500 kHz. For the study, an experimental platform with programmable arbitrary waveform generator and digital data acquisition system is designed to test and optimize the performance of the communication system. The results are compared and analyzed.

II. EMAT THEORY

EMAT can transform the electromagnetic energy into acoustic energy. It consists of a magnet providing the static magnetic field, a metallic sample providing the medium of the ultrasonic signal, and a coil inducing alternating currents. In metallic materials, the ultrasonic signal is generated by Lorentz forces. While in ferromagnetic material, the ultrasonic signal is generated by the Lorentz force, the magnetization force and the magnetostrictive force [7] [8]. In this paper, the communication channels are metallics and made of stainless-steel plate and pipe where the Lamb waves are generated by Lorentz force.

The transduction of EMAT is based on Lorenz force F_l, which is the cross product of the Eddy current J induced by the electric coil and static magnetic field B_0 near the surface of a metallic material. This process is usually described as

$$F_l = J \times B_0 \tag{1}$$

Depending on the geometry of electric coils and the permanent magnet, different modes such as SH (Shear Horizontal) wave, SV (Shear Vertical) wave, and Lamb waves can be generated. Figure 1 shows the structure and geometry of EMAT Lamb wave generator.

Lamb wave is similar to surface wave except that they can only be generated in thin materials only a few wavelengths thick. So, the incident angle of the lamb wave generated by EMAT is 90º and it propagates along a plate or pipe surface. In this paper, the thickness of the stainless-steel pipe and plate is 9mm and 9.5mm respectively, which is around 1.5 times of the wavelength. Lamb waves are complex vibrational waves that propagate parallel to the material surface throughout the thickness of the material. The size of the meander coils determines the working frequency range and wave frequency

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and thickness determines the modes [9] generated by EMAT. After implementing the frequency sweep program, which is introduced in next section, the carrier frequency is selected as 414 kHz.

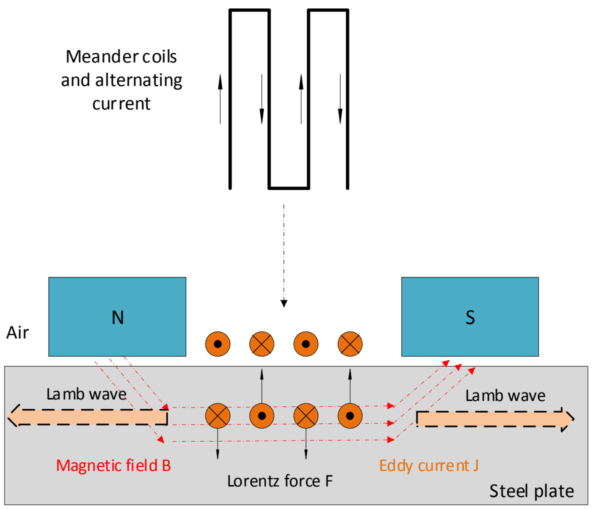

Figure 1. EMAT geometry for Lamb wave generation

III. System Description and Experiment Setup

The communication platform developed for this study consists of EMAT and PZT Transducers, a Binary message generator, a power amplifier for EMAT excitation, a low noise pre-amplifier attached to the PZT receiving transducer, a data acquisition unit and two application programs: *Frequency Sweep Program* and *Communication Test Program*.

A. System Configuration

The EMAT used in the experiment is composed of an XXL size magnet (274A0093-M00) and RF meander coils from INNERSPEC. The recommended frequency range for this EMAT is 200 kHz to 500 kHz. A 500 kHz PZT transducer with angle wedge is utilized as the receiver. Figure 2 shows the schematic of the laboratory communication system. The system is assembled using an arbitrary waveform generator (AWG), PXI oscilloscope, a power amplifier with 50dB fixed gain and a low-noise pre-amplifier. The low noise pre-amplifier has a build in band-pass filter that can improve the SNR of the received signal. The digital information (binary code) is modulated using the amplitude shift keying (ASK) for transmission through a solid channel. The PXI oscilloscope will record the modulated signal and received signal detected by the PZT receiver. The PC will store the data and make it available for signal processing and analysis.

In this study, two channels are used to propagate the ultrasonic signal for performance evaluation. Figure 3A shows a 169cm (5.4 ft) long, 10cm wide and 0.95cm thick stainless-steel plate that is used as a communication channel. Figure 3B shows a 194cm (6.04 ft) long, 6.1cm outer radius and 4.1cm inner radius steel pipe is used as a communication channel. The distance between EMAT transmitter and PZT ultrasonic receiver is set to 1.54m (5 ft).

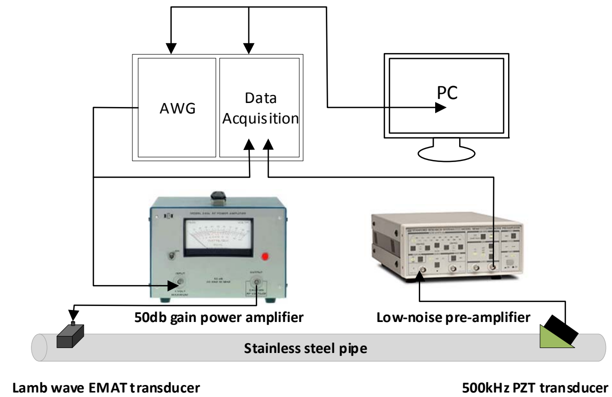

Figure 2. Schematic of the laboratory communication

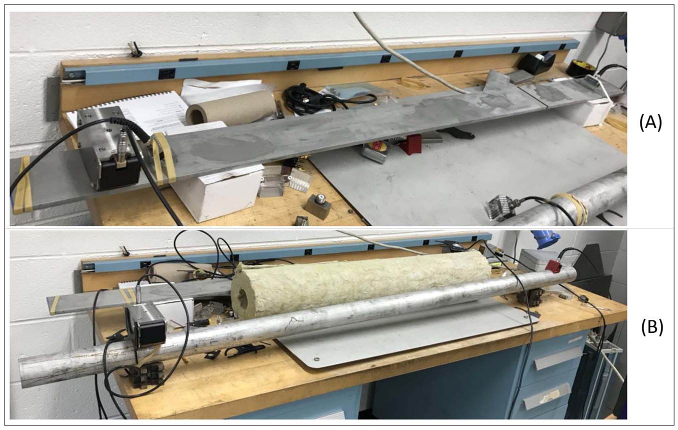

Figure 3. Experimental channels; (A) is a steel plate channel, (B) is a steel pipe channel

B. Program Description

The *Frequency Sweep Program* can help to determine the best frequency response of the EMAT transmitter and the PZT receiver. This program sweeps the frequency and then displays the frequency response of the signals. We can set the transmitted and received signal acquisition time, frequency sweep steps, acquisition delay and sampling rate which is shown in the control panel of
Figure 4. However, the frequency response fluctuates significantly due to the complex modes of the Lamb waves. The aim is to determine a desirable carrier frequency with power concentrated in one mode. The signals displayed in
Figure 4 are the transmitted signal and transmitted spectrum, received signal and received spectrum, and the received signal for optimized frequency detected in 200 kHz to 600 kHz frequency range. For the current pair of transducers, the optimized frequency is within the 405 kHz to 420 kHz frequency range. Based on the experimental results, 414 kHz is selected as the carrier frequency for ASK communications.

ASK shown in equation (2) is a modulation process, which imparts a sinusoid wave with certain frequency into two discrete amplitude levels. These are related to the value of the binary code representing the digital message.

$$s(t) = \begin{cases} A\cos(2\pi f_c t), & binary\ 1 \\ 0, & binary\ 0 \end{cases} \qquad (2)$$

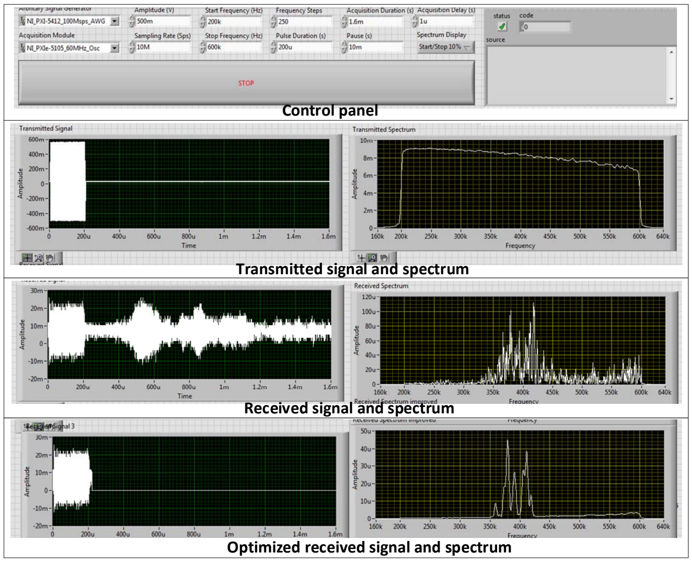

Figure 4. Frequency Sweep program

A coherent demodulation method is implemented to recover the transmitted and received binary waveforms for comparison. This comparison is for bit error detection and estimation of bit error rate (BER).

Figure 5 shows the front panel of the *Communication Test Program*. The program can send 1-1000 bits of binary code that can be random or fixed. With the setting of the pulse duration and number of bits, different bit durations can be selected. For example, if 10 bits are transmitted and the pulse duration is 1ms, bit duration is 100 µs which implies the system can communicate with a data rate of 10 kbps.

The *Communication Test Program* can show the power spectrum in linear or dB scale. The acquisition delay setting is to synchronize the transmitted and received signals. As mentioned in the previous section, the distance between two transducers is 1.54m, the delay depends on the Lamb wave velocity. Lamb wave velocity is determined by the thickness of the channel and carrier frequency. Different modes of Lamb wave velocity can be found in the Lamb wave phase dispersion curve [9] [10]. As a result, the setting of delay varied with different channels and carrier frequency. After demodulating the raw data captured by the receiver, the received binary waveform can be converted into binary code. The received binary code is compared with the transmitted binary code to detect and display errors in the test program front panel. For example, Figure 5 shows the input binary code (0010101010) and the bit duration (100 µs), the system fully recovers the transmitted binary code and the bit error rate is 0.

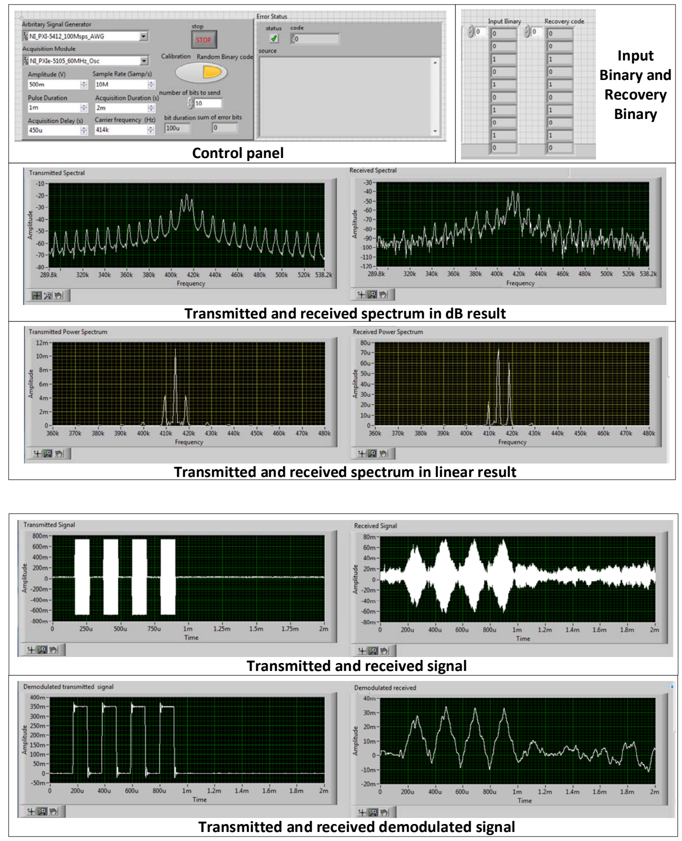

Figure 5. Front panel of communication system program

IV. EXPERIMENT DATA ANALYSIS

To test the EMAT signal and to estimate the velocity of the Lamb wave, experiments are performed using the plate and pipe channels using different lengths. In the experiment (see Figure 6), the position of the receiver is fixed and distance between the receiver and the transmitter is varied: 145cm, 120cm, 95cm, 70cm and 35cm. The received signals using the plate and pipe channels are shown in Figure 7 and Figure 8.

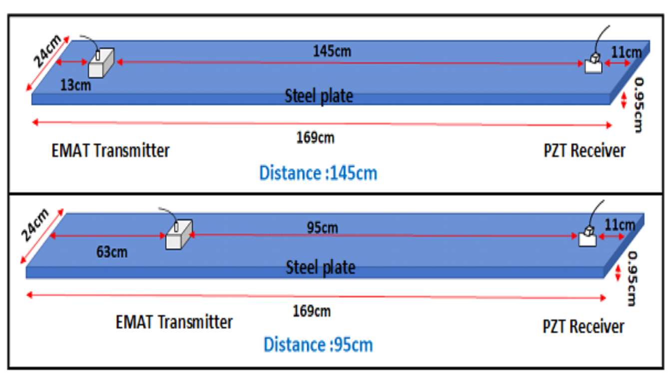

Figure 6. Test experiments

TABLE I. LAMB WAVE VELOCITY ESTIMATION

Distance Transmitter to Receiver	Distance Transmitter to Edge	First Peak Signal Arrival Time	Second Peak Signal Arrival Time	Third Peak Signal Arrival Time	Speed of First Peak Signal	Speed of Second Peak Signal	Speed of Third Peak Signal
145cm	13cm	600 µs	720 µs	1900 µs	2636 m/s	2552 m/s	2515 m/s
120cm	38cm	500 µs	800 µs	1820 µs	2667 m/s	2614 m/s	2478 m/s
95cm	63cm	410 µs	880 µs	1710 µs	2639 m/s	2663 m/s	2515 m/s
70cm	88cm	340 µs	960 µs	1620 µs	2413 m/s	2703 m/s	2554 m/s
35cm	123cm	210 µs	1100 µs	1500 µs	2188 m/s	2676 m/s	2515 m/s

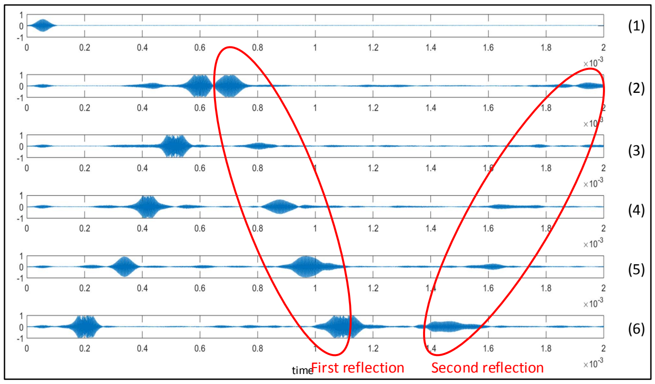

Figure 7. Test results using the plate channel; (1) transmitted signal, (2) received signal when receiver is 145cm away from transmitter, (3) received signal when receiver is 120cm away from transmitter, (4) received signal when receiver is 95cm away from transmitter, (5) received signal when receiver is 70cm away from transmitter, (6) received signal when receiver is 35cm away from transmitter

In Figure 7, the experiment is implemented on the steel plate and the carrier frequency is 414 kHz. The transmitted signal is a 100 µs bit duration Gaussian signal. The RF coupling interference between the transmitter and receiver is insignificant compared with the actual received ultrasonic signal. Several modes exist in the received signal and most of the energy stays in one mode which shows up around 600 µs (see Figure 7, signal number 2). The first plate-edge reflection of the received signal shows up late since the transmitter is far from the edge. The travel path of the second peak signal is equal to the distance from the transmitter to the receiver plus two times of the distance from the transmitter to the edge. Similarly, the travel path of the third peak signal is equal to distance from the transmitter to receiver plus two times of channel length. The arrival time of each signal can be estimated by observing the received signal in the time domain in Figure 7. Since the Lamb wave propagates along the plate, the velocity of each signal can be estimated. Velocity estimations are shown in Table I. There are about 10% variation in calculating the velocity for distance 70cm and 35cm because the actual distance does not consider the signal traveling length within the receiving wedge. The average velocity is 2594 m/s, which matches the Lamb wave phase velocity dispersion.

The test results which are shown in Figure 8 using the pipe channel is similar to the plate channel. In the received signal, the first reflection and second reflection are still visible. However, more modes show up due to the special geometry of the pipe. Received signals with different bit duration have different patterns compared with the test results using the plate channel. Since the thickness of plate and pipe are different, their velocity is different too. The average estimated velocity is 2859 m/s.

After obtaining the Lamb wave velocity with a 414 kHz carrier frequency through the plate and pipe channels, the delay setting can be determined (593 µs for plate channel and 539 µs for pipe channel). In the experiment the distance between the transducers is 154cm and the transmitted signal is set to 0010101010, a 10-bit binary code.

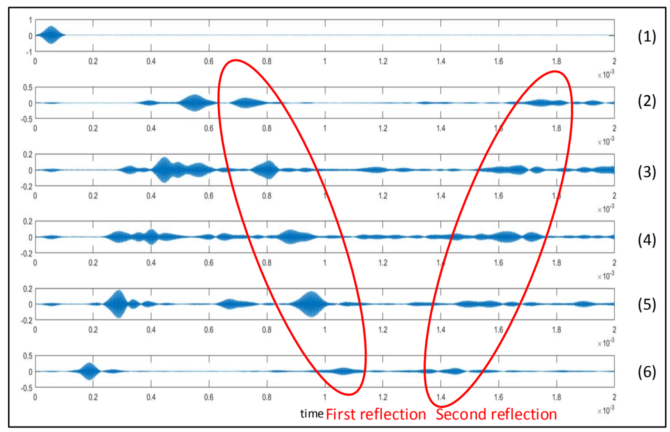

Figure 8. Test result using the pipe channel; (1) transmitted signal, (2) received signal when receiver is 145cm away from transmitter, (3) received signal when receiver is 120cm away from transmitter, (4) received signal when receiver is 95cm away from transmitter, (5) received signal when receiver is 70cm away from transmitter, (6) received signal when receiver is 35cm away from transmitter

The experimental results are shown in Figure 9 and Figure 10. These results indicate that the delay setting is correct and can keep the transmitter and receiver synchronized. The comparison of transmitted signals and received signals will help in transferring the waveform into binary. In the plate channel shown in Figure 9, the received signal is clearly compared with the transmitted signal. When a proper threshold value is set on the waveform, '0' and '1' can be fully recovered into binary codes. In the pipe channel shown in Figure 10, the received signal with 100 µs and 50 µs bit duration is clear and can be recovered but received signal with 33 µs and 25 µs bit duration are highly attenuated and cannot be fully recovered. As a result, for the plate channel, the received signal can recover the binary code with bit duration from 100 µs to 25 µs which corresponds to 10 kbps to 40 kbps. For pipe channel, the system can recover the bit duration from 100 µs to 50 µs and there will be error bit with 33 µs bit duration. The bit duration 25 µs cannot be recovered in the communication system. The results can prove that using EMAT as a transmitter for the communication system is feasible and efficient.

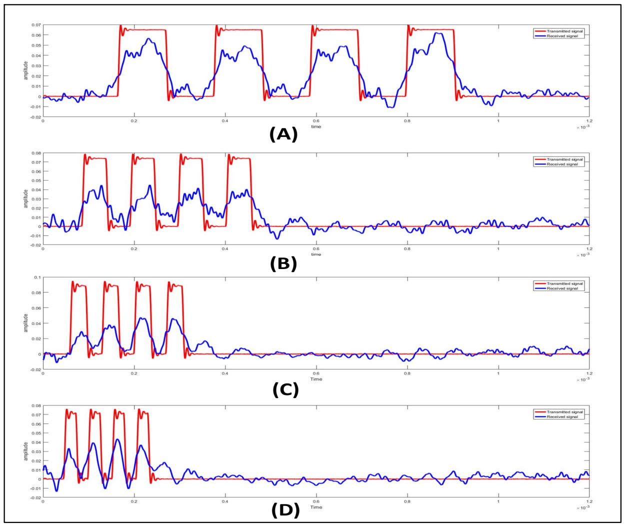

Figure 9. Transmitted and received signal test using the plate channel; (A) bit duration 100 µs, (B) bit duration 50 µs, (C) bit duration 33 µs, (D) bit duration 25 µs

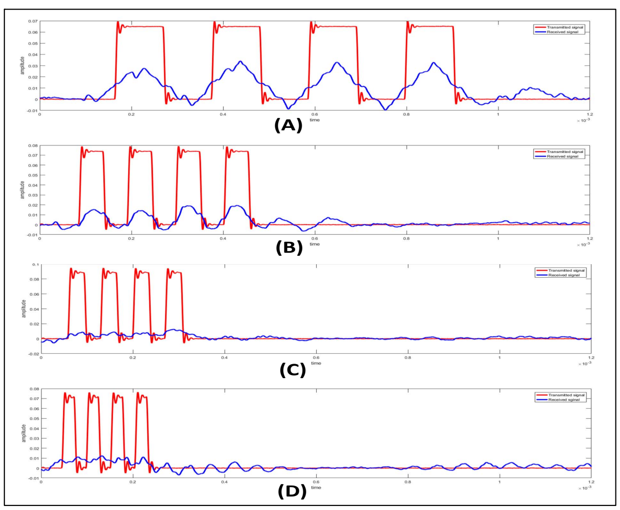

Figure 10. Transmitted and received signal test using the pipe channel; (A) bit duration 100 µs, (B) bit duration 50 µs, (C) bit duration 33 µs, (D) bit duration 25 µs

V. CONCLUSION

This paper discusses the feasibility of using EMAT for ultrasonic communication. An experimental system based on AWG and oscilloscope is introduced. With this test system, experiments of ultrasonic communication are conducted with EMAT as a transmitter and PZT as receiver for data transmission using a 5-foot steel plate and pipe channels. The usage of these two types of transducers guarantees that EMAT can be excited with less power and low RF coupling interference. ASK modulation method is adapted to modulate the baseband signal at the rate of 40 kbps across the plate channel and 20 kbps across the pipe channel. The Lamb wave mode selection is done by the frequency sweep program. The signal of 414 kHz carrier frequency shows the best frequency response in the spectrum. The velocity of the Lamb wave mode is calculated. The system is carefully designed to minimize bit error rate to ensure robust communication.

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