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Time Reversal Signal Processing for Ultrasonic Communication through Metal Channels

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***Abstract*- Achieving a high bitrate (BR) and low bit error rate (BER) in ultrasonic communication through solids are challenging due to bit-wavelet spreading caused by the channel dispersion, attenuation, and multipath effect. This undesirable effect is more pronounced particularly in irregular shape channels like an elbow pipe and bent or warped plates. Time-reversal (TR) signal processing is a promising technique which can compress the spreading of the bit-wavelet and concentrate the signal energy for improving the communication BR. In this study, we examined the performance of the TR technique applied to the elbow shape pipe channel using piezoelectric transducers (PZT) and steel plate channel using electromagnetic acoustic transducers (EMATs). This paper presents an overview of the system design of the TR processing for ultrasonic communication. By comparing the signal-to-noise ratio (SNR) of different pulse duration for generating the TR signal, we determined the optimal pulse duration to be used as one-bit information. An experimental model is used to demonstrate the performance of TR method for ultrasonic communication through complex metal channels. Furthermore, results show the pulse-position modulation (PPM) is highly effective for improving BER in complex channels with severe dispersion, attenuation, and multipath effects.**

Keywords- Time Reversal Technique, Plate and Pipe Channels, Ultrasonic Communication System, EMAT

I. INTRODUCTION

Ultrasonic communication through solid channels such as metallic pipes or plates structures used in a complex industrial environment is challenging due to channel dispersion, attenuation, and multipath effect [1] [2] [3]. For example, when an elbow pipe, a common industrial structure, is used as the communication channel, the welded bent portion of the pipe highly attenuates, disperses and distorts the information bearing acoustic signal. The acoustic wave will be reflected and reverberated in multiple directions resulting in major time-spread. The conventional communication method using on-off keying (OOK) or phase-shift keying (PSK) as modulation fails to provide a practical bitrate (BR) or bit error rate (BER). To explore the adverse effect of signal spreading, we used the time reversal (TR) processing technique to compress the undesirable dispersion of the bit-wavelet [4]. Furthermore, the performance of TR processing has been examined for the pipe and plate channels using two types of transducers: i) piezoelectric transducers (PZT) and ii) electromagnetic acoustic transducers (EMATs).

Using the EMAT as transmitter and receiver in an ultrasonic communication system is a preferable non-contact alternative to other PZT [1] [5]. The EMAT transmitter is employed to excite different modes of shear horizontal wave (SH-wave) with intriguing properties for communications. However, to achieve stable communication, using EMAT is challenging due to low energy transduction and a variety of disturbances present in the channel such as multipath, limited bandwidth, RF interference, and path loss [6] [7]. The SH wave multipath propagation is the main reason for bit-wavelet spreading and causing serious intersymbol interference (ISI), which results in low signal-to-noise ratio (SNR) and BER [5]. TR can compress (refocus) the spreading of the bit-wavelet [4]. The refocus signal has a large amplitude and consequently easy to be detected. Most of the reverberations of the received signals such as the channel crosstalk, multipath and dispersion can be mitigated by the TR technique. TR technique can deliver a low-complexity and energy-efficient communication system. The technique can be applied to software-defined System-on-Chip (SoC) [8] [9]. In this study, an overview of the TR method for ultrasonic communication is introduced. We compare the TR technique applying to the elbow-shaped pipe channel using PZTs, and steel plate channel using EMATs. The experimental results are examined by using a developed TR-based communication platform. The objective of this study is to demonstrate TR method which can be utilized efficiently in the communication system. The transmitted signal and received signal are processed by our developed computer software and the peak detection is employed as the synchronization and decoding method.

II. EXPERIMENTS FOR TIME REVERSAL TECHNIQUE

There are three steps to implement the TR based communication platform which can be seen in Figure 1(a), (b) and (c). In this experiment, EMAT was used to measure the channel response. The excitation signal represents one-bit time and is modulated for energy efficient communication within the channel (Figure 1(a)).

$$a(t) = A * rect(t - \frac{t_1}{2}) * cos(2\pi f_c t)$$
$$rect(t) = \begin{cases} 0 & |t| > t_1 \\ 1 & |t| < t_1 \end{cases} \quad (1)$$

where t_1 is the pulse duration, and f_c is the carrier frequency. For the EAMT, f_c can be selected as 230 kHz, 279 kHz, 395 kHz, 555 kHz, and 700 kHz, which correspondingly excite the SH0, SH1, SH2, SH3, SH4 mode [10]. The pulse duration is selected as 3 µs, 6 µs, 10 µs, 50 µs, 100 µs and 200 µs. There is a tradeoff in signal energy and its SNR. We compare the performance of different pulse duration.

In Figure 1(b), the received pulse response $y(t)$ characterize the acoustic wave propagates through the highly dispersive and bandwidth limited channel. The received signal is captured, and time reversed representing the signal for one-bit information. This is needed in order to refocus and compress the time-spread signal associated with the channel. For improved performance in signal compression, we set the duration of the time reversed signal to 4 and 8 ms which fully signify the channel signal spreading characteristics.

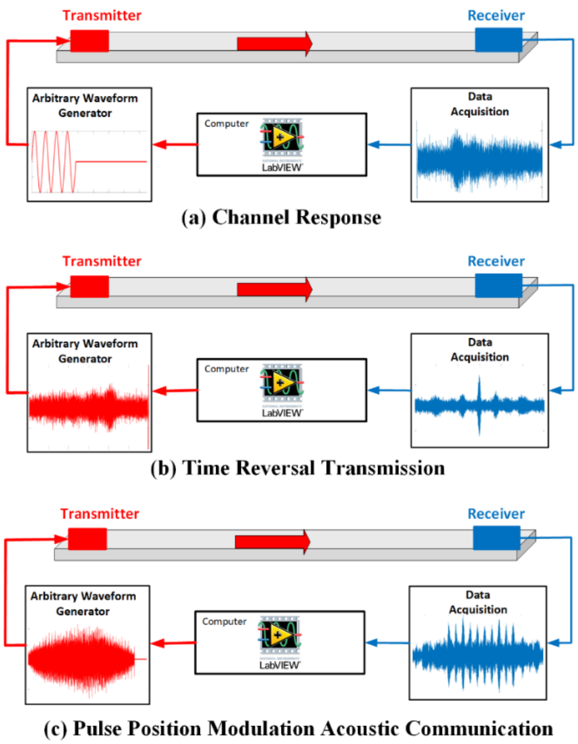


Figure 1. Experimental TR-PPM communication system where (a) represents channel response, (b) represents the time-reversed signal transmission, and (c) represents the compressed PPM received signal

In Figure 1(c), the recorded time reversed signal, $y(-t)$, represents the basic one-bit excitation signal for pulse position modulation (PPM). The transmitted message is a stream of binary information. The '1' or '0' are coded through different pulse shifts. The shift length is determined by the BR of communication associated with one-bit excitation signal, $y(-t)$. Thus, the PPM transmitted signal is defined as

$$s(t) = \sum_{i=1}^{N} A * (y(-t) * \delta(t - i * \frac{1}{BR} - a * \Delta) \qquad (2)$$
$$\begin{cases} a = 1, & if \;\; bit \; value \; is \;\; 0 \\ a = 0, & if \;\; bit \; value \; is \;\; 1 \end{cases}$$

where Δ represents the actual shift for the next bit when the pulse carries the bit '0'. In this case, $\Delta = \frac{1}{2\,BR}$. This study utilized the BR of 5 kbps, 10 kbps, 20 kbps, and 50 kbps which correspond to the frame delay time of 200 µs, 100 µs, 50 µs, and 20 µs. The BR in the signal shown in Figure 1(c) is 10 kbps resulting in a frame delay time of 100 µs.

III. Multipath Propagation Experimental Results

In this section, we present the multipath effect and the time reversal transmission results of using PZTs on the elbow pipe, and EMATs on the plate.

The multipath effect is serious and unpredictable when the acoustic wave propagates through the elbow pipe as shown in Figure 2. This figure also shows the profile of the elbow pipe where the elbow is welded with two straight pipes. The transmitted signal shown in Figure 2 is generated according to (1) where the center frequency is 670 kHz using a PZT transmitter, and the transmitted pulse is 100 µs. As shown in Figure 2, the received signal is captured by a PZT receiver with the center frequency of 670 kHz. The received signal contains multiple wave components and wave are scattered severely. The received waveform spreads and the condition of the welded bent elbow cause reflections. reverberations and mode conversion.

We examined the TR transmitted test results with different bit duration on the elbow pipe channel. The PZT transmitter and receiver are placed 10 cm away from the two ends of the elbow pipe and the carrier frequency is selected 670 kHz. We used 3 µs, 10 µs, 50 µs, 100 µs, and 200 µs pulse channel response as time reversed transmitted signals, as shown in Figure 3(a), as the pulse duration increases, the pulse responses gradually appear in the 4-ms received signals with a growing amplitude. No meaningful pattern can be discovered because of the welded pipe elbow. In Figure 3(b), the refocused peaks indicate the one-bit transmission through the elbow pipe channel. As the pulse duration increases, the amplitude of the refocused waveform and its sidelobes grow. Except for the 3 µs TR received signal, all the other signals have peak pulses significantly higher than their sidelobes and noise. Furthermore, all the dispersed scattered waves are suppressed.

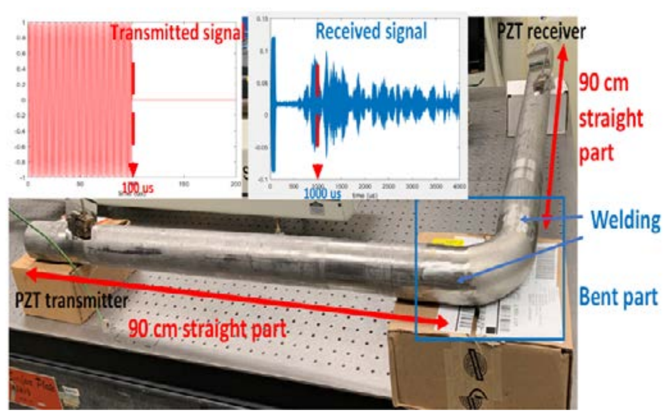
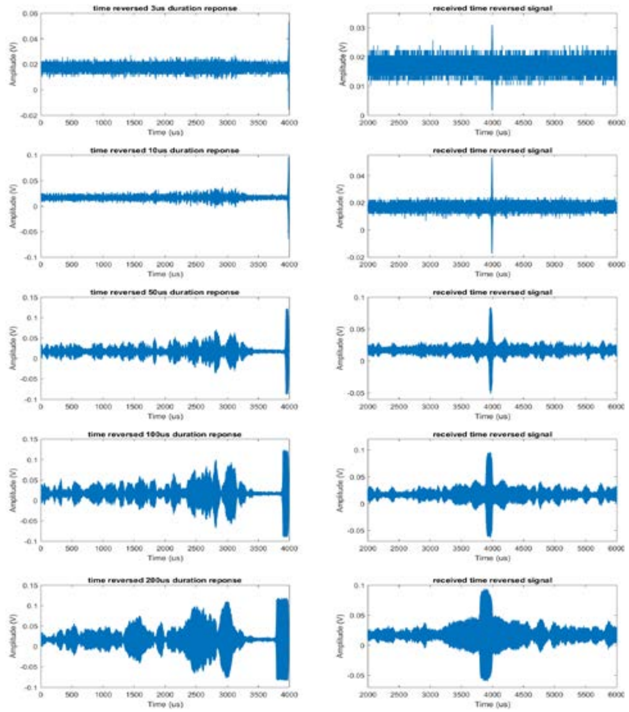


Figure 2. Ultrasonic communications through elbow pipe channel



(a) (b)

Figure 3. Different pulse duration TR communication results using the elbow pipe, PZT transmitter and PZT receiver: (a) Transmitted TR pulse channel response with different bit duration, and (b) Received compressed waveform with different pulse duration

The communication test using EMAT is implemented on the steel plate. The experiment setup is shown in Figure 4. The transmitter is placed 20 cm away from one edge of the plate and the receiver is placed 50 cm away from the other edge. The distance of the transmitter and receiver is 99 cm. The carrier frequency is 702 kHz, which corresponds to the SH4 mode of SH-wave. The SH wave multipath propagation is shown in Figure 4. The received signal is a result of acoustic signals propagate through the plate and interact with plate boundaries. The transmitter and receiver generate and detect the signals on both sides. The reverberations result in severe ISI and degrade the performance of the communication.

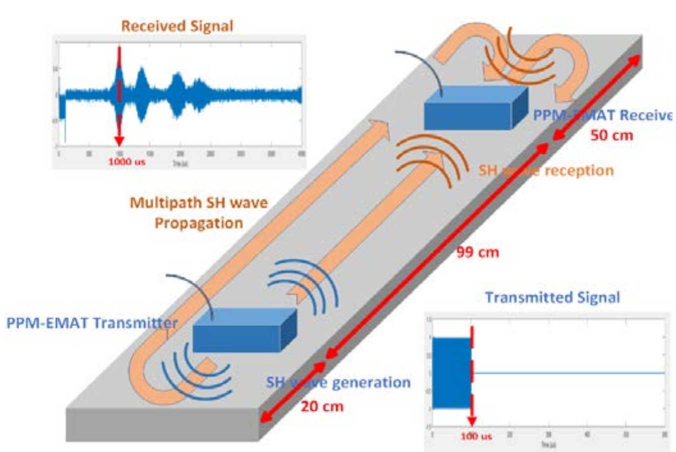
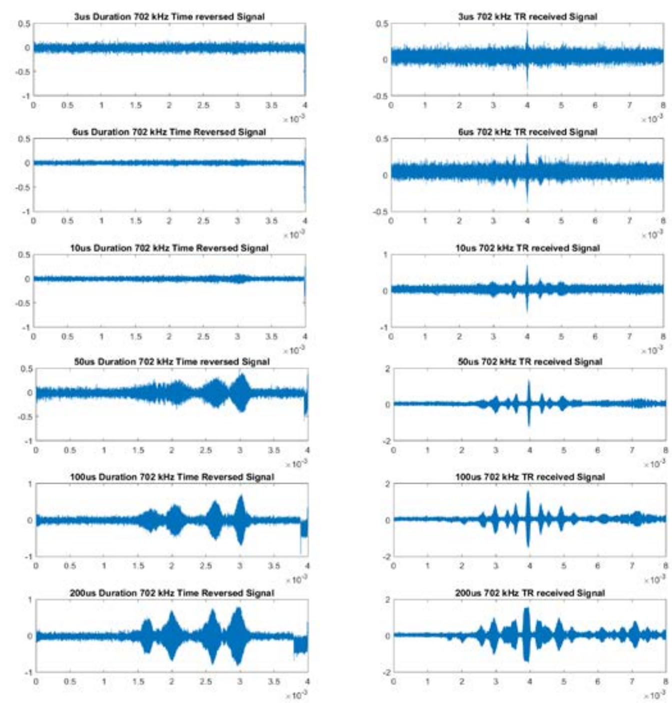


Figure 4. SH-wave generated by EMAT multipath propagation

The TR transmission results with different bit duration on the plate channel are shown in Figure 5. There is 6 pulse response are used as time reversed transmitted signals, which are 3 µs, 6 µs, 10 µs, 50 µs, 100 µs, and 200 µs. As can be seen in Figure 5(a), as the pulse duration increase, the energy of the received signal becomes large and multipath propagation effect is clearer. The received signal and reverberation have the same duration when the transmitted pulse duration is larger than 100 µs. The pattern of the reverberations is related to the structure of the plate channel.

In Figure 5(b), The peak of the received signal indicates that there is one-bit transmission through the channel which has large amplitude and easy to be detected. All the channel reverberations are removed. As the amplitude of 3 µs pulse response is small, the amplitude of its received refocused TR waveform is in consistency very small. This is the reason we can't use impulse response as the basic one-bit information for communication. However, as pulse duration increase, the energy of TR received signal and sidelobes is growing too. The growing sidelobes will cause ISI in TR-PPM communication. The sidelobes of 200 µs TR received signal is on the same scale of refocused peak pulse. We calculate the SNR of each received TR waveform and find the best pulse response as the basic one-bit information of communication.



(a) (b)

Figure 5. TR transmission and reception test results on the plate using EMAT transmitter and EMAT receiver: (a) Transmitted time reversed pulse response with different bit durations, and (b) Received TR waveform with different bit durations

The SNR calculation results for PZTs and EMATs are shown in Figure 6. The trend of the two curves is similar. The 10 µs pulse channel response has the largest SNR for both plate and elbow pipe channels. As the bit duration increases, the SNR of both channels drop. The SNR of the elbow pipe channel using PZT is overall larger than the plate channel using EMAT, which means the elbow pipe channel can achieve a better TR performance for communication.

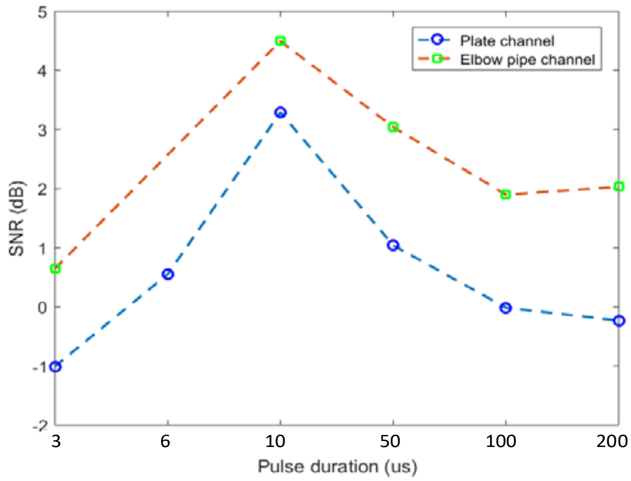


Figure 6. SNR comparison of TR ultrasonic communications

IV. CONCLUSION

In this paper, we discussed the feasibility of applying the TR technique in the ultrasonic communication system using the elbow pipe and plate as the communication channel. TR technique can effectively refocus the waveform into a significant peak regardless of the dispersion, multipath and channel crosstalk. An experimental system is introduced. The different pulse duration of pulse response in two channels is compared. A proper pulse duration response is explored to use as the basic information of the communication. Finally, the pulse position modulation is proposed to transmit and receive binary information through highly attenuative and dispersive steel plate channel. The TR technique shows a large potential in ultrasonic communication through dispersive and complex structure solids.

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