Software-Defined Ultrasonic Communication System Based on Time-reversal Signal Processing

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***Abstract*- Ultrasonic communication through solid channels suffers from channel dispersion, attenuation, and multipath effect. For example, in elbow shape pipes or complex structures, the elastic waves are reflected and reverberated in multipath resulting in a major dispersion of the signals. In solid channels such as flat bar, multipath propagation is the main reason for bit-wavelet spreading and intersymbol interference (ISI). The conventional modulation method like OOK (on-off-keying) or PSK (phase-shift-keying) fails to provide a useful Signal-to-Noise Ratio (SNR). Time-reversal (TR) signal processing method is a promising technique that can compress the spreading of the bit-wavelet and strengthen the peak signal energy on the receiver. In this study, Finite Element Analysis (FEA) using ABAQUS software tools is used to characterize the bit-wavelet spreading effect caused by dispersive communication channels. Also, this study presents the impact of TR ultrasonic communication as a function of excitation pulse width, channel length, and carrier frequency through a flat-bar channel. A Software-Defined System-on-Chip (SD-SoC) platform is examined as a viable solution for the low-complexity and energy-efficient ultrasonic communication system. The proposed TR based SD-SoC ultrasonic communication system can make full use of signal dispersion for peak performance by minimizing the ISI within a dispersive and reverberant metal channel.**

Keywords- Time Reversal Technique, FEM simulation, Software-defined System-on-Chip communication system.

I. INTRODUCTION

Ultrasonic waves are used as an information carrier in ultrasonic communication through a solid channel. Such communication suffers from channel dispersion, attenuation, and multipath effect [1] [2] [3]. The reflection and scattering in the bounded, inhomogeneous, and irregular channels spread the arrival of bit-wavelet and degradation of the SNR. The quality and bandwidth of the communication highly rely on the SNR of the received signal. Thus, the conventional OOK or PSK modulation fails to provide a practical bit rate and Bit Error Rate (BER).

The time-reversal (TR) signal processing method offers an effective alternative for implementing ultrasonic communication in metal communication channels [6]. We use the TR method to compress the undesirable dispersion of the received bit-wavelet for improved SNR. The TR refocusing is frequency-dependent and is governed by channel configuration and materials. This work presents the numerical simulation based on the TR technique for ultrasonic communication. FEA using the ABAQUS software tool is used to characterize the bit-wavelet spreading effect caused by the channel. Furthermore, FEA is used to simulate the TR performance as a function of excitation pulse width, channel length (the distance between the transmitter and receiver), and carrier frequency in an aluminum flat bar channel [7]. The optimal excitation pulse width, carrier frequency, and channel length for peak performance are explored. Results obtained prove that the TR signal processing method can efficiently increase the bitrate and decrease BER, and consequently become a desirable choice for ultrasonic communication through solid channels.

The TR technique can deliver a solution for low-complexity and energy-efficient communication system. This technique can be realized in a flexible software-defined system-on-chip (SoC) platform [8] [9]. Two solutions are provided to implement a time-reversal based ultrasonic communication system. One solution is based on the conventional test equipment such as the arbitrary waveform generator, and a more promising and highly flexible solution is using SD-SoC which can be adapted for various communication environments and channel configuration. In the following sections, we present simulation results, an experimental configuration for using PPM-EMAT [8] [9], and optimal solutions for peak performance in BR with minimal BER.

II. MODELING AND SIMULATIONS

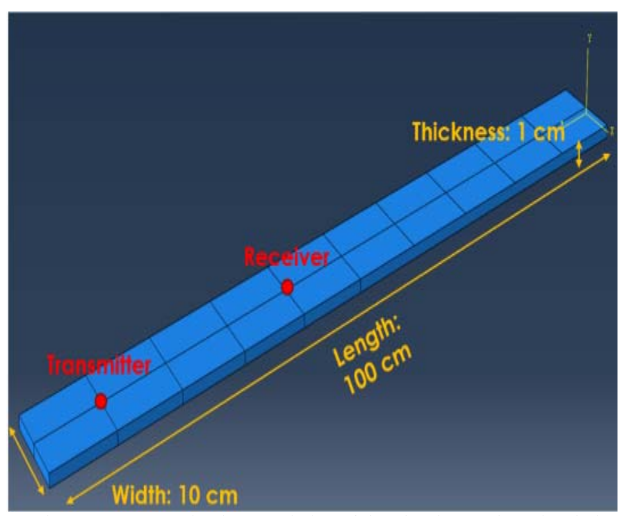

Figure 1. Geometric characteristics of the aluminum plate simulation model

The TR based communication system is a relatively new approach. Several factors such as excitation pulse width of one-bit information (i.e., bit-wavelet), channel length, and the carrier frequency are examined to obtain the peak performance. We chose to examine these factors by simulating the propagation of the TR signal through an aluminum flat bar channel ($100 \times 10 \times 1$ cm). Figure 1 shows the geometric characteristic of the flat bar channel and the position of the transmitter and receiver of the simulation module.

Figure 2 shows the necessary steps to simulate the results associated with the TR method. First, we need to determine the excitation pulse width for the one-bit information. The excitation pulse width was generated on the flat bar and the elastic wave was considered propagating through the bar channel. The transmitter and receiver shown in Figure 1 are positioned on the surface along the length of the bar. The time-reversed channel pulse response is used as one-bit information to be transmitted through the channel. Hence, the TR excitation representing the one-bit information can be detected as a compressed signal with peak performance at the receiver.

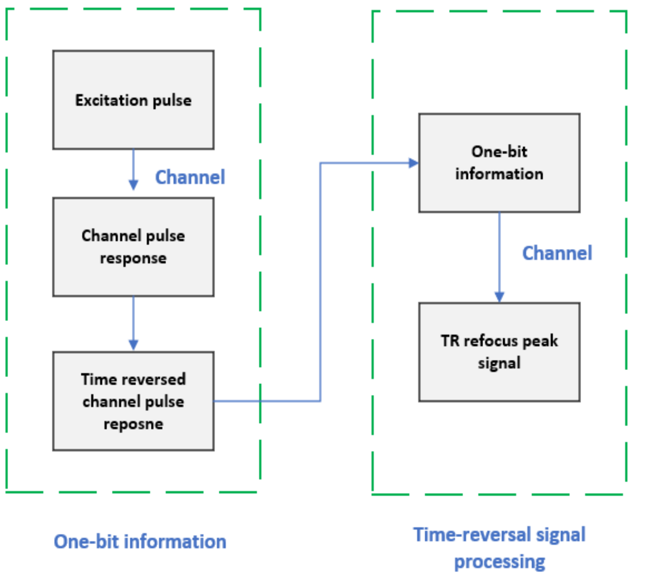

Figure 2. Block diagram for simulating a one-bit TR signal

Conceptually, the impulse response of the communication system is the best option to be used as one-bit information. However, in a practical ultrasonic communication system, signal attenuation and multipath effect caused by channel degrade SNR. Therefore, a practical approach is to select the excitation pulse width through experimentation for optimal performance.

The computer simulation of the excitation pulse width is performed using the ABAQUS software tool. Two excitation pulses with a duration of 7 µs and 10 µs are studied. The distance between the transmitter and receiver is 30 cm and the value of carrier frequency is 400 kHz.

The top, middle, and bottom traces of Figure 3(a) and Figure 3(b) describe the excitation pulse width, channel pulse response, and TR refocus received one-bit signal, respectively. These results show that multiple reflections and mode conversion are happening when the ultrasonic waves propagate and reverberate within a solid communication channel. The received one-bit TR refocus signal is compressed significantly and exhibit high SNR. As the excitation pulse width increases, the time span of the one-bit signal becomes larger and the amplitude of the peak signal becomes higher. Meanwhile, the sidelobes of the TR signal becomes larger as well, resulting in a lower SNR. Considering sidelobe adverse effect, a proper excitation pulse width is selected to achieve the highest SNR for the one-bit TR refocus signal.

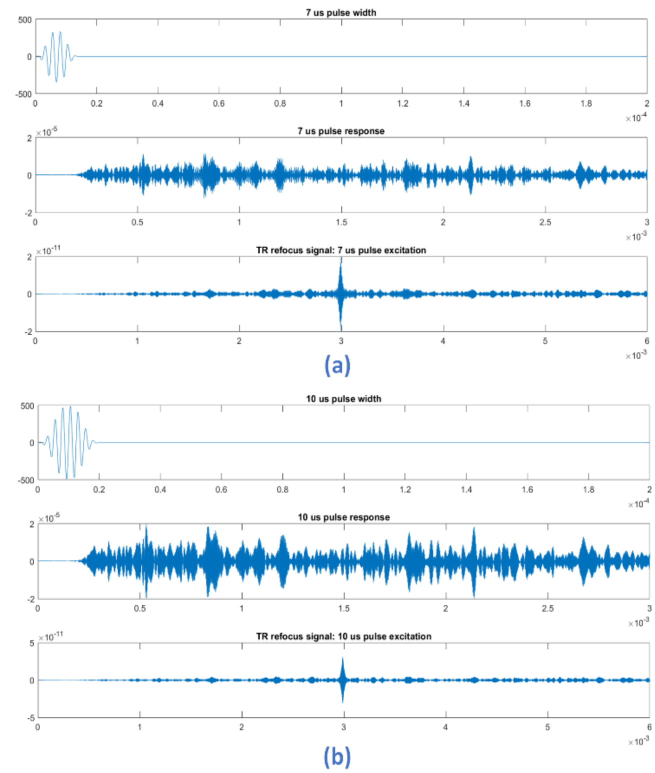

Figure 3. Pulse width performance evaluation using the ABAQUS FEA software tools; (a) represents the results for 7 µs pulse width, (b) represents the results for 10 µs pulse width.

Multiple distances (channel length) between the transmitter and receiver are studied to evaluate the TR performance as a function of channel length. Figure 4 shows the simulation results for 10 cm and 20 cm channel lengths. Results are obtained using 10 µs excitation pulse width and 400 kHz carrier frequency. Since the receiver is placed at a different position, the pulse response varies in channel length. The bottom trace shows the corresponding received one-bit TR refocus signal, which contains the same time span and remarkable amplitude. There is a minor difference in their sidelobes. The results reveal that the channel length is not an issue to implement TR based ultrasonic communication.

Multiple carrier frequencies are selected to evaluate TR ultrasonic communication. Results are obtained using 50 cm channel length and 10 µs excitation pulse width. The channel pulse responses of different carrier frequencies have complex wave modes and multipath effects. Consequently, communication performance is hampered by unavoidable reflections and reverberations. Nevertheless, as shown in Figure 5(a) and Figure 5(b) the TR signal processing method can well compress the spreading regardless of the carrier frequency.

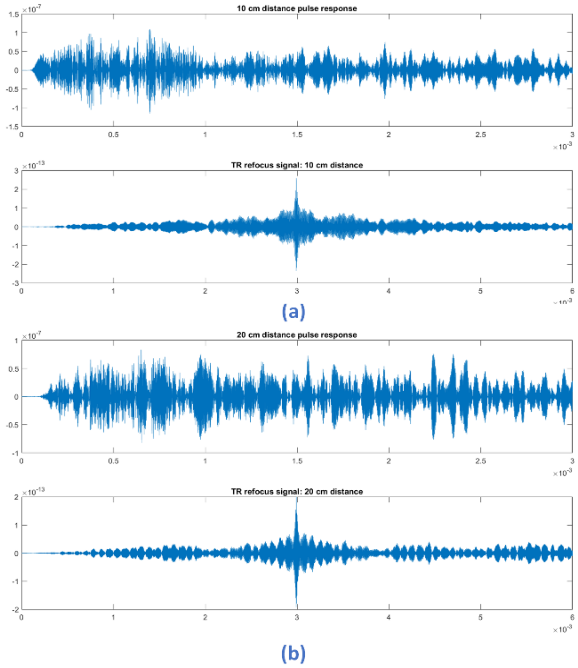

Figure 4. Channel length performance evaluation using the ABAQUS FEA software tool. (a) represents the results of 10 cm channel length and (b) represents the results of 20 cm channel length.

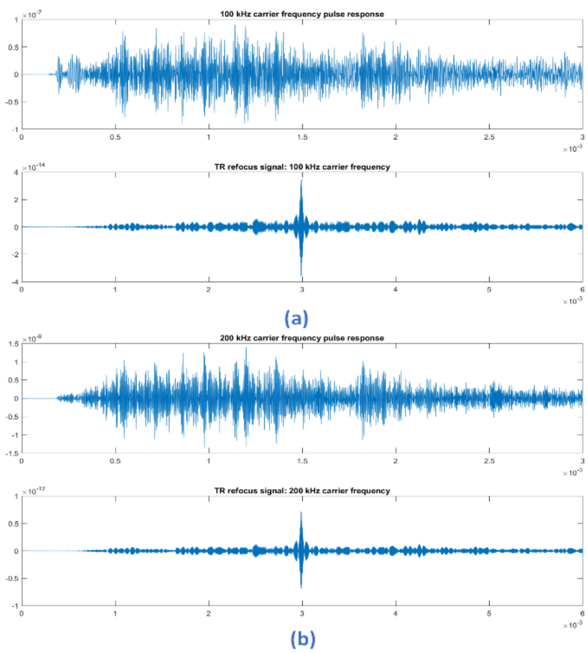

Figure 5. Carrier frequency performance evaluation using the ABAQUS FEA software tool; (a) represents the results of 100 kHz carrier frequency, (b) represents the results of 200 kHz carrier frequency

III. TR Ultrasonic Communication Platforms

We are investigating two possible solutions to implement the TR communication platform. A TR based communication system using conventional arbitrary waveform generator (AWG) and an SD-SoC platform are introduced and compared. The conventional TR based communication system consists of an AWG to generate the excitation message for transmission and a data acquisition unit to acquire and process the received signals. In this study, we use the pulse position modulation method to modulate the data symbol. The time delay of each bit of information is to distinguish the bit '0' or '1'. The frame time determines the data rate that can be achieved. The binary information modulated and being loaded to AWG chunk by chunk. On the receiver side, the amplitude threshold method is used as the demodulation method to recover the digital information. An SD-SoC platform is also examined as a viable solution for the low-complexity and energy-efficient ultrasonic communication system. The proposed TR based SD-SoC ultrasonic communication system can make full use of signal dispersion for peak performance by minimizing the ISI within a dispersive and reverberant metal channel. However, difficulties remain to implement the TR technique in the SD-SoC platform. Table □ presents the pros and cons of the two TR based communication platforms.

TABLE □. Pros and cons of conventional platform vs SD-SoC platform

	Conventional system	SD-SoC platform
Pros	• High precision of one-bit information • Optimal data rate	• Highly customizable • Supported by diverse software tool • Low cost
Cons	• limited system configuration and flexibility	• Low precision of one-bit information

IV. TR Based Ultrasonic Communication Test

When the PPM-EMAT [2] is used as transmitter and receiver through the flat bar channel, the communication suffers from a severe multipath effect. The reverberations of SH0 wave mode generated by 225 kHz spread in the time domain and result in severe ISI. It makes it impossible to implement general communication with conventional modulation methods. We use the TR signal processing method to explore the feasibility of using SH0 mode as the information carrier. Based on the simulation results, 10 μs excitation pulse width response is used as the one-bit information.

The 20-bit experimental results with a bit rate of 20 kbps are shown in Figure 6. Figure 6(a) depicts the TR pulse position modulation waveform and it includes the superposition of 20 one-bit information. Figure 6(b) shows a series of TR refocus signals. The green dashes indicate the position of bit '0' and the red dashes indicate the position of bit '1'. Figure 6(c) is the zoom-in plot of 20 kbps received waveform. The experimental results have the distinguishable peak '0' and peak '1' and can be detected by the expected position. The results reveal that we can achieve at least a bit rate of 20 kbps with TR based ultrasonic communication using SH0 mode as the information carrier.

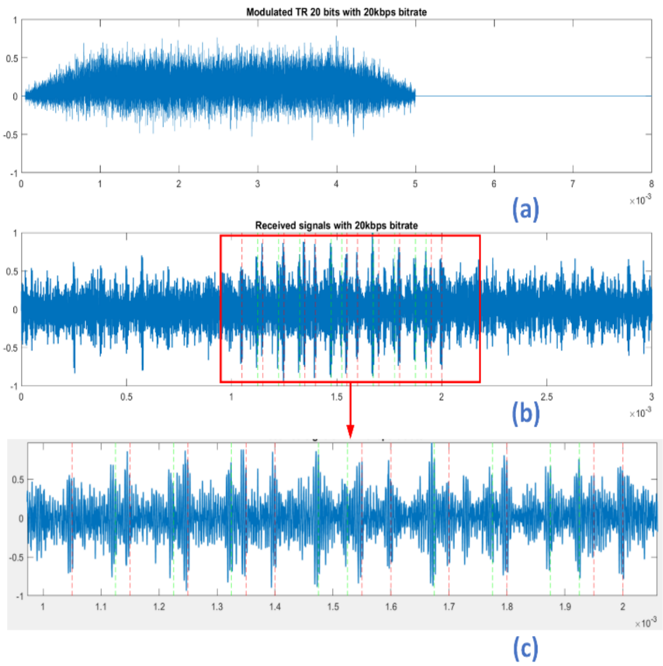

Figure 6. Multiple bits communication test at a bit rate of 20 kbps (a) TR pulse position modulation waveform (b) received waveform (c) details of 20 kbps received waveform

V. CONCLUSION

In this paper, we propose the TR signal processing algorithm to focus the dispersive guided wave though a flat-bar channel. In the FEA simulation, we explored the impact of TR ultrasonic communication as a function of excitation pulse width, channel length, and carrier frequency. The simulation results show that the TR technique can refocus and compact the waveform and improve the SNR and the detectability of information bit efficiently regardless of the position of the transducers and carrier frequencies. Moreover, the appropriate excitation pulse width can overcome the attenuation caused by the channel. TR based communication systems using conventional AWG and an SD-SoC platform are discussed. The experimental results prove the feasibility and effectiveness of the TR method in practice. The TR signal processing method can increase the SNR and bit rate significantly. A bit rate of 20 kbps can be achieved without any error using PPM-EMAT as transmitter and receiver.

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