Performance Evaluation of High-Temperature Ultrasonic Communication System

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***Abstract*- Ultrasonic communication is a technique that allows transmitting information through a solid material such as tubes or bars using high-frequency elastic waves. The communication channels often extend into a high-temperature range in the field of power, oil, or nuclear industry. When the temperature is taken into consideration, the ultrasonic wave propagation through the solid channel is complex and unpredictable. It is necessary to study the influence of temperature on the ultrasonic guided wave to improve ultrasonic communication. In this study, a temperature control system is assembled to adjust the temperature of a steel pipe channel ranging from room temperature to 150 ˚C. The temperature performance evaluation is conducted to estimate the signal-to-noise ratio (SNR) and bit error rate (BER) of transferring the ultrasonic signal. The work aims to develop a reliable ultrasonic communication system in a high-temperature environment. The system temperature can be maintained at 150 ˚C and the $LiNbO_3$ transducers are used as transmitters and receivers. No power amplifier is used in the communication system. The high-temperature ultrasonic communication system (HT-UCS) is feasible at 150 ˚C and can achieve a bit rate of 10 kbps without any error.**

Keywords- HT-UCS, temperature control unit, steel pipe channel

I. Introduction

Ultrasonic communication is a practical method for transmitting information through solid channels such as tubes, plates, or bars [1] [2] [3] [4]. The communication channels penetrate through the enclosures and often extend into a high-temperature range in the field of power, oil, or nuclear industry. The influence of temperature is regarded as an important factor for ultrasonic communication based on the ultrasonic wave propagation. When the temperature is taken into consideration, the solid communication channels made of aluminum, iron, or steel have a thermal expansion effect [5], which leads to changes in its shape, volume, and density in response to the change in temperature. Also, temperature affects the velocity of the longitudinal wave and shear wave [6]. As a result, the distortion and attenuation of ultrasonic waves through solid channels are complex and unpredictable due to temperature variations. The qualitative evaluation of ultrasonic guided waves through a high-temperature channel is necessary to be studied for improving ultrasonic communication performance [7] [8].

In this study, the High-Temperature Ultrasonic Communication System (HT-UCS) is designed for communication through metallic pipe structures often encountered in industrial environments such as nuclear power plants. A temperature control system is assembled to adjust the temperature of a steel pipe channel ranging from room temperature to 150 ˚C. The system can keep the steel pipe channel at a desired stable temperature. The $LiNbO_3$ transducers are used as transmitters and receivers which can be operated under 650 ˚C. The 720 kHz carrier frequency is selected. In addition, the energy-efficient HT-UCS does not need a power amplifier. To explore the influence of the high-temperature environment, we evaluate the signal-to-noise ratio (SNR) and bit error rate (BER) of the ultrasonic communication system. A binary information test with a bit rate from 1 kbps to 10 kbps is implemented for preliminary evaluation. The ultrasonic communication test is conducted through the 150 ˚C steel pipe channel. The HT-UCS can be ported onto a software-defined system on chip platform [9] [10]. We will test the time-reversal ultrasonic communication using HT-UCS in a high-temperature environment in the future [11]. In addition, we will design the high temperature electromagnetic acoustic transducer (EMAT) for the pipe channel [12].

II. HT-UCS Setup and Configuration

This section describes the laboratory setup of the HT-UCS to illustrate the performance of ultrasonic communication. The customized communication system is well developed for transmitting information at room temperature, which includes an arbitrary waveform generator and a data acquisition unit. This work focuses on the hot pipe channel which completely simulates the metal pathway penetrating the thick concrete wall in the nuclear facilities.

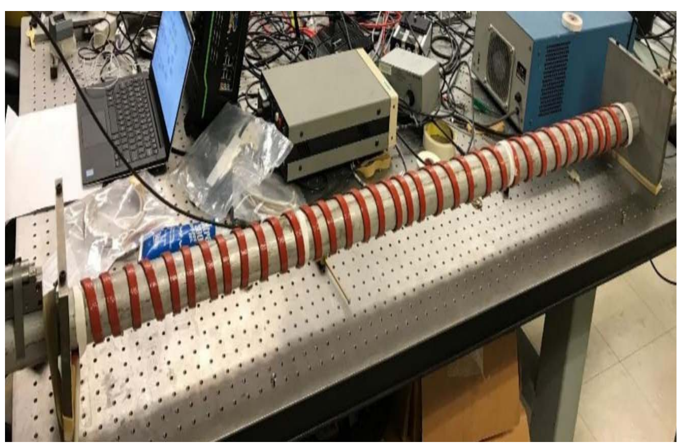


Figure 1. Heating tape installation

As shown in Figure 1, a 182 cm (6 feet) long stainless-steel schedule 160 pipe with an outer radius of 6.1 cm and an inner radius of 4.1 cm is used as the communication channel. The pipe is welded to two baffle plates, which simulate the pipe embedded in the thick concrete wall that prohibits other communication links. The heating tape is used as the heat source to wrap around the main part of the pipe. Since the $LiNbO_3$ transducers need some space to couple with the pipe, aluminum insertion elements connected with a 20 W heater are installed at each end of the pipe channel. Thus, the pipe can be evenly heated. The distance between the transmitter and receiver is 170 cm.

The mineral wool is used as thermal insulation to prevent heat loss. The mineral wool is cut to fit the shape of the pipe and transducer. The gaps are filled with loose wool. Figure 2 shows the setup of thermal insulation.

Figure 2. Mineral wool thermal insulation installation

The thermal insulation is enclosed with stainless-steel cover and is fastened by clamps and wires, which can further reduce the temperature influence of the surroundings. Figure 3 shows the installation of the cover. The setup of the pipe channel is the same as the pipes used in the nuclear facilities.

Figure 3. Stainless-steel cover installation

Thermocouples are used to monitor the temperature of the pipe in real-time. They are installed in the middle and two ends of the pipe channel. The temperature controllers are hooked up with the heating tape and the thermocouple. As depicted in Figure 4, the red LED displays the current temperature of the thermocouple, and the green LED displays preset temperatures. The system takes around 3 hours to raise the temperature of the channel to 150 ˚C. The temperature is then maintained at the desired setting.

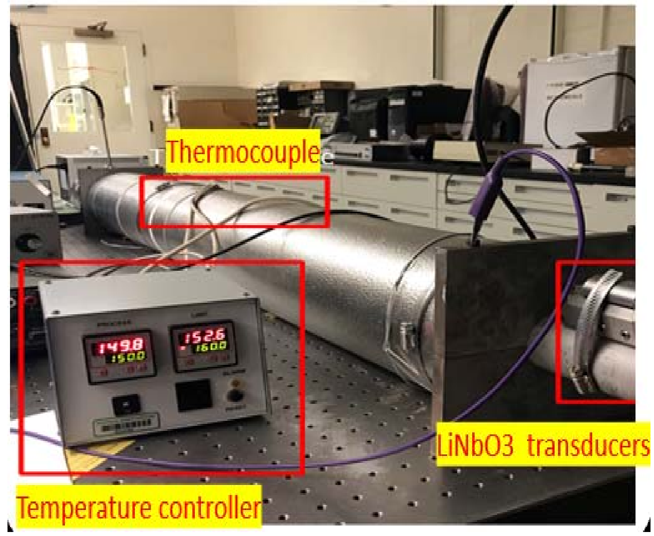


Figure 4. Temperature controller installation

III. Communication Test

To validate if the $LiNbO_3$ transducers can be used as the transmitter and receiver through the pipe channel, we used the same setup to transfer information at room temperature. The binary information consists of a sequence of '10101010' bits. The carrier frequency is selected as 720 kHz. The received signals with bit duration are shown in Figure 5.

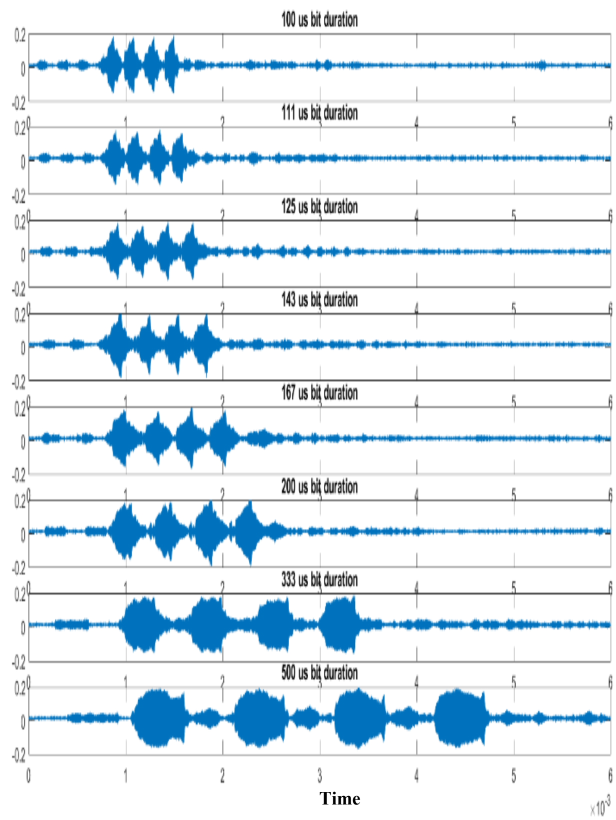
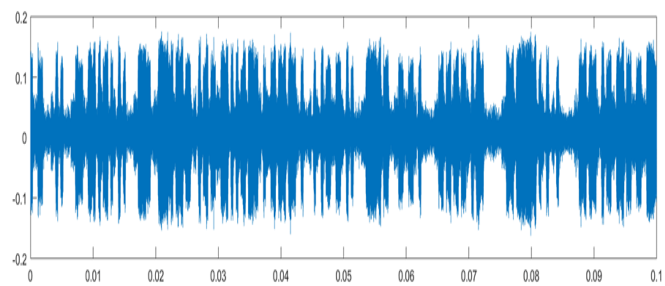


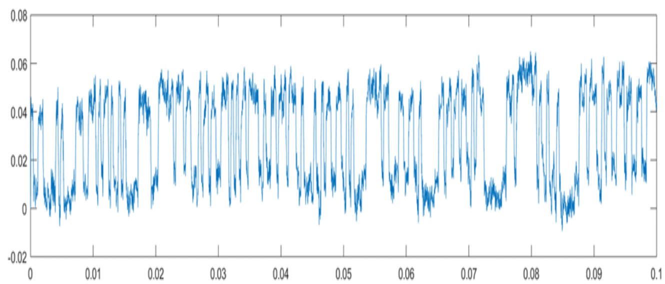
Figure 5. Received binary test pulse with different duration

The binary information is modulated by amplitude shift keying. The pulse width of each bit is 100 µs, 111 µs, 125 µs, 143 µs, 167 µs, 200 µs, 333 µs, and 500 µs respectively, which corresponds to a bit rate of 10 kbps, 9 kbps, 8 kbps, 7 kbps, 6 kbps, 5 kbps, 3 kbps, and 2 kbps. Multiple wave modes and the ringing of the received signal showed up in all received signals. The reverberations cause intersymbol interference (ISI) and degrade the SNR. The SNR of 100 µs pulse duration is low compared with longer pulse duration. The amplitude thresholding is used to remove the reverberations and resolve the digital information.

The communication test is conducted at 150 ˚C under the same condition and the pulse width of one single bit is 100 µs. The results are shown in Figure 6.



(a)



(b)

Figure 6. Communication test results; (a) the received signal, (b) demodulated signal

Figure 6(a) shows that the received signals at 150 ˚C are attenuated and distorted compared with the test results at room temperature. Though the SNR at 150 ˚C decreased, the received signals have a distinguishable bit ‘0’ and bit ‘1’. The digital information can be recovered from the demodulated signal shown in Figure 6(b). The communication test results reveal that we can achieve a bit rate of 10 kbps without any error.

IV. Conclusion

In this paper, we develop a custom HT-UCS to perform ultrasonic communication in a high-temperature environment. The HT-UCS is assembled by installing the heating elements, thermal insulation, cover, and temperature controller. The system can be maintained at the desired temperature for an extended period. The $LiNbO_3$ transducers can be used as transmitters and receivers at room temperature and 150 ˚C. The experimental results indicate that temperature affects the ultrasonic wave propagation and SNR of received signals. The SNR of 150 ˚C heated pipe is sufficient to conduct ultrasonic communication with low BER. The final communication test results reveal that the energy-efficient system can achieve 10-kbps communication through a 170 cm steel pipe at 150 ˚C, which greatly extends the applications of the ultrasonic communication system.

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