Transmission of Images With Ultrasonic Elastic Shear Waves on a Metallic Pipe Using Amplitude Shift Keying Protocol

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***Abstract*— Transmission of information using ultrasonic elastic waves on existing metallic pipes provides an alternative communication option across physical barriers in a highly partitioned industrial complex, such as a nuclear facility. This work investigates the feasibility of the transmission of digital images over metallic pipes. Ultrasonic communication systems for transmission of images on a nuclear-grade stainless steel pipe were assembled for bench-scale demonstration. Information carriers in this system are refracted shear waves transmitted and received with piezoelectric transducers (PZTs) operating at 2-MHz nominal frequency. The refraction and propagation of ultrasonic shear waves were modeled with COMSOL software. An amplitude shift keying (ASK) communication protocol for image transmission was developed and implemented in the GNURadio software-defined radio (SDR) environment. Digital information was converted to analog ultrasonic signals using Red Pitaya electronic boards. The performance of the ASK protocol is evaluated at the output of every block in the GNURadio program by monitoring the transmission of select characters. Using the ASK communication protocol, the transmission of the 32-KB image was demonstrated at 2-Kbps bitrate across 6-ft-long stainless steel pipe. Preliminary evaluation of ultrasonic communication on the piping of a nuclear facility, such as signal transmission on bent pipes, was performed with COMSOL computer simulations.**

***Index Terms*— Amplitude shift keying (ASK), digital images, ultrasonic transducers.**

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I. Introduction

TRANSMISSION of information using ultrasonic waves as information carriers on pipes provides an alternative communication option for scenarios when conventional wired or wireless communications are ineffective or disabled. For example, using existing pipes as communication channels in a nuclear facility provides an option to transmit information to hard-to-reach places and across physical barriers in the post-accident scenario [1]. The main components of a nuclear facility are isolated from the outside world with 3–4-ft-thick concrete walls of a containment building. In most of the designs, the concrete walls of a containment building are also plated with a metallic liner. A barrier of this type blocks a wireless RF communication channel [2]. Existing penetrations of the containment building wall consist of specially designed tunnels for heat exchanger pipes, which deliver water from and back to the ambient reservoir [3]. The tunnels are sealed with metallic plates on both ends, which prevents the insertion of any electrical or fiber optics communication cables. The metallic pipes are not in physical contact with concrete of the tunnel, which allows for the propagation of elastic waves on pipes for sufficient distance to traverse the concrete wall barrier [4]. Because mounting ultrasonic transducers on pipes involves minimal hardware modifications, such a communication system would be compliant with requirements of nuclear facility operations, which are subject to strict regulations. In addition, this approach provides a degree of physical cybersecurity and accident resilience since the channel consisting of a metallic pipe is difficult to sever, compared to conventional communication cables [5].

In general, ultrasonic information transmission involves either free space (acoustic waves in fluids in solids) or guided wave (elastic waves in solids) communications. The majority of work in free space ultrasonic transmission is directed toward underwater acoustic communications [6], [7], but communication through air [8], [9] and metallic media have been studied recently [10], [11]. Guided-wave ultrasonic communication on pipes combines elements of communication theory with ultrasonic transducers and wave propagation in solids, which are traditionally investigated in the context of nondestructive testing [12], [13]. Prior work on ultrasonic information transmission with guided elastic waves on metallic pipes has considered energy-efficient low bitrate (∼100 bps) communication using ON/OFF keying (OOK) modulation and chirped OOK to mitigate frequency selectivity of the channel [14], and explored several approaches to modulation/demodulation using time-reversal position modulation [15], and cyclic frequency shifting [16]. In addition, using different types of ultrasonic transducers, such as the electromagnetic acoustic transducers (EMAT), for communications using elastic guided waves on plates has been studied recently [17], [18].

In this article, we investigate the ultrasonic transmission of a large volume of data, such as images, at a high bit rate, along the metallic nuclear-grade pipes. Because of the limited bandwidth of ultrasonic transducers, amplitude shift keying (ASK) modulation, which is one of the realizations of OOK protocol, was used for information transmission. A preliminary description of an ultrasonic communication system on pipes was presented in [5]. The communication scheme is implemented using GNURadio software-defined radio (SDR) environment. Recent studies investigated SDR-based communications using longitudinal wave transmission through solids and guided elastic waves communication on plates [19]–[21]. Transmission of small volumes of data, such as text, has been demonstrated [21]. This article contains a detailed analysis of the image transmission protocol developed in the GNURadio SDR environment and demonstration of the communication protocol performance in transmitting an image with ultrasonic shear waves on a pipe. Images were transmitted along the metallic pipe using ultrasonic carrier frequency elastic shear waves at 2-Kbps bitrate. The analysis presented in this article allows us to evaluate the performance of the ultrasonic communication system and investigate strategies for further improvement.

This article is organized as follows. Section II discusses the hardware and software of the ultrasonic communication system. Section III presents the analysis of the communication protocol by monitoring transmission of a simple message through the communication system. Section IV briefly discusses potential challenges for deployment of the ultrasonic communication in a nuclear facility. Section V contains the summary and conclusions.

II. Ultrasonic Communication System Design

A. Ultrasonic Communication System Hardware

A literature review of common reactor designs has identified a chemical volume and control system (CVCS) water carrying pipe, which penetrates the reactor containment building wall in several reactor designs, as a viable conduit for communications [3]. A laboratory bench-scale system consisting of a nuclear-grade CVCS-like stainless steel pipe and ultrasonic piezoelectric transducers (PZTs) was assembled for a preliminary communication system analysis. The pipe used in the bench-scale study is a 6-ft-long schedule 160 stainless steel 304 L with 2.375-in outer diameter and 0.344-in wall thickness.

This study used commercial paintbrush PZTs operating at a nominal frequency of 2 MHz. While other types of ultrasonic transducers, such as high-temperature compatible electromagnetic transducers (EMATs), can be used for data transmission, PZT has better coupling efficiency for non-ferromagnetic pipes. The PZT is mounted on a commercial acrylic angled wedge, and the angle of which exceeds the first critical angle of 27.6° for the acrylic/stainless steel interface. Although the nominal frequency of the PZTs is 2 MHz, it was determined that, once coupled to the pipe through angled wedges, the largest amplitude signal was obtained by operating PZT at 1.8 MHz.

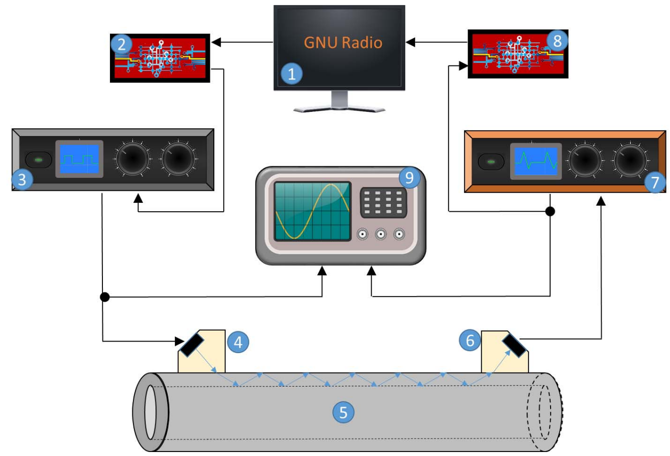

Fig. 1. Hardware of OOK shear wave acoustic communication on pipe setup. (1) Digital computer with GNURadio software. (2) Red Pitaya transmitter board. (3) Power amplifier. (4) Angled-wedge mounted PZT transmitting refracted shear waves. (5) Stainless steel pipe. (6) Angled-wedge mounted PZT receiving shear waves. (7) Low-noise amplifier. (8) Red Pitaya receiver board. (9) Digital oscilloscope.

Communication with shear waves is advantageous because they do not couple into the water, which could be present inside the pipe. In addition, the excitation of multiple modes that travel at different velocities along the pipe can lead to intersymbol interference. Below the first critical angle, a refracted wave consists of both longitudinal and shear wave components, while above the critical angle only shear wave is refracted. The study utilized a commercial 45° wedge, for which it was determined experimentally that the received signal consisted of shear waves only.

In principle, in nondestructive testing applications, elastic waves on pipes are frequently generated with the radially symmetric collar-type transducer. However, the CVCS pipes are part of the thermal-hydraulic system, and as such are enclosed by a layer of thermal insulation. Thermal insulation materials, such as mineral wool, are poor transmitters of acoustic waves. To achieve efficient coupling of acoustic waves into the pipe, the insulation material has to be removed for the transducer to be directly in contact with the metal pipe. Thus, it is preferable to use a transducer with the smallest form factor so that minimal amount of thermal insulation needs to be removed and no thermal imbalances in the coolant system are created.

A schematic depiction of the communication system is shown in Fig. 1. A digital signal is generated by the GNURadio program (1), which is next converted into an analog signal through modulation of the amplitude of the carrier ultrasonic wave by Red Pitaya electronic board (2). In our study, we encoded information using binary ASK. The analog wave is amplified with a 50-dB power amplifier (3) and converted into an ultrasonic pressure wave with a PZT (4). The incident longitudinal wave is mode-converted into a shear wave, which subsequently propagates down the stainless steel pipe (5). By symmetry, the shear wave is refracted into the angled wedge at the receiving end of the pipe to become a longitudinal wave, which is converted by the receiving PZT (6) into an electrical signal. The received signal is amplified with a 20-dB low noise amplifier (LNA) and demodulated with receiver Red Pitaya board (8) and passed through a low-pass filter to recover the information encoded in the amplitude of the carrier. The analog signal is decimated to create a digital signal, and the bits are repacked with GNURadio software. In this study, transmitted signals from PA and received signals from LNA were sampled with a digital oscilloscope (9) to analyze the performance of the communication protocol for transmission of images.

Preliminary studies have shown that ultrasonic information transmission over the pipe is resilient to low-frequency noise. Proof-of-principle demonstrations were performed with mechanical shaker vibrating the pipe at frequencies from 100 Hz to 10 KHz, with no observable effects on information transmitted with 1.8-MHz carrier shear wave [5].

B. Computer Modeling of Refracted Shear Wave Coupling

Computer simulations were performed with the COMSOL Multiphysics Solid Mechanics Module software package to model generation of refracted shear waves with an angled wedge-mounted transducer on a CVCS-like pipe.

In the COMSOL model, refracted shear waves are generated at the boundary of the acrylic wedge and stainless steel pipe through a direct solution of elastodynamic equations in COMSOL. Instead of explicitly modeling PZT, the source of longitudinal waves is a boundary load applied to the acrylic wedge surface, which would in contact with the PZT surface in the experiment. As could be seen in the graphics in Fig. 2, PZT structure is absent from the COMSOL model. Ultrasonic frequency of 500 KHz was used in the computer simulations to reduce memory requirements due to coarser grid meshing for longer wavelength. While this frequency is smaller than the 2 MHz of the transducer used in the experiment, the physics of refracted shear wave generation and transmission does not change appreciably with frequency. The pipe in the COMSOL model has the same diameter and thickness as the experimental article (2.375 in outer diameter and 0.344 in wall thickness), but the length is shortened to 60 cm (2 ft). The amplitude of the ultrasonic elastic wave is visualized with a pseudo-color map of pressure distribution, with green being zero, and warmer and colder colors corresponding to positive and negative values, respectively. To increase the visibility of wavefronts in this coloring scheme, the amplitude of the elastic wave was taken to be 4×10^7 N/m^2.

Fig. 2 (top) shows the pressure distribution of 40 μs after the start of the simulations when the refracted shear wave is coupled into the pipe. Fig. 2 (middle) shows the pressure

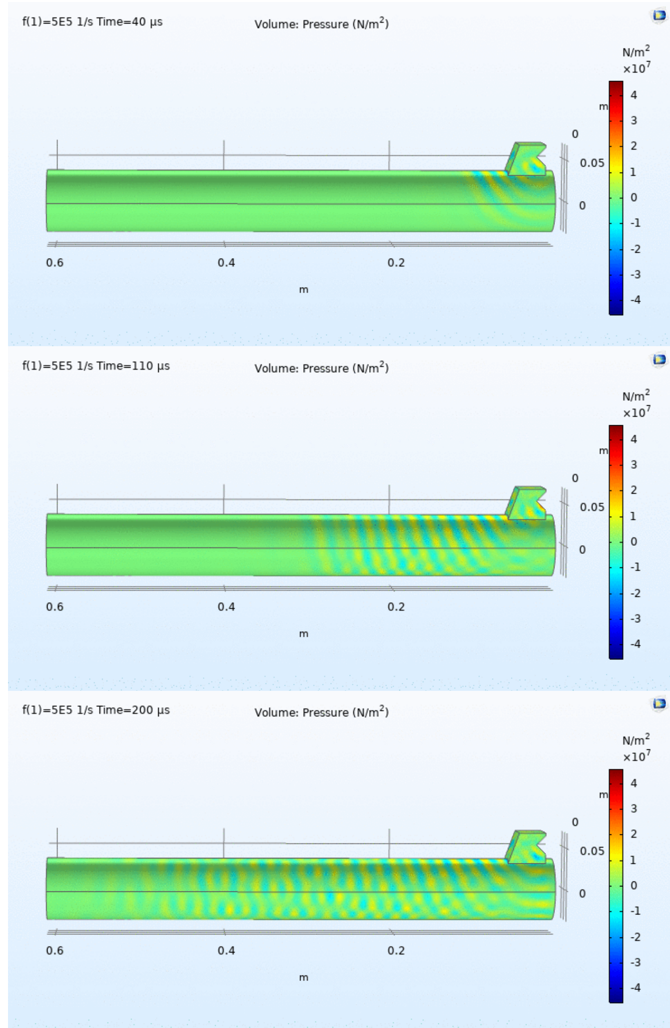

Fig. 2. Computer simulations of coupling and propagation of refracted shear wave on the pipe, excited with 500-kHz PZT on a 45° angle wedge. Ultrasonic wavefronts are visualized with a pseudo-color map of pressure distribution at 40, 110, and 200 μs.

distribution after 110 μs when the wave reaches approximately the middle of the pipe (30 cm mark). Since the shear wave velocity in stainless steel is 3100 m/s, after 110 μs the propagation distance is 34 cm, which is qualitatively in agreement with COMSOL simulations. The longitudinal wave velocity is 5790 m/s so that in 110 μs the longitudinal wave would have traversed 63 cm distance, which is the entire length of the pipe. This is not observed in COMSOL simulations shown in Fig. 2. Therefore, these observations confirm that the COMSOL model generates refracted shear waves on a pipe. Fig. 2 (bottom) shows the pressure distribution at 200 μs after the start of the simulations. The pseudo-color map of pressure distribution indicates that the wave has reached the end of the pipe. This is consistent with estimations based on shear wave velocity, which predict propagation distance of 62 cm after 200 μs. This simulation confirms qualitatively that pure ultrasonic shear wave is generated in the experimental configuration.

Visualizations of ultrasonic wavefronts in Fig. 2 indicate that while the wave is initially propagating at an angle to the pipe axis, after propagating for approximately 30 cm distance, the wave is collinear with the pipe axis. For example, in the far field, the wave from a single transducer has a similar radial profile as that generated by a ring of transducers. Experiments on transmitting single pulses across the pipe have shown that the amplitude of the received signal does not change appreciably when the receiving transducer is positioned at 90° and 180° relative to the transmitting PZT. This indicates that the communication system is resilient to the misalignment of transducers.

C. Overview of GNURadio Communication Protocol

The data transmission program was implemented in GNURadio, which is a freeware Defined Radio (SDR) programming environment. The flowchart of the ASK communication program developed in GNURadio is shown in Fig. 3. The program consists of blocks performing modulation and demodulation functions. While more elaborate forms of shift keying exist that allow for more information to be encoded per key, we chose ASK technique due to the fact that the constellation symbols are maximally spread out, reducing the impact of noise on the channel compared to a setup that encodes more than one bit per symbol.

ASK communication consists of a binary stream of information. Since an image data has a non-binary format, we have chosen a portable pixel map (PPM) file type to be the image data structure. The PPM file type stores the image dimensions in the first three lines. The rest of the PPM file contains the image stored as a matrix of ASCII character. We will refer to the three lines of the PPM file as the "image header" and call the rest as the "image payload." Error-free transmission of the image header is critical to the successful reconstruction of the received image. The imaging payload, on the other hand, has a lower tolerance to errors since a few errors are not likely to make the file unreadable.

Transmission of the image involves the conversion of the PPM, data structure into a binary one, and reassembling the received binary data into the original PPM format. To accomplish these tasks, we first disassemble the file into a stream of ASCII characters, in the form of bytes (1 byte = 8 bits). These characters are then converted into a bitstream with an attached packet header. After demodulation, the bit stream is parsed to remove the packet header, the bits are converted into their original bytes, and the file is reassembled. If error correction is added to the protocol, after the bytes are converted into bits, they are multiplied by a convolution matrix. Once the communication packet is received, the bits are decoded by an inverse matrix.

III. Analysis of GNURadio Communication Protocol Performance

A. Communication Protocol Testing and Analysis

To analyze the performance of the data transmission program, a simple message with characters "!s!" was passed through the system and monitored in the output of each block in the flowchart in Fig. 3. Output signals from select blocks in the communication program, plotted with Python Matplotlib software, are displayed in Figs. 4–11.

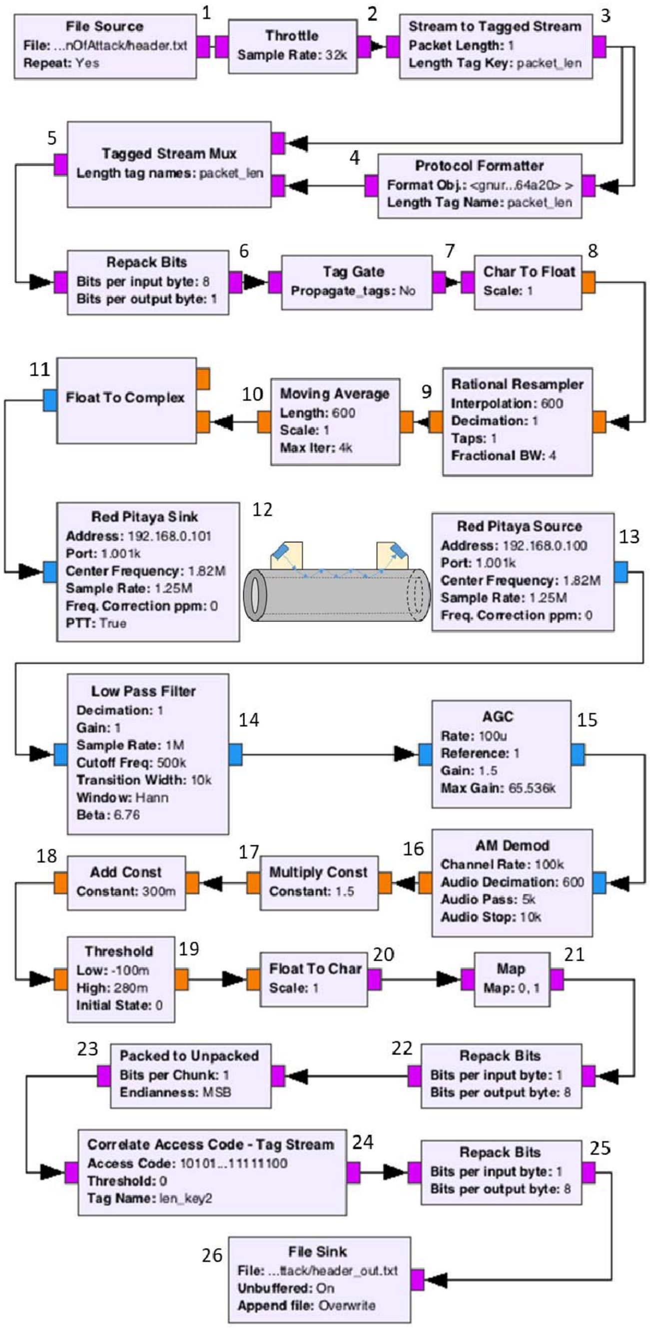

Fig. 3. ASK communication protocol signal flow graph created in GNURadio. Each block is numbered at the output.

In the File Source block #1, the file is disassembled into three ASCII values: 33, 115, 33. The value of 33 corresponds to "!" and the value of 115 corresponds to "s." The Protocol Formatter block #4 creates a tagged stream of 1's and 0's that will be attached to the payload. We use the default preamble of "1010010011110010" and access code of "1010110011011101101001001110001011110010100011000010000011111100." Fig. 4 visualizes the result of combining the header file with the payload in Tagged Stream MUX block #5. The first 12 bytes (0–11) are from the protocol formatter, while the last three (12, 13, and 14) correspond to the ASCII values of the characters "!s!" from the file source.

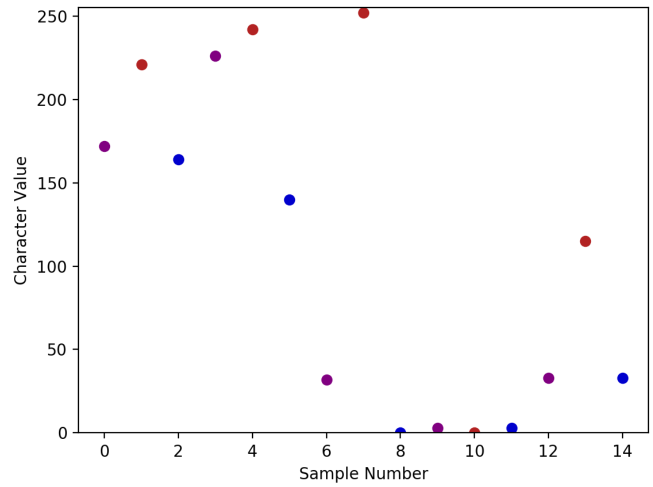

Fig. 4. Tagged Stream MUX block #5 output (data colored as individual bytes).

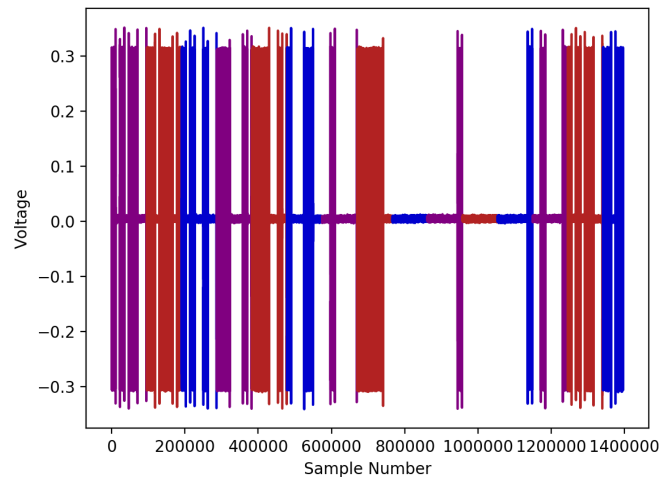

Fig. 6. Transmitted wave output of Red Pitaya Sink block #12, recorded with a digital oscilloscope (data colored as individual bytes).

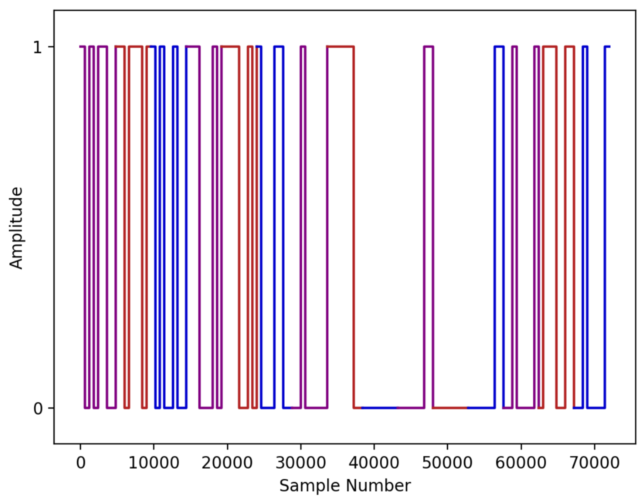

Fig. 5. Analog square wave at the Moving Average block #10 output (data colored as individual bytes).

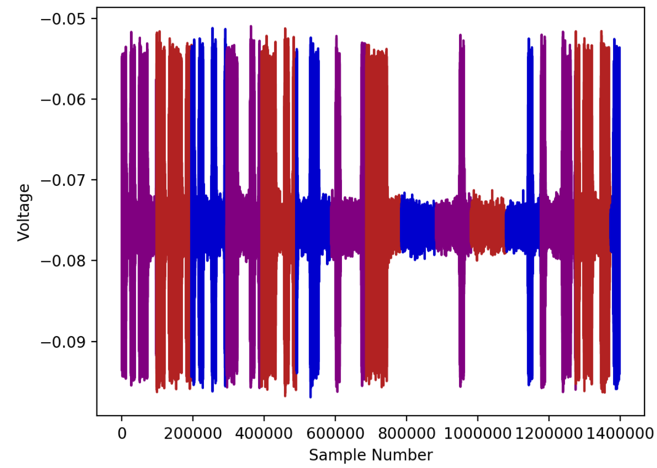

Fig. 7. Received wave on the pipe before demodulation in Red Pitaya Source block #13 (data colored as individual bytes).

The Repack Bits block #6 unpacks each byte into eight bits. There are 15 bytes in the packet, which means that 120 samples are sent through the system ($15^*8 = 120$). Fig. 5 shows the signals at the output of the Moving Average blocks #10, following the Rational Resampler block #9. The digital signal generated with Repack Bits block #6 is converted into an analog square wave. Each bit is interpolated to create 600 bits so that the total number of samples increases from 12 to 72 000 ($120^*600 = 72\,000$).

The spectrum of the time-domain signal in Fig. 5, calculated via digital Fast Fourier Transform (FFT), indicates that the effective bandwidth of the square wave is less than 50 kHz. Fig. 6 displays the transmitted wave output of Red Pitaya Sink block #12. The carrier frequency is 1.8 MHz. The data in Fig. 6 is recorded with the digital oscilloscope (#9 in Fig. 1) at a sampling rate of 25 Ms/s, which is much higher than GNURadio's rate of 100 Ks/s. The number of samples for the same signals is 250 times higher than in GNURadio ($250 * 100\,000 = 25\,000\,000$). The individual bytes from the square wave are all translated into a signal with amplitude ranging from −0.3 to 0.3 V. Note that in the experimental setup in Fig. 1, this signal passes through a 50-dB power amplifier (#3), and the PZT (#4) senses a signal with approximately 95-V amplitude. One can observe in Fig. 6 that the Red Pitaya board introduces ringing noise into the system in every pulse ON/OFF transition. This behavior is the reason why binary ASK is preferable to quad ASK since ringing noise would be amplified in each additional OOK event.

Fig. 7 displays the received signal waveform from Red Pitaya Source block #13, but before demodulation is performed. The data are recorded with the digital oscilloscope (#9 in Fig. 1). The received signal is amplified with an LNA (#7 in Fig. 1) but still appears to be attenuated by an order of magnitude relative to the transmitted signal in Fig. 6. In addition, a dc offset of −0.075 V is added to the signal. Compared to the transmitted signal in Fig. 6, there are more distortions on the peaks of the received waveform, as well as a much larger amount of noise around the dc offset.

Fig. 8 shows the received signal with the Red Pitaya board demodulated with Red Pitaya Source block #13.

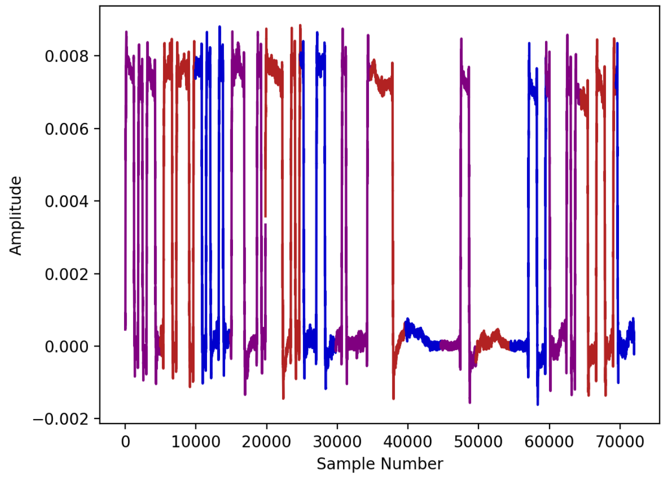

Fig. 8. Received signal with Red Pitaya board after demodulation with Red Pitaya Source block #13 (data colored as individual bytes).

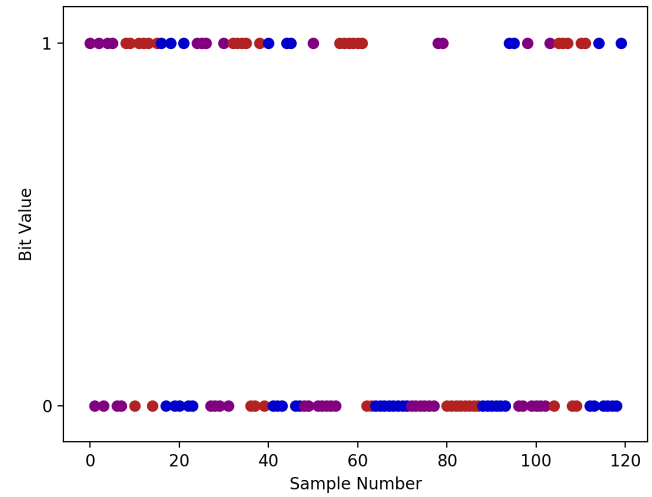

Fig. 9. Data recovered from Threshold block #19 after decimation (data colored as individual bytes).

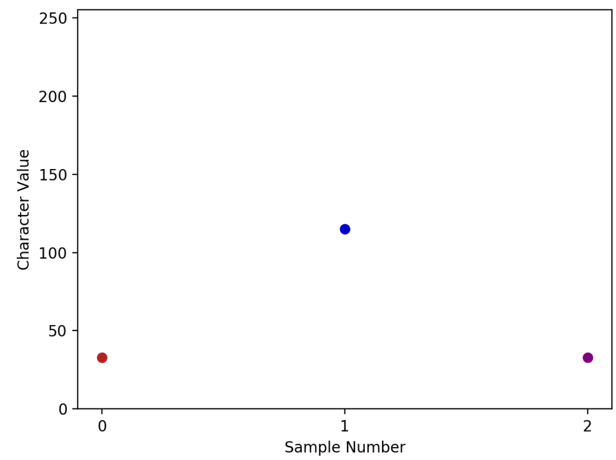

Fig. 10. Data from File Sink block #26 (data colored as individual bytes).

The system produces a noisy waveform lacking information (sample numbers <500 000) but then stabilizes and produces a regular waveform. Since the sampling rate is 100 KS/s, we conclude that the system has to transmit for at least 5 s for the information can be recovered successfully. Fig. 8 provides a zoomed-in display of bytes in the received demodulated signal. Compared to the plot of the transmitted waveform envelope in Fig. 5, one can qualitatively note much more ringing in the received signal compared to the transmitted one.

The signal subsequently passes through the automatic gain control (AGC) block #15. The amplification step is performed to condition the signal for the thresholding operation, which would result in fewer errors for a greater difference in amplitude between "ON" and "OFF" pulse states, representing logical "0" and "1." The function of AGC is to compensate for demodulated signal amplitude reduction due to the random phase difference in the received and reference waveforms. The average or peak output signal level is used to dynamically adjust the gain of the amplifiers. This enables the circuit to work with a wide range of input signal levels so that optimal thresholds can be selected for logical "1" and "0." The AGC effectively reduces the amplitude if the signal is strong and raises the amplitude if the signal is weak. The AGC is implemented with a single rate parameter according to the following equation:

$$\text{Gain} = \text{Gain} + \text{Rate} * (\text{Reference} - \text{abs}(\text{Input})). \quad (1)$$

Here, the "rate" is an indicator of how fast AGC decreases (increases) the gain when the signal becomes larger (smaller). The "reference" is the value the AGC tries to maintain.

Fig. 9 displays information recovered from the Threshold block #19 after decimation, following demodulation performed by AM Demod block #16. The recovered information follows the same pattern as the transmitted bits.

The Correlated Access Code block #24 removes the bits from the stream that follow originate from the protocol formatter, leaving the original information. The Repack block #25 repacks the bits into bytes and stores the information into the File Sink block #26, successfully recovering the transmitted file. The output data of the File Sink block is displayed in Fig. 10. Note that the bytes in Fig. 10 are the same as those of the source file (last three bytes in Fig. 4), which proves the success of data transmission.

B. Demonstration of Image Transmission

Using the ASK communication protocol implemented in GNURadio, a 32-KB digital image of the Argonne National Laboratory (ANL) logo was transmitted across the pipe. Fig. 11 shows a screen capture of received image reconstruction in GNURadio. The image was transmitted at 2-Kbps bit rate (a logical "1" was encoded with 500-μs pulse). The total time to transmit and reconstruct the image is 100 s. Bit error rate (BER) in the reconstructed image is calculated to be less than 10^{-3}.

IV. Potential Deployment Challenges

Deployment of the ultrasonic communication system on a pipe in a nuclear facility could potentially face several challenges, such as deterioration of the communication channel due to environmental stresses, and signal attenuation due to

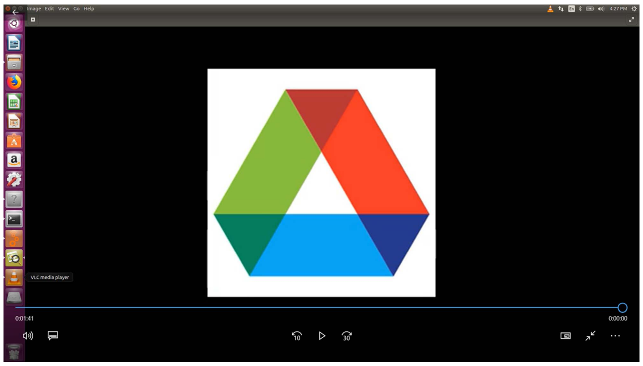

Fig. 11. GNURadio screen capture of recovered received image of ANL logo.

propagation over complex piping structures. Detailed analysis of practical deployment considerations is beyond the scope of the present study. In this section, we briefly review several possible challenges and their potential resolution.

In principle, piping deterioration, in particular, corrosion and cracking, could have a negative impact on the data transmission performance. However, the condition of the nuclear facility pipes is rigorously maintained through controlling pH and filtering out debris in the fluid, as well as performing thorough inspections during regular reactor shutdown periods. Therefore, deterioration of piping is not expected to have a major impact on the ultrasonic communication at a nuclear facility.

The study in this article focused on ultrasonic data transmission on a straight pipe. In principle, a straight section of piping might not be available for mounting transducers. Piping elbows and bends are fairly common at nuclear facilities, and transmission of over such piping manifolds could be necessary to connect specific locations in the facility with a piping communication channel. We conducted a preliminary evaluation of the signal transmission across a bent piping structure with a 90° turn using COMSOL computer simulations. The model of the structure, consisting of two 30-cm-long straight sections joined with an elbow, is shown in Fig. 12. All other parameters of the metallic structure in the COMSOL model are the same as those in Fig. 2. Longitudinal ultrasonic waves at 500-kHz frequency were coupled as boundary pressure load to the acrylic wedge angled at 45°. Elastic waves are visualized with a pseudo-color plot of pressure distribution. The amplitude of the pressure is amplified compared to actual experimental values to enhance the elastic wave visibility.

Fig. 12 (top) shows the pressure distribution of 40 μs after the start of the simulations when the refracted shear wave is coupled into the pipe. Fig. 12 (middle) shows pressure distribution after 110 μs when the wave reaches the elbow. Note that the propagation distance to the geometrical center of the bent section is slightly larger than 30 cm because the elbow increases the length of the overall piping structure by approximately 10 cm. Fig. 12 (bottom) shows the pressure distribution at 200 μs after the start of the simulations. At this point, the ultrasonic shear wave has propagated across the elbow and reached the middle of the second straight section.

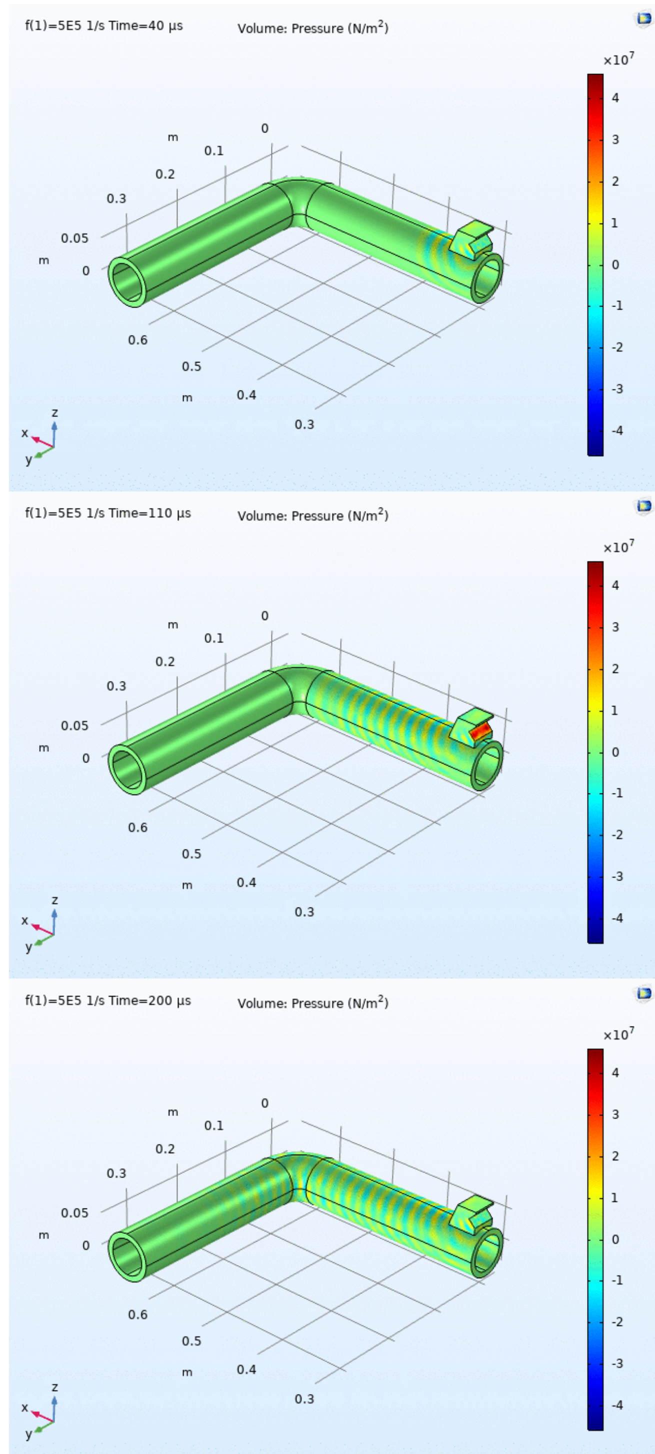

Fig. 12. Propagation of 500-kHz refracted shear wave on a metallic bent pipe, visualized with pseudo-color map of pressure distribution at 40, 110, and 200 μs.

Since the shear wave velocity in stainless steel is 3100 m/s, in 110 and 200 μs the propagation distances are 34 and 62 cm, respectively, which is in qualitative agreement with COMSOL simulations. No reverberations or scattering from the elbow bend are observed in computer simulations. This confirms qualitatively that ultrasonic shear waves travel across uniform piping bend without mode conversion, which is consistent with prior studies [22].

However, it should be noted that piping bends are typically formed by welding of several piping sections. The welds introduce discontinuities in the piping material, which can cause significant scattering of the ultrasonic shear wave. A test article consisting of a stainless steel pipe bent at 90° was developed for preliminary laboratory analysis. The bent piping test article developed by welding two straight three-foot-long pipes to an elbow. For consistency, the diameter and wall thickness of the bent pipe is the same as that of the straight pipe (6-ft-long schedule 160 pipes with 2.375-in outer diameter). Industrial-grade welding was performed to achieve leak proof under the 2000 psi pressure test. After welding, the outer surface was ground to achieve a visibly smooth finish. Preliminary results of 500-kHz ultrasonic refracted shear wave transmission across the bent piping structure indicate that the shear wave is significantly distorted by the welds. One possible mitigation strategy is to use time-reversal modulation (TRM) to remove noise from the received signal. Integration of TRM filter into ultrasonic communication on complex piping manifolds will be investigated in future studies.

V. Conclusion

In this article, we discussed the design and performance evaluation of an ultrasonic communication system on a nuclear-grade stainless steel pipe. A laboratory bench-scale system consisting of a nuclear-grade chemical volume control system (CVCS)-like pipe and commercial PZT ultrasonic transducers were assembled for a preliminary communication system demonstration. Carriers of information are ultrasonic refracted shear waves on the pipe. ASK communication protocol for image transmission was developed using the GNURadio software environment. Detailed analysis of the communication protocol, including the output of each block, is presented in this article. Using the communication system, a 32-KB image was transmitted at a data bitrate of 2 Kbps across the stainless steel pipe. The next phase of this work will investigate the strategy for increasing communication bitrate. In addition, instead of PZTs designed for operation, data transmission with high-temperature ultrasonic transducers will be investigated. Finally, signal processing strategies for ultrasonic signal transmission over complex piping manifolds will be investigated.

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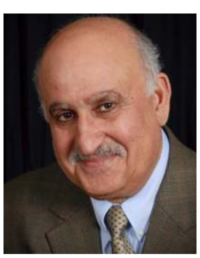

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