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Final Report for Transmission of Information by Acoustic Communication along Metal Pathways in Nuclear Facilities

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Nuclear Science and Engineering Division

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Transmission of Information by Acoustic Communication along Metal Pathways in Nuclear Facilities

prepared by
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Abstract

Transmission of information using elastic waves on existing metallic pipes provides an alternative communication option for a nuclear facility. The advantages of this approach consist of transmitting information through barriers, such as the containment building wall. A viable candidate for acoustic communication channel is a chemical volume control system (CVCS) stainless steel pipe, which penetrates through the containment building wall. A laboratory bench-scale system consisting of a nuclear grade CVCS-like pipe and ultrasonic transducers was assembled for a preliminary communication system analysis. Because of low bandwidth and spectral dispersion of ultrasonic transducers, on off keying (OOK) protocol was chosen for data communication. Operation of the acoustic communication during normal and post-accident conditions involves data transmission on the CVCS pipe, which according to literature guidelines, will be at 50ºC and 150ºC, respectively. Preliminary communication system development was performed using paintbrush PZT transducers capable of continuous operation at temperatures up to 80ºC.

Next, high-temperature $LiNbO_3$ acoustic transducers, originally developed for flow metering applications of EBRII reactor at Argonne, were utilized to develop a high-temperature acoustic communication system. A Gaussian pulse shape filter was introduced to suppress ringing and thus reduce inter-symbol interference. This resulted in enhancement of data transmission bitrate. Heating tapes, temperature controllers, and thermal insulation were installed on the laboratory pipe to study acoustic communication at elevated temperature. This included development of custom insertion heating elements for controlling temperature at pipe ends. Demonstrations of communication at high temperature included transmission of images and text files. Main achievements thus far include demonstration of transmission of 90KB image at the bitrate of 10Kbps with bit error rate smaller than 10^{-3} across the pipe heated to 50ºC and 150ºC.

Final phase of project development involved investigating strategies for deployment of the ultrasonic communication system in a representative environment. Mechanisms Engineering Test Loop (METL) facility at ANL was chosen as a viable candidate for communication system demonstration. Analysis of piping manifolds at METL has shown that in a typical scenario, ultrasonic signals have to be transmitted over straight and bent piping sections. This report describes preliminary studies on transmission of information with ultrasonic shear waves across bent piping sections. A test article consisting of a stainless steel pipe bent at 90º was developed for laboratory analysis of ultrasonic signal transmission. The bent piping test article developed by welding two straight pipes to an elbow. For consistency, the diameter and wall thickness of the bent pipe is the same as that of the straight pipe utilized in prior studies. COMSOL computer simulations were performed to study ultrasonic refracted shear wave coupling and transmission across bent piping. Preliminary evaluations of ultrasonic shear wave transmission were conducted with piezoelectric (PZT) and $LiNbO_3$ transducers, with the signals recorded with previously developed LabView interface. Preliminary results have shown significant dispersion of

transmitted signals, most likely due to reflections and scattering by piping welds. Signal distortion compensation algorithm based on time reversal modulation (TRM) was initially investigated for transmission through solids, and demonstrated for signals transmitted over the bent pipe. Using TRM, it was shown that communication bitrates of 100Kbps were achievable, in principle.

1. Introduction

1.1. Background

Integration of advanced communication technologies into nuclear facility operation has the potential for enhancing safety and efficiency of the existing fleet of aging light water reactors, as well those of future advanced reactors [1]. Conventional wired and wireless communication systems face implementation challenges at nuclear facilities due to the presence of thick reinforced concrete walls with steel liners, such as those of the containment building. In addition, concerns related to security vulnerabilities in conventional communication networks have to be addressed when developing communication systems for nuclear facilities. In this report, we describe recent progress on developing a wireless communication system for a nuclear facility, in which information is carried with elastic waves propagating on metallic pipes. Traditionally, elastic wave propagation has been a frequent technique for non-destructive testing (NDT) of steel pipes [2]. In our approach, ultrasonic NDT techniques are combined with methods of communication theory to develop and acoustic communication system for a nuclear facility. Such communication system would take advantage of the existing piping infrastructure to transmit information in and out of containment building, as shown in Figure 1 [3]. Furthermore, information sent over this system would only be accessible through direct physical contact with the pipes, thus establishing a protection layer against unauthorized eavesdroppers.

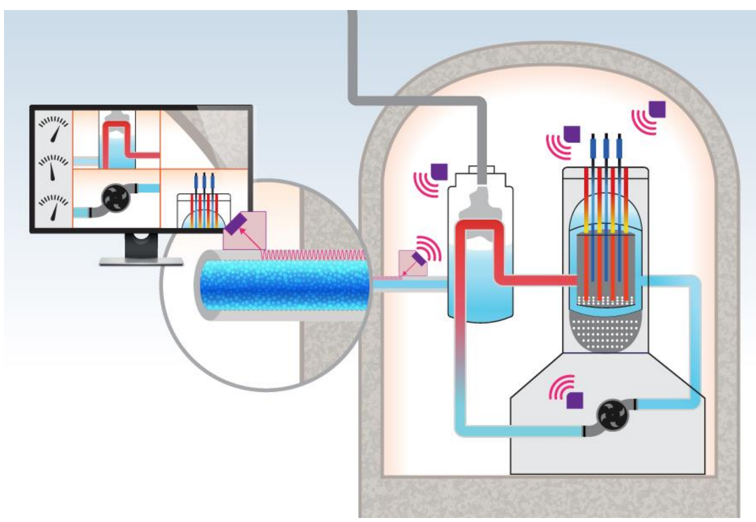


Figure 1 – Proposed acoustic communication system at a nuclear facility would transmit information on steel pipes already in place for nuclear reactor operation [3].

The charging line of CVCS (chemical and volume control system) was previously identified as a promising channel for acoustic information transmission in and out of the containment building [4,5]. The CVCS pipe passes through a specially designed tunnel through concrete wall, in which the pipe is not in direct contact with concrete. The CVCS pipe is welded to two metallic baffle plates, which are bolted to both sides of the concrete wall at the openings of the tunnel. The baffle plates seal the tunnel, which prevents insertion of any communication link through the tunnel, such as an electrical or fiber optic cable. As described in prior reports, CVCS pipes contain water during normal and post-accident operating conditions. Therefore, acoustic shear waves, which do not couple into water, were selected as the information carries on the pipe to minimize losses due to propagation in the channel. A laboratory bench-scale prototype of a CVCS pipe, consisting a six-foot long stainless steel schedule 160 pipe with 2.375in outer diameter and stainless steel baffle plates was developed for proof-of-principle demonstrations [6]. Because of limited bandwidth of ultrasonic transducers, on-off-keying (OOK) digital communication protocol was chosen for information transmission over an acoustic channel [7,8]. Amplitude shift keying (ASK) communication protocol was developed and implemented using GNURadio software defined radio (SDR) environment [9-11]. Prior results included demonstration of information transmission, such as images, text files, and sound, using 2MHz paintbrush piezo electric transducers (PZT) on the room-temperature pipe. The PZT's were mounted on angled wedges to generate refracted shear waves in the metallic sheath of the pipe. A proof-of-principle demonstration consisted of transmitting a 32KB image at 2Kbps bitrate with bit error rate (BER) smaller than 10^{-3}.

1.2. Introduction

The acoustic communication system under development is expected to function under normal and post-accident environment at the nuclear facility. This implies that transducers installed on the CVCS pipe inside the containment should be resilient to the worst-case scenario temperature, humidity, and radiation environments. Typical value of environmental stresses of containment isolation function components inside the PWR containment, are listed in Table 1 [12]. Note that in post-accident conditions, the acoustic communication system is expected to operate continuously at least for the first 72 hours. Therefore, ability to function at 300^oF or 150^oC is a critical requirement for acoustic communication system.

Table 1 – Typical environmental stresses of containment isolation function components [12]

Parameter	Normal	Accident
Temperature	50-120 °F	300 °F
Pressure	Atmospheric	70 psig, max
Relative Humidity	30-100 %	100 %
Radiation	50 rads/hr	150 Mrads/hr

After installing heaters and controllers on the laboratory pipe, acoustic data transmission was performed on a pipe heated to 50^oC and 150^oC to simulate communication on a pipe during normal and post-accident nuclear facility operation. Conventional PZT transducers and edges used in prior work on this project for development of ASK communication protocol are not compatible with high-temperature environment (above 50^oC) [13]. Specialized high-temperature $LiNbO_3$ shear wave transducers, previously developed at Argonne for liquid sodium flow metering in EBRII pipes, were utilized for data transmission at elevated temperature. Spectral response of $LiNbO_3$ was characterized to determine optimal center frequency of the carrier acoustic waves. Transducer ringing following short temporal duration pulse generation, which led to inter-symbol interference, was determined to be one of the key factors limiting data transmission bit rate. A pulse shaping Gaussian filter was implemented in software to suppress transducer ringing, which allowed increasing communication data transfer rate upward from previously achieved 2Kbps bitrate with commercial PZT transducer at room temperature [14]. Heating tapes and temperature controllers were installed on the pipe to achieve controlled temperature elevation to 150°C. This included development of heating elements for insertion into pipe ends to raise the temperature at transducer mounting points to 150°C. High-temperature $LiNbO_3$ transducers were installed on the pipe and enclosed by insulation material. The high-temperature $LiNbO_3$ transducers were integrated into previously developed ASK acoustic communication system implemented with RedPitaya electronic boards and GNURadio software. Main achievements thus far include demonstration of transmission of 90KB images at 10Kbps bitrate on 150°C pipe with BER smaller than 10^{-3}.

We have identified the Mechanisms Engineering Test Loop (METL) facility at Argonne as a viable candidate for demonstration of the ultrasonic communication in a representative environment. METL facility is an intermediate-scale liquid metal experimental facility that provides purified R-grade sodium to various experimental test vessels to test components that are required to operate in a prototypical advanced reactor environment [15]. Analysis of piping manifolds at METL has shown that in a typical scenario, ultrasonic signals have to be transmitted over straight and bent piping sections. Preliminary studies investigated transmission of information with ultrasonic shear waves across bent piping sections. A test article consisting of a stainless steel pipe bent at 90° was developed for laboratory analysis of ultrasonic signal transmission. The bent piping test article developed by welding two straight pipes to an elbow. For consistency, the diameter and wall thickness of the bent pipe is the same as that of the straight pipe utilized in prior studies. COMSOL computer simulations were performed to study ultrasonic refracted shear wave coupling and transmission across bent piping. Preliminary evaluations of ultrasonic shear wave transmission were conducted with piezoelectric (PZT) and LiNbO3 transducers, with the signals recorded with previously developed LabVIEW interface. Preliminary results have shown significant dispersion of transmitted signals, most likely due to reflections and scattering by piping welds. Signal distortion compensation algorithm based on time reversal modulation (TRM) was proposed and demonstrated for signals transmitted over the bent pipe [16,17]. Using TRM, it was shown that communication bitrates of 100Kbps were achievable, in principle.

2. Design and characterization of high-temperature communication system

As described in Section 1 of this report, one of the requirements of the acoustic communication system is ability to perform continuous operation for 72 hours on a pipe at 150°C. Majority of acoustic transducers are not suitable for operation at elevated temperature. For example, paintbrush PZT transducers utilized for proof-of-principle acoustic communication system development have a limiting operating temperature of 50°C. Beyond this threshold, the transducer material degrades rapidly. To perform measurements on high-temperature pipe, the transducer is coupled to the pipe with a high-temperature wedge. However, most commercial wedges are designed for touch mode operation, where a measurement is made in a brief period of time (e.g., 10s), followed by a longer cool-off period (e.g., 60s). In other designs, a long metallic waveguide could be in contact with the high-temperature pipe surface, while transducer would be placed at the opposite end of the waveguide, which is at lower temperature. However, this would require insertion a relatively large wide diameter waveguide through the insulating material to couple to the pipe. This approach could lead to considerable heat losses. A preferred method would be to embed a high-temperature compatible transducer under the insulation, with a narrow communication channel piercing the insulation material. High-temperature compatible transducers include electromagnetic acoustic transducers (EMAT) [18,19] and $LiNbO_3$ transducers.

2.1. High-temperature compatible $LiNbO_3$ ultrasonic transducers

Specialized high-temperature compatible $LiNbO_3$ shear wave ultrasonic transducers were developed at Argonne for EBRII liquid sodium flow metering applications. The $LiNbO_3$ crystal Curie temperature of 1145°C, which allows for long-term deployment of these transducers on pipes carrying liquid sodium, for which the operating temperature is typically under 650°C [20]. In this project, these $LiNbO_3$ transducers were utilized for the first time for information transmission applications. The transducer consists of a single $LiNbO_3$ crystal in stainless steel case, and couples to metallic pipe with metallic foil. The transducer attached to the stainless steel pipe with metallic hose clamp is shown in Figure 2. The transducer is dry-coupled to the pipe with copper foil. Communication with the transducer takes place through the long rigid metallic BNC cable. This allows embedding the $LiNbO_3$ into thermal insulation material enclosing the pipe. The narrow rigid BNC cable would penetrate thermal insulation, which would cause relatively small thermal losses. The end of the long BNC rod cools off to room temperature, which allows for coupling to regular commercial BNC cables, as shown in Figure 2.

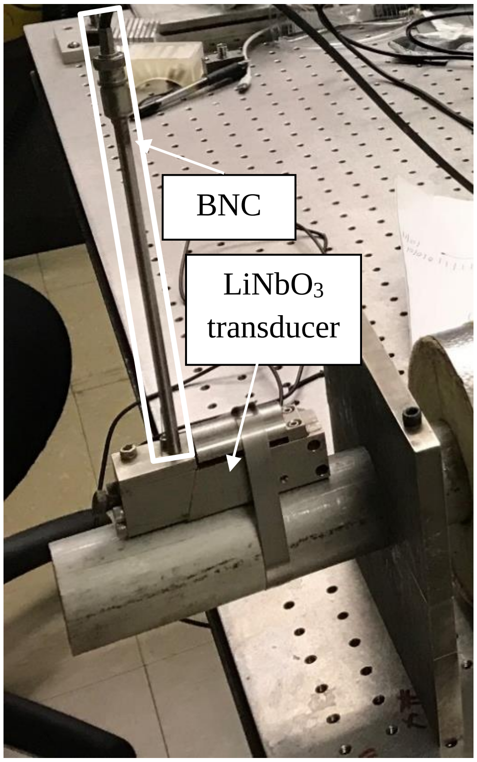


Figure 2 – High temperature $LiNbO_3$ transducer mounted on a stainless steel pipe.

2.2. Characterization of $LiNbO_3$ ultrasonic transducers performance

Preliminary evaluation of high-temperature $LiNbO_3$ transducers for data transmission application consisted of characterization of their frequency response. The spectrum of received signal for two $LiNbO_3$ transducers separated by 170cm (~5.5 feet) on a stainless steel pipe is shown in Figure 3. The transmitted signal was amplified with 50dB power amplifier, and the received signal was amplified with 20dB low noise amplifier. Frequency response characterization was performed at room temperature. The spectrum was acquired using LabView software. The spectral response of $LiNbO_3$ transducer has a maximum at approximately 730KHz, with approximately 10% full width half maxima (FWHM) bandwidth.

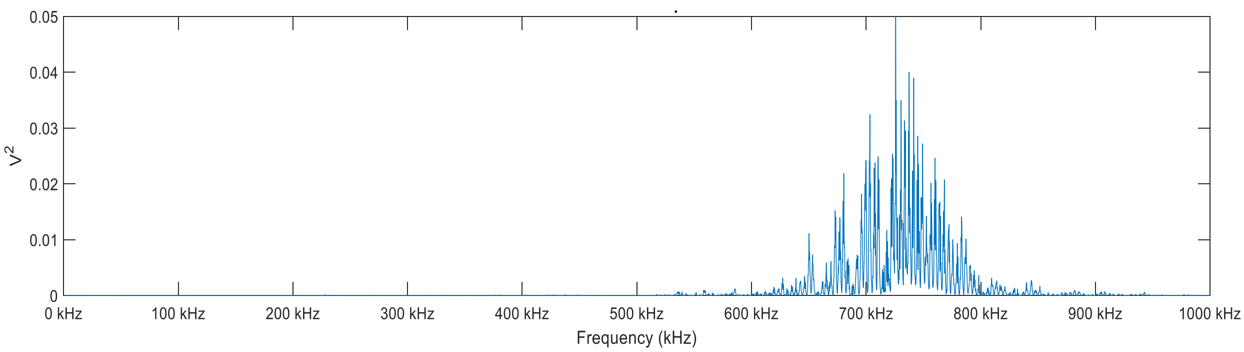


Figure 3 – Frequency response of high-temperature temperature $LiNbO_3$ transducer mounted on a stainless steel pipe.

Performance of LiNbO3 transducers in data transmission applications was characterized by generating a train of binary signals and detecting the received signals using LabView software. The center frequency of the carrier was chosen to be 728 KHz, which corresponds to maximum of transducer spectral response as shown in Figure 3. Transmitted and received amplitude shift keying (ASK) signals are shown in Figure 4. The strip chart shows a string of pulses transmitted over 100ms. Bit pulse duration shown in the figure is 200 µs, which corresponds to 5Kbps bitrate. The transducers are separated by 170cm distance on a pipe. Transmitted signal is amplified with 50dB power amplifier, and received signal is amplified with 20dB low noise amplifier. The experiment was performed at room temperature. The data in Figure 4 demonstrates qualitatively that $LiNbO_3$ high-temperature can be used for ASK transmission and reception of pulses representing logical "1" and "0."

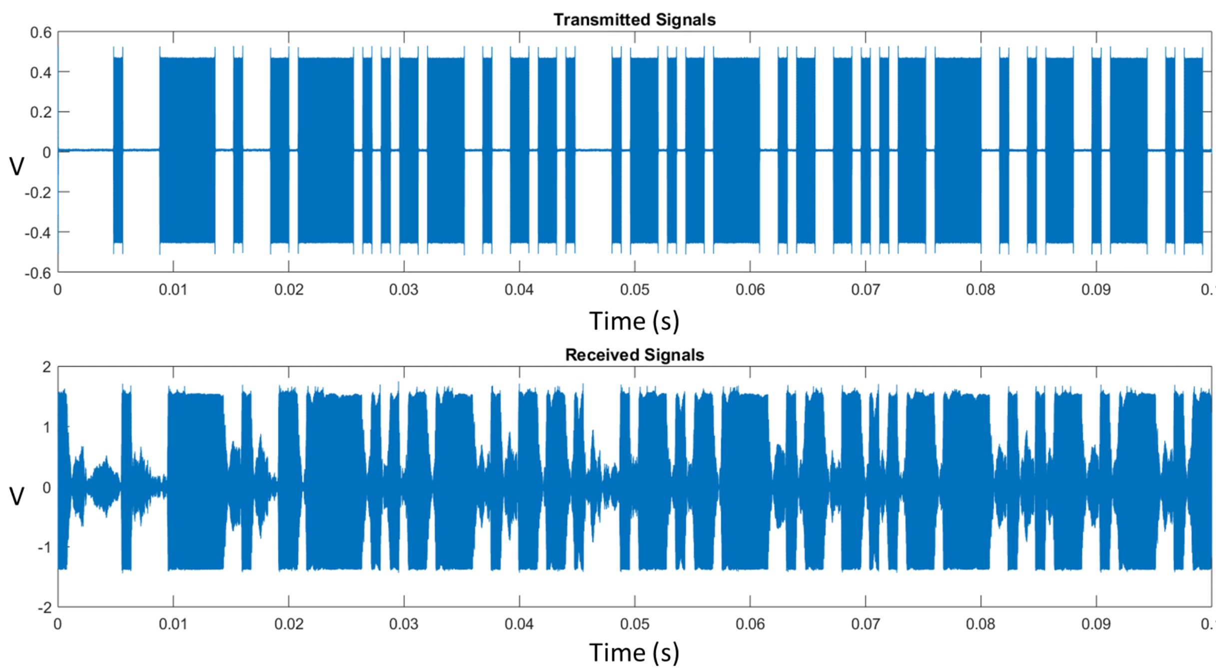
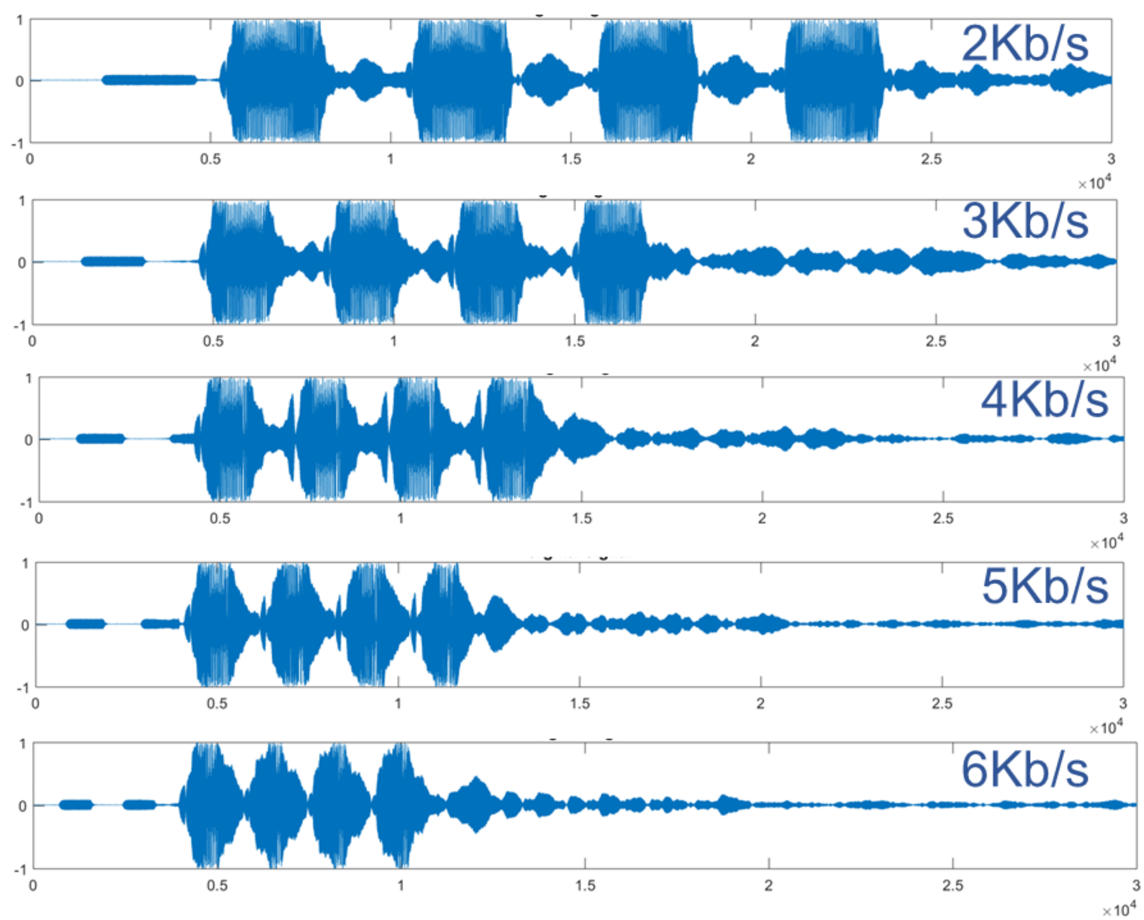


Figure 4 – Transmitted and received ASK pulses with 5Kbps bitrate

2.3. Limitations on data transfer rate due to transducer ringing

Following preliminary evaluation, which confirmed that high-temperature $LiNbO_3$ can be used for OOK communication, we have investigated factors which limiting data transfer rate. Using the setup with $LiNbO_3$ transducers described in section 2.2, we recorded transmission of a byte of information consisting of a sequence of 10101010 bits. All measurements were performed at room temperature. Received signals for different data transmission rates, encoded via amplitude shift keying (ASK) communication protocol, are shown in Figure 5. The data was recorded with LabView software. The panels in Figure 5 show received signal with a sequence of logical "1" and "0" bits were represented by acoustic pulses with 500µs, 333µs, 250µs, 200µs, 167µs, 143µs, 125µs, 111µs, and 100µs temporal duration. These correspond to bitrates of 2Kbps, 3Kbps, 4Kbps, 5Kbps, 6Kbps, 7Kbps, 8Kbps, 9Kbps, and 10Kbps. One can observe from the panels in Figure 5 that as the data rate increases, transducer ringing caused by short temporal pulse duration makes it difficult to resolve logical "0" from logical "1." Therefore, the factor limiting data transmission rate in the inter-symbol interference (ISI). For lower data rate values, such as the top panel showing data transmission at 2Kb/s, thresholding can remove the weak ringing signal appearing in the time interval allocated for logical "0." However, for higher data rate values, such as for panels displaying received signals at 6Kb/s data rate and above, residual ringing from logical "1" pulse injects sufficiently large signal into the time slot allocated for logical "0" which cannot be removed by thresholding or averaging. Thus, the probability that the decimation procedure will mis-identify "0" as "1" is relatively high. It was observed in several experiments that transmission of images, such the image of ANL logo used in previous reports [4], resulted in relatively low bit error rate (BER <10^{-3}) for data transfer rate of 2KB/s. However, at higher data transfer rates, BER increased substantially to the point that transmitted images became unrecognizable. Several strategies for suppressing ringing were investigated, including matched filtering and Gaussian pulse shaping filter.



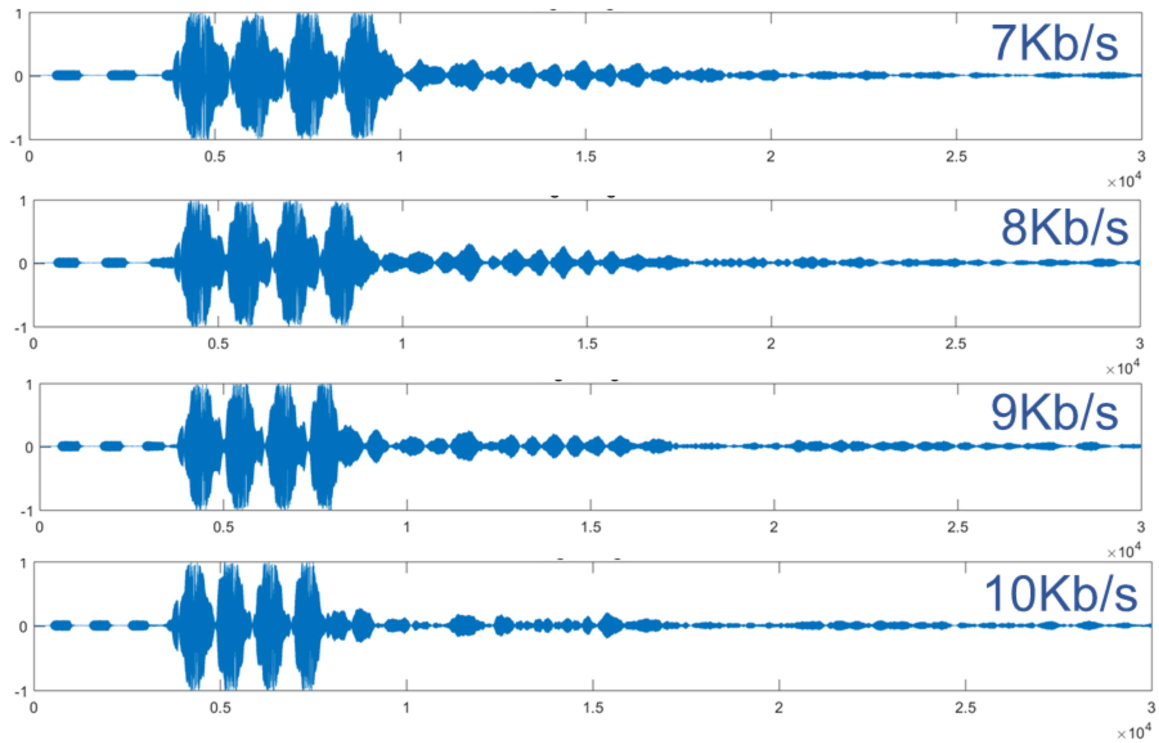


Figure 5 – Received ASK pulses with bitrate ranging from 2Kbps to 10Kbps

2.4. Enhancement of data transfer rate with Gaussian pulse shape filter

In our study of transducer ringing suppression to increase data transfer rate, application of Gaussian pulse shape filter proved to be the most efficient solution. In this approach, instead of a square pulse representing logical "1", a Gaussian pulse of the same amplitude is used for encoding an ASK signal [14]. Because of the gradual rise and decay of Gaussian pulse amplitude, the result of using a Gaussian filter is a significant suppression of transducer ringing. This effect can be observed in Figure 6, which shows a string of transmitted and received bits represented by 100μs (10Kbs bitrate) temporal duration Gaussian shape pulses. The segment shown in Figure 6 corresponds to "1011001001010110110001010110010010010011" Time delay between received and transmitted signals due to propagation time across 170cm distance on a pipe is approximately 350μs. Thus, the first pulse in the transmitted signals strip chart shows up at the time mark of 350μs, as indicate by the arrow in the Figure. The data in Figure 6 can be compared with the last panel in Figure 5, which shows received square wave pulses with 100μs temporal duration, or equivalent 10Kbps bitrate.

The train of transmitted and received pulses in Figure 6 is a subset of data showing the first 200ms of transmission. The entire data set consisting of 1s-long strip chart of transmitted and received pulses is shown in Figure 7. One can observe that implementation of Gaussian pulse shape filter results in considerable improvement in received signal quality. After the received signal is thresholded, weak residual signal appearing in time slots corresponding to logical "0" can be suppressed. When the decimating procedure converts the analog signal to digital, the probability that a logical “0” is misidentified as logical “1” is significantly reduced compared to the case when communication is performed with analog square pulses. Thus, Gaussian pulse shape filter enables higher bitrate communications with relatively low BER. Demonstration of this approach in transmission of images on a pipe is discussed in Section 4.

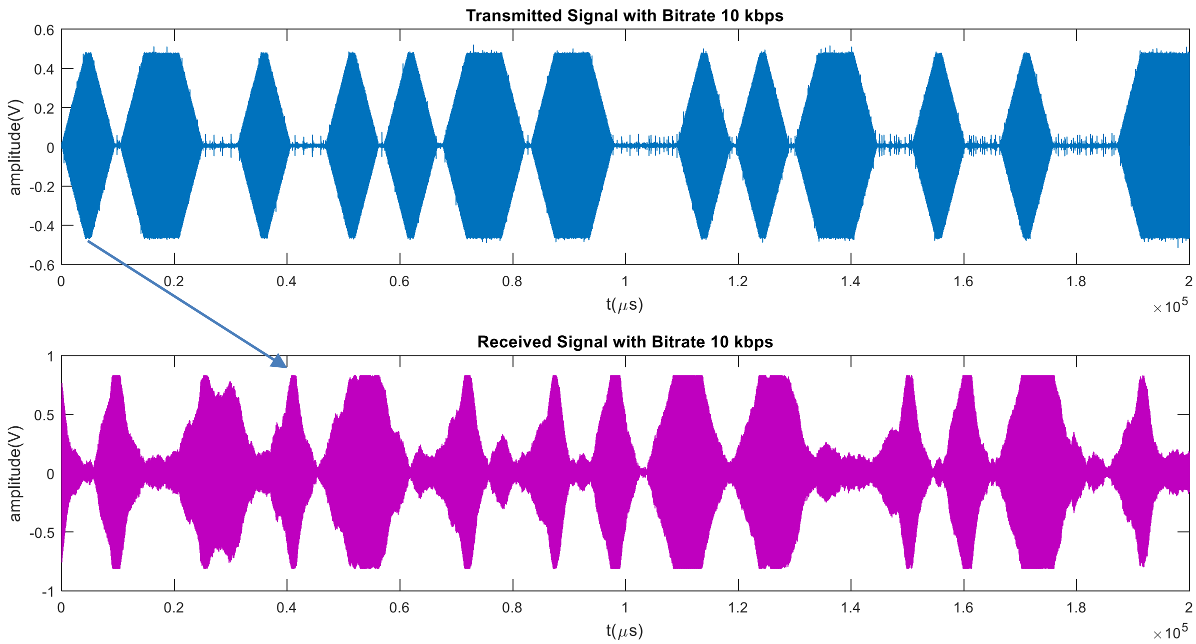


Figure 6 – Subset of transmitted and received Gaussian pulses with bitrate 10Kbps

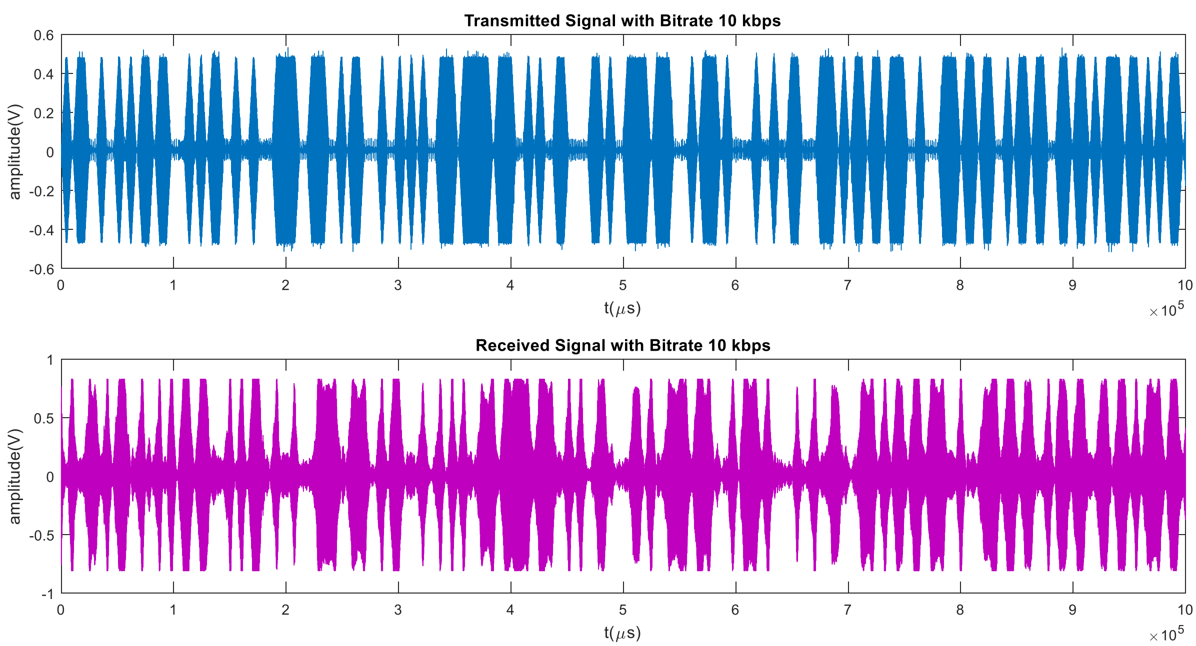


Figure 7 – Longer train of transmitted and received Gaussian pulses with bitrate 10Kbps

3. Development of High-Temperature Communication Channel

As described in Section 1, the requirements of acoustic communication system include the ability to transmit information on a pipe at 50^{o}C prior work on the project consisted of development of acoustic communication protocols and performing proof-of-principle demonstrations of acoustic communication at room temperature. Prior work on the project consisted of developing and demonstrating acoustic communication on a stainless steel schedule 160 pipe with 2.375in outer diameter at room temperature [4]. This section describes development of a laboratory setup for demonstration of acoustic communication on a stainless steel pipe at elevated temperature.

3.1. Installation of heating tape and insulation on pipe

Temperature controllers, heating tapes and thermocouples were purchased from commercial Amptek vendor. This hardware was used to convert existing bench scale acoustic communication on setup into a high-temperature one. Figure 8 shows modifications to the existing setup with the heating tape wound on the stainless steel pipe. Heating tape cannot be wound over sections of the pipe where $LiNbO_3$ transducers are mounted because the transducer coupling requires a several inches long clear section of the pipe.

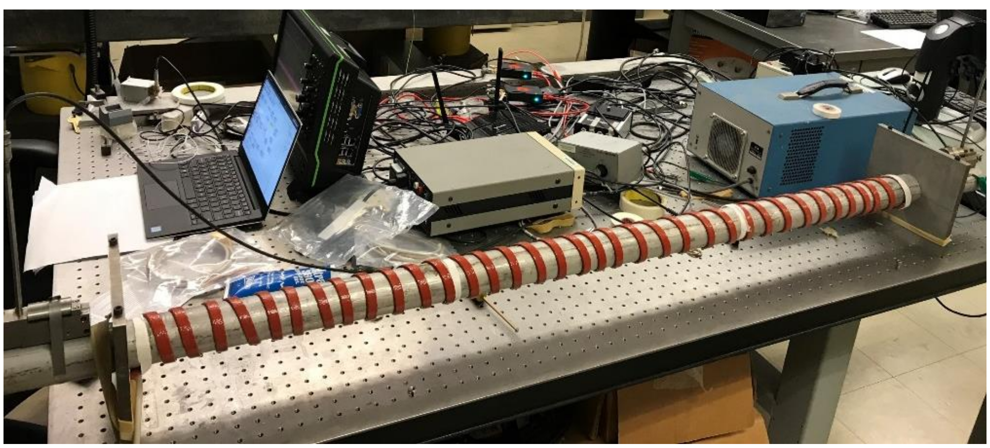


Figure 8 – Heating tape installed on stainless steel pipe

Mineral wool thermal insulation was wrapped around the pipe and fastened with wires to prevent heat losses. Mineral wool sections cut out to contour around the transducers were installed as well. Thermocouples were installed at the center of the pipe to monitor temperature. Figure 9 shows the setup with thermal insulation on the pipe. Thermal insulation was enclosed with thin stainless steel cover, as shown in Figure 10. Thermal insulation enclosing transducers was wrapped in Aluminum foil. Preliminary tests have shown that with the new setup the temperature of the pipe could be raised to 150^{o}C in approximately three hours. Once raised to this value, pipe temperature could be maintained steadily at 150^{o}C.

Figure 9 – **Mineral wool thermal insulation installed on the pipe**

Figure 10 – **Metal sheet cover and foil placed over mineral wool thermal insulation**

3.2. Installation of insertion heating elements at pipe ends

Because of heat losses at the ends of the pipe, it was observed that the temperature at the transducer mointing points saturated at 50ºC while the temperature at the center of the pipe was reaching 150ºC. A solution to heating pipe ends was found by designing and fabricating cylindrical insertion elements matched to the pipe inner diamter. Figure 11 shows the Aluminum insertion element containing the cable from a 20W heater and thermocuple wires. Separate set of heaters and temperature controllers was installed for each end of the pipe. The final assembly for laboratory testing of high-temeprature acoustic communication is shown in Figure 12. Preliminary tests have shown that the temperature at the center and at the ends of the pipe can be raised to 150ºC in approximately three hours, and maitained steadily at the set-point value. During the laboratory tests, it was determined that the ends of transducers BNC metallic rods have cooled off to room temperature to allow coupling to standard laboratory BNC cables with plastic jackets.

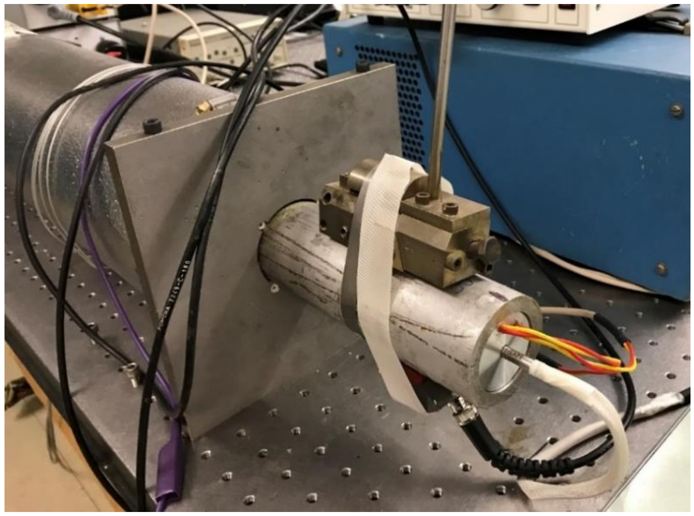


Figure 11 – Specially designed insertion heating elements for controlling temperature at pipe ends

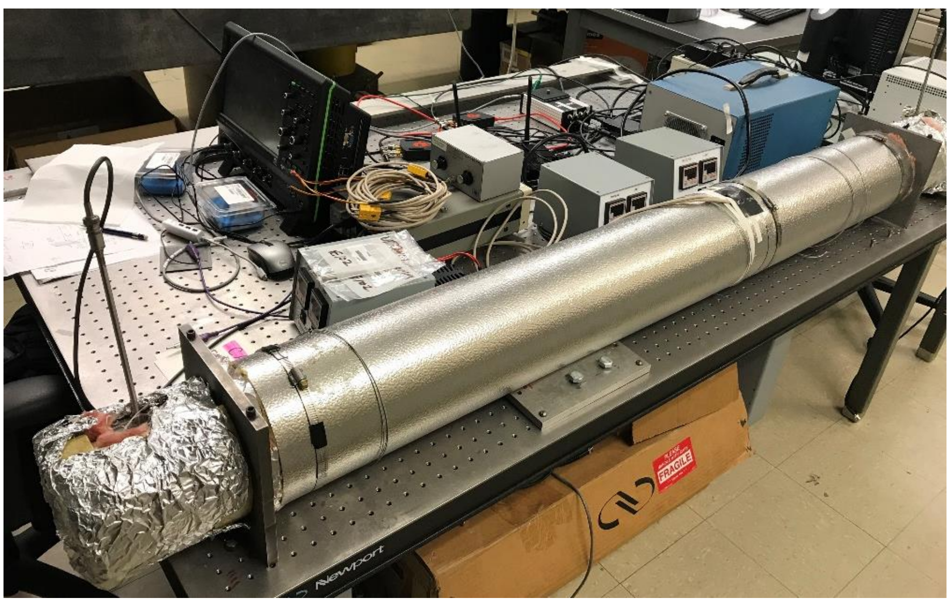


Figure 12 – Final laboratory setup for acoustic communication at elevated temperature

4. Demonstration of Data Transmission on Pipe at High Temperature

Prior work on the project consisted of developing of ASK communication system using GNURadio software defined radio (SDR) programming environment [8-11]. User uploads a digital file into GNURadio program, where the file is converted into a string of bits. A digital wave is generated by the GNURadio program, which is next converted into an analog wave by transmitter Red Pitaya electronic board. The analog wave is sent to the ultrasonic transducer through a power amplifier. Ultrasonic shear waves generated with the transducer propagate along the pipe, where they are picked up by the receiving transducer. Electrical signal from the transducer is amplified with low noise amplifier, and converted back into a digital wave by the receiver Red Pitaya board. Digital information is further processes within GNURadio software and displayed to the user. Impedance matching networks was designed and implemented to improve communication system performance. The objective to match the power amplifier and transmitting ultrasonic transducer (achieve R_{o1}=50Ω), and the low-noise pre-amplifier and the receiving ultrasonic transducer (achieve R_{i2}=50Ω). The schematics of the impedance matching network are shown in Figure 13.

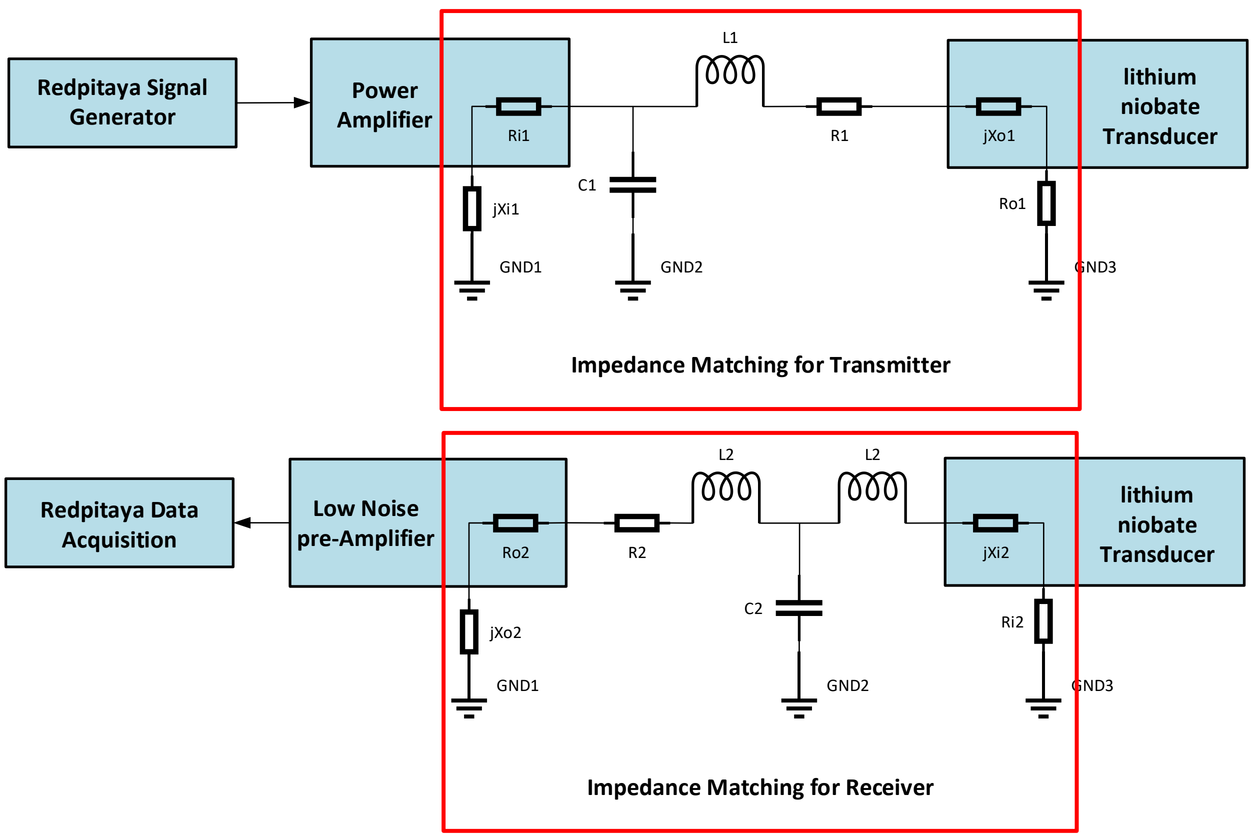


Figure 13 – Schematics of impedance matching networks for the transmitter and receiver ultrasonic transducers

4.1. Examples of transmitted data

Data types considered in transmission experiments included text files and images. Similar data types were utilized in data transmission demonstrations on a pipe at room temperature. Transmission of images is most challenging because a few errors might render the reconstructed image unreadable. GNURadio screen capture of 90KB image of ANL logo used in data transmission demonstrations is shown in Figure 14. Another example of transmitted data type is a text file. GNURadio screen capture of a text file containing repeating string of characters "Hello World!" is shown in Figure 15.

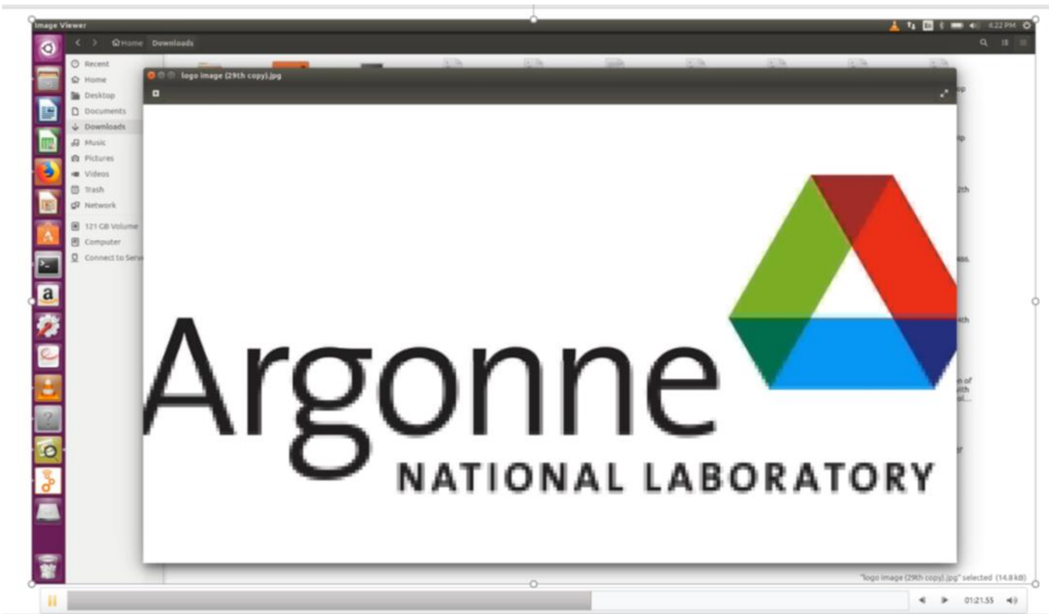


Figure 14 – GNURadio screen capture of an image file used in data transmission demonstration

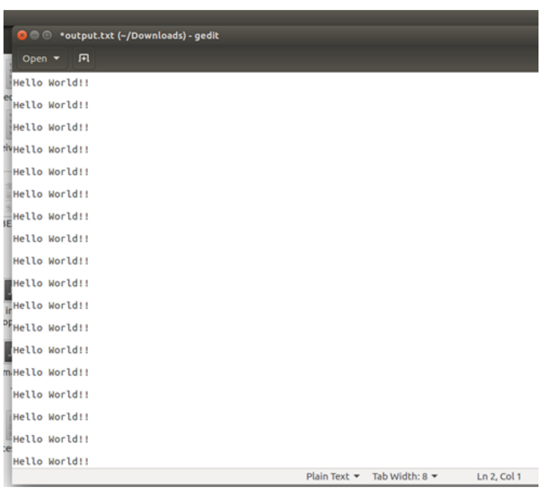


Figure 15 – GNURadio screen capture of text file used in acoustic data transmission demonstration

4.2. Bit error rate as a function of bitrate

To evaluate the communication system performance, we plot bit error rate (BER) as a function of bitrate on linear-log scale. The BER was calculated using GNURadio built-in pseudo-random test bit sequence (PRBS) modes which can produce known long strings of whitened bits. The results are shown in Figure 16. For each bitrate, error rate was obtained by transmitting 100 packets, each consisting of approximately 36,000 bits. Error rates for each packet were averaged to obtain the number for BER. The observed dependence is for BER to increase with bitrate. The curve is not smooth because of the errors generated due to unstable performance of GNURadio.

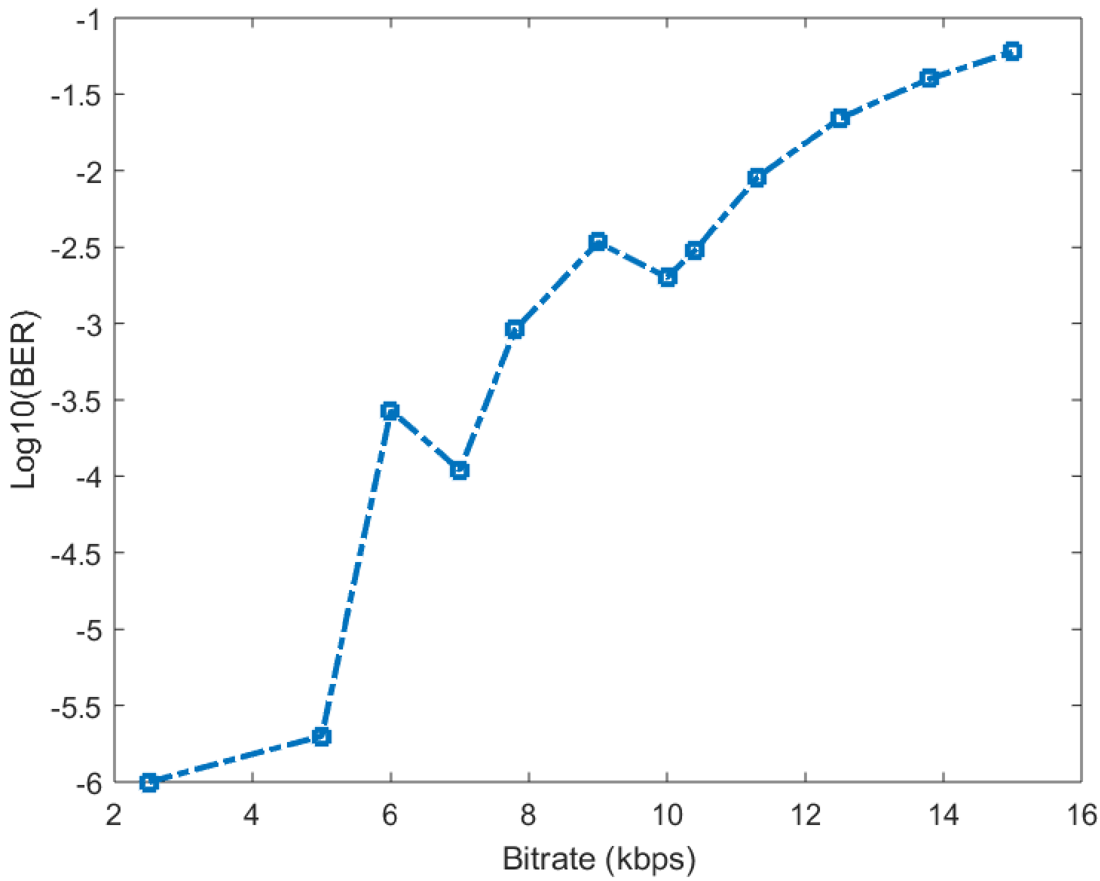


Figure 16 – Bit error rate (BER) vs. bitrate

4.3. Summary of transmission results

Transmission of data files was performed using ASK communication protocol with Gaussian pulse shape filter described in Section 2, and $LiNbO_3$ transducers installed on thermally insulated and heated pipe described in Section 3. A summary of data transmission results is presented in Table 2. The 1st row in the table lists the results obtained using room-temperature 2MHz paintbrush PZT transducer mounted on 45° angled wedge [4]. This result was obtained in the previous year of the project, and is listed in Table 2 for reference. The 2nd through 4th rows of the table list the results of data transmission with $LiNbO_3$ transducer. The 2nd row shows the results obtained at room temperature. The 3rd and 4th rows show the results of data transmission on a pipe heated to 50°C and 150°C, which represent normal and post-accident conditions according to Table 1. In all cases, data was transferred at 10KBps bitrate with BER<10^{-3}. Note that the spectrum of $LiNbO_3$ changed slightly with temperature, and the exact center frequency used for different temperature transmission varied by a few KHz.

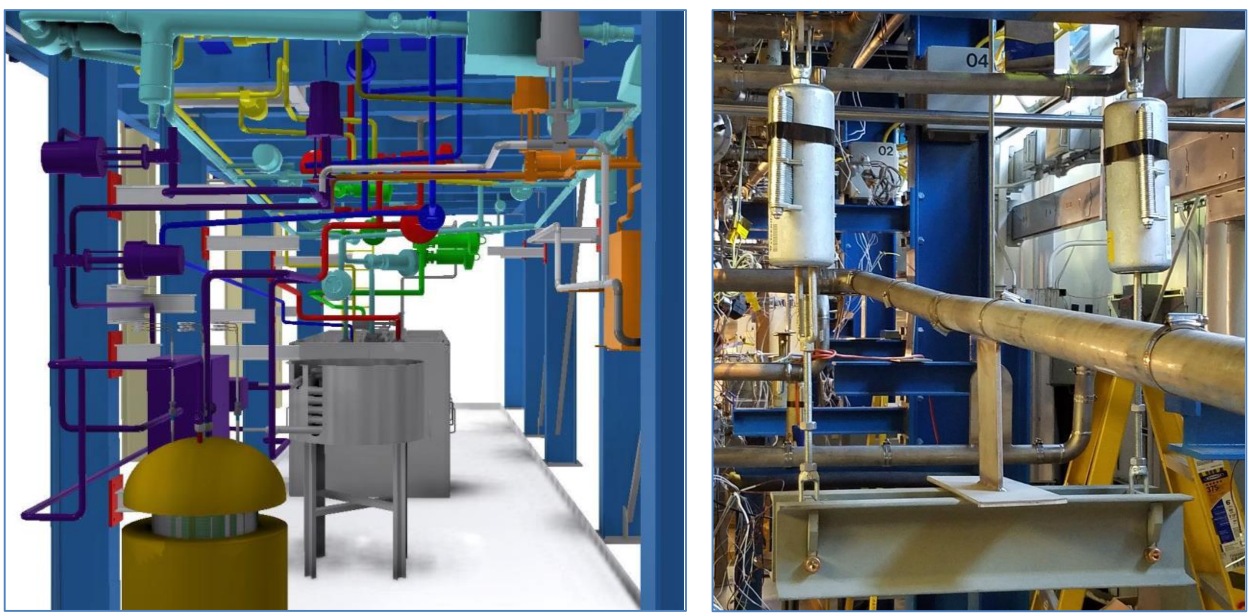
Table 2 – **Summary of achieved data transmission rates**

Transducer Type	**Temperature (C)**	**Bitrate (Kbps)**
Paintbrush 2MHz PZT with 45° flat wedge	20	2
High-temperature 700KHz $LiNbO_3$	20	10
High-temperature 700KHz $LiNbO_3$	50	10
High-temperature 700KHz $LiNbO_3$	150	10

5. Data Transmission on Bent Pipe

5.1. Analysis of piping topology in a representative environment

Stainless steel piping in a METL facility at Argonne provides a viable platform for proof-of-principle demonstration of the ultrasonic communication system in a prototypical advanced reactor environment. Analysis of piping manifolds at METL has shown that in a typical scenario, ultrasonic signals have to be transmitted over straight and bent piping sections. Examples of piping bent at 90^{o} are shown in Figure 17 [15]. Figure 17(a) displays a 3D computer generated model of representative piping elements, and Figure 17(b) shows a photograph of a section of METL piping. The bent section of piping is formed by welding of straight sections with an elbow. Prior studies on this project have been focused on coupling carrier elastic shear waves into metal pipes and developing of communication protocol on data transmission. A straight section of piping has been used for proof-of-principle laboratory studies. Before embarking on ultrasonic signal transmission over the complex piping network at METL facility, a preliminary study evaluating signal transmission losses due to piping bends is required.

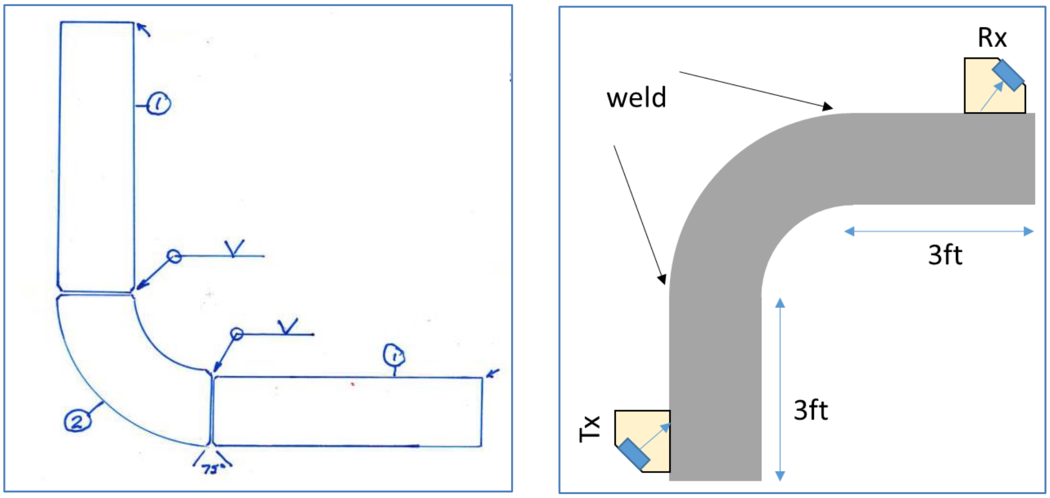


(a) (b)

Figure 17 – (a) A 3D model of the uninsulated elements of piping system (b) Photograph of a section of METL piping [15]

5.2. Development of a bent pipe test article

A test article consisting of a stainless steel pipe bent at 90^{o} was developed for laboratory analysis of ultrasonic signal transmission. The bent piping test article developed by welding two straight three-foot-long pipes to an elbow at the ANL Central Shops. For consistency, the diameter and wall thickness of the bent pipe is the same as that of the straight pipe utilized in prior studies (schedule 160 pipe with 2.375in outer diameter). Figure 18(a) shows the blueprint drawing of the straight pipes and the elbow section. The edges of the components were chamfered to insert straight piping sections into the elbow. Welding was performed to the same leak-proof quality as typical for piping in METL facility. After welding, the outer surface was grinded to achieve visibly smooth finish. Figure 18(b) shows the schematics of the welded piping laboratory assembly.



(a) (b)

Figure 18 – (a) Blueprint drawings of straight sections and elbow (b) Schematics of welding piping assembly

The photograph of welded piping assembly installed on an optical bench in the laboratory is shown in Figure 19. Angled wedge-mounted piezoelectric (PZT) and LiNbO3 transducers were coupled to the pipe to conduct signal transmission studies. Distances between the transducers were kept approximately the same as in the previous studies involving ultrasonic signal transmission on a straight pipe.

Figure 19 – Bent piping assembly in the laboratory

5.3. COMSOL modeling of ultrasonic signal transmission on a bent pipe

COMSOL Solid Mechanic Module computer simulations were performed to study ultrasonic refracted shear wave coupling and transmission across the bent piping structure. In the computer model, angled wedge mounted PZT generates longitudinal waves at the contact surface with acrylic wedge. COMSOL direct solution of elastodynamic equations leads to generation shear waves at the acrylic/metal pipe surface. In previously developed COMSOL model, PZT was modeled as iron block vibrating at an ultrasonic frequency perpendicular to the acrylic wedge surface [4]. The amplitude of displacement of the iron block is on the order of a micrometer. However, because of explicit modeling of PZT mechanical vibration, this COMSOL model required very fine meshing, which demanded significant computing resources. For example, modeling wave propagation on a 5in-long section of piping required 40GB of memory. Because of computer workstation memory limitations, only short piping sections could be modeled with this approach. To improve computational efficiency of COMSOL simulations and to model larger piping structures, we developed a new approach, which allowed reducing COMSOL model memory size from 40GB to 3GB for the same problem. In the new approach, the longitudinal waves are modeled as a boundary load applied to the acrylic wedge surface, which would in contact with PZT in the experiment. However, as could be seen in the graphics in Figure 5, PZT structure is absent from COMSOL model. As in the previous models, refracted shear waves are generated at the boundary of acrylic wedge and stainless steel pipe through direct solution of elastodynamic equations in COMSOL. The new approach allows performing computer simulations with a coarser mesh, while still maintaining sufficiently high resolution. Because of reduced memory requirement, the new approach allows to model much larger piping structures.

In this project, we modeled a bent piping structure with a 90^{o} turn, which is shown in Figure 20. All parameters of the metallic structure in the COMSOL model were the same as those of the experimental assembly in Figure 19, except that the straight piping sections were 30cm each. Reducing the size piping structure allowed performing COMSOL simulations faster and with less computer memory, while still capturing all essential physics of the problem. Longitudinal ultrasonic waves at 500KHz frequency were coupled as boundary pressure load to the acrylic wedge angled at 45^{o}. This angle exceeds the first critical angle of 27.6^{o} for the acrylic/stainless steel interface. Therefore, the incident longitudinal wave is expected to be mode-converted into a shear wave, which would subsequently propagates down the stainless steel pipe. This is, in fact, what we have observed in the output of COMSOL simulations shown in several panels in Figure 20. Elastic waves are visualized with pseudo-color plot of pressure distribution. Amplitude of the pressure is amplified compared to actual experimental values to enhance elastic wave visibility.

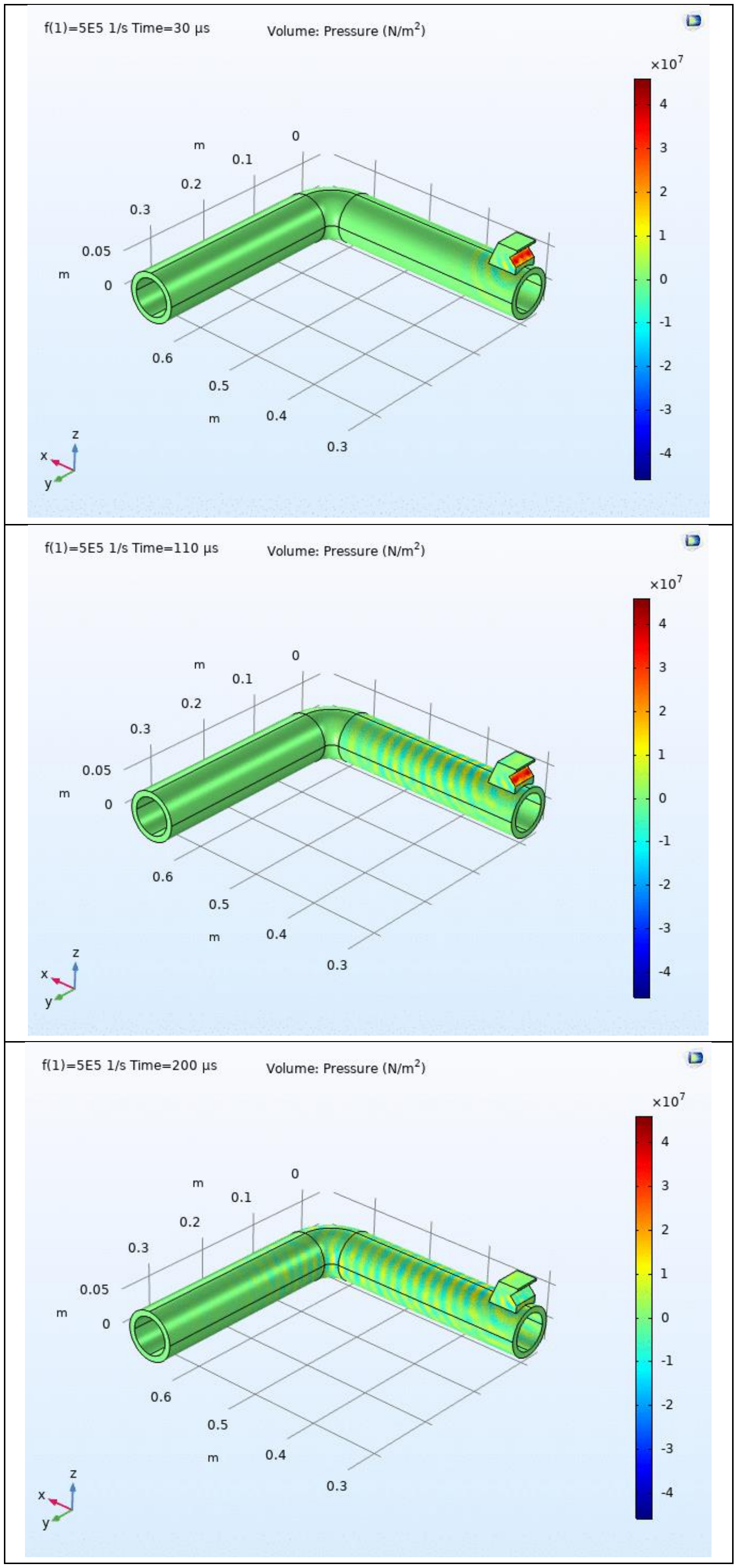


Figure 20 – **Propagation of 500KHz refracted shear wave on a metallic pipe visualized with pseudo-color map of pressure distribution at 30μs, 110μs, and 200μs**

The top panel in Figure 20 shows pressure distribution 30μs after the start of the simulations, when refracted shear wave is coupled into the pipe. The middle panel in Figure 20 shows pressure distribution after 110μs, when the wave reaches the elbow. Note that the propagation distance to the geometrical center of the bent section is slightly larger than 30cm because the elbow increases the length of the overall piping structure by approximately 10cm. Since the shear wave velocity in stainless steel is 3100m/s, in the 110μs the propagation distance is 34cm, which is qualitatively in agreement with COMSOL simulations. The longitudinal wave velocity is 5790m/s, so that in 110μs the longitudinal wave would have traversed 63cm distance, which is almost the entire bent piping structure. This is not observed in COMSOL simulations in Figure 20. Therefore, these observations confirm that COMSOL model generates refracted shear waves on a pipe. The bottom panel in Figure 20 shows pressure distribution at 200μs after the start if simulations. At this point, ultrasonic shear wave has propagated across the elbow and reached the middle of second straight section. This confirms qualitatively that ultrasonic waves travel across the piping bends. Quantitative analysis of ultrasonic wave attenuation will be perform in later studies.

5.4. Characterization of ultrasonic signal transmission on a bent pipe

Preliminary evaluation of ultrasonic signal transmission across the bent piping laboratory test article pictured in Figure 19 was performed with a pair of angled-wedge mounted 500KHz PZT's and high-temperature $LiNbO_3$ transducers operating at 750KHz. The PZT's were mounted on 45° angled wedge transducers to generate refracted shear wave. The total length of the bent piping structure is approximately seven feet, with the combined length of six feet of straight sections, and approximately one foot length of the elbow. The transmitted signal was amplified with 50dB power amplifier, and the received signal was amplified with 20dB low noise amplifier. The signals were acquired with LabVIEW software interface. Figure 21 shows received 100μs-duration pulse, transmitted with PZT's across the bent piping assembly. Delay time is approximately 700μs, which is consistent with the shear wave travel velocity of 3100m/s. One can observe in Figure 21 that the received signal is significantly distorted and dispersed in time, with effective temporal duration of the pulse stretched to 500μs. We hypothesize that such distortions are due to scattering of ultrasonic waves by welds at the piping joints. The ripples in the received signal are separated by approximately 100μs time delays, which is consistent with the time it takes she shear wave to traverse the length of the elbow between the weld joints. Similar results were observed when transmitting signals with $LiNbO_3$ transducers.

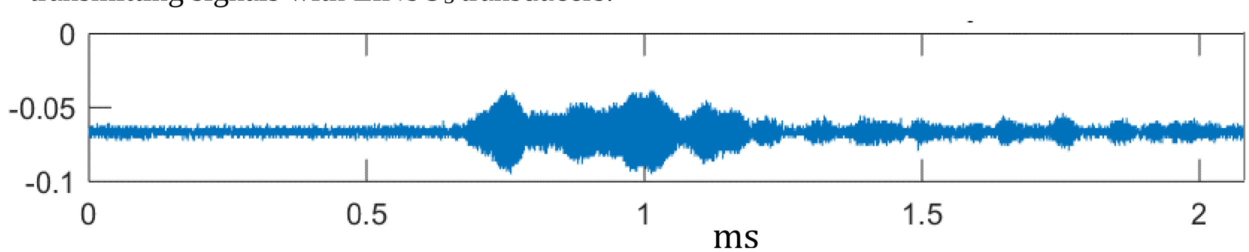


Figure 21 – Transmission of 100μs pulse with 500KHz PZT's across bent piping assembly

6. Matched Filtering via Time Reversal Modulation

As described in Section 5, transmission of ultrasonic signals over a bent pipe results in significant temporal distortion of the received signals compared to those transmitted over the same length on a straight pipe. This distortion presents a significant challenge to communication due to effective decrease in bitrate and possible increase in inter-symbol interference. Since signal distortions are likely due to welds at piping joints, which are difficult to model in advance, we chose to develop a matched filter based on time reversal modulation (TRM) signal processing technique.

6.1. Theory of time reversal modulation

Time-reversal modulation, also called phase conjugation in optics, is a general method for compensation of distortions in signal caused by propagating through random scattering media. The basic principle of this method consists of cross correlating a signal with its time-reversed replica, which results in elimination of random noise. Mathematical theory of matched filter based on TRM consists of using a waveform sampler at time t = T, which contains signal s(t) with amplitude *a* and noise *n(t)* with variance σ_n. The instantaneous ratio of signal power to average noise power is

$$\left(\frac{S}{N}\right)_T = \frac{a^2(t)}{\sigma_n^2(t)} \tag{1}$$

The signal and noise can be related to frequency response of the filter transfer function *H(f)* as

$$a(t) = \int_{-\infty}^{\infty} H(f)S(f)e^{j2\pi ft}df \tag{2}$$

$$\sigma_n^2 = \frac{N}{2}\int_{-\infty}^{\infty} |H(f)|^2 df \tag{3}$$

Where S(f) is the spectrum of the signal. We wish to find the transfer function *H(f)* which maximizes the ratio

$$\left(\frac{S}{N}\right)_T = \frac{\left|\int_{-\infty}^{\infty} H(f)S(f)e^{j2\pi ft}df\right|^2}{\frac{N_0}{2}\int_{-\infty}^{\infty} |H(f)|^2 df} \tag{4}$$

This ratio is maximized when

$$S(f) = H(f)e^{-j2\pi ft} \tag{5}$$

So that

$$\max\left(\frac{S}{N}\right)_T = \frac{2}{N}\int_{-\infty}^{\infty}|H(f)|^2 df \tag{6}$$

In time domain

$$h(t) = s(T-t) \tag{7}$$

That is, the impulse response of a filter produces the maximum signal to noise ratio when the filter is the mirror image of the message signal in time domain.

Implementation of TRM filter in ultrasonic communication on pipes would require channel calibration prior to communication session. That is, a copy of calibration ultrasonic signal transmitted over the pipe has to be sent back to the transmitter though some other means. It is assumed that the piping channel will not change over the course of the communication session. Any change in the channel will require re-calibration of the TRM filter.

6.2. Application of time reversal modulation to signal transmission over bent pipes

TRM filter concept for acoustic communications was initially developed and tested using solid bodies as channels [16], and subsequently applied to signals transmitted across the laboratory bent piping test article. Figure 22 shows the results of filtering of signals transmitted and received with $LiNbO_3$ transducers. These transducers generate ultrasonic shear waves at 750KHz frequency. Shear waves are generated due to appropriate orientation of the $LiNbO_3$ crystal. Results in different panels in Figure 22 are shown for ultrasonic pulses with 200µs, 100µs, 50µs, and 10µs temporal duration, respectively. The graphics in the left column of Figure 22 show the original received signal with significant temporal spreading and distortion. The pulse showing up near the origin of the time axis in each figure is the RF pickup of the transmitted ultrasonic signal, which is an artifact of the laboratory-based communication system. The right column in Figure 22 contains graphics showing application of the TRM filter to each respective signal. In each case, the TRM filter was developed by time reversing the waveform in the left column. After application of TRM, each pulse has signal to noise ratio SNR>2, which allows for unambiguous detection of the pulses. It should be noted that capability of receiving signals with 10µs temporal duration can lead to implementation of communication system with 100Kbps bitrate. This is would constitute and order of magnitude improvement of communication bitrate of 10Kbps reported in our most recent work.

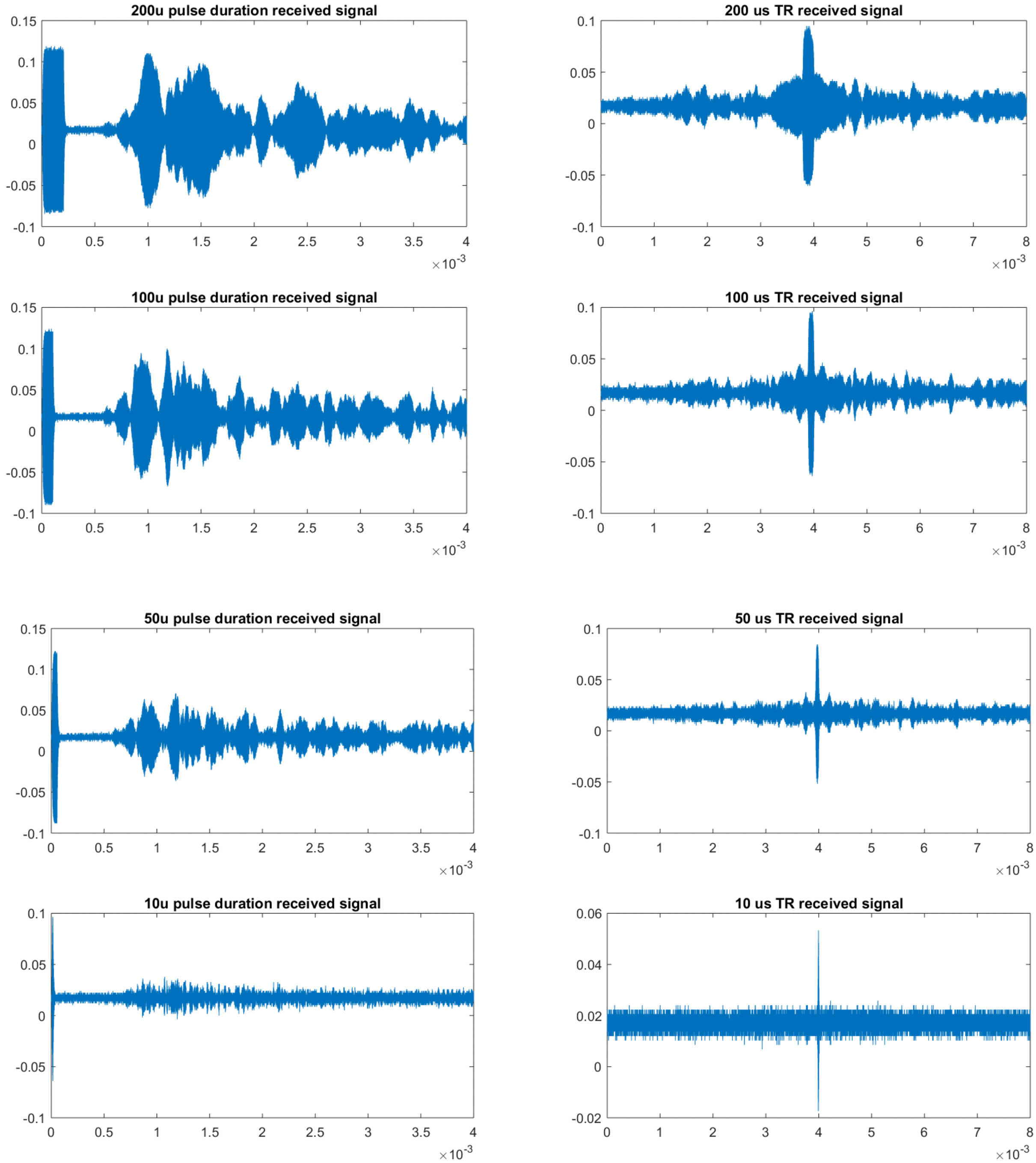


Figure 22 – TRM filter applied to 200μs, 100μs, 50μs, and 10μs pulses transmitted with $LiNbO_3$ across bent piping assembly

To evaluate applicability of TRM to high bitrate communication system, we have applied TRM to improvement of SNR for a train of 10 bits, each represented by pulses with 10μs temporal duration. The pulses were transmitted on bent piping test article with $LiNbO_3$ transducers. The train of pulses obtained after matched filtering with TRM is shown in Figure 23. All pulses have SNR > 2, which allows unambiguous detection of logical "1" and logical "0". This result demonstrates that communication at 100Kbps is, in principle, possible. Further work on high bitrate information transmission would involve incorporating TRM module into GNURadio communication protocol.

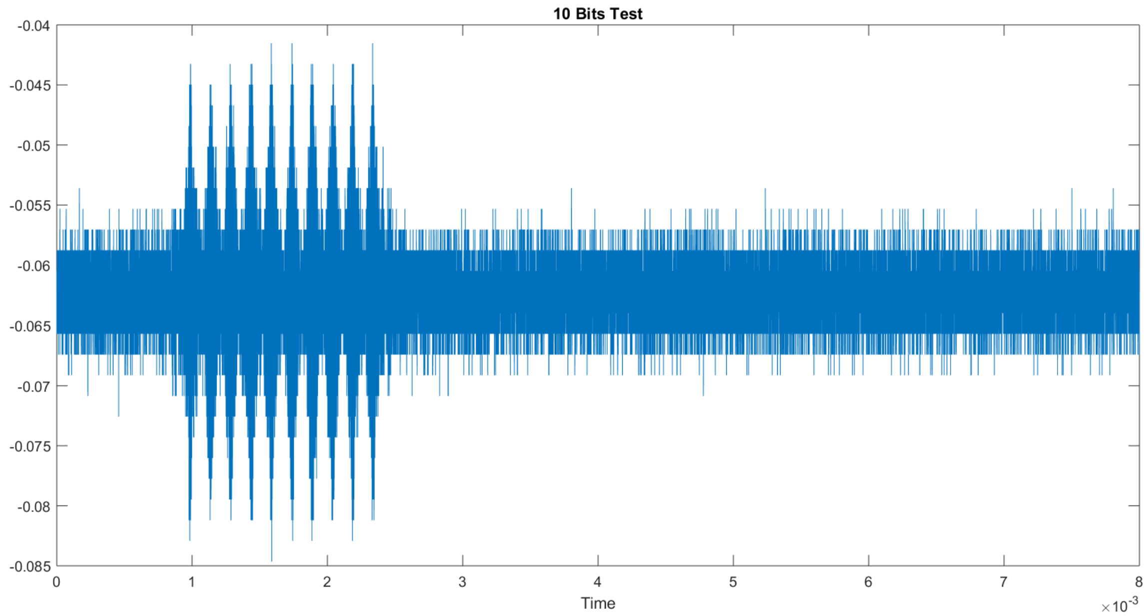


Figure 23 – TRM filter applied to a sequence of ten pulses, each of 10μs duration, transmitted with $LiNbO_3$ transducer across bent piping assembly

7. Conclusions

The objective of this project is to develop and demonstrate methods for transmission of information in nuclear facilities across physical barriers as acoustic/elastic guided waves along existing in-place metal piping infrastructure. A viable candidate for acoustic communication channel is a chemical volume control system (CVCS) stainless steel pipe, which penetrates through the containment building wall. A laboratory bench-scale system consisting of a nuclear grade CVCS-like pipe and ultrasonic transducers was assembled for a preliminary communication system analysis. Because of limited bandwidth of ultrasonic transducers, on-off-keying OOK digital communication protocol was chosen for information transmission over an acoustic channel. Design considerations of the OOK communication protocol are connected to physical characteristics of the communication channel, and involve tradeoffs of design parameters. In this report, we discuss acoustic communication system design considerations for transmission of information on a stainless steel pipe at elevated temperature, corresponding to normal and post-accident environmental conditions at the facility. The temperature values of the pipe used this project are taken from NUREG report guidelines [12].

Ultrasonic PZT's used in prior phases of the project for proof-of-principle communication system development in prior work on the project are not suitable are not suitable for operation at high temperature. To perform ultrasonic data transmission at temperatures up to 150^{o}C, we have utilized custom-made high-temperature compatible $LiNbO_3$ ultrasonic transducers, originally developed at Argonne for liquid sodium flow metering application at EBRII. Preliminary evaluation at room temperature showed that $LiNbO_3$ transducers can be used for OOK communications on a pipe. The bitrate of data transmission was further enhanced by developing a Gaussian pulse shape filter to suppress transducer ringing. A high-temperature laboratory setup was developed by installing heaters, temperature controllers and thermal insulation on the pipe. This included development of custom insertion heating elements for controlling temperature at pipe ends. Data transmission on heated pipes was demonstrated using a text file and a 90KB image of Argonne logo. In particular, transmission with 10Kbps bitrate of data was achieved on the pipe heated to 50^{o}C and 150^{o}C, which represented communication during normal and post-accident environment at the facility.

Preliminary analysis of ultrasonic signal transmission over complex piping manifolds was conducted in preparation for demonstration of the ultrasonic communication system performance in a representative environment. Mechanisms Engineering Test Loop (METL) facility at ANL was chosen as a viable candidate for communication system demonstration. Analysis of piping manifolds at METL has shown that in a typical scenario, ultrasonic signals have to be transmitted over straight and bent piping sections. This report describes preliminary studies on transmission of information with ultrasonic shear waves across bent piping sections. A test article consisting of a stainless steel pipe bent at 90^{o} was developed for laboratory analysis of ultrasonic signal transmission. The bent piping test article developed by welding two straight pipes to an elbow. For consistency, the diameter and wall thickness of the bent pipe is the same as that of the straight pipe utilized in prior studies. COMSOL computer simulations were performed to study ultrasonic refracted shear wave coupling and transmission across bent piping. Preliminary evaluations of ultrasonic shear wave transmission were conducted with piezoelectric (PZT) and $LiNbO_3$ transducers, with the signals recorded with previously developed LabView interface. Preliminary results have shown significant dispersion of transmitted signals, most likely due to reflections and scattering by piping welds. Signal distortion compensation algorithm based on time reversal modulation (TRM) was proposed and demonstrated for signals transmitted over the bent pipe. Using TRM, it was shown that communication bitrates of 100Kbps were achievable, in principle. Next steps on the project will involve developing communication protocol for transmission of images across bent piping assembly. This would require modification of the existing GNURadio communication protocol to incorporate TRM filter in the information modulation scheme.

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