Time Reversal Data Communications on Pipes Using Guided Elastic Waves - Part I: Basic Principles

Yuanwei Jin *, Deshuang Zhao †, and Yujie Ying ♭

*Engineering and Aviation Sciences, University of Maryland Eastern Shore, Princess Anne, MD 21853
†Institute of Applied Physics, Univ. of Electronic Science and Tech. of China, Chengdu 610054
♭Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA 15213

ABSTRACT

Piezoelectric sensors that are embedded in large structures and are inter-connected as a sensor network can provide critical information regarding the integrity of the structures being monitored. A viable data communication scheme for sensor networks is needed to ensure effective transmission of messages regarding the structural health conditions from sensor nodes to the central processing unit. In this paper we develop a time reversal based data communication scheme that utilizes guided elastic waves for structural health monitoring applications. Unlike conventional data communication technologies that use electromagnetic radio waves or acoustical waves, the proposed method utilize elastic waves as message carriers and steel pipes as transmission channels. However, the multi-modal and dispersive characteristics of guided waves make it difficult to interpret the channel responses or to transfer correctly the structural information data along pipes. In this paper, we present the basic principles of the proposed time reversal based pulse position modulation and demonstrate by simulation that this method can effectively overcome channel dispersion, achieve synchronization, and delivery information bits through steels pipes or pipe-like structures correctly.

Keywords: Guided elastic waves, time reversal, pulse position modulation, data communication, dispersive channels

1. INTRODUCTION

Piezoelectric sensors have long been used for inspecting the integrity of large civil structures such as pipes, offshore platforms, etc. Upon excitation, active acoustic sensor, or actuators, can generate elastic waves that propagate a long distance, interrogate structures for possible defects, thus providing information of the operating conditions of the structure. With the advancement of sensor technology and emerging signal and data processing techniques, much effort has been devoted to the development of integrated monitoring systems for large civil structures. Structural health monitoring (SHM) is a systematic methodology for continuously assessing the integrity of a structure for the identification of damage. SHM is increasingly being deployed to monitor and predict vulnerabilities in large civil infrastructures to prevent critical failure. Unlike conventional nondestructive techniques, a SHM system would utilize permanently mounted or embedded sensors on the structure to provide continuous assessment of structural integrity. The sensors in a SHM system will inter-connect and become an integrated network for defect monitoring and assessment to ensure the normal operation of the structure. Various studies have been conducted that use sensor networks for monitoring and detecting of defects or damage in civil structures.[1,2,3]

One of the future SHM applications using piezoelectric sensor networks is the monitoring of structural integrity for pipelines or pipe-like hollow structures in offshore platforms. Early research demonstrates that a...
network of piezoelectric sensors that are mounted on steel pipes provide improved performance in terms of detection and classification compared with conventional inspection methods. One of the important aspects of sensor networks for SHM applications is its ability of data communication between sensors. This is because the operating status and conditions of the structure must be sent through the network to a center processing unit so that human operators can take necessary actions. Data communication within a sensor network could occur between two or multiple sensor nodes or between sensor nodes and a central processing unit. In the classic communication theory, information bearing signals are modulated and excited from a transmitter; the excitation signals propagate through physical medium, such as air, water, or cable, and are received by a receiver. The received signals are demodulated. The transmitted information is then recovered. For example, in wireless communication systems, electromagnetic signals are used as carriers for data transmission. The transmission medium is air. In underwater acoustic communication, acoustical signals are utilized for transmitting information. The transmission medium is water. In many existing SHM sensor network applications, conventional schemes such as wireless radio communication and acoustical communication are adopted and modified for data communication. However, research has shown that in many real-life applications, conventional communication schemes are inapplicable or undesirable. For example, for pipes that are buried underground or for hollow subsea structures in offshore platforms, radio communication is difficult to realize because electromagnetic wave signals suffer severe decay in soil or water which results in very short transmission range.

In this paper, we develop a time reversal based guided elastic wave communication scheme that utilizes steel pipes as transmission channels. The contribution of this paper lies in the following two perspectives: First, we use steel pipes as communication medium for data transmission and reception. Unlike the conventional transmission modalities, modulated guided elastic signals that can propagate on steel pipes will be transmitted and received by piezoelectric sensors mounted on or embedded in steel pipes. Although communication inside a pipe using electromagnetic or acoustics (i.e., treating the pipe as an acoustic waveguide) has been reported, to the best of our knowledge, the research of using guided elastic waves for data communication is very limited. Some earlier work on elastic wave communication includes drill string communication or Lamb wave communication. However, there has not been systematic study of data communication schemes using elastic waves. Second, we utilize time reversal based pulse position modulation (TR-PPM) method to compensate for the signal and channel dispersion in the communication system design. Time reversal has emerged as a viable approach for overcoming signal dispersion in many applications such as underwater acoustics, electromagnetics, etc. Time reversal provides a novel mechanism for adaptively transmitting signals that match with the propagation medium in order to enhance signal detection. Recently, a growing amount of research has been devoted to time reversal based waveform transmission for the applications of detection, localization, and classification. Time reversal is considered as an adaptive waveform transmission scheme that implements iterative probing and learning from the returned sensing signals based on the interaction of the sensor and the environment. Our previous research has shown that time reversal provides significant benefit in signal detection and classification for SHM applications. In this paper, we will demonstrate that time reversal PPM can effectively overcome dispersion of guided elastic waves, achieve signal synchronization, and thus enabling data communication through steel pipes.

This paper presents the theoretical part (Part I) of the proposed elastic wave communication scheme. The experimental results will be presented as Part II in this SPIE conference. The remainder of the paper is organized as follows. Section 2 discusses the characteristics of pipe wave propagation. Section 3 presents the basic principles of TR-PPM data communication using pipe waves. Section 4 presents simulation based results for data communications. Conclusion is drawn in section 5.
2. CHARACTERISTICS OF PIPE WAVE PROPAGATION

Guided waves, i.e., waves that travel along a rod, tube, pipe, or plate-like structure, form as a result of the interaction between ultrasonic excitation signals propagating in a medium and the medium’s boundaries. Conventionally, we use Lamb waves to refer to the elastic waves that propagate in thin plates. Here we use pipe waves to refer to the guided waves propagating in pipes or thin cylindrical shells. The excitation of guided ultrasonic waves has become a popular tool for the nondestructive inspection of pipes and other physical infrastructures due to their potential to travel great distances. However, there are three fundamental difficulties when guided waves are utilized for pipe inspection or data communication, i.e., dispersion, multi-mode, and ambient noise. First, the elastic guided wave signals are highly dispersive. Signal dispersion stems from the elastic wave propagation mechanism that signal transmission speed varies with frequencies. Acoustic signal dispersion causes signal time spreading, as well as phase and frequency shift. In the communication theory, this phenomenon is called multipath propagation. The delayed arrivals of propagating signals may overlap destructively causing severe signal attenuation, or signal fading, which results in poor system performance in many stages of the communication flow including synchronization, signal detection, and demodulation, etc. Second, pipe waves are characterized by an infinite number of dispersive longitudinal and torsional modes and a

![Dispersion curves (group speed)](image1)

![Dispersion curves (phase speed)](image2)

Figure 1. (a) Group speed versus frequencies. (b) Phase speed versus frequencies. The plots are generated by the PCDISP software for a 4 mm thick steel pipe. $L(0, n)$ is the longitudinal mode, $T(0, n)$ is the torsional mode, and $F(m, n)$ is the flexural mode.
doubly infinite number of flexural modes. The longitudinal and torsional modes are both axisymmetric while each flexural mode exhibiting an infinite number of non-axisymmetric circumferential mode orders. Thus a proper selection of wave modes for signal transmission would be a critical but difficult task. Fig. 1 depicts the group speed and phase speed versus the frequencies for a steel pipe with inner radius of 31 mm and outside radius of 35 mm in the frequency range of 10 kiloHertz to 500 kiloHertz. The longitudinal modes, flexural modes, and torsional modes are clearly present. The plots in the figure are generated using the PCdisp software. Third, ambient noise exists in the received signals. Ambient noise refers to the addition of a random signal of specific mean value and variance. A high noise level reduces the signal-to-noise power ratio at the receiver, which yields poor performance for signal detection. Adaptive filtering methods should be employed to reduce the level of ambient noise.

3. BASIC PRINCIPLE OF PIPE WAVE COMMUNICATION

A complete communication system design is very complicated. In this paper, we focus on a proof-of-concept design which shows that information bits ‘0’s and ‘1’s can be transmitted using pipes waves and be recovered correctly in spite of severe channel dispersion that exists in elastic medium.

3.1 Pulse Position Modulation (PPM)

In this section, we present the data communication scheme based on pulse position modulation (PPM) for pipe waves. The developed communication scheme will overcome channel dispersion and achieve symbol synchronization for signal detection. Pulse-position modulation is a form of signal modulation in which the message information is encoded in the time delay between pulses in a sequence of signal pulses. Time hopping PPM has been widely used in impulse-radio ultra-wideband (UWB) system. For elastic wave communication, we will use wide band pulses for signal modulation in which every transmitted symbol is composed of repeated pulses called frame. Let \( T_s \) and \( T_f \) denote the symbol duration and frame duration, respectively, then

\[
T_s = N_f T_f, \tag{1}
\]

which means there is one pulse per frame. A general wideband symbol signature waveform transmitted during the acquisition process for a single user can be expressed as a series of wideband monocycles

\[
g_s(t) = \sum_{j=0}^{N_f-1} g(t - j T_f - a_j T_c) \tag{2}
\]

where \( a_j \in [0, N_c - 1] \) represents user-specific pseudorandom time hopping (TH) code for separating receive sensors. The hopping pattern may take on different forms, such as fast hopping or slow hopping. Furthermore, the data symbols are modulated during transmission. Each frame contains \( N_b \) chips, each of duration \( T_c \). The PPM modulated wideband pipe wave signal transmitted by the desired sensor is described as

\[
s(t) = \sum_i g_s(t - i N_f T_f - c_i \Delta) \tag{3}
\]

where \( c_i \in \{0, 1\} \) represent the data symbols that are modeled as binary independent and identically distributed (i.i.d.) random variables, and \( \Delta \) represents the time shift imposed on all the monocycles of a given block by a unit data symbol. Each excitation pulse \( s(t) \) is of ultrashort duration \( T_p \ll T_f \) at the microsecond scale, occupying a wide bandwidth. Note that, we will choose \( N_b = 1 \) and \( N_f = 1 \) in this paper.
Next, we discuss the propagation channel. For elastic waves, the characteristics of the propagation channel between any two locations are very complicated, in that the response of the channel is governed by the propagation wave equations as well as the boundary conditions. However, for point-to-point data communication on steel pipes, we can model the propagation channel for wideband signal communications as a stochastic tapped delay line,

\[ h(t) = \sum_{l=0}^{L-1} \alpha_l f_l(t - \tau_l) \]  

where \( L \) is the number of taps in the channel response, \( \alpha_l \) is the path gain at excess delay \( \tau_l \) corresponding to the \( l \)-th propagation path. The function \( f_l(t) \) model the combined effect of the transmit and receive sensors and the propagation channel corresponding to the \( l \)-th path of the transmitted pulse. Here we consider \( f(t) \) is the superposition of various wave modes within the excitation frequency range. Based on the linear system theory, the received signal from the receiver sensor can then be written as

\[ r(t) = s(t) * h(t) + w(t) \]  

\[ = \sum_{i=-\infty}^{\infty} q(t - iN_f T_f - c_i \Delta - \tau) + w(t) \]

where the symbol * denotes linear convolution, and

\[ q(t) = \sum_{l=0}^{L-1} \alpha_l \psi_l(t - \tau_l) \]

is the received waveform corresponding to a single pulse. The signal

\[ \psi_l = f_l(t) * s(t) \]

is the received wideband elastic signal pulse from the \( l \)-th path. \( w(t) \) is the additive noise with zero-mean and complex Gaussian distribution. The symbol \( \tau \) is the direct propagation delay between the transmitter and the receiver. One of the challenges in enabling pulsed wideband communication is synchronization, i.e., before the signal can be demodulated, each frame of the received signals needs to be aligned by correlating the received signal with the originally transmitted signal. This process is called synchronization. Most existing synchronizers are based on the maximum likelihood principle that requires a “clean template” of the received pulse. However, the latter is not available when the unknown propagation channel is highly dispersive and multipath rich. Other existing schemes are usually very complicated. Thus, in order to realize PPM in highly dispersive elastic wave channel, we need to estimate the timing offset \( \tau \) accurately. In this paper, we use time reversal method to achieve accurate timing acquisition for synchronization.

### 3.2 Time Reversal PPM for Data Communication

In this section, we describe the time reversal based PPM scheme for signal synchronization and detection. We consider two sensors that are mounted on a steel pipe with sensor \( A \) being the transmitter sensor and sensor \( B \) being the receiver sensor. In a conventional data communication configuration, the information will be modulated by waveform \( s(t) \) and sent from sensor \( A \) to sensor \( B \). The channel impulse response \( h(t) \), often called the Green’s function, characterizes the structural response of the pipe in the time domain between sensor \( A \) and sensor \( B \). Fig. 2 illustrates the proposed time reversal PPM scheme, which can be described as follows:

**Step-1: Channel Sounding** This step probes the channel \( h(t) \) between the sensor \( A \) and \( B \). In the time reversal PPM scheme, rather than sending information carrying signal \( s(t) \) directly from the source sensor \( A \) to the
destination sensor $B$, we will first probe the propagation channel $h(t)$ by sending a pilot signal $p(t)$ from the destination sensor $B$ to the source sensor $A$. After $p(t)$ propagates through the channel, the received signal at sensor $A$ is expressed by

$$y(t) = p(t) \ast h(t),$$

where the symbol $\ast$ represents the linear convolution. We choose a modulated Gaussian pulse

$$p(t) = A e^{-\left(\frac{t-t_0}{T}\right)^2} \cos(2\pi f_c t)$$

as the probe signal, where $f_c$ is the center frequency of the modulation signal, $T$ is the pulse width, $t_0$ is the time offset from $t = 0$, and $A$ is the amplitude. The transmission energy for signal $p(t)$ is given by

$$E_p = \int_{-\infty}^{\infty} |p(t)|^2 dt$$

Step-2: Time Reversal In this step, $y(t)$ is recorded and time reversed in the time domain. The time reversing operation is equivalent to reading the data by first-in-last-out. After time reversal, the waveform that will be used for signal modulation and transmission becomes

$$\bar{s}(t) \triangleq y(-t) = p(-t) \ast h(-t)$$

where $y(-t)$ is called the time reversed waveform. The signal $\bar{s}(t)$ is the information carrier for transmission.

![Figure 2. Illustration of time reversal pulse position modulation (TR-PPM) enabled data communication over steel pipes. (i) A pilot signal is sent through the pipe for probing the dispersive channel; (ii) The received signal is time spread. (iii) The received signal is time-reversed in the time domain; (iv) TR-PPM is applied to the received signal for information bit transmission; (v) Synchronized received signal is detected and demodulated for information retrieval.](image)
**Step-3: Time Reversal Pulse Position Modulation (TR-PPM)**

Next, the signal \( \tilde{s}(t) \) in (12) will be modulated using PPM. Notice that the channel impulse response \( h(t) \) is also time reversed when \( y(t) \) is time reversed. The time reversed channel impulse response, \( h(-t) \), plays an important role in the time reversal transmission because it compensates for the time delays that result from different propagating paths and wave modes in the channel. If we retransmit \( y(-t) \) back to the channel, by the channel reciprocity condition, the retransmitted waveform will focus the scattered multipath energies on the initial source receiver temporally and spatially by time reversal. Thus, the intensity of the signal received by the receiver is increased significantly and the time spread is compressed substantially. The TR-PPM modulated signal takes the form of

\[
s(t) = \sum_{i=1}^{Q} k y(-t) \delta(t - iT_f - c_j \Delta)
\]

where \( c_j \in \{0, 1\} \) is the binary data to be transmitted, \( T_f \) is the frame time to send one bit data, \( \Delta \) is the additional time shift to distinguish between the pulses carrying the bit “0” or “1”. \( \delta(\cdot) \) is the Dirac delta function.

The energy-normalization coefficient obtained in (13) is given by

\[
k = \sqrt{\frac{E_p}{E_y}}
\]

where

\[
E_y = \int_{-\infty}^{\infty} y^2(-t) dt
\]

**4. SIMULATION STUDIES**

In this section, we present the time reversal PPM modulation and demodulation for signals transmitted through a simulated dispersive channel. We conduct simulation studies under two scenarios to examine the performance of the proposed data communication scheme. In the first scenario, the retransmitted signal \( \tilde{s}(t) = y(-t) \) as described by (12). In the second scenario, the signal \( \tilde{s}(t) \) is the truncated \( y(-t) \) in the time domain. The waveform truncation is necessary because the time span of the signal \( y(-t) \) could be too long due to channel dispersion.

**4.1 Performance with full waveform transmission**

Under this scenario, the total received signal will be time-reversed and re-transmitted. Fig. 3(a) depicts the transmitted Gaussian pilot signal \( p(t) \). Fig. 3(b) shows a simulated multipath channel \( h(t) \). This channel shows severe time spreading. Assume that the information bits to be transmitted are \([0 \ 1 \ 0 \ 1 \ 1]\). Fig. 4(a) depicts a focused peak which allows for accurate synchronization and demodulation, while Fig. 4(b) showing that the received signal is significantly spread, which causes inaccurate synchronization and demodulation.

**4.2 Performance with waveform truncation**

We let \( T_0 \) denote the time duration of the signal \( y(-t) \). We notice that in guided wave excitation and reception, \( T_0 \) would be very large number relative to the original pulse duration \( T \) for \( p(t) \), thus, waveform truncation becomes necessary. Under this scenario, the received signal will be truncated before time reversal for re-transmission. The truncated signal becomes

\[
\tilde{s}(t) = \begin{cases} 
  y(-t) & 0 < t < T_0' \\
  0 & T_0' \leq t < T_0 
\end{cases}
\]

where

\[
T_0' = \frac{\Delta}{\Delta + T_f}
\]

and

\[
\Delta = \frac{1}{2} T_f / c_j
\]
where $T'_0$ is the waveform duration of the truncated signal in (16). The amount of signal truncation is determined by the energy ratio given below

$$\rho = \frac{E_s}{E_0}$$

(17)

where $E_0$ is the signal energy of the re-transmitted signal without truncation. The waveform duration for $s(t)$ is $T_0$. We let $E_s$ denote the signal energy with truncation. The truncated waveform is of duration $T'_0 < T_0$. The energy expressions are give by

$$E_0 = \int_0^{T_0} |\tilde{s}(t)|^2 dt$$

(18)

$$E_s = \int_0^{T'_0} |\tilde{s}(t)|^2 dt$$

(19)

A value of $\rho = 0.5$ means that fifty percent of the signal energy is retained after truncation. Fig. 5(a) and (b) depict the received TR-PPM modulated waveform when signal truncation is performed. The truncation ratio, defined as $1 - \rho$, is at 20% and 50% respectively. The results show that waveform truncation yields focusing peaks with reduced peak amplitude compared with the un-truncated case. However, the information carrying signals can still be demodulated accurately.

5. CONCLUSION

This paper develops a time reversal based pulse position modulation scheme that realizes data communication on steel pipes using guided elastic waves. Unlike conventional communication modalities such as wireless radio communication and underwater acoustic communication, the developed data communication scheme utilizes steel pipes as a communication channel and elastic waves as message carriers. In order to overcome the severe channel dispersion due to guided channel and elastic waves as message carriers. In order to overcome the severe channel dispersion due to guided elastic wave propagation, we utilize time reversal method to compensate for the dispersion thus achieving signal synchronization for signal detection. Simulation studies demonstrate the success of the developed scheme.

![Figure 3](https://example.com/figure3.png)

Figure 3. (a) Transmitted Gaussian pilot signal $p(t)$. (b) Simulated channel impulse response function $h(t)$. 
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Figure 4. Received signals for demodulation. The originally transmitted information bits are \([0\ 1\ 0\ 1\ 1]\). The goal is to produce synchronized and focused waveforms for demodulation and detection. The received signal should show the displacement of 0, Δ, 0, Δ, and Δ, respectively, which enables accurate synchronization and demodulation. (a) Received signal under ideal non-dispersive channel. (b) Received time-focused signals using time reversal PPM modulation. (c) Received time spread signals using conventional PPM modulation. Received signals show severe time spreading due to channel dispersion thus resulting in poor synchronization and detection.
Figure 5. Received Time Reversal PPM signals for demodulation with waveform truncation. The original transmitted information bits are \([0 \ 1 \ 0 \ 1 \ 1]\). (a) Received time-focused signals using time reversal PPM modulation with twenty percent energy reduction. (b) Received time-focused signals using time reversal PPM modulation with fifty percent energy reduction.