Time Reversal Focusing for Pipeline Health Monitoring

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Abstract. This paper investigates the use of time reversal processing techniques to compensate for multimodal and dispersive effects in a low-power structural health monitoring system for pipelines. We demonstrate the use of time reversal as a pitch-catch operation between two transducer arrays to illuminate changes caused by damage on a pipe. We then show and discuss how differences in the severity of damage affect the signals recorded at the receiving transducer array and demonstrate how these results can be interpreted to measure those changes. Our results are demonstrated through experimental observation.

Keywords: Time Reversal, Structural Health Monitoring, Nondestructive Testing
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INTRODUCTION

Over the last decade, the deterioration of the United States' infrastructure has become a subject of increasing concern. Pipeline networks are particularly difficult to maintain. The United States has approximately 305,000 miles of interstate and intrastate pipelines dedicated to the transmission of natural gas to local distribution plants [1].

Ultrasonic guided wave technology has become an important tool for evaluating the integrity of many civil structures. Guided waves can travel long distances in many materials and propagate through the entire thickness of the object under test [2]. These properties make them appealing for nondestructive inspection. Many ultrasonic pipeline inspection systems use large rings of transducers to excite guided waves and listen for echoes produced by cracks, corrosion, or other damage [3].

In a structural health monitoring environment, transducers are permanently attached to the structure. These systems can be used to monitoring large networks of pipelines in real-time. Processing techniques can also take advantage of the transducers' spatial diversity to improve detection performance while reducing power requirements.

In this paper, we demonstrate a monitoring technique using a method called Time Reversal Change Focusing (TRCF). In time reversal focusing, the response between a source and an array receiver is obtained. A time-reversed version of the response is then propagated backwards through the medium from the same array. These waves propagate as if traveling backward in time and focus spatially and temporally back at the original source. Time reversal focusing has been extensively investigated for pulse-echo ultrasonic inspection by Fink and others [4, 5, 6]. In TRCF, changes in medium caused by damage can be illuminated using time reversal's focusing properties. Through experimentation, we demonstrate how this method provides a metric for classifying the magnitude of damage in a pipe while relaxing the restrictions on excitation frequency and bandwidth that are imposed on many other nondestructive techniques.

PIPE WAVES AND WAVE MODES

When a guided wave is excited into a thin, solid pipe, the waves decompose into several orthogonal wave modes. Each of these wave modes propagate through the medium at different velocities. Pipe wave modes can be grouped into three distinct categories: longitudinal waves, flexural waves, and torsional waves [7]. Each mode group respectively oscillates in the direction of propagation, in the direction orthogonal to the surface of the pipe, and in the direction tangential to the surface of the pipe. Both longitudinal and torsional modes are axisymmetric, while flexural modes vary across both the length and circumference of the pipe. As the frequency of excitation increases, new modes are excited at various discrete frequencies. There are a countably infinite number of possible longitudinal and torsional modes and a doubly countably infinite number of possible flexural modes. These wave modes are also dispersive, such that their velocity changes as a function of frequency [8, 9].

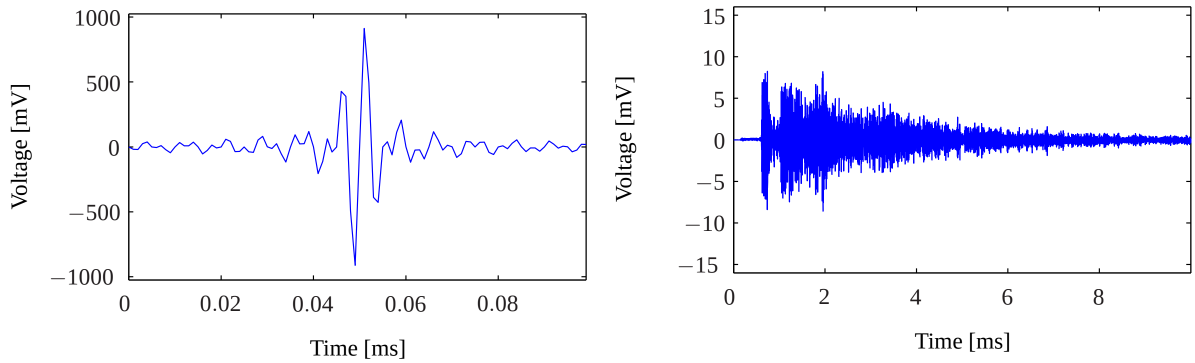

FIGURE 1. (left) A 200 kHz bandwidth sinc pulse modulated by a 200 kHz carrier excitation used in experiments. (right) The response of the above excitation after traveling across a 3 meter long pipe.

At the receiving array, modes (without dispersion) appear as replicas of the original excitation waveform that arrive at different times. This closely resembles the effects seen from multipath wave propagation, which is common in many fields. Since no real life signal contains a single frequency, dispersion further distorts the waveforms as they propagate through the medium. As an example, the response of a wideband, 200 kHz signal after traveling across a 3 meter long pipe is shown in fig. 1. Due to the multimodal and dispersive effects, the responses from existing ultrasonic inspection and structural health monitoring systems are often difficult to interpret. To reduce these distorting effects, many systems are designed to operate at low frequencies and with small bandwidths [2]. Unfortunately, a monitoring system's frequency response depends on the properties of the structure under test and is not optimal at low frequencies. Transducer geometries can also be manipulated in order to excite specific modes, but this can reduce signal strength and the guided wave's sensitivity to particular defects [10].

While multimodal, dispersive, and multipath effects are seen as detrimental to conventional ultrasonic methods, these effects are actually beneficial for time reversal systems. Time reversal has been tested extensively in radar [11, 12], underwater acoustics [13], and non-destructive testing [4] applications to coherently focus signals across a channel. It has been shown that in the presence of multipath behavior, caused by boundaries or scatterers, the focusing achieved through time reversal improves detection and imaging significantly with respect to other conventional methods [14]. Further, it has also been shown that time reversal's focusing is further improved by more pronounced multimodal and dispersive effects [15].

PHYSICAL TIME REVERSAL CHANGE FOCUSING

Time reversal focusing is a technique used to improve, over other conventional methods, the spatial and temporal focusing of waves through inhomogeneous media. In time reversal focusing, an array of transducers records a finite length response from a single source over a time interval $0 < t < T$. T must be large enough so that the entire time response exists within the interval. The measured response at each transducer is then normalized, reversed in time, and propagated backwards through the channel at time T. The waves return across the channel as if traveling backward through time and, at time $2T$, coherently focus at the original source. Throughout this process, we assume the channel is reciprocal [4]. This assumption, which is generally valid, ensures that the channel does not change when the direction of the propagating waves change. This section mathematically describes how background subtraction and time reversal are used in order to focus changes caused by damage in the pipe.

Consider a pipe or section of a pipe with, at one end, a single transducer A and, at the other end, a circular array B of N transducers around the pipe's circumference. When a signal $s(t)$ is transmitted from transducer A to array B, the Fourier transform of the received signal at transducer n for $1 \leq n \leq N$ is

$$Y_n(\omega) \quad = \quad H_n(\omega)S(\omega) + V_n(\omega) \tag{1}$$

where $H_n(\omega)$ denotes the transfer function, or the Fourier transform of the Green's function, from the transmitter A to the location of transducer n in array B. The term $V_n(\omega)$ denotes additive noise. We model $V_n(\omega)$ as a zero mean circularly symmetric complex Gaussian random variable.

We assume that we are able to observe and accurately measure the response of the pipe before any damage occurs and that this response is stationary over time. Therefore,

$$Y_{C,n}(\omega) = H_{C,n}(\omega)S(\omega), \tag{2}$$

which we refer to as the background clutter response, is known. Further, since $S(\omega)$ is also known, then $H_{C,n}(\omega)$, the transfer function of the clutter, can be determined. When damage is present within the pipe, we can express the response at each of the N receivers as

$$\begin{aligned} Y_{C+T,n}(\omega) &= H_{C+T,n}(\omega)S(\omega) + V_n(\omega) \\ &= \left[H_{C,n}(\omega) + H_{T,n}(\omega)\right]S(\omega) + V_n(\omega), \end{aligned} \tag{3}$$

where $H_{T,n}(\omega)$ denotes the target transfer function. Here target refers to damage in the environment. In (3), the background $H_{C,n}(\omega)S(\omega)$ is known and so can be subtracted to yield

$$Y_n(\omega) = H_{T,n}(\omega)S(\omega) + V_n(\omega). \tag{4}$$

In (4), the response is a function of changes due to damage. The response $Y_n(\omega)$ is then time reversed. In the frequency domain, time reversal, or time negation, is equivalent to frequency conjugation for real time signals. The signal is also scaled by the constant

$$k = \sqrt{\frac{\int_{-\infty}^{\infty}|S(\omega)|^2 d\omega}{\sum_{n=1}^{N}\int_{-\infty}^{\infty}|Y_n(\omega)|^2 d\omega}} \tag{5}$$

so that the total energy of the responses from all N transducers is equal to the energy in the original excitation signal.

The time reversed, scaled signal is sent backwards. Since the medium is reciprocal, the transfer function between transducer n in array B and transducer A will remain $H_{C+T,n}(\omega)$. The signal received at transducer A is then expressed as a superposition of each of the responses from the N transducers in array B

$$X_{C+T}(\omega) = \sum_{n=1}^{N}(H_{C,n}(\omega) + H_{T,n}(\omega))Y_n^*(\omega) + W_n(\omega), \tag{6}$$

where $Wn(\omega)$ is another additive noise term represented by a zero mean, circularly symmetric normal random variable, and where $(\cdot)^*$ denotes the complex conjugate operation. As stated previously, $H_{C,n}(\omega)$ and $Y_n^*(\omega)$ are known, and therefore the clutter component can be subtracted from (6). After the background subtraction, the resulting expression is only a function of the changes in the medium

$$X(\omega) = \sum_{n=1}^{N} H_{T,n}(\omega)Y_n^*(\omega) + W_n(\omega). \tag{7}$$

When the expression for $Y_n^*(\omega)$ is inserted into (6), the equation becomes

$$\begin{aligned} X(\omega) &= \sum_{n=1}^{N} H_{T,n}(\omega)(H_{T,n}^*(\omega)S^*(\omega) + V_n^*(\omega)) + W_n(\omega) \\ &= \sum_{n=1}^{N} |H_{T,n}(\omega)|^2 S^*(\omega) + H_{T,n}(\omega)V_n^*(\omega) + W_n(\omega). \end{aligned} \tag{8}$$

Since the noise components are zero mean and we assume the two measurements are independent observations, than the expected value of $X(\omega)$ is

$$E\left[X(\omega)\right] = \sum_{n=1}^{N} |H_n(\omega)|^2 S^*(\omega). \tag{9}$$

Equation (9) shows that, by back-propagating the time reversed signal, the response due to changes in the medium can be expressed as the magnitude-squared of the target transfer function times the time reversed excitation signal. This indicates that any phase information, which represents time delay information in the time domain, only derives from the excitation signal. This causes the time domain signal to be symmetric and to have a large peak in the center of that symmetry.

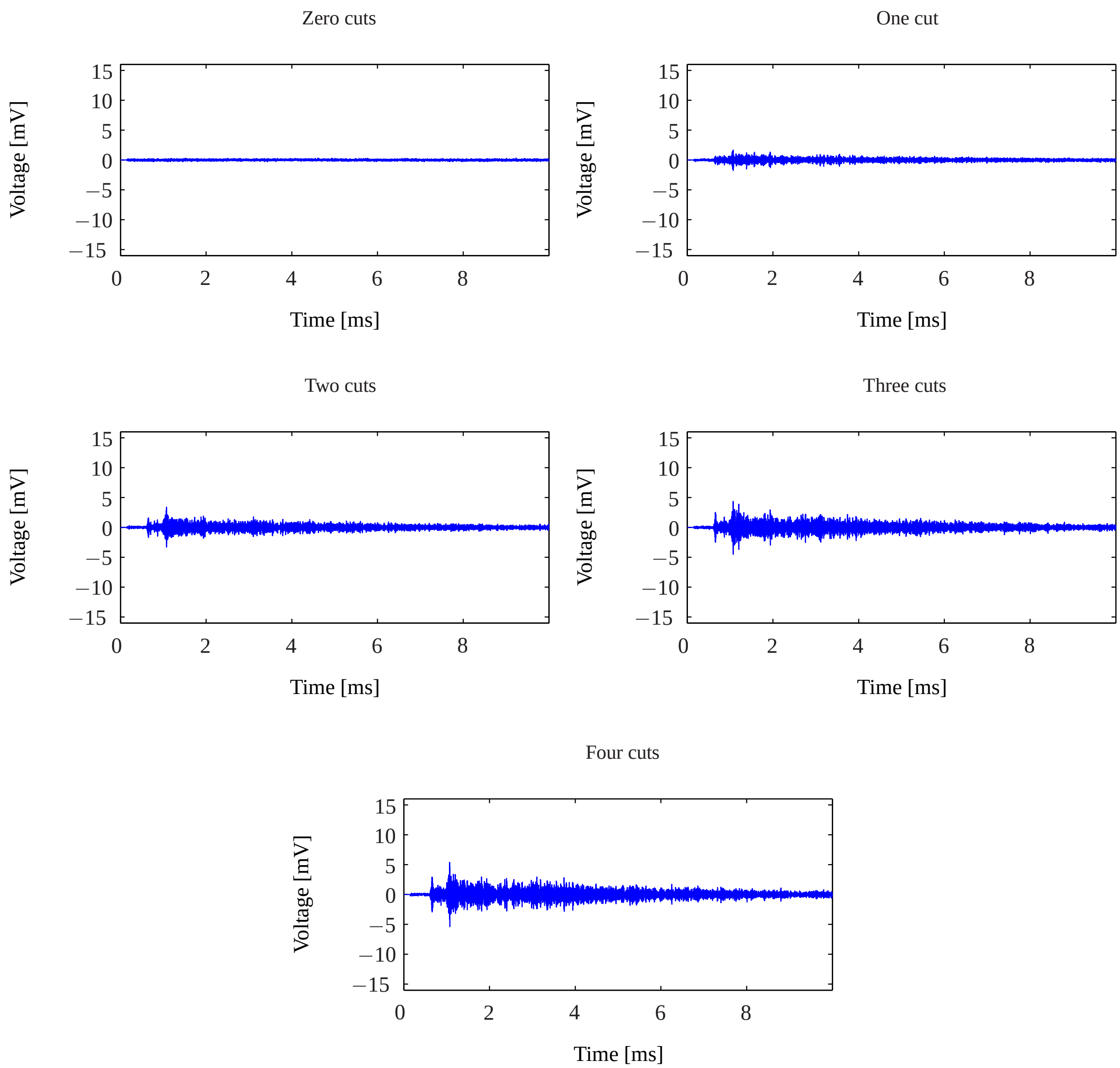

FIGURE 2. The differences between the background response in fig. 1 and the responses corresponding to the presence of zero, one, two, three, and four saw cuts on the pipe.

MATHEMATICAL TIME REVERSAL CHANGE FOCUSING

The previous section described time reversal processing when physically performed through experimentation. Often, we do not perform physical time reversal. To accomplish physical time reversal, the single transducer A and the transducer array B require the ability to transmit and receive signals, which may not be appropriate for all situations. In this section, we derive the mathematical time reversal solution in which A only acts as a transmitter and the transducers in B only need to act as receivers. Instead of receiving a signal at B, time reversing it, and retransmitting it, we transmit and receive two independent sets of signals from A to B. Those two sets of signals will be expressed as

$$\begin{aligned} Y_{1,n}(\omega) &= H_{T,n}(\omega)S(\omega)+V_{1,n}(\omega) \\ Y_{2,n}(\omega) &= H_{T,n}(\omega)S(\omega)+V_{2,n}(\omega). \end{aligned} \tag{10}$$

The equations in (10) assume that background subtraction, shown previously, has already been performed.

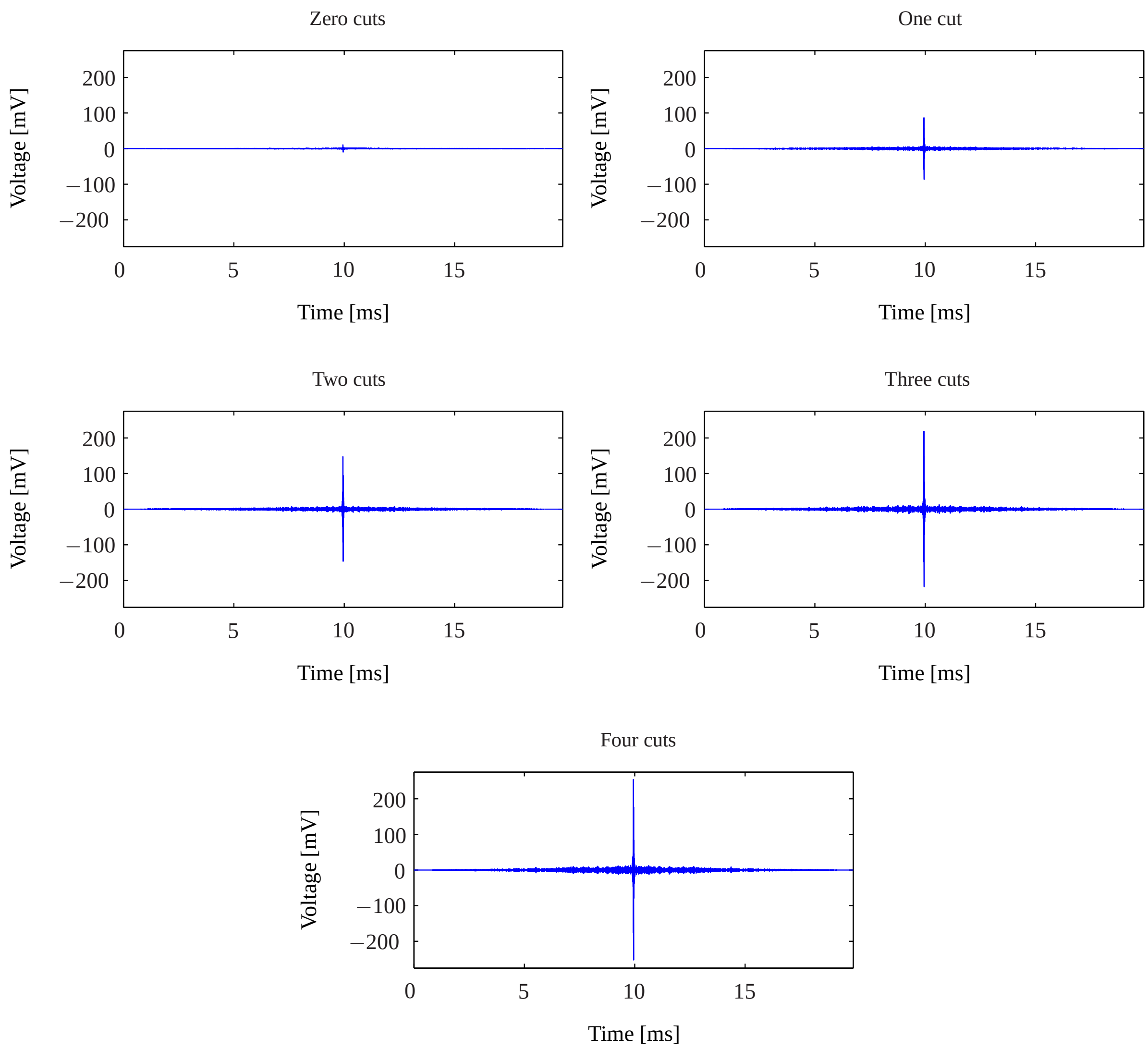

FIGURE 3. The result of performing time reversal change focusing on the difference responses found in fig. 2. The plots correspond to the presence of zero, one, two, three, and four saw cuts on the pipe.

Physical time reversal can then be approximated as

$$\begin{aligned} X(\omega) &= \frac{1}{S(\omega)} \sum_{n=1}^{N} \left(Y_{1,n}(\omega)\right)\left(Y_{2,n}(\omega)\right)^{*} \\ &= \sum_{n=1}^{N} |H_{T,n}(\omega)|^{2} S(\omega) + H_{T,n}^{*}(\omega) V_{w,1,n}(\omega) + H_{T,n}(\omega) V_{w,2,n}^{*}(\omega) + V_{w,1,n}(\omega) V_{w,2,n}^{*}(\omega). \end{aligned} \tag{11}$$

When the expected value of (11) is taken, we see that it is equivalent to the expected value of the physical time reversal derivation,

$$E\left[X(\omega)\right] = \sum_{n=1}^{N} |H_{T,n}(\omega)|^{2} S(\omega). \tag{12}$$

Therefore, both physical and mathematical time reversal depict a focused signal resulting from change due to damage. In our experimental results, we will use mathematical time reversal to compute the time reversal change focusing results.

EXPERIMENTAL RESULTS

Our experiments use a single PZT wafer as our A transducer and an array of eight individual transducers that comprise array B. Each of the PZTs are directly bonded to the surface of a pipe and are 5mm wide, 10mm long, and 1mm thick. The pipe is 3050mm in length, has an inner radius of 30.15mm, and has outer radius of 36.75mm. The A transducer is positioned at one end of the pipe and each of the transducers in array B circle around the pipe at the opposite end. Transducer A operates as a transmitter, while each transducer in B acts as a receiver.

Fig. 1 shows the sinc excitation signal transmitted from A to B and the signal received from one of the eight transducers in the array. Similar responses were then obtained after creating several saw cuts in the pipe. Each saw cut is approximately 1 mm deep (about one-quarter of the pipe wall thickness), 1 mm wide, and 25 mm in arc dimension (less than one-tenth of the pipe's circumference). To simulate damage, we added a line of four saw cuts positioned 590 mm, 1170 mm, 1760 mm, and 2510 mm away from the receiving array. Measurements were taken after adding each cut.

Fig. 2 shows the collection of responses after background subtraction, characterized by $Y_{1,n}$ in (10). This results from subtracting the background signal in fig. 1 with the responses from each damage scenario. These signals exhibit a weak structure and are complex and difficult to interpret. When we perform mathematical time reversal focusing using these signals and the counterparts from the other transducers in the array, the results focus with peaks that monotonically increase with the amount of damage in the pipe. These focusing results are shown in fig. 3.

The maxima of the signals in fig. 3 are (fewest to most cuts) 10.5 mV, 86.4 mV, 147.0 mV, 218.1 mV, and 254 mV. These focusing results show a clear monotonic correlation between the amount of damage present and the peak of the received signal. These results indicate that the peak can act as a useful metric or statistic to detect the presence and estimate the magnitude of damage on the pipe.

CONCLUSION

The ability of time reversal to focus improves as the number of modes and propagation paths as well as waveform dispersion increase. This stands in contradiction with traditional ultrasonic structural health monitoring systems that use low frequency and small bandwidth excitations. The peaks of the Time Reversal Change Focusing show a clear indication of the presence of damage in the pipe. Further, as the amount of damage in the pipe increases, so does the time reversal peak. This explains the efficacy of time reversal based detection algorithms [11, 12]. Further work will investigate how Time Reversal Change Focusing is sensitive the stationarity of the clutter response.

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