Title: *Focusing of Ultrasonic Waves in Cylindrical Shells using Time Reversal* for Proceedings of the **7th International Workshop on Structural Health Monitoring 2009**

Authors:
Joel Harley
Nicholas O'Donoughue
Joe States
Yujie Ying
James Garrett
Yuanwei Jin
José M.F. Moura
Irving Oppenheim
Lucio Soibelman

ABSTRACT

This paper investigates time reversal focusing techniques for the development of low-power, long-range, structural health monitoring applications for pipelines. We analytically examine time reversal's ability to compensate for unwanted multi-modal and dispersive behavior that are characteristic of guided waves travelling through pipes. We then develop a method to illuminate changes caused by structural damage using time reversal focusing as a pitch-catch operation. Using experimental and finite element simulation results with two transducers, we demonstrate these concepts and show that time reversal focusing provides a clear, interpretable metric for the characterization of damage in a pipe.

INTRODUCTION

The excitation of guided waves has become a popular tool for the nondestructive inspection of pipes and other physical infrastructures due to their potential to travel great distances [1,2]. Current pipeline inspection technologies often use rings of transducers pneumatically fastened to a pipe and operate in a pulse-echo mode [2,3]. Unfortunately, the inspection of buried pipelines is often expensive since it requires excavation and uses high transmission powers to achieve long distance guided wave propagation [3].

J. Harley, N. O'Donoughue, J.M.F. Moura, Dept. of Electrical & Computer Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, U.S.A.

J. States, Y.Ying, J.Garrett, I.Oppenheim*, L.Soibelman, Dept. of Civil & Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, U.S.A., *ijo@cmu.edu

Y. Jin, Dept. of Engineering and Aviation Sciences, Univ. of Maryland Eastern Shore, Princess Anne, MD 21853, U.S.A.

This paper provides motivation for the use of time reversal acoustic methods for increasing low-power propagation distances and for the detection of damage within pipes. We demonstrate time reversal's applications for focusing waves, compensating for mode and dispersive effects, and illuminating damage through change detection. Unlike other time reversal experiments for pulse-echo pipeline inspection conducted by Deng [4], our work focuses on the use of pitch-catch operations for implementing low-cost, low-power, permanently installed monitoring systems.

THEORY

Guided Waves in Pipes

Guided waves form as a result of the interaction between harmonic waves propagating in a medium and those medium's boundaries. Guided waves that form in thin cylindrical shells, or pipes, (which will be referred to as pipe waves) share several characteristics with Lamb waves, which form in thin plates. Lamb waves are commonly used and have been widely studied [5,6]. Pipe waves are characterized by an infinite number of dispersive longitudinal and torsional modes and a doubly infinite number of dispersive flexural modes [7]. The longitudinal and torsional modes are both axisymmetric while each flexural mode exhibits an infinite number of non-axisymmetric circumferential mode orders [8].

Many pulse-echo systems use reflections from defects to localize and characterize damage. However, due to the reflections of numerous dispersive modes and the mode conversions that occur at the defects, the received echoes may be difficult to interpret. Figures 1a and 1b show that a 400 kHz Gaussian pulse is significantly distorted after traveling a distance of 1.8 meters in a pipe. This unwanted clutter resulting from multi-modal and dispersive behavior is sometimes referred to as coherent (not random) noise [2].

To reduce coherent noise, users and developers often use narrowband, low frequency, single mode excitations to suppress unwanted modes and to reduce the influence of dispersion. Transducer geometries and designs can often be exploited for mode selectivity [2,8,9]. Unfortunately, these solutions can often limit the effectiveness of guided wave propagation.

Time Reversal Focusing

Time reversal focusing is a technique developed and used to achieve improved spatial and temporal acoustic focusing over conventional methods in inhomogeneous mediums [10, 11]. The process relies on the reciprocity and linearity of a medium and the principle that physical processes, when reversed in time, will result with the time-reversed initial conditions of the original process. Time reversal has been studied for applications in pulse-echo nondestructive testing and imaging [12,13,14], radar [15,16,17], and communications [18]. It has been shown that time reversal is particularly effective in mediums with high concentrations of scatterers [15,16,17,19].

Time Reversal Compensation of Multiple Modes and Dispersion

Consider a pipe with two transducers. Waves traveling between transducers exhibit multiple modes and dispersion. When a signal $s(t)$ is transmitted from one transducer, the signal received at the second transducer can be expressed in the frequency domain as [20]

$$R(\omega) = K_e(\omega)K_r(\omega)G(\omega)S(\omega), \tag{1}$$

where $G(\omega)$ is the pipe transfer function (or the Fourier transform of the Green's function), $K_e(\omega)$ and $K_r(\omega)$ are the exciting and receiving transducer transfer functions, $S(\omega)$ is the Fourier Transform of $s(t)$, and ω is the angular frequency.

The pipe transfer function can be expressed as a linear combination, for each angular frequency ω, of M arbitrary modes

$$G(\omega) = \sum_{m=0}^{M} b_m(\omega)e^{-j\omega(d/v_m(\omega))}, \tag{2}$$

where d is the distance between the two transducers and $v_m(\omega)$ is the dispersive velocity of the mode. The complex exponential represents the travel time between the two transducers and $b_m(\omega)$ accounts for any propagation effects on that mode.

In the frequency domain, time reversal is equivalent to the negation of angular frequency ω. If we assume that $v_m(\omega)$ has even symmetry in frequency such that $v_m(\omega) = v_m(-\omega)$ and that $b_m(\omega)$ is real, then negating the angular frequency in $G(\omega)$ is equivalent to taking its complex conjugate and so

$$G(-\omega) = G^*(\omega). \tag{3}$$

To demonstrate that the benefits of time reversal derive from focusing and not from an overall increase in the excitation energy, we transmit the time reversed signal with the same energy as the original excitation. The excitation is scaled by

$$k = \sqrt{\frac{\int_{-\infty}^{\infty}|S(\omega)|^2\,d\omega}{\int_{-\infty}^{\infty}|R(\omega)|^2\,d\omega}}. \tag{4}$$

Now when the time reversed signal is transmitted back through the pipe, the received signal is expressed as

$$\begin{aligned} Y(\omega) &= kK_e^*(\omega)K_e(\omega)K_r^*(\omega)K_r(\omega)G^*(\omega)G(\omega)S^*(\omega) \\ &= k|K_e(\omega)|^2|K_r(\omega)|^2|G(\omega)|^2 S^*(\omega) \end{aligned}. \tag{5}$$

Due to the absolute values, the complex exponentials that represent time delays between each path and mode in (3) disappear. As a result, the delayed signals, which are generated by the modes and dispersion, focus at the receiver and significantly enhance the received signal.

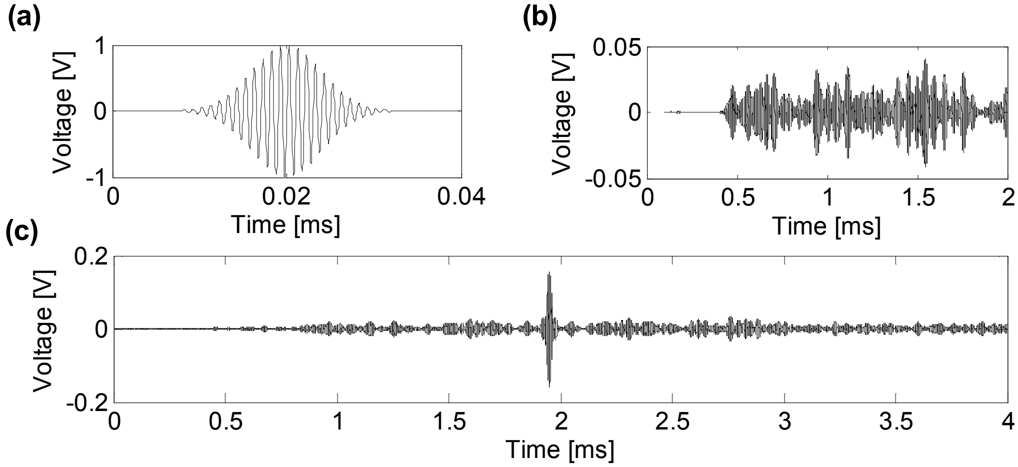

Figure 1. Experimental (a) 400 kHz Gaussian windowed excitation, (b) Received signal, (c) Time reversal focused signal

Time Reversal Focusing of Changes (Flaw-Induced Scattering)

A common method for detecting damage with pitch-catch experiments is change detection, where the change is caused by scattering from a flaw. Unfortunately, damage typically causes only small changes in the received signal. However, if those changes are time reversed and retransmitted through the medium, they are also focused. This provides a metric for detection of damage in the pipe.

Consider again a pipe with two transducers. For simplicity, assume that $K_e(\omega) = 1$ and $K_r(\omega) = 1$ so that the signal can be expressed as [17]

$$R(\omega) = G_{C+T}(\omega)S(\omega) = \left(G_C(\omega) + G_T(\omega)\right)S(\omega). \tag{6}$$

Here $G_C(\omega)$ represents the "clutter" response found when no damage is present on the pipe. The term $G_T(\omega)$ represents the "target" response generated by damage. Assuming the clutter response can be measured before any damage occurred and is therefore known, it can be subtracted from the received signal,

$$X(\omega) = R(\omega) - G_C(\omega)S(\omega) = G_T(\omega)S(\omega). \tag{7}$$

If the difference signal $X(\omega)$ is then normalized, time-reversed, and sent back though the pipe, the signal received can be expressed as

$$Y(\omega) = G_{C+T}(\omega)kX^*(\omega) = k\left(G_C(\omega) + G_T(\omega)\right)G_T^*(\omega)S^*(\omega). \tag{8}$$

Since $G_C(\omega)$ has been assumed to be known and $X^*(\omega)$ calculated, then $kX^*(\omega)G_C(\omega)$ can be subtracted from (8), resulting in the equation

$$Y_T(\omega) = kG_T(\omega)G_T^*(\omega)S^*(\omega) = k\left|G_T(\omega)\right|^2 S^*(\omega). \tag{9}$$

The final result is similar to (5), except the focused signal is now composed exclusively from signals scattered by damage. It should be noted that while (5) and (9) can be obtained experimentally, they can also be computed mathematically from the measurements of (1), (6), and (7).

RESULTS

Experimental Results

The experiments were conducted using two PZT wafers bonded to the surface of a pipe with inner radius 30.15mm, outer radius 36.75mm, and length 3050mm. Each wafer was 5mm wide, 10mm long, and 1mm thick, and the two wafers were positioned 1.8m apart. One transducer operated as a transmitter and one as a receiver. Due to the principle of reciprocity, the response between the two transducers should be equivalent regardless of direction. Figure 1b shows the signal received from the 400 kHz Gaussian pulse excitation shown in figure 1a to contain a large amount of coherent noise and few distinguishable features. By contrast, after performing the time reversal focusing process, figure 1c shows a distinguishable peak in the center of the plot. This peak is formed as a consequence of the focusing and compensation of modes and dispersion as explained by (5).

In this demonstration of time reversal focusing, a narrowband excitation with a 400 kHz center frequency and 37 kHz bandwidth was chosen for two reasons. First, that center frequency excited a large number of modes and dispersive effects, as evident from the coherent noise in figure 1b. The frequency also provided a significant gain in signal-to-noise ratio over many lower frequencies with fewer modes and less dispersion. By significantly reducing the coherent noise associated with high frequency excitations, time reversal techniques allow for a greater degree of freedom when choosing excitations. This freedom also allows us to benefit from the use of wideband signals to extract and utilize more frequency information as in the following experiment results.

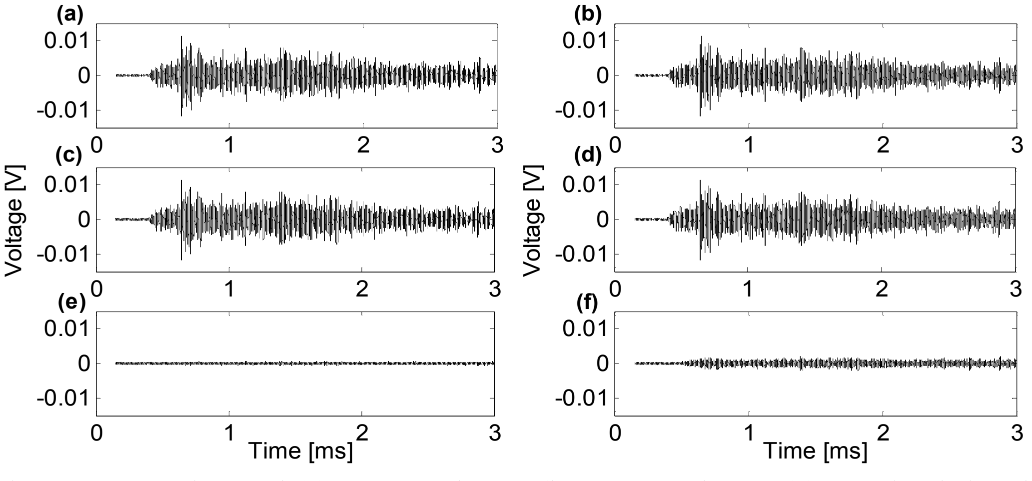

Figure 2. Experimental (a) Known clutter, (b) Known clutter, (c) Received signal with no damage present, (d) Received signal with damage present, (e) Difference of (a) and (c), (f) Difference of (b) and (d)

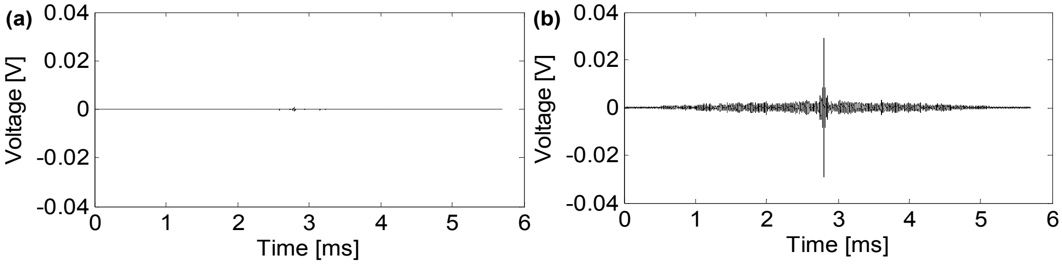

Figure 3. Experimental (a) Time reversal focusing of changes with no damage present, (b) Time reversal focusing of changes with damage present

To illustrate damage detection using time reversal, we used a wideband excitation. Figure 2 shows changes in a received signal from damage. The transmitter was excited by a wideband sinc pulse with a 300 kHz center frequency and 600 kHz bandwidth. To simulate damage physically, we created a small, partial-thickness sawcut. The cut is 1.5 mm deep, or only one-quarter of the pipe wall thickness, 1 mm wide, and 20 mm in arc dimension, less than one-tenth of the pipe's circumference; it is located 1095mm from the transmitting wafer. Figure 3 shows the signals which result by performing time reversal change focusing on figures 2e and 2f. In this instance, the plots in figure 3 were generated mathematically from the measured records using (9). The large peak in figure 3b is seen as an indication of change in the pipe due to the saw cut. The peak value with no damage is 1.05 mV whereas the peak value with damage measures 29.3 mV, a difference of almost 30 times or 29.5 dB.

Simulation Results

The experimental results were compared to simulation results obtained using the commercial PZFlex software suite. We matched the pipe and damage model to the specimen used in the laboratory. The excitation signal was modeled as a voltage across the two terminals of a PZT5a patch and the received signal modeled as the voltage induced at a second PZT5a patch, located 1.8m down the pipe. The received signal was recorded for 1.2ms during the forward transmission and 2.4ms while retransmitting.

Figure 4 illustrates the changes in the received signal for the undamaged and damaged cases. Figures 4a and 4b display the known background clutter with no noise. Figure 4c shows the received signal with no damage present and injected with white Gaussian noise to simulate additive measurement noise. Figure 4d displays the received signal with the simulated damage and injected white Gaussian noise. In both cases, the noise provided a signal-to-noise ratio of 40dB. Figures 4e and 4f show the two difference signals.

We performed time reversal change focusing on the two difference signals by transmitting them back through the channel and subtracting the extraneous information as in (8) and (9). We can see in figure 5 that the peak is 2.8mV when no damage is present and 35.3mV after damage has been added. This provides an increase of almost 13 times or 22dB. The reduced focusing gain, compared with the experimental results, can be explained by the shorter record length used.

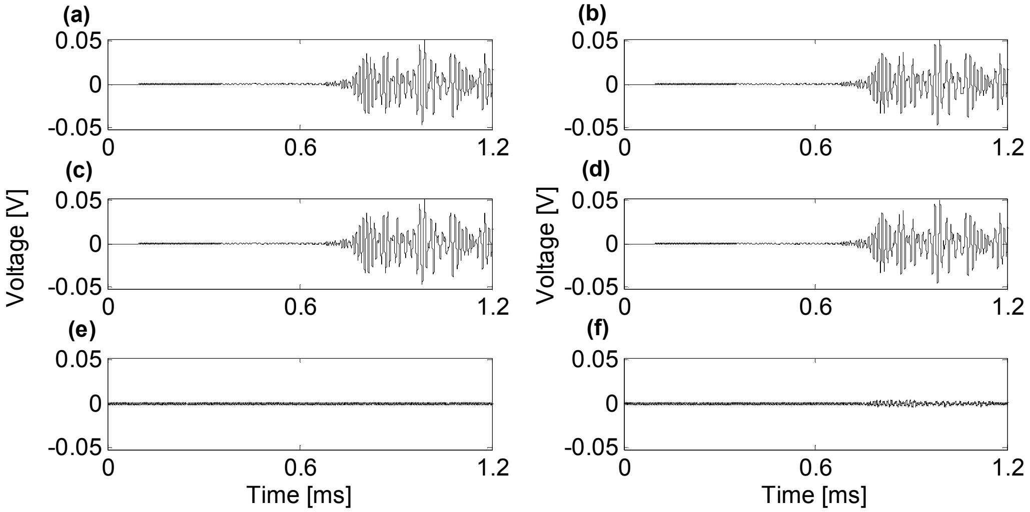

Figure 4. Simulation (a) Known clutter, (b) Known clutter, (c) Received signal with no damage present, (d) Received signal with damage present, (e) Difference of (a) and (c), (f) Difference of (b) and (d)

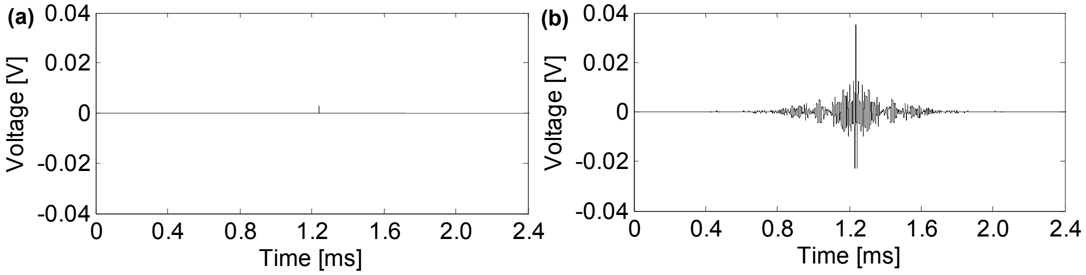

Figure 5. Simulation (a) Time reversal focusing of changes with no damage present, (b) Time reversal focusing of changes with damage present

CONCLUSIONS

The potential uses for time reversal focusing in pipes are numerous. Time reversal's ability to compensate for multiple modes and dispersion allow for the coherent transmission of waves between transducers. This allows investigators greater discretion when choosing a signal of excitation to achieve the greatest propagation distance and largest signal-to-noise ratios. Focused signals also present a distinguishable peak that can be used to better characterize a medium. For example, that peak is used as a metric for the presence of damage when performing a time reversal change focusing experiment. Due to its ability to compensate for modes and dispersion, time reversal also has much potential for nondestructive testing and structural health monitoring applications in other physical infrastructures as well as pipes.

ACKNOWLEDGMENTS

National Energy Technology Laboratory (NETL) is the funding source for this effort with Cost Share being provided by Carnegie Mellon University (CMU). Concurrent Technologies Corporation (CTC) is funded under a cooperative agreement with NETL. CMU is funded under a Subcontract Agreement with CTC. Nicholas O'Donoughue is supported by a National Defense Science and Engineering Graduate Fellowship, sponsored by the Army Research Office.

REFERENCES

1. Ditrai, John J. 1994. "Utilization of guided elastic waves for the characterization of circumferential cracks in hollow cylinders," *J. Acoust. Soc. Am.*, 96(6):3769-3775.
2. Cawley, P. 2003. "Practical Long Range Guided Wave Inspection - Managing Complexity," in *Rev. Prog. Quant. NDE*, 657:22-40.
3. Cawley, P. and M. J. S. Lowe. 2006. "Long Range Guided Wave Inspection Usage – Current Commercial Capabilities and Research Directions," Department of Mechanical Engineering, Imperial College London, London.
4. Deng, F., C. He, B. Wu. 2008. "Time Reversal Method for Pipe Inspection with Guided Wave," in *Rev. Prog. Quant. NDE*, 975:131-138.
5. Viktorov, I. A. 1967. *Rayleigh and Lamb waves: physical theory and applications.* Plenum Press.
6. Lowe, M. J. S., D. N. Alleyne, and P. Cawley. 1998. "The Mode Conversion of a Guided Wave by a Part-Circumferential Notch in a Pipe," *J. Appl. Mech.*, 65(3):649-656.
7. Li, J. and J. L. Rose. 2001. "Excitation and propagation of non-axisymmetric guided waves in a hollow cylinder," *J. Acoust. Soc. Am.*, 109(2):457-464.
8. Demma, A., et al. 2003. "The reflection of the fundamental torsional mode from cracks and notches in pipes," *J. Acoust. Soc. Am.*, 114(2):611-625.
9. Wilcox, P. D., M. J. S. Lowe, and P. Cawley. 2001. "Mode and Transducer Selection for Long Range Lamb Wave Inspection," *J. Intell. Matls. Sys. & Struct.*, 12(8):553-565.
10. Fink, M. 1992. "Time reversal of ultrasonic fields. I. Basic principles," *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, 39(5):555-566.
11. Fink, M., C. Prada, F. Wu, and D. Cassereau. 1989. "Self focusing in inhomogeneous media with time reversal acoustic mirrors," in *IEEE Ultrasonics Symposium Proceedings*, 2:681:686.
12. Chakroun, N., M. Fink, and F. Wu. 1995. "Time reversal processing in ultrasonic nondestructive testing," *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, 42(6):1087-1098.
13. Prada, Claire, et al. 2002. "Time reversal techniques in ultrasonic nondestructive testing of scattering media," *Inverse Problems*, 18(6):1761-1773.
14. Scalerandi, M., et al. 2008. "Selective source reduction to identify masked sources using time reversal acoustics," *J. Phys. D: Appl. Phys.*, 41(15):155504(12pp).
15. Moura, J. M. F. and Y. Jin. 2007. "Detection by Time Reversal: Single Antenna," *IEEE Trans. on Signal Processing*, 55(1):187-201.
16. Moura, J. M. F. and Y. Jin. 2008. "Time Reversal Imaging by Adaptive Interference Canceling," *IEEE Trans. on Signal Processing*, 56(1):233-247.
17. Jin, Y. and J. M. F. Moura. 2009. "Time-Reversal Detection using antenna arrays," *IEEE Trans. on Signal Processing*, 57(4):1396-1414.
18. Blomgren, P., et al. 2008. "Spatial Focusing and Intersymbol Interference in Multiple-Input–Single-Output Time Reversal Communication Systems." *IEEE Journal of Oceanic Engineering*, 33(3):341-355.
19. Prada, C., F. Wu, and M. Fink. 1991. "The iterative time reversal mirror: A solution to self-focusing in the pulse echo mode," *J. Acoust. Soc. Am.*, 90(2):1119-1129.
20. Prada, Claire, et al. 1996. "Decomposition of the time reversal operator: Detection and selective focusing on two scatterers," *J. Acoust. Soc. Am.*, 99(4):2067-2076.