Three-dimensional time reversal communications in elastic media

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Abstract: This letter presents a series of vibrational communication experiments, using time reversal, conducted on a set of cast iron pipes. Time reversal has been used to provide robust, private, and clean communications in many underwater acoustic applications. Here the use of time reversal to communicate along sections of pipes and through a wall is demonstrated to overcome the complications of dispersion and multiple scattering. These demonstrations utilize a single source transducer and a single sensor, a triaxial accelerometer, enabling multiple channels of simultaneous communication streams to a single location.

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1. Introduction

Time reversal (TR) is a wave focusing technique,[1,2] which, among many other applications, can be used to provide secure communications between two locations. The first known use of TR technology was for underwater communications between two vessels;[3,4] at the time, it was called a matched signal technique. This experiment utilized what has been termed reciprocal time reversal (RTR),[2] where a signal is broadcast from location A, a recording of the signal is made at location B, this recording is then flipped in time, sent electronically to location A, subsequently broadcast from location A, and a TR focus is then created at location B. This TR focus is localized in space and provides a reconstruction of the original signal that was broadcast from location A. Obviously if electronic communication can happen between locations A and B, then there is no practical need for TR. However, if it can be assumed that the impulse response between locations A and B and between B and A are reciprocal, then, for demonstration purposes, it does not matter whether the forward propagation step is done from A to B or from B to A.

TR communications have been the subject of many papers for underwater acoustics applications (Ref. 5 provides a recent example), but it has not been exhaustively studied for communications in solid media. Hanafy and Schuster[6] recently demonstrated the use of TR for communicating 6-bit segments through seismic signals between two locations using a sledgehammer source. Their work utilized a reference signal with which the subsequent received signals were correlated with to optimally detect the time sequence of the sledgehammer impacts, thus they did not broadcast a reversed signal to create a TR focus in the ground medium. In the use of TR for underwater communications, the focused communication provides a single channel of information to a sensor. The work of Ulrich *et al.* demonstrated that TR could be used to independently focus elastic energy in each of the three orthogonal components of motion at a single location in space.[7,8]

In this letter, we present experiments to demonstrate the use of TR through an elastic medium to provide three independent communication channels as has been done in underwater acoustics.[9] A shaker source inputs energy into one end of a set of cast iron pipes, and a triaxial accelerometer receives the signal and a RTR procedure is used. The intention of the paper is to demonstrate three independent channels of communication between one source and one receiver location. Individual applications of the technique would require adaptation of the technique to the system of interest. One application could involve a three component transducer (or three mode piezoelectric transducer) that emits three successive chirp signals, from Ax, Ay, and Az. The transducer at B knows to expect these signals, and the three impulse responses can thus be obtained from each component of motion at A to perhaps one component of motion at B. From location B, three independent streams of information can then be transmitted back to Ax, Ay, and Az. Here we transmit from A to Bx, By, and Bz in the forward and backward steps, but due to reciprocity, we can consider these forward transmissions as being equal to those that would be sent from Bx, By, and Bz to A. We use RTR here for simplified demonstration purposes since it is unnecessary to communicate with two active transmissions through the medium from A to B when an electronic link is available.

2. Experiment setup

A set of cast iron pipes having an inner diameter of 35 mm and an outer diameter of 41 mm is used for the experiments. The ends of the pipes are threaded, and couplers are used to connect multiple pipes together. Two 1.22 m pipes were connected on one end before being connected to a 3.05 m pipe section that was encased in concrete. The other end of the concrete cased pipe was connected to another two 1.22 m pipes with a 90° elbow junction between the last two pipes. The total length of the pipe system, including 2.5 cm extra length for each end cap and pipe connection and 5 cm for the elbow junction, was 8.10 m (26.6 ft). Thus the wave signals pass through 12 changes in media with 10 of these changes being in and out of pipe junctions and the other 2 when the pipe enters and exits the concrete enclosure. The source attached to an end cap with duct tape and the accelerometer was epoxied to an end cap on the other end of the pipe system. Figure 1 displays a photograph of the setup. The source transducer was a 7 W Mighty Dwarf vibration speaker and the triaxial accelerometer was a PCB 356A02 model with a specified sensitivity of 10 mV/g.

The training of the focus is achieved by sensing an individual vector component of the motion by a sensor, such as a triaxial accelerometer, or a three-dimensional (3D) laser vibrometer, during the forward propagation step of a time reversal experiment. Recording of the forward propagation by a selected component of motion allows a focus to be created, through a RTR procedure, only in the component of motion recorded during the forward propagation. The recording of the three components of motion during the forward propagation, from a single component source, allows for three independent foci of energy to be produced in each of the three motion components, which allows three independent channels of communication to be established.

Signals were generated and acquired with a sampling frequency of 200 kHz, a 262 144 point time span (1.310 72 s), a 12-bit D/A converter card for the source signal, a 14-bit A/D converter card for the recording of signals from the triaxial accelerometer, and 30 synchronous averages. The normalized signals sent to the transducer had a peak to peak voltage of 2.0 Vpp for both forward and backward signals to maximize the energy broadcast for our amplifier. The time between the start of each synchronous average was set to 1.500 s. The dynamic range of the digitizer was set to 400 mVpp.

The forward signal, $s(t)$, constituted of a linear chirp signal spanning 0.8–12 kHz beginning at time 0 and ending at time 1.0000 ms. Each of the three components, (x, y, z), of motion is then recorded by the triaxial accelerometer, $r_{x,y,z}(t)$. The source signal is then cross correlated with each of the three recordings to obtain band limited impulse responses, $h_{x,y,z}(t)$, between the source location and each component of motion at the receiver location. A deconvolution operation,

$$G_{x,y,z}(\omega) = \frac{R^*_{x,y,z}(\omega)}{[|R(\omega)|^2 + 0.9 \cdot \text{mean}(|R(\omega)|^2)]}, \qquad (1)$$

where $R_{x,y,z}(\omega)$ is the Fourier transform of $h_{x,y,z}(t)$, and the $0.9 \cdot \text{mean}(|R(\omega)|^2)$ term was empirically selected as an optimal regularization parameter, is then performed on each of the impulse response recordings.[10] The inverse Fourier transform of the deconvolution result, $g_{x,y,z}(t)$, is then used as the backward propagation signals for TR deconvolution communication results where $g_x(t)$ should result in a focusing only in

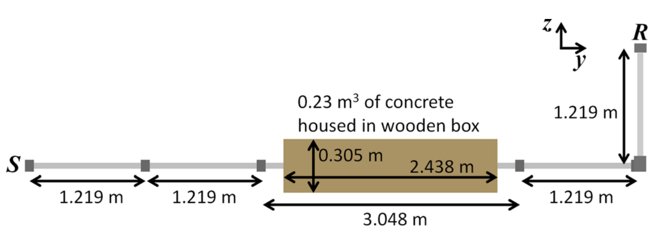

Fig. 1. (Color online) Schematic of the pipe system used for experiments. S denotes the location of the source vibration shaker and R denotes the location of the triaxial accelerometer.

the x direction and similarly for the y and z directions. Each $g_i(t)$ signal was broadcast, one at a time, while recordings, $f_{i,j}(t)$, were made by the triaxial accelerometer in each component of motion, where $f_{i,j}(t)$ corresponds to the motion recorded in the j direction when the $g_i(t)$ signal was broadcast.

Figure 2 illustrates sample signals, to create a focusing in the $i = z$ direction, used in the deconvolution TR processes. Figure 2(a) displays the chirp signal, $s(t)$, broadcast by the shaker to obtain the forward propagation signal $r_z(t)$ displayed in Fig. 2(b). Figures 2(c) and 2(d) displays $h_z(t)$ and $g_z(t)$, respectively. Figures 2(e) and 2(f) display the frequency spectra corresponding to $h_z(t)$ and $g_z(t)$, respectively. $g_z(t)$ is then broadcast by the shaker to create a focus in the z direction. Note the presence of the peaks in Fig. 2(e) corresponding to propagating modes within the 0.8–12 kHz band. The deconvolution operation reduces these peaks and amplifies the non-resonant frequency content.

3. Discussion

Figures 3(a)–3(c) display the $f_{i,j}(t)$ signals obtained by transmitting $g_i(t)$ and recording the motion in $j = (x, y, z)$ directions. Figures 3(d)–3(f) display the signals obtained by transmitting $g_y(t)$ and recording the motion in $j = (x, y, z)$ directions. Figures 3(g)–3(i) display the signals obtained by transmitting $g_z(t)$ and recording the motion in $j = (x, y, z)$ directions. Thus each row in Fig. 3 represents the motion recorded when transmitting the $g_i(t)$ signal intended to focus in the i direction, whereas each column represents the j motion recorded in either the x, y, or z directions. As expected, one can note the strong peak observed in each of the diagonal Figs. 3(a), 3(e), and 3(i) [i.e., when $i = j$, $f_{i,i}(t)$]. The columns in Fig. 3 are each normalized with respect the amplitude of the peak produced for the focusing in the corresponding direction of motion.

If we define a focusing quality metric, $\alpha_{i,j}$, as the magnitude of the ratio of the peak acceleration to the acceleration of the next highest amplitude peak (whether the peaks are positive or negative), this allows quantification of how distinct the focal peak is in the signals depicted in Fig. 3. For the focusing in the x direction, this ratio equals $\alpha_{x,x} = 2.6$, $\alpha_{x,y} = 1.1$, and $\alpha_{x,z} = 1.2$. For the focusing in the y direction, this ratio equals $\alpha_{y,x} = 1.2$, $\alpha_{y,y} = 2.8$, and $\alpha_{y,z} = 1.0$. For the focusing in the z direction, this ratio equals $\alpha_{z,x} = 1.0$, $\alpha_{z,y} = 1.3$, and $\alpha_{z,z} = 2.7$. When $i = j$, the average $\alpha_{i=j} = 2.7$, and when $i \neq j$, the average $\alpha_{i \neq j} = 1.1$, and thus the peak in a focal signal is 2.4 more distinct than the next highest peak in focal signals than in non-focal signals. It should be noted that the focal peaks, when $i = j$, occur at the intended focal time, whereas when $i \neq j$ the peaks are generally not at the intended time of focus, therefore regular spacing of focal peaks can aid in communication error checking.

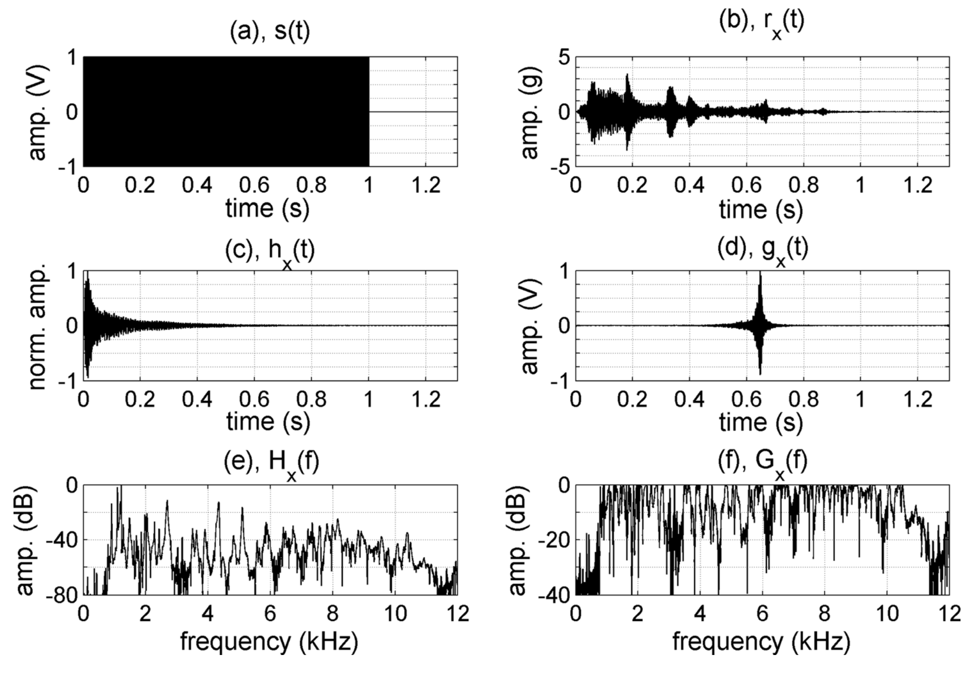

Fig. 2. Sample signals used in the time reversal process: (a) chirp source signal, (b) signal received at R in the x direction, (c) impulse response between S and R, (d) inverse filter signal obtained from signal displayed in (c), (e) Fourier transform of signal displayed in (c), and (f) Fourier transform of signal displayed in (d).

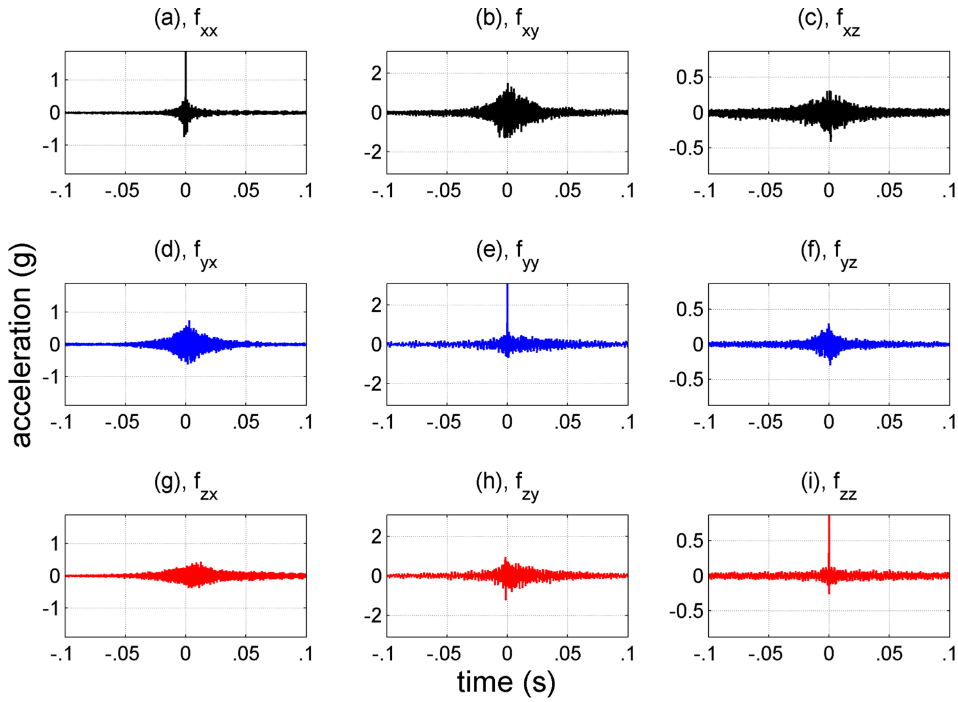

Fig. 3. (Color online) Signals recorded by the triaxial accelerometer when focusing in the x direction [(a), (b), and (c)], when focusing in the y direction [(d), (e), and (f)], and when focusing in the z direction [(g), (h), and (i)]. Signals displayed in the first column [(a), (d), and (g)] represent the motion recorded in the x direction, signals displayed in the second column [(b), (e), and (h)] represent the motion recorded in the y direction, and signals displayed in the third column [(c), (f), and (i)] represent the motion recorded in the z direction. Focal signals are displayed in (a), (e), and (i) and have a single positive half-cycle peak at the focal time ($t=0$).

As a demonstration of the ability of the deconvolution TR process to communicate information clearly, the signals $h_x(t)$, $f_{x,y}(t)$, and $f_{x,x}(t)$ are convolved with a speech sample extracted from a movie. The convolution of $h_x(t)$ with the speech signal simulates sending the speech signal directly into the pipe system with the shaker and the subsequent recording made by the accelerometer in the x direction at the other end (listen to Mm. 1). The convolution of $f_{x,y}(t)$ with the speech signal simulates encoding the speech signal with $g_x(t)$ prior to transmission, producing an unfocused communication at the accelerometer in the y direction (listen to Mm. 2). The convolution of $f_{x,x}(t)$ with the speech signal simulates encoding the speech signal with $g_x(t)$ prior to transmission, producing a focused communication at the accelerometer in the x direction (listen to Mm. 3). The speech signal was upsampled six times prior to the convolution and then the result was downsampled six times to match the speech signal frequency content with the actual transmitted frequency content (0.8–12 kHz). The Mm. 3 recording contains the most intelligible speech, though it is not perfect. A fourth audio recording, Mm. 4, is included from a similar pipe setup to the one used here, using eight piezoelectric source transducers, and a frequency range of 100–250 kHz. The Mm. 4 clip illustrates the vast improvement time reversal encoding can provide for signal transmissions over unencoded signal transmissions. The Mm. 4 clip illustrates not only the increase in transmission clarity but also the relative increase in transmission amplitude between direct transmission and a time reversal transmission.

Mm. 1. Audio recording of the convolution result between $h_x(t)$ and a speech signal. This is a file of type "wav" (0.7 MB).

Mm. 2. Audio recording of the convolution result between $f_{x,y}(t)$ and a speech signal. This is a file of type "wav" (0.7 MB).

Mm. 3. Audio recording of the convolution result between $f_{x,x}(t)$ and a speech signal. This is a file of type "wav" (0.7 MB).

Mm. 4. Audio recording of $h_x(t)$ and $f_{x,x}(t)$, played one right after the other, from a similar pipe setup, but using 8 source channels and conducting the transmissions with a 100–250 kHz frequency range. This is a file of type "wav" (1.7 MB).

To demonstrate three independent communication channels to transmit bits of information, the focal signals could be linearly superimposed onto one another with selected time delays between adjacent bits, τ, and with selected time delays between communication streams on each channel, γ. These focal signals could be focused with a positive or negative phase simply by multiplying $f_{i,j}(t)$ by -1 prior to transmission, for up $(+1)$ or down (-1) binary information transmission. Three 8 bit words, or bytes, were constructed, using standard ASCII to binary definitions, representing the letters $t = [\,-1\;\;+1\;\;+1\;\;+1\;\;-1\;\;+1\;\;-1\;\;-1\,]$, $l = [\,-1\;\;+1\;\;+1\;\;-1\;\;+1\;\;+1\;\;-1\;\;-1\,]$, and $m = [\,-1\;\;+1\;\;+1\;\;-1\;\;+1\;\;+1\;\;-1\;\;+1\,]$. To construct a signal to transmit a particular byte, the signal $f_{i,i}(t)$ was multiplied by the appropriate phase, ± 1, and was delayed and summed 8 times, with a fixed delay τ. The bytes detailed in the preceding text were transmitted to x, y, and z, respectively, with a delay γ between the start of each byte transmission [$f_{y,y}(t)$ was delayed γ relative to $f_{x,x}(t)$ and $f_{z,z}(t)$ was delayed 2γ relative to $f_{x,x}(t)$]. Care was taken to ensure the realistic simulated transmission of these signals by adding in the corresponding streams of unfocused, summed signals. For example, when constructing the simulated transmission in x, the $f_{x,x}(t)$ byte construction was added to the appropriately delayed $f_{y,x}(t)$ and $f_{z,x}(t)$ byte streams to simulate the intended focal transmission in x interfering with the unfocused transmissions to y and z detected by x. A simple peak detection algorithm was used to detect the transmitted bits of information. The threshold for up or down peak detection was set to be 0.66 times the overall peak of the magnitude of the signal representing a byte. The delays τ and γ were adjusted to be as small as possible until the bytes were no longer transmitted and detected with 100% accuracy. We found that $\tau = 55$ ms and $\gamma = 20$ ms were the minimum delays necessary for successful communications, corresponding to a bit rate of 18.2 bits/s per channel or 54.5 bits/s total. Figure 4 displays the communicated bytes with the short delays indicated in the preceding text.

The successful communication rate depends on a number of factors determined by the system, sound and receiving transducers, frequency bandwidth, and peak detection criteria. Additionally any advanced signal processing used for improved detection, such as a cross correlation technique to compare an expected focal bit (from a system calibration step) with the actual communicated information, could improve the transmission rate. System attenuation is a significant issue because the forward signal $h_i(t)$ is required before a time reversal transmission step can occur. Here we have used a chirp signal to obtain $h_i(t)$ to maximize the signal to noise ratio of the forward transmission step. In the case of a pipe system, many propagation modes exist. The lower frequency modes are not attenuated as much but the use of lower frequencies reduces the available communication bit rate. The use of more transducers to broadcast the signals to create a focus would improve the transmission quality. Imaging conditions, such as the symmetry imaging condition,[11] could be used to further enhance the transmission quality.

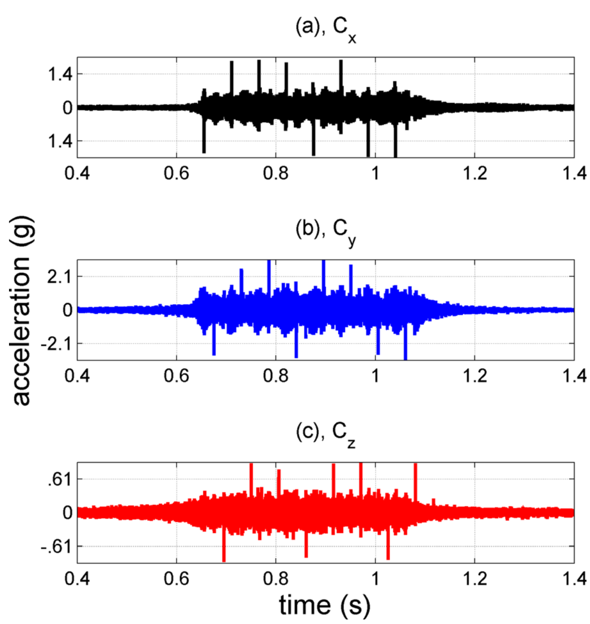

Fig. 4. (Color online) Transmitted communication byte signals representing the ASCII binary letters "t," "l," and "m." (a) signal recorded in the x direction, (b) signal recorded in the y direction, and (c) signal recorded in the z direction.

4. Conclusions

Simultaneous communications of three independent information bytes from a single source to a single, triaxial sensor have been demonstrated, using time reversal, at a total communication rate of 54.5 bits/s. Three forward-propagation (calibration) signals, recorded by a three axis sensor from a single source broadcast, are necessary to train the time reversal system to focus to each axis of the sensor independently. The focal peaks could be focused with an up or down phase for binary communication of bits. The focal signals' peak values were 2.7 times higher in amplitude than the next highest peaks in the signal, constituting a clear impulsive communication bit. The transmissions were made over an 8.10 m distance through 12 impedance changes (including into and out of junctions). Audio recordings demonstrated the transmission enhancement due to time reversal and the channel focusing independence.

As mentioned in Sec. 1, the RTR procedure used here does not represent a practical situation because we are utilizing an electronic link between A and B. One application is to transmit three chirp signals from each of the three components of a three component transducer at A to a single component transducer at B for the forward step. In the backward step, a signal could be constructed by a computer at B that utilizes the three reversed impulses responses from Ax, Ay, and Az to B to communicate three channels of information from B back to Ax, Ay, and Az. These three channels might be temperature, pressure, and humidity monitoring levels from inside of a sealed container, etc.

Acknowledgments

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