Time-reversal focusing of elastic surface waves with an asymmetric surface layer

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Abstract: The effectiveness of time-reversal focusing is evaluated in the presence of an asymmetric surface layer that changes the direction of the propagating waves, but does not continually scatter or block the propagating wave front. Interactions between the wave front and the surface layer are dependent on the depth and material properties of the asymmetric surface layer and its orientation in the medium with respect to the incident wave. Time-reversal focusing is shown to perform significantly better than other excitation methods for the purpose of delivering energy to the location of a buried land mine.

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1. Introduction

Time-reversal focusing is a powerful technique that allows propagating waves to be focused to a particular location. Time-reversal focusing is most useful when it is difficult or impossible to characterize the clutter and wave propagation speed in an area of examination. While other focusing methods require some knowledge of the propagation medium characteristics such as propagation speed, time reversal does not require this information. Because of its insensitivity to clutter and variations in wave-propagation velocity, elastic-wave time reversal shows great promise for application to the detection of buried objects.

The primary experimental and numerical investigations of time-reversal focusing have been in the ultrasound frequency range and in the far field.[1–3] Time-reversal focusing has been investigated in both fluid and solid media, including liquid-solid interfaces. In fluid media, homogeneous backgrounds have been augmented with scattering objects to create high order scattering of incident waves.[4] In these scenarios, time-reversal focusing has been shown to be effective in inhomogeneous media,[5] even producing super-resolution effects in some cases.[4,6,7] The investigation of time-reversal focusing of Rayleigh waves in elastic solids was first motivated by the detection of surface and subsurface flaws in a solid.[8,9]

These experiments provide a strong foundation in the investigation of acoustic time reversal, but the experimental cases that have been examined are still significantly different from those encountered in the buried object detection problem. For buried land mines, the frequency range of interest is typically centered around 400–1000 Hz, and the detection problem must be carried out in an elastic solid background medium. Inhomogeneity may be encountered by the addition of hard solid objects, such as rocks or other near-surface scatterers, by voids in the medium, or variations in the background material properties.

The work presented in this letter investigates the performance of time-reversal focusing in soils, with a particular emphasis on the detection of buried targets, especially buried land mines, in the presence of an asymmetric surface layer. In field conditions, many types of surface layers may be present between a land mine and excitation sources. Compacted road beds or tire tracks, soil stratification, concrete slabs, and other types of surface layers may significantly alter the propagation direction of any wave front incident on them. In these cases, an excitation wave

Fig. 1. (Color online)The experimental facility. The seismic transducer array is on the right and the ground-contacting sensor array is positioned over the sand tank. The plywood wedge-shaped asymmetric surface layer is buried flush with the surface of the sand.

front may fail to deliver significant energy to the desired location. Time-reversal focusing is an appealing way to deliver energy because it can provide tight and accurate focusing even in the presence of inhomogeneity, such as surface layers.

While time-reversal focusing has been studied extensively in fluids, and even in some solid media, studying the phenomenon in soil entails a significantly different analysis. Only limited-scale studies in any type of granular media have been performed,[10,11] indicating a need for further study. The complexity of wave propagation in soil goes beyond that of many common fluids or elastic media. Soil is a complicated nonlinear particulate medium in which the interparticle interactions along with the specific physical characteristics of the particles define the behavior of waves supported in the medium.[12]

2. Experimental method

2.1 Experimental setup

The experimental results are obtained in a laboratory at the Georgia Institute of Technology (Fig. 1).[11,13] A large concrete wedge-shaped tank is filled with approximately 50 tons of damp compacted sand. Sand is chosen as the background medium because its seismic properties are similar to many types of soil, and because it is straightforward to recondition disturbed sand. This allows for easy burial and removal of scattering objects and targets in the tank.

The seismic waves are generated by an array of six electrodynamic shakers. Each source is made from an 8.7 cm diameter transducer from an Aura bass shaker that has a flat frequency response over the frequency range of interest. A short metal bar foot is attached to each electrodynamic shaker. The shaker and metal foot are placed in contact with the sand and the 12.5 cm × 1.27 cm × 2.54 cm aluminum bar foot couples seismic energy into the sand.

Once the shakers are used to excite elastic waves in the sand tank, an array of specially designed ground contacting accelerometers[14] is used to record the acceleration of the surface of the ground. These sensors are inexpensive, compact, and couple to the ground lightly enough to be safe for use in land mine detection applications. The array used in these experiments consists of 30 accelerometers in a 3×10 array spaced 3.429 cm apart in x and 10.287 cm in y. The measurements are interlaced along the y direction to synthetically generate a grid of measurement points with a spacing of $\Delta x = \Delta y = 3.429$ cm between measurement points in both x and y. By making many measurements, each at a different location on the surface, the acceleration of the entire scan region can be constructed synthetically. After the entire scan has been completed, a data array of acceleration information is available, $A(x_i, y_j, t_k)$, where

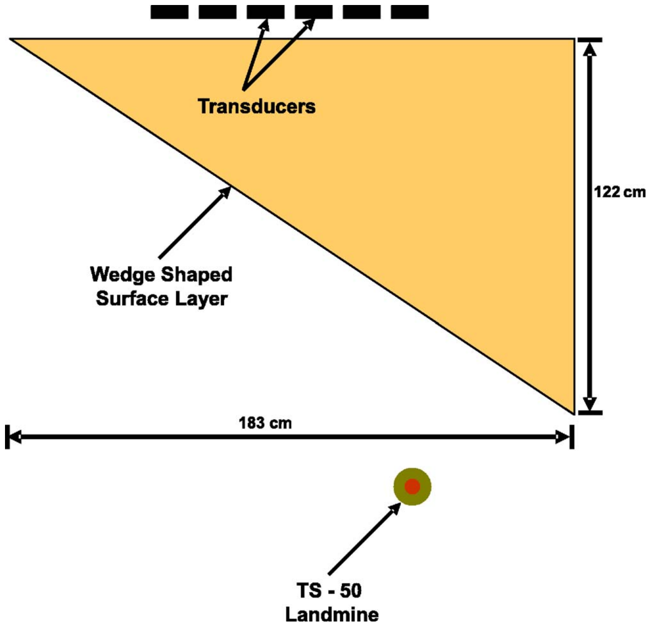

Fig. 2. (Color online) The experimental configuration for experiments using an asymmetric surface layer with a TS-50 land mine at the focusing point.

$$x_i = i\Delta x, \quad i = 0,1, \ldots, \frac{X}{\Delta x}$$

$$y_j = j\Delta y, \quad j = 0,1, \ldots, \frac{Y}{\Delta y}$$

$$t_k = k\Delta t, \quad k = 0,1, \ldots, \frac{T}{\Delta t}, \tag{1}$$

and where $X=202.311$ cm and $Y=150.876$ cm are the dimensions of the scan region, and $T=4.096$ s is the duration of time for which each measurement is recorded.

Time-reversal drive signals are created by first transmitting individual signals from each source in the array of sources and recording the response at the desired focus point. These signals are then time-reversed and retransmitted from the sources and the response is recorded over the entire scan region. The signal used to interrogate the soil is a swept frequency chirp signal that sweeps from 30 Hz to 2 kHz.[15] For display purposes, the results are presented as the response to a differentiated Gaussian pulse with a center frequency of 900 Hz. The process used to create the time-reversal drive signals is described in earlier work.[15,16]

2.2 Surface layer

An asymmetric surface layer is introduced into the experiment by embedding a plywood layer into the sand. The purpose of this layer is to alter the propagation direction of surface waves. The plywood layer is created using a wedge-shaped piece of 3/4 in. plywood cut into a 4 ft by 6 ft wedge. The shape of the surface layer is made asymmetrical with respect to the propagation direction of the surface waves as shown in Fig. 2.

The plywood wedge is tested in two configurations. The first configuration employed a single sheet plywood wedge that is buried flush to the surface of the sand (Case A) [Fig. 3(a)]. A second configuration uses two identical 4 ft by 6 ft by 3/4 in. plywood wedges. The upper sheet

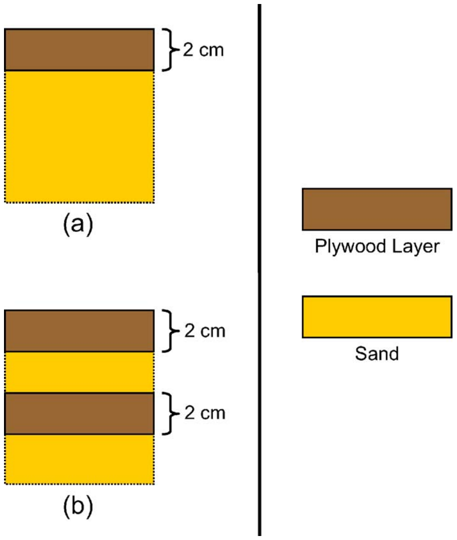

Fig. 3. (Color online) The *X-Z* plane cross section of the two surface layer configurations used in the experiments: (a) single sheet plywood surface layer, (b) multilayer plywood and sand surface layer.

of plywood was buried flush to the surface, with a thin layer (2 cm) of sand between the upper and lower sheets (Case B) [Fig. 3(b)]. In each configuration, a TS-50 land mine is buried at the focus location as indicated in Fig. 2.

3. Results: Focusing through an asymmetric surface layer

A comparison can be made of the performance of the three different excitation types; time-reversal focusing, time-delay focusing, and uniform excitation. Uniform excitation excites all sources with identical, in-phase signals. Time-delay focusing excites sources with signals that are time-delayed based on a constant velocity estimate for the Rayleigh wave propagation speed in the medium. If the estimate is accurate, the dominant Rayleigh wave from all the sources will arrive and focus coherently at a focus location at the same time. A comparison of these two excitation methods to time-reversal focusing is performed for both configurations of the asymmetric surface layer (Fig. 4).

The results are presented in Fig. 4 as pseudocolor graphs and animations of the magnitude of the vertical component of the particle acceleration at the surface. The pseudocolor scale used in the figures is a 40 dB logarithmic scale from white (0 dB) to black (−40 dB). In order to compare the different focusing methods, the results are normalized with respect to the energy contained in the excitation signals for each of the three excitation methods. An examination of time-domain movies and snapshots of wave propagation for each type of excitation is useful to visualize the effects of a surface layer on surface wave propagation.

3.1 Case A: Single sheet plywood surface layer

Because of the higher propagation speed in the plywood than in sand, the wedge shape of the plywood layer causes the surface-bound wave to turn in Fig. 4 (Case A). A second wave front travels under the surface layer, coming back to the surface of the sand on the other side of the plywood wedge. As can be seen in Fig.4 (Case A), this wave arrives at the land mine location later in time. As its speed is less affected by the plywood wedge on the surface, the change in its propagation direction is almost imperceptible.

While the direction change of the second wave front is small, the initial wave front is turned away from the land mine location. This initial wave contains a substantial portion of the excitation energy. Because of this, the maximum amplitude at the land mine location using

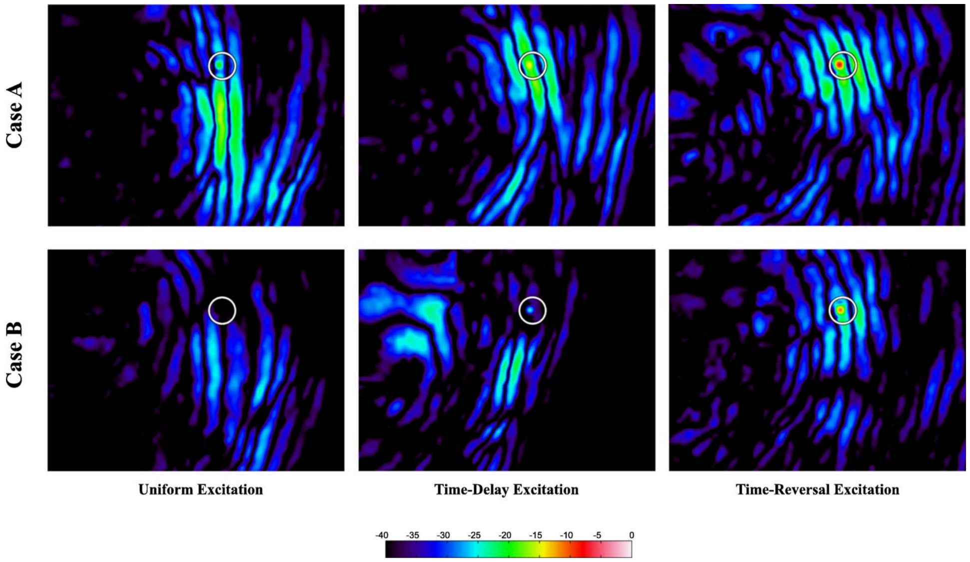

Fig. 4. (Color online) Time-domain animations of wave propagation through the single sheet plywood surface layer (Case A) and the multilayer plywood and sand surface layer (Case B). The white circle denotes the desired focus location, and the location of a buried TS-50 land mine. Images are on a 40 dB pseudocolor scale: 0 dB (white) to −40 dB (black). (Click on the image to view the animation.)

time-delay focusing is adversely affected. Time-reversal focusing shows a 7 dB improvement in peak excitation amplitude over time-delayed focusing and a peak signal level of approximately 13 dB over uniform excitation (Table 1).

3.2 Case B: Multilayer plywood and sand surface layer

The multilayer plywood and sand surface performs similarly to the single sheet plywood surface layer except that it turns the wave more effectively. Because the multilayer plywood and sand surface is more than twice the thickness of the single sheet plywood surface layer, more energy is captured in the surface layer, causing the relative amplitude of the turned wave to be larger in comparison to the second unturned wave. Most of the energy is turned away from the land mine location by the surface layer, as observed in Fig. 4 (Case B). Because of the discrepancy between the actual, inhomogeneous wave velocity, and the constant estimate used to calculate time delays, time-delay focusing concentrates energy in the wrong location. This effectively turns the wave away from the desired focus point. Time-reversal focusing shows an 8 dB improvement in peak excitation amplitude over time-delayed focusing and a peak signal level of approximately 18 dB over uniform excitation (Table 1).

Table 1. The peak amplitude (dB) and the background contrast (Δ dB) at the focus point for each excitation type and surface layer configuration.

Surface layer type	Uniform excitation (dB)	Time-delay excitation (dB)	Time-reversal excitation (dB)
Plywood single layer	−20	−14	−7
	Δ7	Δ5	Δ10
Plywood and sand multilayer	−28	−18	−10
	Δ5	Δ7	Δ10

4. Conclusions

The effectiveness of elastic wave time-reversal focusing was examined in the presence of an asymmetric surface layer. The surface layer changes the propagation velocity and direction of the elastic waves and can steer them away from the location of a buried land mine. The surface layer further complicated the wave field since waves could propagate under as well as through the surface layer. Even with these effects, time-reversal focusing was effective and performed significantly better than time-delay focusing. Table 1 summarizes the results.

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[1] M. Fink, “Time-reversal of ultrasonic fields. I. Basic principles,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control **39**, 555–566 (1992).

[2] F. Wu, J.-L. Thomas, and M. Fink, “Time-reversal of ultrasonic fields. II. Experimental results,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control **39**, 567–578 (1992).

[3] D. Casserau and M. Fink, “Time-reversal of ultrasonic fields. III. Theory of the closed time-reversal cavity,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control **39**, 579–592 (1992).

[4] A. Derode, P. Roux, and M. Fink, “Robust acoustic time reversal with high-order multiple scattering,” Phys. Rev. Lett. **75**, 4206–4209 (1995).

[5] M. Fink, C. Prada, F. Wu, and D. Cassereau, “Self focusing in inhomogeneous media with time reversal acoustic mirrors,” Proc.-IEEE Ultrason. Symp. Vol. **5**, 681–686 (1989).

[6] P. Blomgren, G. Papanicolaou, and H. Zhao, “Super-resolution in time-reversal acoustics,” J. Acoust. Soc. Am. **111**, 230–248 (2002).

[7] L. Borcea, G. Papanicolaou, and C. Tsogka, “Theory and applications of time reversal and interferometric imaging,” Inverse Probl. Eng. **19**, S139–S164 (2003).

[8] R. Ing, M. Fink, and O. Casula, “Self-focusing Rayleigh wave using a time reversal mirror,” Appl. Phys. Lett. **68**, 161–163 (1996).

[9] N. Chakroun, M. A. Fink, and F. Wu, “Time reversal processing in ultrasonic nondestructive testing,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control **42**, 1087–1098 (1995).

[10] A. Sutin, J. TenCate, and P. Johnson, “Single-channel time reversal in elastic solids,” J. Acoust. Soc. Am. **116**, 2779–2784 (2004).

[11] P. D. Norville and W. R. Scott, Jr., “An investigation of time reversal techniques in seismic land mine detection,” J. Acoust. Soc. Am. **118**, 735–744 (2005).

[12] J. C. Santamarina, K. A. Klein, and M. A. F. N. Bracewell, *Soils and Waves* (Wiley, West Sussex, UK, 2001).

[13] W. R. Scott, Jr., J. S. Martin, and G. D. Larson, “Experimental model for a seismic land mine detection system,” IEEE Trans. Geosci. Remote Sens. **39**, 1155–1164 (2001).

[14] J. S. Martin, G. D. Larson, and W. R. Scott, Jr., “An investigation of surface-contacting sensors for the seismic detection of buried land mines,” J. Acoust. Soc. Am. **120**, 2676–2685 (2006).

[15] P. D. Norville, W. R. Scott, Jr., and G. D. Larson, “An investigation of time reversal techniques in seismic land mine detection,” Proceedings of the SPIE Defense and Security Symposium, 2004, Vol. **5415**.

[16] P. D. Norville, “Time-reversal techniques in seismic detection of buried objects,” Ph.D. thesis, Georgia Institute of Technology, 2007, Atlanta, GA (http://etd.gatech.edu/theses/available/etd-03292007–143303/).