Linear and Nonlinear Time Reverse Acoustics in Geomaterials

P. A. Johnson[1], A. Sutin[2] and J. TenCate[1]

[1]Geophysics Group, Los Alamos National Laboratory of the University of California, MS D443, Los Alamos, NM 87545, paj@lanl.gov
[2]Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ 07030, asutin@stevens.edu

Abstract

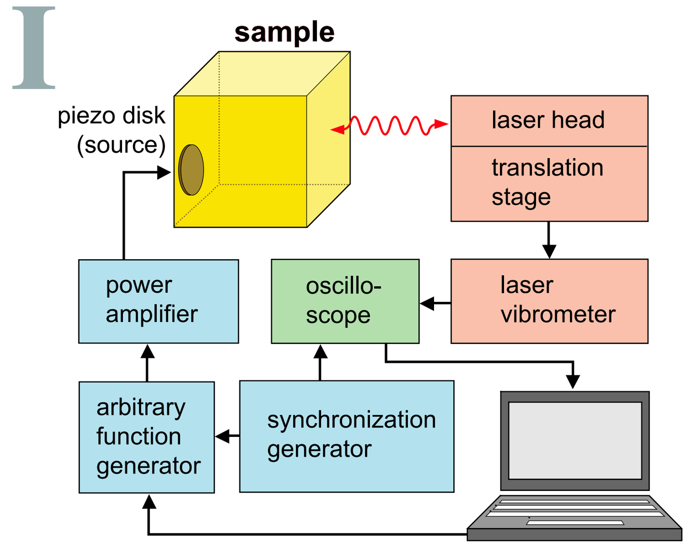
Time Reversal Acoustics (TRA) is one of the most intriguing topics to have emerged in modern acoustics in the last 40 years. Much of the seminal research in this area has been carried out by the group at the Laboratoire Ondes et Acoustique at the University of Paris 7, who have demonstrated the ability and robustness of TRA (using Time Reversal Mirrors) to provide spatial control and focusing of an ultrasonic beam (e.g. Fink, 1997). The ability to obtain highly focused signals with TRA has numerous applications, including lithotripsy, ultrasonic brain surgery, nondestructive evaluation and underwater acoustic communication. Notably, the study of time reversal in solids and in the earth is still relatively new. The problem is fundamentally different from the purely acoustic one due to the excitation and propagation of both compressional (bulk) and shear waves as well as the scattering and potentially high dissipation of the medium.

We conducted a series of TRA experiments in different solids using direct-coupled transducers on solids in tandem with a large bandwidth laser vibrometer detector. Laboratory experiments were conducted in different geomaterials of different shapes and sizes, including Carrera marble, granite and Berea sandstone. We observed that, in spite of potentially huge numbers of wave conversions (e.g., compressional to shear, shear to compressional, compressional/shear to surface waves, etc.) for each reflection at each free surface, time reversal still provides significant spatial and temporal focusing in these different geophysical materials. The typical size of the focal area is approximately equivalent to the shear wave length and the focal area, but becomes larger with increasing wave attenuation (Sutin et al., 2004a; Delsanto et al., 2003)).

The TR-induced focusing of wave energy at a point in space and time is ideal from the perspective of enhancing elastic wave, nonlinear response (e.g., higher harmonic generation or wave modulation effects). We call this technique Nonlinear Time Reverse Acoustics (NLTRA) (Sutin et al., 2004b). We investigated the harmonic generation in TRA signals focused above a small crack (2 mm) in a glass cube. Large second harmonic amplitudes were observed above the crack. Scanning of the surface by applying the laser vibrometer simultaneous with TRA focusing of the signal to an array of corresponding scanning points, provided nonlinear imaging of the surface, showing cracks located in the scanned region.

Time Reverse Acoustics (TRA) in Sandstone

I

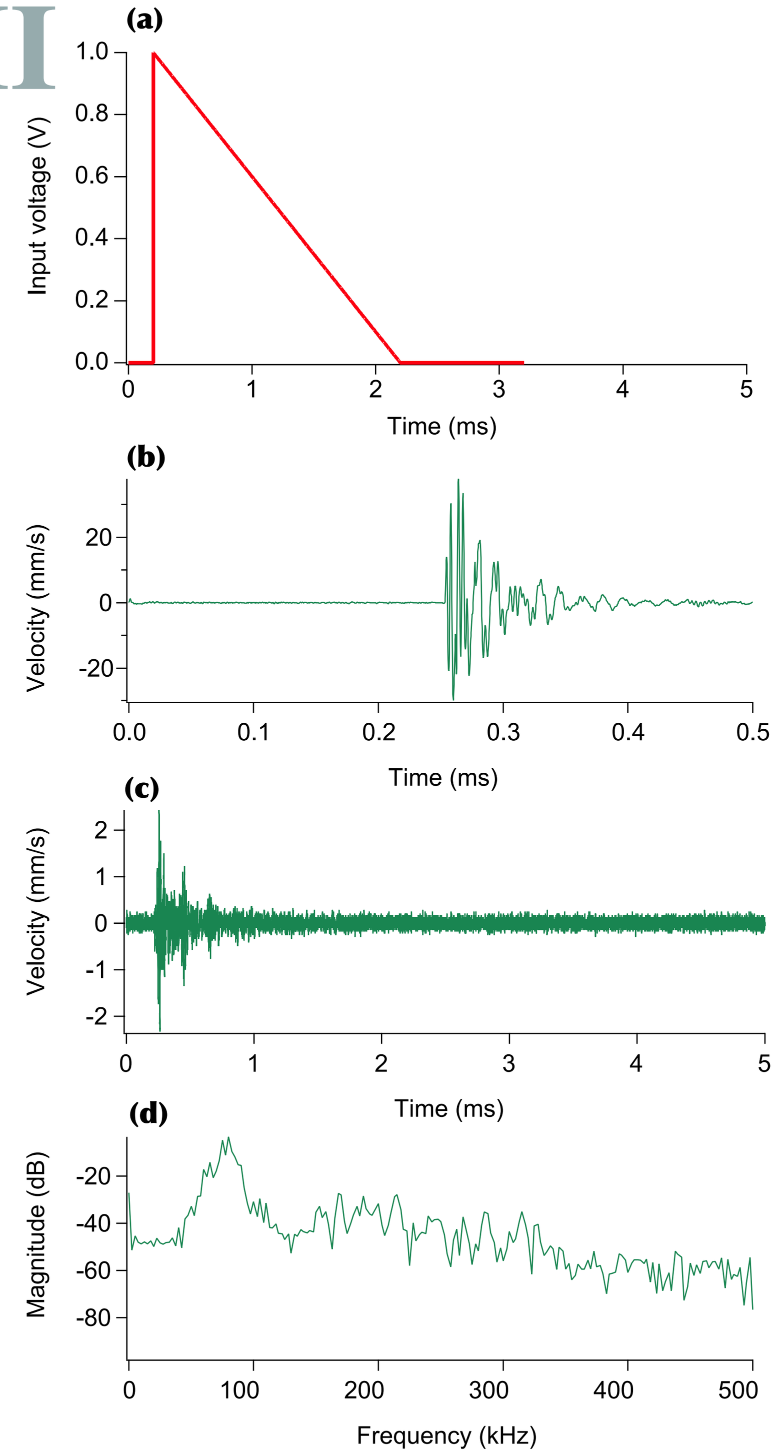


Experimental set-up for measurements of single-channel, time reversal in solids (above)

The signal source is a piezoelectric ceramic bonded to the sample surface. The detector is a laser vibrometer (Polytech 301 with 303 laser head) with a flat response from DC to 1.5 MHz. Samples of various sizes and geometries were interrogated.

We present results from a sample of Berea sandstone of dimension 75 x 75 x 254 mm3 where the average grain size is 100 microns, compressional wave velocity is 2200 ms and Q = 50.

II



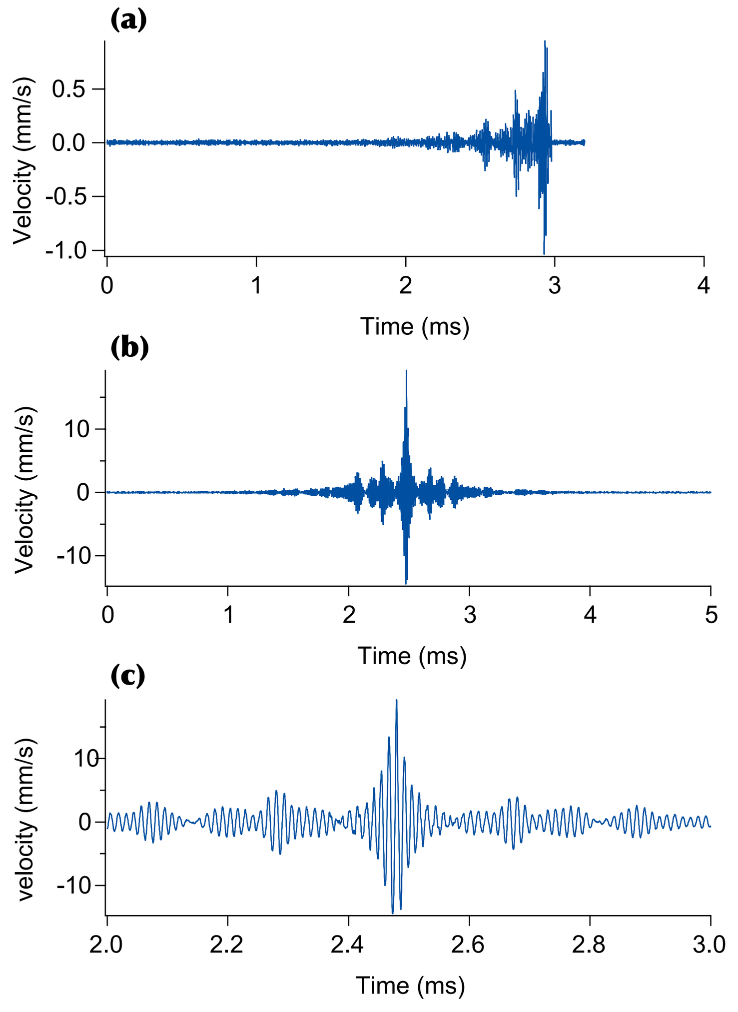
Input and detected waves in the Berea sandstone (above)

(a) Electrical input

(b) Signal measured on backside of source

(c) Detected signal across sample, frequency band-passed between100–700 kHz

(d) Spectrum of detected signal



Time reversal results in Berea sandstone frequency bandpassed 70–700 kHz (above)

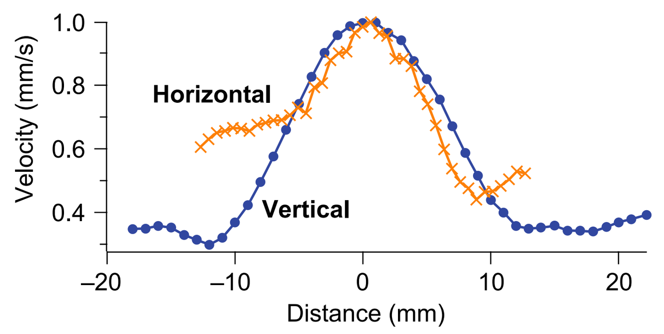
(a) Detected signal, time reversed (TR)

(b) TR and transmitted signal

(c) Zoom of (b)

Note pulse compression of the final signal, very similar to the auto correlation of the input signal. (See Delsanto et al., 2003 for model results).

III



Spatial distribution of TR detected signal in Berea sandstone measured along perpendicular lines crossing at the TR focal point (above)

Lines serve to connect the points. Amplitudes were obtained by measuring the peak amplitude of TR and transmitted (as in b and c, above right). Amplitudes are normalized to the maximum. The focal width at –3dB is about 8 mm. The fact that attenuation is high (Q = 50) restricting the number of wave reflections or "virtual sources," restricts the focal width in comparison with high-Q fluids or solids.

IV Conclusions on TRA in Sandstone

It is remarkable that one can virtually ignore the complications of mode conversion and treat the TR process blindly. Due to mode conversion, it is not obvious that reciprocity holds as it does in acoustical media, however this point still needs rigorous study. To our knowledge, this is the first demonstration of time reversal in granular solids.

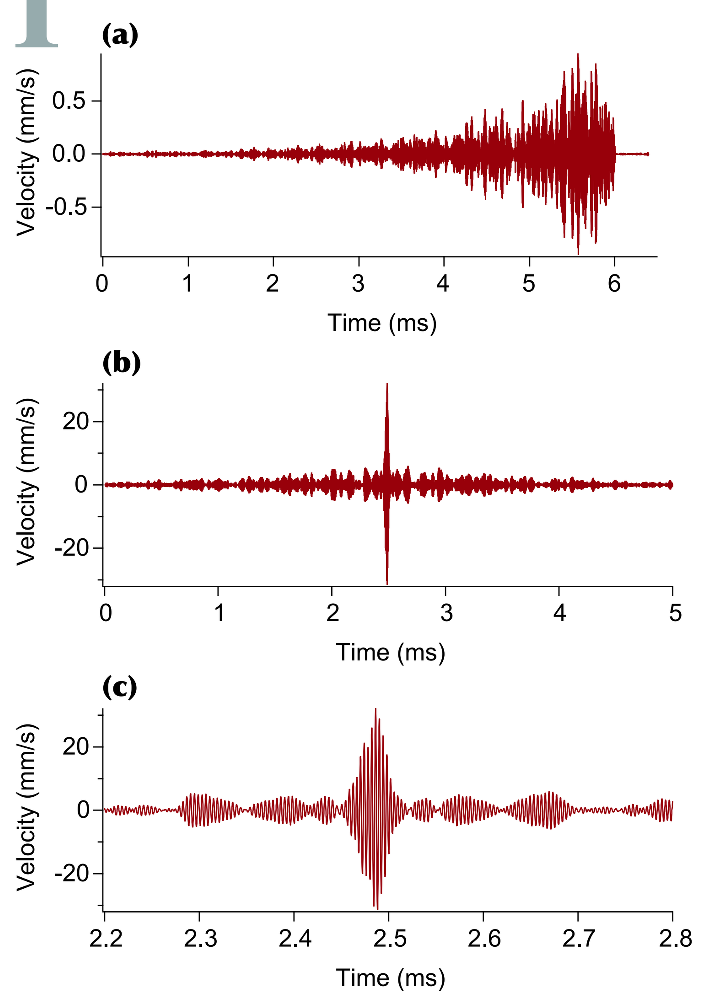
Nonlinear Time Reverse Acoustics (NLTRA) Applied to Damage Detection

V

Solids that exhibit a large dynamic nonlinear response are damaged. It is the damage that creates the response. The damage can be distributed (micro-nanoscale) as in a sandstone, or local, as in a solid containing a single crack (Guyer and Johnson, 1999). Nonlinear response in the form of wave distortion and associated harmonics increases with wave amplitude (Ostrovsky and Johnson, 2001). Thus, the high amplitudes and localization from TR can easily induce a significant nonlinear response making the combination promising for imaging of damage in solids. In the following we show how the second harmonic of the TR signal can be used to localize damage in glass.

Nonlinear experiments were conducted in a glass parallelpiped measuring 101 x 89 x 89 mm3 ("sample" in photo at left). A piezo-ceramic disc was epoxied to its surface for a source, and the laser vibrometer used for the sandstone was again applied as detector (see schematic diagram at left). The experimental setup is the same as that for the linear TR measurements in sandstone. A small, 3-mm crack oriented perpendicular to the glass surface is located near the glass surface.

VI



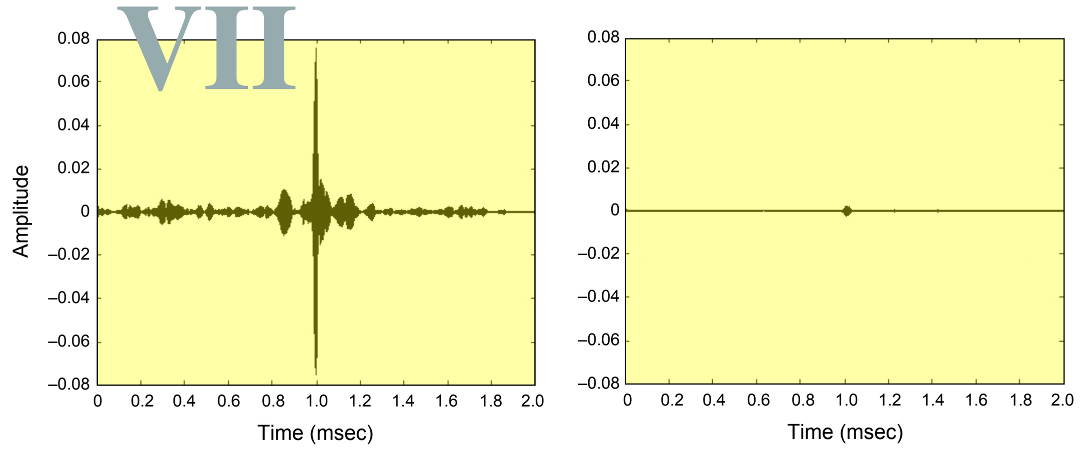
Experiment in cracked glass sample showing TR focusing on the crack (left)

(a) Detected signal, TR. Input was a short Gaussian-shaped electrical pulse with carrier frequency of 260 kHz.

(b) TR signal after transmission

(c) Zoom of (b)

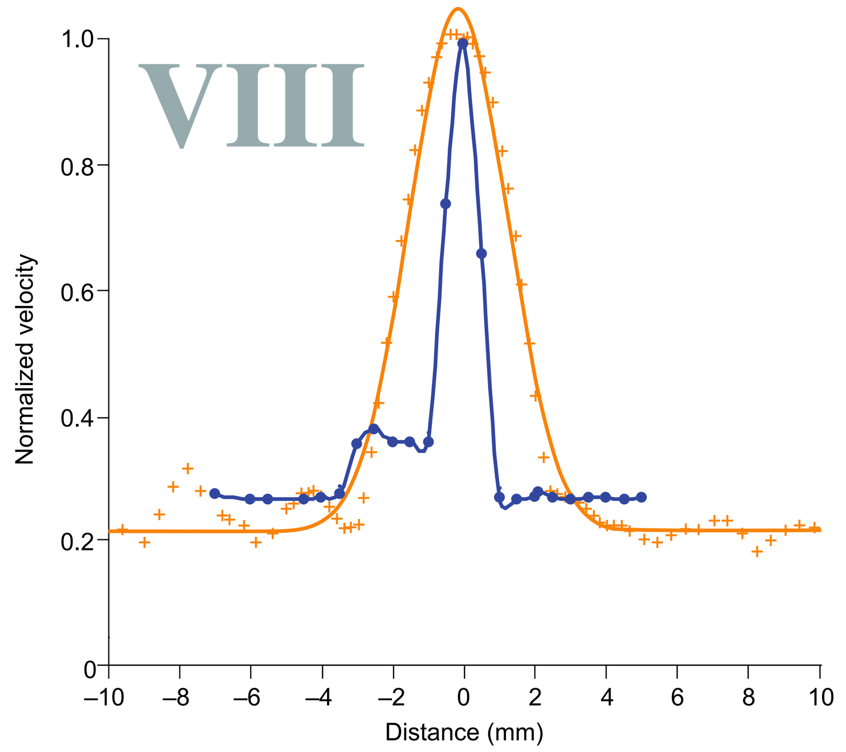
VII



Second harmonic detected on the crack (above left) and on an intact surface (above right)

The TR signal bandpass filtered around the second harmonic (520 kHz) detected above the crack with the laser vibrometer (left), and 30 mm away from the crack (right). The fact that energy at the second harmonic is observed means that strong nonlinear response exists at the crack, as we expect. By scanning along the crack, it can be mapped or imaged. See also Sutin et al., 2003; 2004.

VIII



Spatial distribution of the fundamental and second harmonic taken over the crack in the glass sample (above)

Both are normalized to the maximum amplitude. The amplitudes were obtained by band-pass filtering the TR and detected signal around the second harmonic, and measuring the peak-peak amplitude of this signal, as is shown in the figure above.

IX Conclusions on NLTRA as Applied to Imaging Damage

We are currently developing NLTRA to scan two dimensional surfaces for fast imaging of damage. Three dimensional imaging is also in development. We are also applying NLTRA to remote location of antipersonnel mines, and this approach is working very well.

Overall Summary

We have shown that Time Reverse Acoustics (TRA) works well in elastic media where the complications of mode conversion can be virtually ignored. Further, we have shown that Nonlinear Time Reverse Acoustics (NLTRA) can be applied to image localized damage. Potential applications of TRA and NLTRA in solids and in the earth include imaging of localized damage, location of antipersonnel mines, and general source location. We are currently working on all of these applications with a number of collaborators.

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