DEVELOPMENT OF NONLINEAR TIME REVERSED ACOUSTICS (*NLTRA*) FOR APPLICATIONS TO CRACK DETECTION IN SOLIDS

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Abstract

Nonlinear acoustic methods of Nondestructive Evaluation (NDE) exhibit extremely high sensitivity to the presence of cracks. Time Reverse Acoustical (TRA) methods provide the means to focus acoustic energy to any point in a solid. In combination, we are applying the focusing properties of TRA and the elastic nonlinear properties of cracks to locate them. The experiments were conducted using a glass parallelepiped containing a small crack near the surface. The TR signal was focused on the crack and compared with a signal focused elsewhere on the surface. The spectrum of the narrow band TR signal focused on the crack exhibited a level of higher harmonics several orders larger than the level of those obtained from a wave focused away from the crack. The results of experiments demonstrate the possibility of isolating linear from nonlinear scatterers in general, ultimately providing the means to locate and discern cracks from voids for instance. These are the first measurements we are aware of combining elastic nonlinearity and time reversal in solids.

Introduction

Much of the seminal research in TRA has been carried out by the group located at the University of Paris VII (Laboratoire Ondes et Acoustique, ESPCI) [1-5], who have demonstrated the ability and robustness of TRA (using Time Reversal Mirrors) to provide spatial and temporal focusing of an ultrasonic wave. A significance aspect of TRA is that it provides one the ability to focus an ultrasonic wave, regardless of the position of the initial source and regardless of the heterogeneity of the medium in which the wave propagates. TRA systems have a range of applications, including destruction of tumors and kidney stones and long-distance communication in the ocean. The Nondestructive Evaluation (NDE) applications of TRA to date include detection of small, low-contrast defects within titanium alloys [3,4] and detection of cracks in a thin air-filled hollow cylinder [5]. A review of TRA applications to NDE is given in [3].

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 (for example, higher harmonic generation or wave modulation effects). Over the last two decades, studies of nonlinear wave methods in NDE have steadily increased demonstrating that the nonlinear elastic response of material may radically increase in the presence of “damage” (cracks or other flaws) [6-9]. The combination of TRA and elastic nonlinear response (NLTRA) due to the presence of damage, has the potential of greatly enhancing the diagnostic capability of both TRA and nonlinear diagnostics at many scales.

Experimental setup

We conducted the experiment in a glass parallelepiped with dimensions of 101 x 89 x 89 mm^3. A piezoceramic disk, 50 mm in diameter and 2.8 mm thick, was glued using epoxy near the corner of one side of the glass parallelepiped as shown in Figure 1. A laser vibrometer (Polytech) was used as detector. A photograph of the glass with the laser head is shown in Figure 2. Figure 3 shows a schematic of the crack dimensions on block. Both cracks are studied in this work.

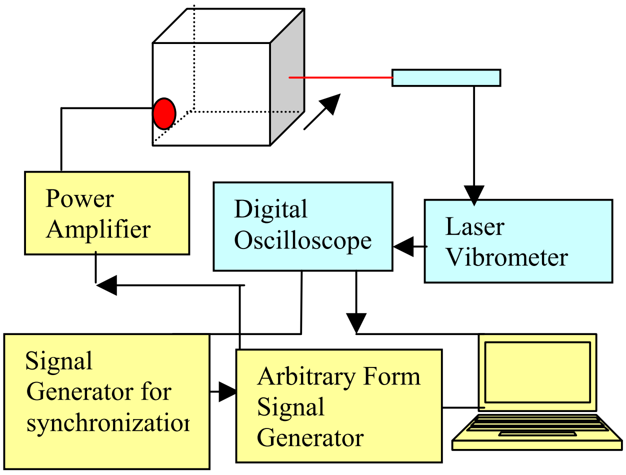

Figure 1. The experimental setup for TRA focusing in a glass parallelepiped sample.

Figure 2. Glass sample with the laser detector.

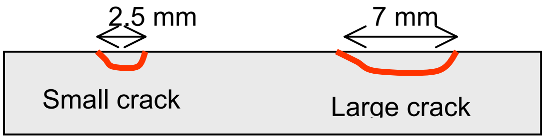

Figure 3. Schematic of cracks

Observations

A typical time reversal experiment was carried out in the following way. A short, triangular-shaped electric pulse was applied to the transmitter (Fig. 4a). The signal measured on the backside of the transducer using the laser vibrometer is shown in Fig. 4b in order to view the signal broadcast into the solid. The signal that arrived on the opposite side (not far from the sample center) was measured by the laser vibrometer and is shown in Fig. 4c. The detected signal was then band-pass filtered from 100-700 kHz to eliminate low frequency noise; its frequency spectrum is shown in Fig. 4d. Notice that the direct signal consists of the first arrival and almost 10 ms of coda.

The recorded signal was time reversed as shown in Fig.5a (normalized to 1V p-p) and then fed into an arbitrary waveform generator and radiated from the original source as done by Draeger et al. [11]. In an acoustic medium, because of reciprocity, the method is identical to radiating the time reversed signal from the laser detector location, and simplifies the experimental procedure considerably. In solids, using the same source to transmit the initial tone burst and the time-reversed wave train—while not strictly necessary—eliminates any confusion which might arise from site effects (transducer and coupling variations); they are the same for the initial and time reversed waves. Reciprocity does not truly hold in an elastic medium in this case, but the technique is robust enough to overcome this issue. The time-reversed signal then propagates through the sample and is detected by the laser vibrometer. The resulting refocused signal (shown in Fig.5b; zoom shown in Fig. 5c) was well reconstructed.

Application of a narrow bandpass filter demonstrates that time reversal works well using just a portion of the signal and focusing can be enhanced by only using high frequency [12]. In addition, in order to easily see elastic nonlinear effects, we radiate a signal with a narrow frequency band to observe high harmonics. We chose to bandpass filter the received signal at a spectral peak—210 to 310 kHz (center frequency 260 kHz) for the nonlinear measurements. This signal is shown in Fig.6.

The spatial distribution of the TR focused signal amplitude for the above frequency band is presented in Fig. 7. Amplitudes are the measured peak amplitudes of the TR signal at each position, normalized to the maximum measured amplitude. The points are the actual data values and the lines are Gaussian fits. The width measured at –3 dB is approximately 2.4 mm for the bandpass-filtered signal. Note that the longitudinal (compressional) and shear wavelengths for these frequencies are 11.5 mm 6.4 mm, respectively. The high degree of focusing is due to the numerous reflections of the acoustic signal from the walls of the solid that act as virtual sources.

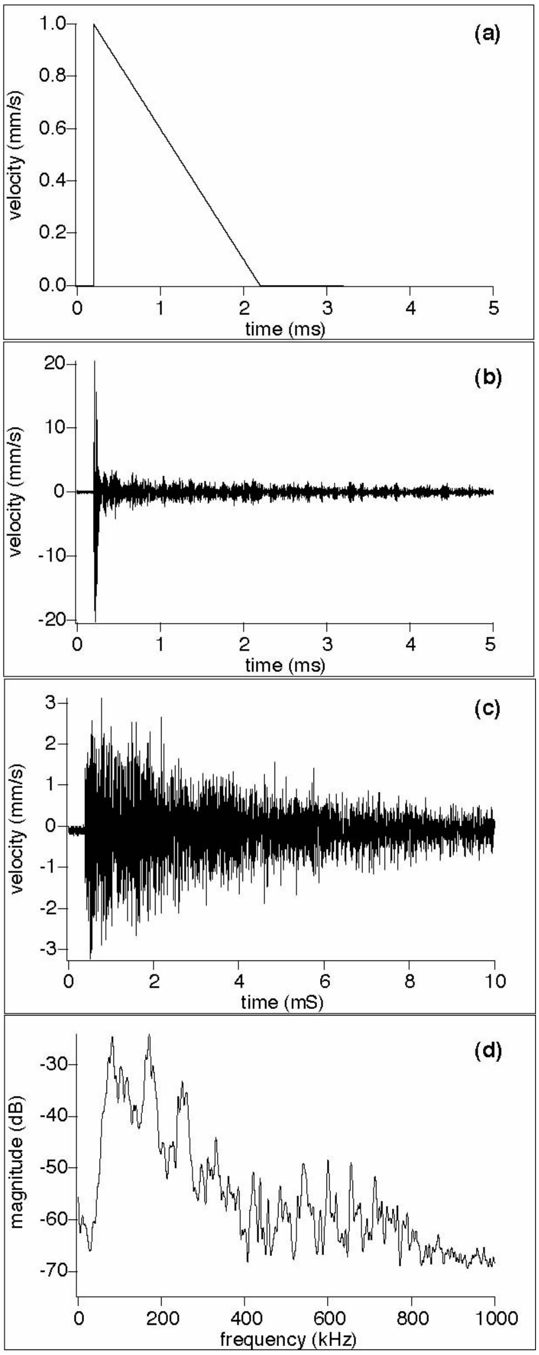

FIGURE 4. Input and detected wave properties in the doped glass sample. (a). The electrical input into the ceramic. (b) the signal detected using the laser vibrometer on the back side of the ceramic. (c) The detected signal after traversing the sample, measured with the laser vibrometer, frequency band-between 100-700 kHz. (d) The spectrum of the detected signal.

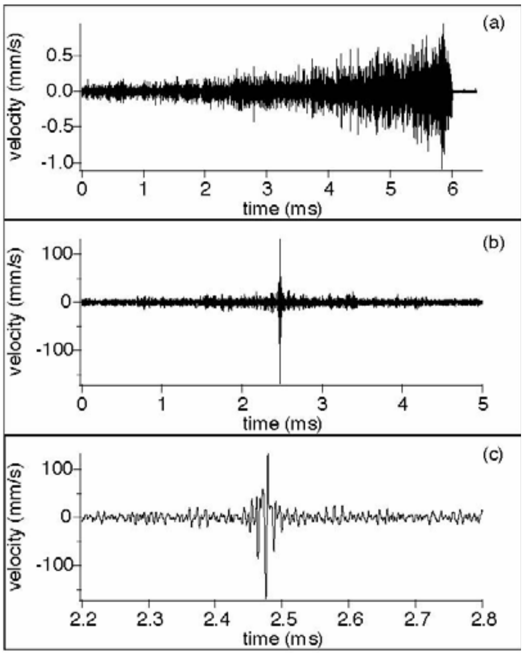

Figure 5. TR results in the glass for wide frequency band 100-700kHz: (a) radiated TR signal, (b) detected focused TR signal, (c) its zoom.

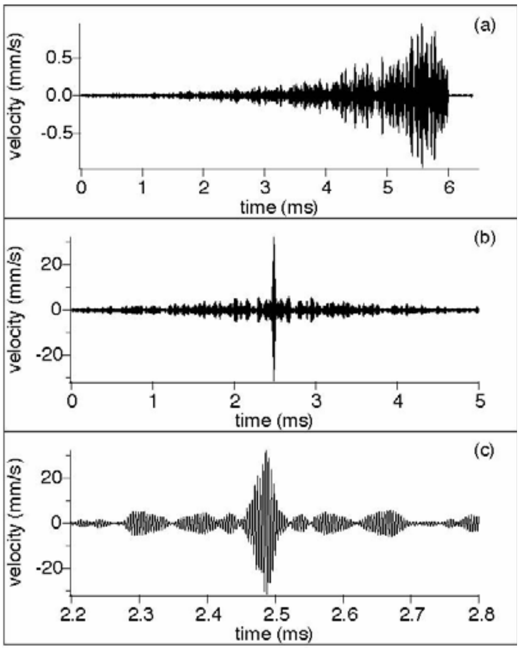

Figure 6. TR results in doped glass for a frequency band of 210-310kHz: (a) radiated TR signal, (b) detected focused TR signal, (c) its zoom.

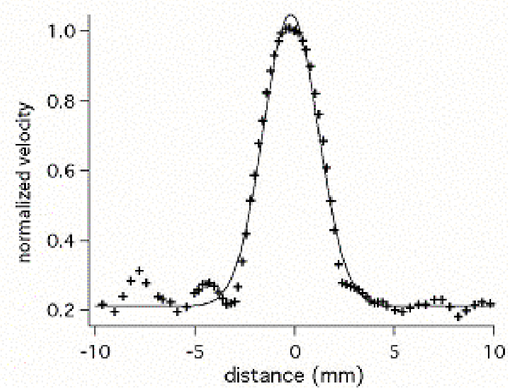

Figure 7. TR focusing from time reversal in the doped glass for frequencies 210-310 kHz. The solid line is Gaussian fit to the measurement points.

NLTRA Measurements

The concentration of wave spatial and temporal energy in TR is ideal for elastic nonlinear studies and their ultimate applications. As noted a crack in a solid is extremely nonlinear, much more so than the material itself. In order to study this behavior, we introduced several small cracks just beneath the material surface of the sample. Our goal was to observe whether or not the nonlinear response of focused wave energy at a crack existed, and, if so, to compare it to that of a signal focused elsewhere in the sample. In addition, we wanted to be certain that the observed nonlinearity was of the “nonclassical” type observed due to the presence of cracks in solids observed by other means [9-10, 12]. This type of nonlinear response has characteristic scaling relations, including that of the dependence of the second and third harmonic wave amplitudes on the fundamental wave amplitude [12]. This is accomplished by re-emitting the TR signal at progressively increasing amplitudes and inspecting the respective, detected spectra.

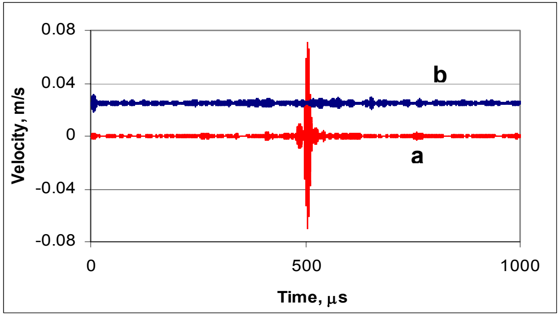

Figure 8. The measured third harmonic signal. TRA signal at the crack (a) and on an intact surface (b).

In the experiment we used the narrow band signal with central frequency 260 kHz shown in Fig.5. For measurements of the harmonic level the detected signals were filtered around the fundamental, 2nd and 3rd harmonics respectively (260kHz, 520 kHz and 780 kHz +/-30). Figure 8 shows the detected TRA signal filtered at 780 kHz for the laser detector recording at the large crack, and from an intact surface respectively, for an amplitude of 100 V(p-p).

Figures 9 and10 show the harmonic amplitudes for the second and third harmonics measured at the two positions, obtained by progressively increasing drive levels. From nonclassical theory [e.g., 12], we expect that the scalings of the second and third harmonic to be proportional of the square of the applied voltage. The scaling of the second and third harmonics on applied voltage (solid lines in figs.9,10) show that, for signal obtained at the crack , $(A_{f2,f3} \sim A_{f1}^{2})$. Indeed the second and third harmonics exhibit nonclassical scaling, and the amplitudes are far larger than those measured from an intact region of the glass parallelepiped (~ 40 dB difference).

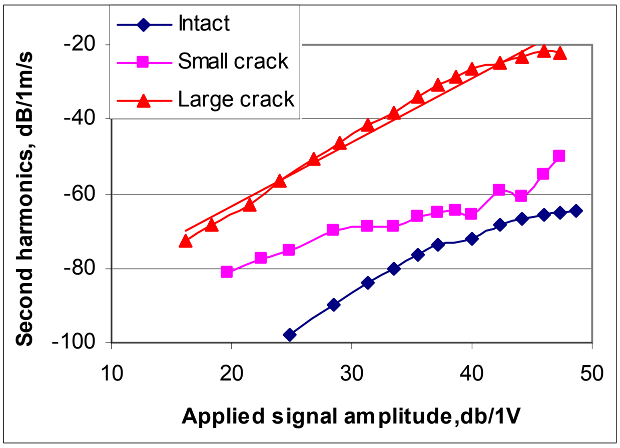

Figure 9. Scalings of the second harmonic on drive voltage for TRA signal focused on the two cracks.

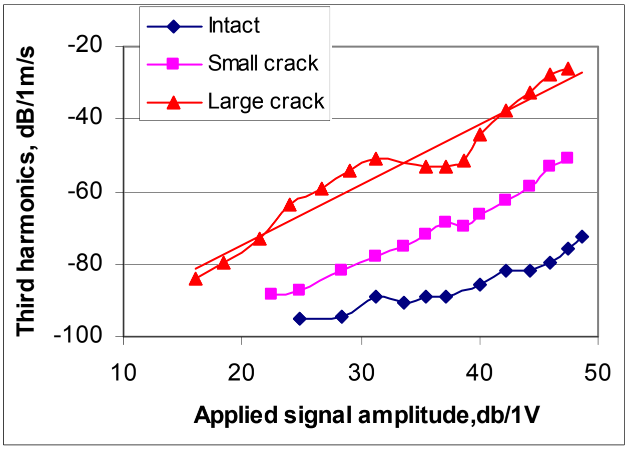

Figure 10. Scalings of the third harmonic on drive voltage for TRA signal focused on the two cracks.

Conclusions

The results show that indeed, we are measuring a well focused signal both on and away from the crack. The harmonic amplitudes, obtained from TR signals emitted at progressively increasing drive level, scale close as they should for a crack in a solid. This work shows the first demonstration of nonlinear behavior using time reversal in a solid. Our goal is now use NLTRA for imaging damage.

Acknowledgment

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References

[1] M.Fink, D.Cassereau, A.Derode, C.Prada, P.Roux, M.Tanter, J.-L.Thomas, F.Wu, “Time-reversed acoustics, Rep. Prog. Phys., vol.63, pp. 1933–1995, 2000.

[2] M.Fink, “Time reversed acoustics”, Scientific American, pp.91-97, 1999.

[3] C.Prada, E.Kerbrat, D.Cassereau,M.Fink, “Time reversal techniques in ultrasonic nondestructive testing of scattering media”, Inverse Problems, vol.18, pp.1761–1773,2002.

[4] N.Chakroun, M.Fink, F.Wu, “Time reversal processing in non destructive testing”, IEEE Trans. Ultrason. Ferroelec. Freq. Contr., vol.42, pp.1087-1098, 1995

[5] E.Kerbrat, D.Clorennec, C.Prada, D.Royer, D.Cassereau, M.Fink, “Detection of cracks in a thin air-filled hollow cylinder by application of the D.O.R.T. method to elastic components of the echo”, Ultrasonics International, vol.40, pp.715-720, 2002

[6] P.A.Johnson, “The new wave in acoustic testing”, Materials World, the Journal of the Institute of Materials, vol.7, pp.544-546, 1999

[7] O.Buck, W.L.Morris, J.N.Richardson, “Acoustic harmonic generation at unbonded interfaces and fatigue cracks”, Appl. Phys. Letters, vol.33, pp.371-373, 1978.

[8] K.Van Den Abeele, P.Johnson, A.M.Sutin, “Non-linear Elastic Wave Spectroscopy (NEWS) techniques to discern material damage. Part I: Non-linear Wave Modulation Spectroscopy”, Res. Nondestr. Eval, vol.12, pp.17-30, 2000.

[9] K.E-A.Van Den Abeele, A.M.Sutin, J.Carmeliet, P.A.Johnson, “Micro-damage diagnostics using nonlinear elastic wave spectroscopy (NEWS)”, NDT&E International, vol.34, pp.239-248, 2001.

[10] C.Draeger and M.Fink, “One-channel time reversal of elastic waves in a chaotic 2D-silicon cavity”, Phys. Rev. Lett., vol.79, pp. 407–410, 1997.

[11] A.Sutin, J.TenCate, P.Johnson, “Single channel time reversal in elastic solids”, J. Acoust. Soc. Am., (2003) in press.

[12] R. Guyer, P.Johnson, “The astonishing case of mesoscopic elastic nonlinearity|, Physics Today, vol.52, pp.30-35, 2000