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Probing materials damage at various depths by use of Time Reversal Elastic Nonlinearity Diagnostic: Application to concrete

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Time Reversal Elastic Nonlinearity Diagnostic (TREND) is based on the use of time reversal to focus energy at a prescribed location. This focused elastic wave energy is then analyzed for nonlinear frequency content. By varying the frequency content of the focused waveforms, the technique can be used to probe different depths relative to the surface, i.e., the TREND will probe the surface and penetrate to a depth defined by the wavelength of the focused waves. We show the validity of this concept by comparing the results obtained from nonlinear resonant ultrasound spectroscopy and the present results in the presence of homogeneously diffused damage in concrete.

1 Introduction

The principle of time reversal acoustics is based on a simple principle. In any medium, send a pulse from a source and that pulse propagates into the medium. The wave is eventually reflected many times at boundaries and other scatterers, during which time the resulting signal is recorded at a given location by a receiver. If the recorded signal is time reversed and sent back from the receiver, the wave will play this propagation history backward (as a movie played backward), then the energy will focus at the precise emitter location at a given time (namely the focal time). Thanks to the reciprocity principle, the same scenario can be reached even if the time reversed signal is sent back from the initial source. In this case the focus will occur at the receiver location. This is true with a single emitter but the multiplication of emitters allows reaching a higher amplitude at the focal time.

This physical principle has been under study for many years, and has been largely developed by M. Fink [1] with most of the application in liquids or tissues for the medical field. The application of this principle to solids was developed at LANL with the idea to use the high energy focus to extract some nonlinear properties of solids. It has been successfully applied to locate and image cracks in a metal component [2], to evaluate the quality of diffusion bonds [3], and many other advances made in the field. However, the idea of using various frequencies to probe the material at different depths (with respect to the wavelength) has never been studied. This is the purpose of the present study.

To validate this idea, the comparison of the TREND results is achieved with respect to those obtained by a reference Nonlinear Resonant Ultrasound Spectroscopy (NRUS) measurement for the same samples [4]. Refer to this paper for details about samples and NRUS results. The concrete samples are chosen as they exhibit the largest nonlinear behavior (from [4]).

2 Experiments

The experimental protocol given Fig. 1 is based on reciprocal time reversal. The sample is placed onto a reverberant cavity which is a simple aluminum block with 8 piezoelectric discs (emitters) bonded to the surface at various locations. This cavity allows multiple reflections to occur, delaying the information available over time, and so, increasing the efficiency of the time reversal process. It is important to notice that we use a standard ultrasonic coupling agent; this point will be underlined at the end of the report. The laser records the signal at the top of the sample. An 8 channel 14-bit generator/digitizer system associated with 8 channels power amplifier is used. A PC

controls the TR experiments and allows to move the sample with a synchronized motion controller.

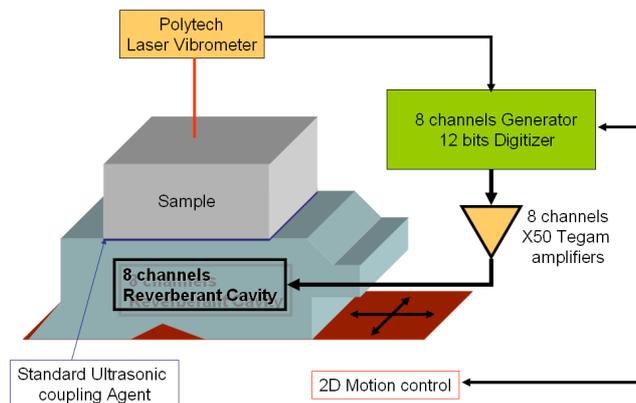


Figure 1: Experimental protocol

The signal processing is given in Fig. 2. Five frequencies ($f=50, 100, 200, 300$ and 400 kHz) corresponding to various wavelengths are selected. Note that the wavelength varies as a function of speed of sound v as $\lambda=v/f$. With the support of Fig. 2, the following steps occur:

1. A chirp signal (sinusoid with frequency varying in a given range) is sent to one emitter.
2. The signal is recorded by the laser, cross-correlated with the initial chirp signal (this operation allows getting the impulse response of the sample in the selected frequency range) and recorded by the system.
3. The same chirp is emitted from another emitter and stored too. (This process is applied for each channel).
4. When the 8 impulse responses are recorded, all of them are time reversed and sent back from their initial emitter at the same time.
5. The laser records the resulting focused signal.

In order to measure the nonlinearity, we need to measure the effect of amplitude. Thus, step 4 is repeated for 16 various amplitudes for each channel, providing 16 focused signals with different amplitudes. This protocol is repeated at 2 other locations on the sample.

The nonlinearity is extracted by the Scaling Subtraction Method (SSM). This method introduced by Scalerandi [Scalerandi, 2008] allows evaluating the nonlinearity from propagating waves. This principle can be explained by: send a signal s_1 with an A_1 amplitude and record it (r_1) after propagation. Send a signal s_2 with an amplitude A_2 and record it (r_2) after propagation. In a perfect linear medium, the scaled subtracted signal (SSM signal) $ssm = r_2 - A_2/A_1 * r_1$ will be zero. But, in a nonlinear medium, as the amplitude affects the propagation, the ssm signal will not be zero. One can measure the maximal amplitude or the energy of the SSM signal to get information about the amount of nonlinearity.

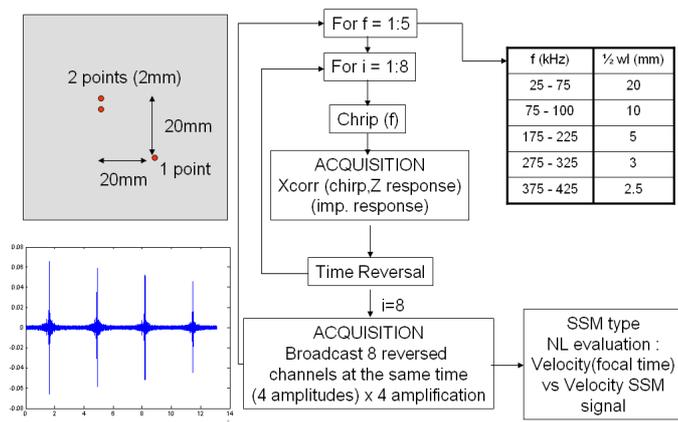


Figure 2: Data processing

The penetration depth is expected to correspond to the half pressure wave wavelength. This assumption is checked in the following section by the help of numerical simulation.

3 Numerical simulation

A 2D time reversal experiment has been modeled using Comsol to validate our hypothesis of the penetration depth that may correspond to the half pressure wave (i.e., compressional) wavelength. Figure 3 presents this simulation. To simplify the simulation, the standard Time Reversal process is modeled instead of reciprocal TR. A pulse is sent at the laser spot location, then the resulting signal is recorded by the transducers (direct signals Fig. 27). The receivers then become emitters and send back the time reversed signal they recorded, providing a focus at the laser spot location. An image of the volumetric strain inside the sample is provided in fig. 4.

This result validates our hypothesis about the penetration depth. The evolution of strain at the surface is due to surface waves, but at the focal time in the focal zone, pressure waves dominate. The pear shape observed is coherent with the results available in the literature [5].

This validation made, full 3D simulations should be performed to quantitatively link the measured velocity at the laser spot to the true volumetric strain (as for simulations in the NRUS section) for various frequencies.

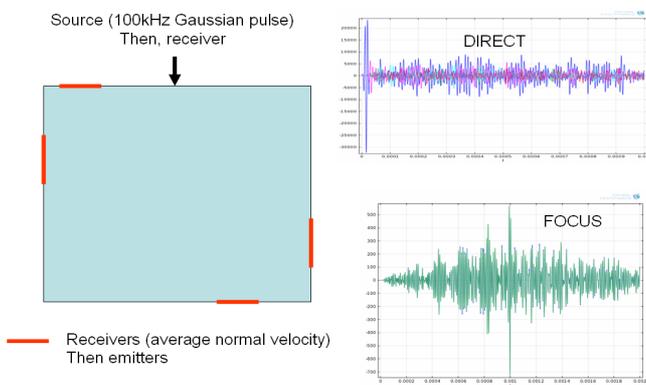


Figure 3: Numerical simulation configuration

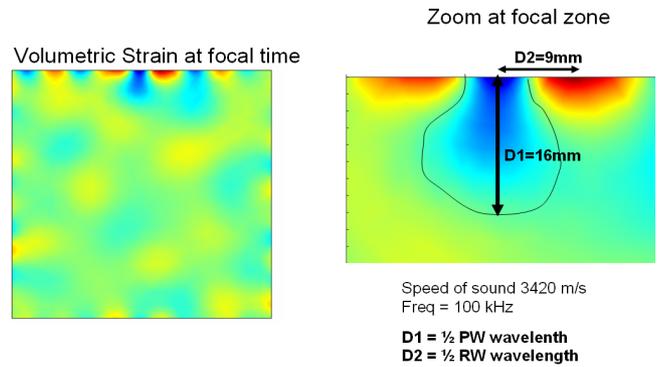


Figure 4: Volumetric strain at focal time. PW : pressure waves, RW : Raleigh waves

4 Results and discussions

The results for concrete samples are provided in Figs. 5 - 9. Note that for a comparison purposes, the procedure is also applied to the linear Plexiglas sample. The blue, green and red dots are respectively the 1st, 2nd and 3rd measurement points (refer to Fig. 2). The nonlinear indicator is evaluated as the ratio of the SSM signal energy by the fundamental energy (energy recorded at the focus). The 3 points for each penetration depth level correspond to the 3 measurements points. The 50kHz results are shown but as the sample size is about $5 \times 10 \times 10 \text{ cm}^3$, this frequency produces wavelengths comparable to the thickness of the samples, so these frequencies may not be very representative (i.e., possibly corrupted due to edge effects). The same observation can be made for 400kHz frequency because the wavelength corresponds to a small scale with regards to the concrete spatial variability. The compilation of the results (Fig. 10) presents the average of the measured nonlinearity at the 3 points for each wavelength.

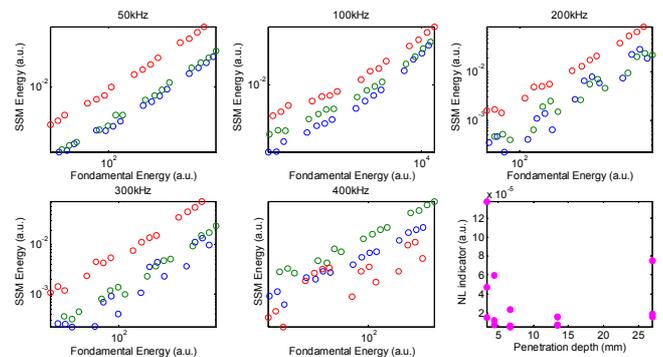


Figure 5: TREND result for the Plexiglas sample

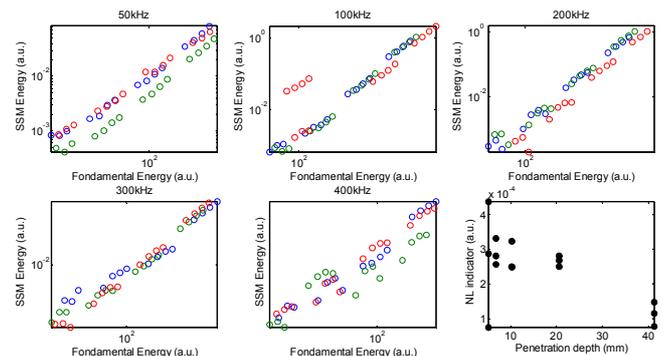


Figure 6: TREND result for the OC20 sample

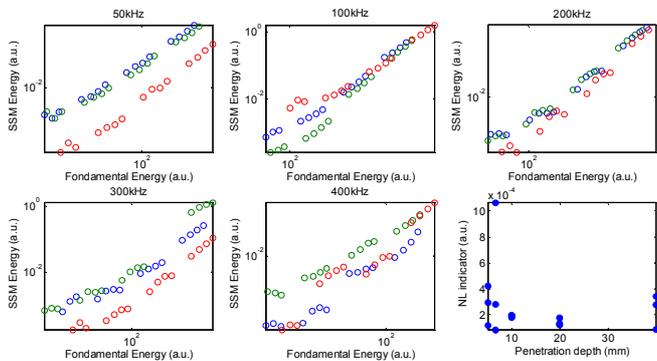


Figure 7: TREND result for the OC120 sample

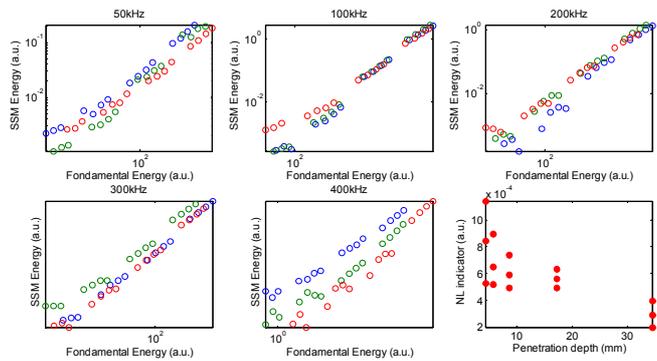


Figure 8: TREND result for the OC250 sample

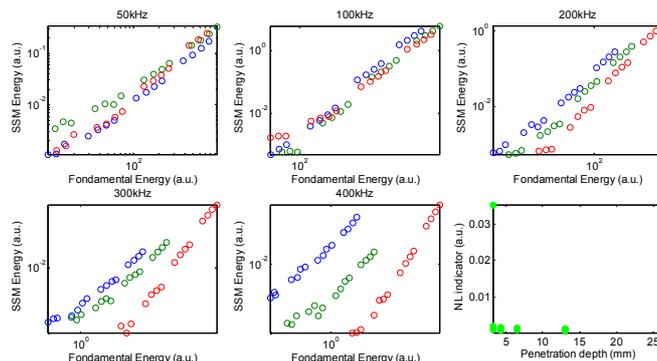


Figure 9: TREND result for the OC400 sample

We take part to provide the "raw" results even if they may be smoothed by rejecting some points that seems to be non-physical or by additional data processing. As is, these results from Figs. 5-9 and Figs. 10-11 highlight:

1. The reference Plexiglas sample, as expected, exhibits nonlinearity an order magnitude lower than concrete samples (as for NRUS).
2. For each wavelength, the nonlinearity of OC400 is 10 times the one of OC20 (as for NRUS).
3. For each wavelength, the nonlinearity of OC20 is comparable to the one of OC120 (as for NRUS).
4. The average nonlinearity evolution for each sample (other 3 points and each wavelength) matches NRUS results very well (Fig. 11).

The data scatter increases with increasing frequency and at low frequency, which may be due to:

1. The variability of concrete at low penetration depths (few mm). That should be solved by applying this procedure to more points at the surface.
2. The 8 piezoelectric discs used are the same ones, with the same frequency characteristics. So by using an adapted cavity for a given frequency range should be valuable.

3. At low frequency, the wavelength is of the size of our samples, so some particular undesired effects may appear such as resonance modes.

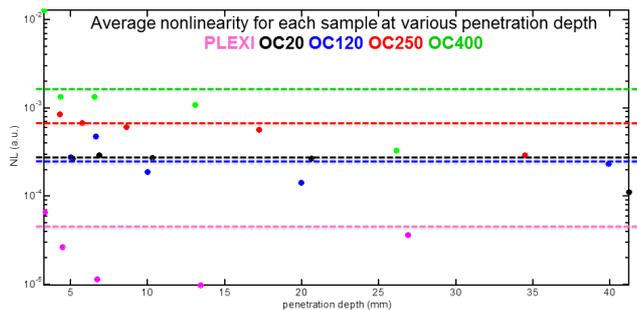


Figure 10: Compilation of TREND results for Plexiglas (pink), OC20 (black), OC120 (blue), OC250 (red) and OC400 (green) samples. Dotted lines are the average nonlinearity for each sample.

Globally, the nonlinearity seems to decrease with the penetration depth. This point is under study but no conclusion can be drawn at this point. By looking at the best frequency range (100-300 kHz), the one for which the piezoelectric discs are the more efficient and the wavelength is not too low with regard to concrete variability, the nonlinearity is more or less constant. This question will be answered by numerical simulation that may allow understanding of the strain evolution as a function of the penetration depth.

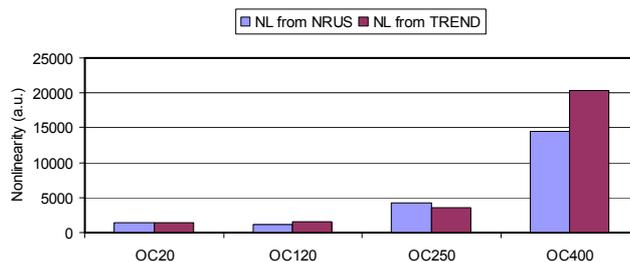


Figure 11: Average Nonlinearity evolution over each wavelength (normalized / OC20's NRUS nonlinearity)

5 Conclusion

We show in this paper the feasibility of using TREND at various frequencies to probe concrete nonlinearity at various depths. This represents an advance in the field. Even without changing the frequency, this is the first time that time reversal is employed to probe nonlinearity in the presence of diffuse damage. The correlation with NRUS results (refer to [4]) was not expected with such a confidence. Thus, even if further studies are needed to become quantitative, using TREND to evaluate concrete integrity is very promising.

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