Simulations of Nonlinear Time Reversal Imaging of Damaged Materials

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Abstract. The combination of classical time reversal techniques and nonlinear elastic wave response, induced by the presence of a localized area of damage, brings about a significant enhancement of nonlinear imaging. In this paper, this concept is discussed from a numerical point of view, using multiscale Finite Difference Time Domain and PseudoSpectral Time Domain elastic wave solvers.

Introduction

There is a strong growing interest for nondestructive testing methods based on nonlinear elastic effects in solids. It has been shown that micro-inhomogeneities such as cracks lead to an anomalously high level of “nonclassical” nonlinearity [1-3]. Based on this principle, Nonlinear Elastic Wave Spectroscopy (NEWS) techniques have been developed that comprise a relatively new class of innovative non-destructive techniques with extreme sensitivity in detecting incipient damage in the form of microcracks or delaminations, weakening of adhesive bonds, thermal and chemical damage, etc [4-7]. On the other hand, wave phase conjugation (or time reversal) in nonlinear regime has been demonstrated highly useful in ultrasonic imaging in fluids [8].

In this contribution we concentrate on numerical simulations of a NEWS based microdamage imaging technique, called NEWS Time Reversal (NEWS-TR) Imaging, which is believed to be a good candidate for sensitive imaging of microdamaged zones. In NEWS-TR, the information of the wave trains received at multiple (or a single) receivers is filtered (retaining only the “nonlinear” information) before sending it back from the receivers in reversed time. As a result, the wave energy will retrofocus at the microdamaged zone.

In the field of NDT, virtual experiments are extremely useful, not to replace actual experiments, but to confirm the soundness of the underlying ideas and to optimize the choice of parameters. In this respect, we developed two- and three-dimensional models for macroscopic wave propagation simulations, which account for the effects of nonlinear and hysteretic stress-strain relations at the microlevel (describing microdamaged zone), and we investigated the influence of several fundamental parameters used in the NEWS-TR technique. In particular, we investigated the effect of the filtering method, such as the high pass harmonic filtering and the phase inversion filtering. A companion article focuses more on experiments related to combination of NEWS methods and Time Reversal elasticity to defect imaging [9]. Preliminary results on the simulations have already been published in [10].

1. Methodology and numerical model

1.1 NL-TRA methodology

Two different methods of defect detection by combination of NEWS and Time Reversal (TR) methods can be envisaged as shown in Figure 1. The first one, which has been experimentally validated by Sutin *et al.* [11-12], aims at a localized increase of the stress field using properties of linear time reversal in a reverberant cavity, and a subsequent nonlinear analysis. This method will be called TR-NEWS, because NEWS signatures are used as a post processing for linear TR.To measure the local nonlinearity, it is compulsory to repeat the TR procedure many times and to retrofocus the stress-field energy on each point of the simulation area. This makes it difficult from a simulation point of view to implement it. The second application is based on a signal retrofocusing on the defect position when only the non linear components of the received signal are time reversed. In this case, which is not yet validated in experiments, except for some examples in our companion paper [9], implementation is easier because only one (or two in case of the pulse inversion method) direct wave propagation recordings is necessary. With the same terminology as for the preceding method, this second one will be called NEWS-TR, because now nonlinear components (NEWS signatures) are time reversed.

In both cases, various signatures of nonlinearity can be measured with NEWS-TR: harmonic generation and intermodulation. In our study, for each signature, two filtering techniques have been investigated.

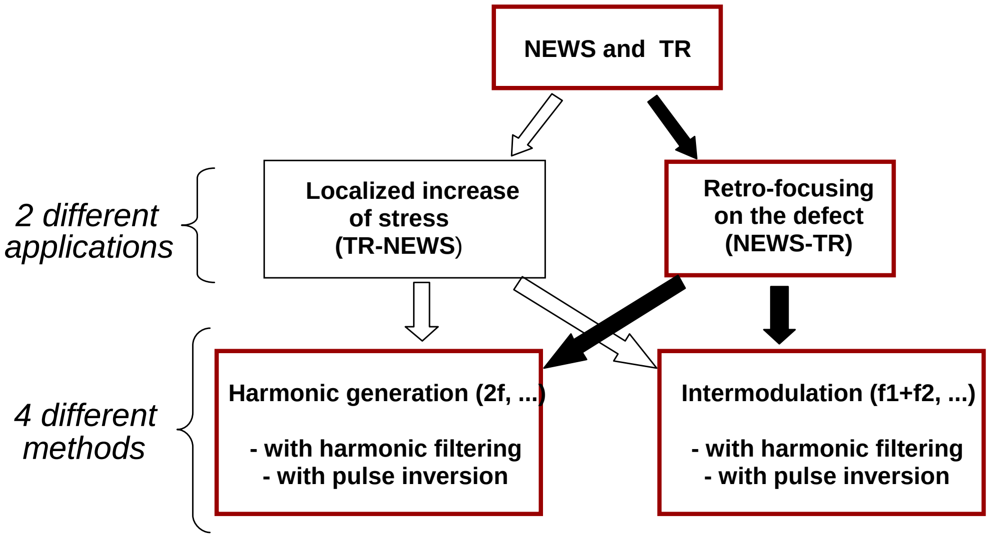

Figure 1: Representation of the methods of defect detection and measured effects with NL-TRA.

1.2 numerical models

2D and 3D finite difference time domain (FDTD) and pseudo-spectral time domain (PSTD) algorithms have been developed for solving the elastic wave equation in nonlinear hysteretic heterogeneous solids. In both methods, stress and particle velocity are updated at alternating half time steps, to integrate the solution forward in time. Hysteretic nonlinearity is introduced with the multiscale Presach Mayergoz (PM) space model introduced by Van

Den Abeele *et al.* [13]. In this model for hysteretic elasticity, no analytical expressions of the elastic constants can be given. In 1D, the bulk modulus is calculated by summation of the strain contribution of a large number of elementary hysteretic elements. Each hysteretic element unit (HEU) is described by two characteristic stresses P_c and P_o, corresponding to the transition between two states when the stress is increased or decreased, respectively. One state corresponds to an "open" state and the other one to a "closed" state. For each cell of the calculation grid (representing a mesoscopic level of the medium description), a statistical distribution (density) of hysteretic units is considered with differing values of the two stresses characteristic. The 2D and 3D elastic wave solvers are based on a Kelvin notation method [14]. Using this notation, the 3 eigenvectors of the elastic constants tensor (in 2D) correspond to 3 eigenstress / eigenstrain vectors. These vectors represent directions where applied stress and response strain are in the same direction. Doing so, it is possible to use for each of these 3 directions a scalar "PM space" model similar to the one used for 1D simulations. Each PM space associated to the different directions modifies the associate eigenstiffness. Finally, with these new eigenstiffness, the "effective" elastic coefficients are consequently calculated at each time step.

2. Example of 2D simulations

In order to demonstrate the possibility of retrofocusing wave energy on a defect in a solid sample when only the nonlinear components of the received signal are time reversed, we considered a 2D simulation area (300mm×500mm), corresponding to an aluminum plate (Figure 2). The emitter is positioned in the bulk (10mm×50mm) and the emitted signal waveform is a pulse given by:

$$f(t) = \pm p_0 . \sin\left(2\pi f_c \left(t - t_0\right)\right) . e^{-\frac{1}{2}\left(\frac{t-t_c}{w}\right)^2} \left(1 - e^{-\left(\frac{t}{s_w}\right)^2}\right) . e^{-\frac{1}{2}\left(\frac{x-x_s}{w_x}\right)^2} . e^{-\frac{1}{2}\left(\frac{z-z_s}{w_z}\right)^2} . \quad (1)$$

where f_c = 200 kHz is the center frequency, $t_0 = t_c = 0$, $w = 2/f_c$, $s_w = 3/f_c$, w_x = 0,15, w_z = 0,75, x_s = 12,5 cm et z_s = 15 cm. The receivers are also positioned in the bulk and correspond to 4 lines with variable length: 300 mm, 165 mm or 50 mm. The elementary hysteretic elements, that are used to describe a 56,25 mm² damage zone, have a triangular stress-strain characteristic (with an elastic behavior before closing and a rigid one after closing). Six different defect positions are considered in order to show the influence of the defect position (Figure 2) on the retrofocusing quality.

To investigate the retrofocusing quality in elastic TR imaging for solid material (Figure 3), we have first performed simulations for the classical case when the signals received by the 4 lines are returned and remitted by receivers into the solid medium.

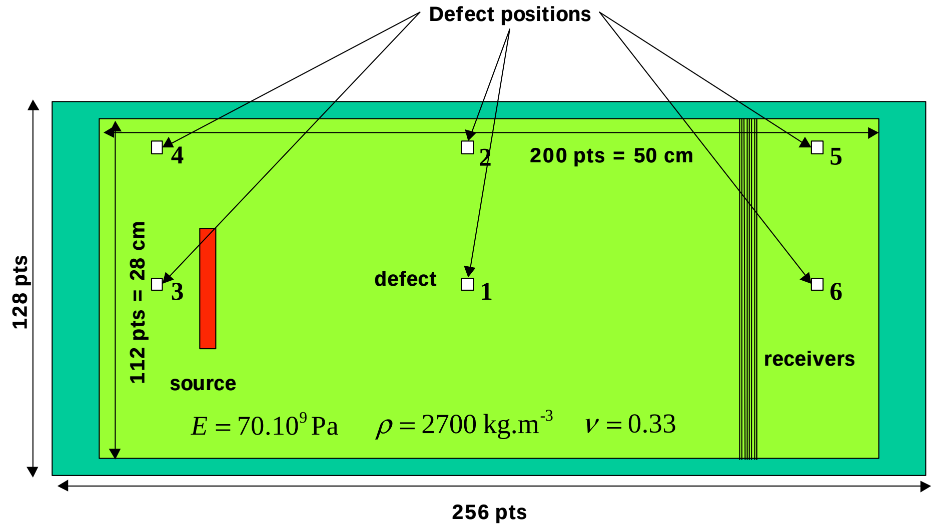

Figure 2: Simulation area with material parameters and source, receiver and defect positions.

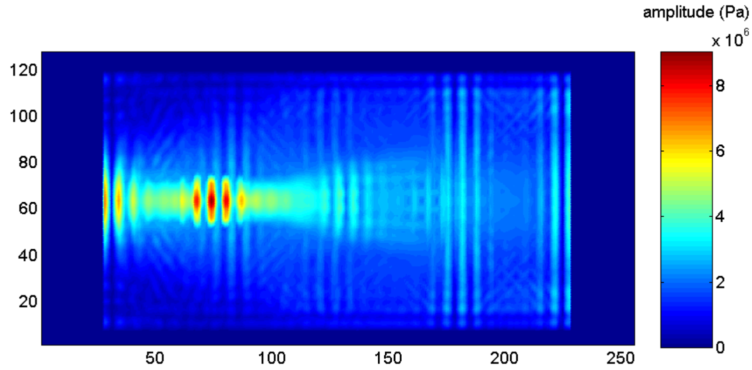

Figure 3: Simulation of the classical TR procedure applied for elastic waves in a solid plate (geometry as in Figure 1).

The maxima of amplitude during the back propagation are measured on each point of the bulk and the obtained matrix is plotted in Figure 3. This matrix layout shows that, as in classical TRA, the returned signal focuses on the direct wave source position. The width of the focal zone depends on the frequency of the returned signal. It can be seen that in the simulated case the defect at position 1 is not visible in the present map.

In order to localize possible defects in the plate, it is essential to combine NEWS with TR. The response signal, that has propagated in the sample and is received by the 4 lines of receivers, is once again time reversed, but now after filtering out the linear component and retaining only the nonlinear part of the response. To return only the nonlinear parts (harmonics) of the received signal for the NEWS-TR, two filtering methods have been investigated. One option consists in selecting only the nonlinear/harmonic energy contained in the response signals and returning merely this part back into the medium by the time reverse mirror. An alternative filtering procedure is based on the fact that the phase inversion of a pulsed excitation signal (180° phase shift) will lead to the exact phase inverted response signal within a linear medium. In a nonlinear (or microdamaged) material, this is not the case due to the generation of harmonics. We can take advantage of this observation by adding the responses from two phase-inverted pulses (positive and negative) and sending back the sum at the receivers. We call this operation 'phase-coded pulse-sequence (PC-PS) filtering" or "pulse inversion'. Doing so, only the relevant information on the local nonlinearities is reversed and sent back into the material.

Simulations have been done with defects in different positions and for both methods of filtering. For the harmonic filtering method only the 3rd harmonic components in the response signals were returned into the bulk to retrofocuse on the defect position. For the pulse inversion method, the response signals for two opposite waves have been calculated from the emitter to receivers and the sum of the two received signals was returned.

Figure 4 illustrates the maximum amplitude plots for four different simulations: two with a central defect (position 1) and two with defect near the edge (position 4).

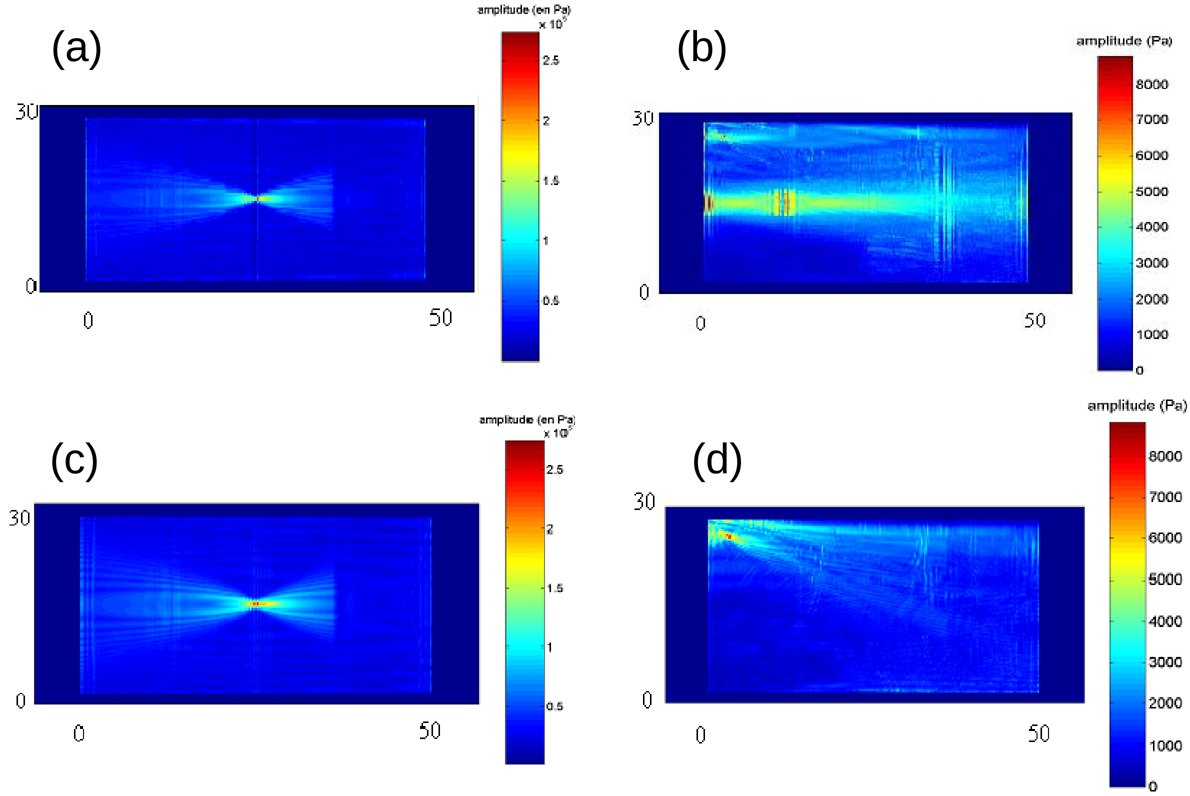

Figure 4: Matrix of the maximum amplitude for the retrofocusing signals with pulse inversion method (a-b) and harmonic filtering method (c-d) for two different defect positions (left: defect in the center; right: defect near the edge).

The quality of the retrofocusing on the defect is different according to the defect position and the method of filtering:

- If the defect is on the middle of the bulk (*i.e.* between emitter and receivers), the retrofocusing spot is smaller when applying the harmonic filtering method. This fact can be explained by the dependence of the spot size on the frequency; the higher the frequency, the smaller the spot size will be (Figure 4). Moreover, the smaller the source, the smaller the focalisation spot. Using the harmonic filtering, we have returned the 3rd harmonic while with the pulse inversion filtering, it is mainly the 2nd harmonic which is returned.
- If the defect is near an edge of sample, the retrofocusing is only on the defect when applying the pulse inversion filtering. This can have several reasons. First of all, the energy contained in the harmonics is smaller if the defect is in position 4 than when it is in the middle position. Moreover, when applying the harmonic filtering, there is always small part of the fundamental frequency which is not filtered out of te signal, whereas one can be sure that this part is not present with pulse inversion filtering. The ratio between the PCPS part and the filtered harmonic (3rd for example) is higher in the case of edge position (less energy).

These remarks can be verified and checked in Table 1, which summarizes all simulated cases.

Table 1: Comparison between the two methods of filtering for 6 defect positions and for three source sizes.

	Ratio between amplitude maximum mean and amplitude maximum on bulk (with PI)	Ratio between amplitude maximum mean and amplitude maximum on bulk (with harmonic filtering)	Ratio between ratio with PI and ration with harmonic filtering
position 1			
300mm-source	6,44	9,31	0,69
165mm-source	5,67	9,66	0,59
50mm-source	3,93	4,34	0,90
position 2			
300mm-source	5,86	6,39	0,92
165mm-source	5,38	5,30	1,02
50mm-source	3,44	2,97	1,16
position 3			
300mm-source	7,08	6,88	1,03
165mm-source	6,24	6,15	1,01
50mm-source	3,36	3,28	1,02
position 4			
300mm-source	7,27	2,88	2,53
165mm-source	6,10	2,10	2,91
50mm-source	4,25	1,00	4,28
position 5			
300mm-source	7,35	6,38	1,15
165mm-source	6,00	5,68	1,06
50mm-source	4,12	4,13	1,00
position 6			
300mm-source	6,62	5,91	1,12
165mm-source	5,63	4,50	1,25
50mm-source	4,05	2,35	1,72

A similar simulation process has been used for the combination of nonlinear intermodulation processes and time reversal imaging . In this case, two monofrequency waves, with closely valued frequencies $f_1 = 200$ kHz and $f_2 = 300$ kHz, have been sent simultaneously in the plate from the same source as in the preceding example. This allows us to study the retrofocalisation of the sum frequency ($f_+ = f_1 + f_2$) at a spectral line that is not too close to f_1 or f_2. For the selection of the nonlinear contribution in the response signals, one can apply the same two filtering techniques. In Figure 5, it can clearly be seen that with pulse inversion filtering, retrofocusing on defect position is better than this with harmonic filtering.

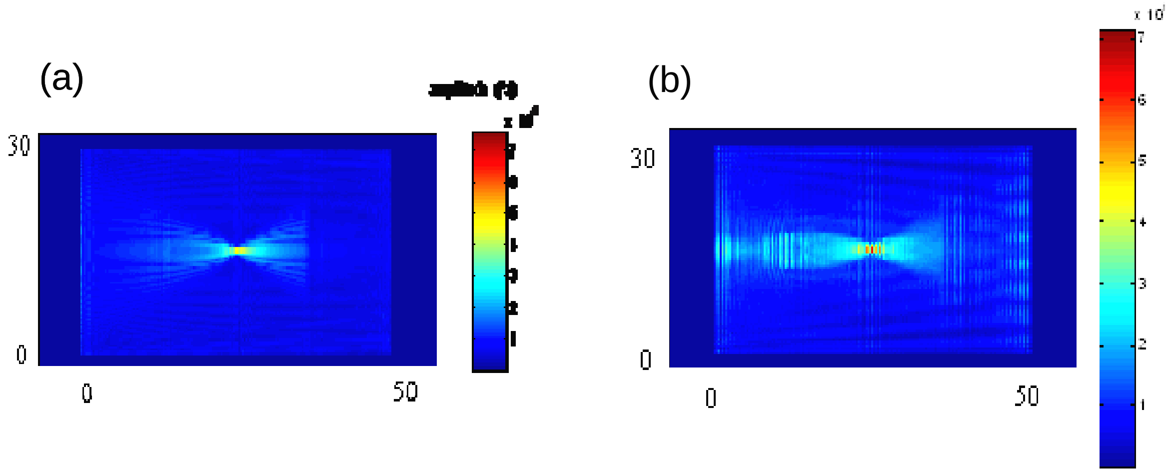

Figure 5: Matrix of the maximum amplitude during the back propagation of the nonlinearity contained in the intermodulation signals (a) with pulse inversion method and (b) with harmonic filtering at $f_+ = f_1 + f_2$.

Two main differences between the method of filtering (harmonic filtering and pulse inversion) can be highlighted as a result of this 2D simulation study:

- Pulse inversion filtering is better for the defect detection near the edge of the sample; all information related to the linear propagation in the bulk is eliminated with pulse inversion filtering contrary to that with harmonic filtering ;
- Harmonic filtering is more precise than pulse inversion filtering when the defect is located between the emitter and receiver: the higher the frequency (3rd harmonic), the smaller the spot size will be.

This conclusion allows us to tell that for the experiments, considering that emitter and receiver have finite size, it is better to move both emitter and receiver in order to place defect between them.

3. Examples of 3D simulations

In this example, we consider a numerical investigation of the distribution of harmonics in the point-by-point retrofocalisation of energy for a 3D sample (200 by 140 by 2 mm) with a surface defect (see Sutin et al. [11] for an experimental example). The surface defect, located at (150,70,0), is modeled by a zone with a nonlinear stress-strain behavior. A fixed source, located at the same surface as the defect (50,70,0), is sending out a pulsed signal which is received at a point (x,y,0), again located at the same surface. This signal is time reversed and sent back from the original source without filtering (1 channel classical time reversal [15-16]). The newly received signal at point (x,y,0), which is highly focused in time and space, is then filtered using a high pass filter and the amplitude of the remaining signal at the focus in time is recorded. Figure 6 shows the evolution of the local harmonic content as function of the position in the direction of the source-defect and in the orthogonal direction. The localization of the defect is obvious.

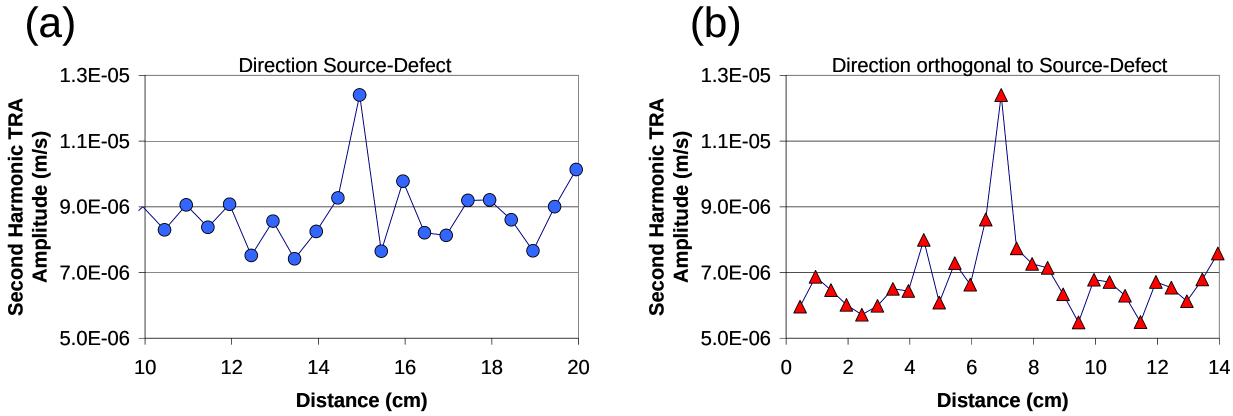

Figure 6: Numerical calculation of the locally present harmonic energy in the retrofocalized TRA signals as function of the distance to the nonlinear (microdamaged) zone, in (a) the source – defect direction, and (b) a direction orthogonal to source - defect.

Conclusion

In this paper, sensitive defect localization in solid plate by combination of Nonlinear Elastic Wave Spectroscopy and Time Reversal has been demonstrated by numerical simulations in 2D and 3D. The outcome of the simulations reinforces our belief in the feasibility and usefulness of the NEWS-TR methodology as a tool for microdamage imaging.

Acknowledgments

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