Acousto-mechanical evaluation of multiscale hysteretic parameters of complex material with nonlinear time reversal imaging

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Abstract
The paper presents a Nonlinear Time Reversal based device which is associated to optimized signal processing tools for the development of a phenomenological characterization of material local elastic properties allowing the measurements of degradation and aging of complex structures. The experimental device is improved with V3 calibration blocks, designed and specially scaled in order to access to a wide range of parameters: mechanical properties, ultrasonic parameters (celerity and attenuation) and local geometric data. In this work the reciprocal Time Reversal with Nonlinear Elastic Wave Spectroscopy (TR-NEWS) is used. It has been developed for complex materials and increases the signal-to-noise ratio by using the internal reflections of the medium as additional wave sources coupled with symmetrized excitations optimized with Symmetry Analysis concept. The focusing relies on signal processing and requires no a priori knowledge of the geometry or physical properties of the test sample. It can be used with various TR-NEWS methods to detect, excite and localise the sources of nonlinearities in the material.

1. Introduction
Nonlinear ultrasonics has become increasingly important during the last forty years due to the increase of higher sensitivity of electronic instrumentation and its associate signal processing algorithm [1-4]. Applications include nonlinear nondestructive testing (NDT), harmonic medical ultrasound imaging and development of new materials such as nanocomposite and memory based materials [5]. Since the last 2006 ECNDT in Berlin where the basis of the Time Reversal (TR) based Nonlinear Elastic Wave Spectroscopy (NEWS) have been presented to the NDT community [6-8], several experiments have shown a massive interest in TR-NEWS methods for local nonlinear imaging of scatterers in complex materials [9-11]. For example in the microwave domain, the nonlinear nature of the diode-based device is exploited, caused by the re-emission of nonlinear signatures into the cavity. By measuring the intensity of the second harmonic at an arbitrary position away from the defect, an indirect, unsolicited and blind feedback about the ambient field intensity at the defect is measured [12-13]. As demonstrated before [14-18], NEWS methods have been shown to improve crack detection and might, therefore, be also advantageous in studying complex structures. Consequently, the invariance of the stationary properties of a complex medium would be supposed to be associated to a signature of the degradation, that will be extracted with advanced signal processing [19-21] like Pulse Inversion (PI), Excitation Symmetry Analysis Method (ESAM) and new coded signal processing tools using multiscale analysis and PM spaces [22-23] exploring symmetry properties [24-30].
2. Nonlinearity with symmetrisation of optimized excitations

Nonlinear imaging based on TR-NEWS (Fig.1) continues to develop, with new systems being designed to obtain better focus and optimal images. Using symbioses of these systems, the fundamental results of Symmetry Analysis (TR, reciprocity, PI, ESAM, etc.) and NEWS methods, TR-NEWS were integrated into applications for improving identification of nonlinear scatterers, such as bubbles, landmines, cracks in complex aeronautic materials and these techniques are now widely recognized as extremely reliable for future nonlinear tomography imaging. Let us recall the ESAM results [31] associated to a third order nonlinear system described by

\[ y(t) = NL[x(t)] = N_1 x(t) + N_2 x^2(t) + N_3 x^3(t) \]  \hspace{1cm} (1)

where \( N_3 \) is the third order coefficient. Let us define optimized excitations given by:

\[
X_E = U_E(x(t)) = x(t), \\
X_E' = U'_E(x(t)) = x(t)e^{2i\pi/3}, \\
X_E'' = U''_E(x(t)) = x(t)e^{-2i\pi/3}.
\] \hspace{1cm} (2)

After some calculation, one can defined optimized responses coming from optimized combinations of responses from equations (9):

\[
\Phi_{A1} = 3N_3 x^3(t), \\
\Phi_{A2} = N_3 x^3(t) - 2d(N_2 x^2(t) + cN_1 x(t)), \\
\Phi_E = N_3 x^3(t) + (2 - c')N_2 x^2(t) + (2 - c)N_1 x(t).
\] \hspace{1cm} (3)

The most interesting application of this method is obtained using Eq.(3) which yields the extraction of the third harmonic component \( N_3 \) without any perturbation of \( N_1 \) and \( N_2 \) components. The objective is to compare the detection of the third harmonic generated by the output when one applies a classical tone-burst excitation \( x(t) = \Pi(t) \cos(2\pi f_0 t) + \gamma(t) \), where \( \Pi(t) \) is the window function of duration \( \tau = 90 \mu s \), \( f_0 = 1 \text{MHz} \) is the frequency, \( \gamma(t) \) a uniformly distributed white noise. Comparison (Fig.2) consists of evaluating the FFT amplitude of direct output response \( y(t) \) and ESAM eigen-response \( \Phi_{Ai} \) given by Eq.(3). For Fig.2 right, chirp-coded input signal \( x(t) \) was chosen because of its interest in most nonlinear acoustics experiments applied to medical ultrasound and NDT testing. As shown in Fig.2, the FFT amplitude of nonlinear response \( y(t) \) (direct output response) presents classical behaviour showing odd signature related to the presence 3rd order nonlinearity.
Figure 2. Sensitivity comparison between direct output response $y(t)$ and eigen-reponse $A_1$ extracted with ESAM. Parameters of the nonlinear system are: $N_1 = 10; N_2 = 0.158; N_3 = 0.0348$. Detection of the fundamental and second harmonic is possible with $y(t)$ but difficult for the third harmonic, whereas ESAM dynamic for this third harmonic is about 20 dB. Calibration of the ESAM responses using the V3 aluminium block within set-up given by Fig. 3 right, showing the interest of $N_3$ coefficient describing the “delayed/memory” signature of the medium under test [32]

3. Memory effects, viscoelastic multiscale behaviour, and aging
The viscous property of the skin is shown to be influenced by the stress relaxation process [33]. In this approach, all these viscoelastic effects could be associated to multiscale pragmatic and phenomenological parameters that could be modelled by fractional models where viscoelasticity appears naturally as a direct consequence of the multiscale property of the skin[34]. Since the multiscale properties is assumed in our approach, energy transfer flux should also be present at all scales, and should induce physical phenomenon at all scales, from the mechanical domain (at low frequency) to the acoustical domain (at 20 MHz, involving solid-solid, solid-fluid and fluid-fluid interaction at the mesoscopic scale). Energy losses appears also in all medium showing hysteresis effects[22] which is difficult to analyse with classical theory of nonlinear elasticity. The analogy between the memory effects of the memristor and hysteresis effects in the skin allow us to suggest the same physical origin of aging[35,36].

Figure 3. Self-calibration of the TR-NEWS set-up using V3 calibration block under several pragmatic configuration where transducers $Tx$ and $Rx$ are placed arbitrary. Cracks in the medium under test are supposed to have multiscale nonlinear coefficients $N_{i1},N_{i2}$,etc. for crack $i$ statistically distributed in a “delayed-multiscale” complex space (PM space) producing odd harmonics

In [5], we consider memristors as a plausible solution for the realization of transducers as an autonomous linear time variant system for TR-NEWS applications, especially for measuring nonclassical nonlinearities. Such highly nonlinear behaviour produces strongly nonlinear frequency spectrum broadening containing odd harmonics. This consequence induce naturally the problem of duration of any experiment showing this nonlinear signature and the importance of “delayed phenomena” [19,28]. This
phenomenon could explain the high number of relaxation parameters present in any uniaxial loading. In our approach, by including memory effects (or memristive effects) in our multiscale phenomenological model, it is naturally assumed that long time behaviour could be naturally evaluated by assuming a statistical distribution of parameters\[21\].

4. The chirp-coded TR-NEWS set-up

The chirp-coded TR-NEWS method uses TR for the focusing of the broadband acoustic chirp-coded excitation[11-15]. The method consist in the successive steps : (1) emission of a linear frequency sweep signal (the chirp-coded excitation); (2) recording of the response to the emitted signal (the chirp coded coda); (3) computation of the pseudo-impulse response which is the correlation between the chirp-coded excitation and its response ; (4) recording of the pseudo-impulse response (Fig.4) to the time reversed emitted pseudo-impulse excitation (chirp-coded TR-NEWS coda).

Figure 4. Nonlinear signature extracted with PI process without (left) and with crack (right). Normalized signal processing shows an increase of global (nonlinear) noise coming from the presence of the crack

The sensitivity improvement of chirp-coded signal processing has been validated in various domains [18-19]. Coded excitation techniques, used in communication systems such as radar and sonar provides improved SNR without increasing the amplitude of excitation. The typical TR-NEWS test equipment consists of a preamplifier Juvitek TRA-02 (0.02 - 5 MHz) connected to a computer, an amplifier ENI model A150 (55 dB at 0.3-35 MHz), a shear wave transducer Technisonic (2.25 MHz), and a longitudinal wave transducer Panametrics V155 (5 MHz). For specific applications, like tooth, bone, tuffeau sandstones or other systems [21-22], some of these parameters could be changed. Firstly the chirp-coded excitation \( c(t) = A \sin(\varphi(t)) \) is applied to the transmitted transducer. The instantaneous phase \( \varphi(t) \) is optimized as a linearly varying instantaneous frequency in the bandwidth imposed by transducers. Then the chirp coded coda response \( y(t) \) with a time duration \( T \) is recorded according to the convolution equation :

\[
y(t) = h(t) * c(t) = \int_{\mathbb{R}} h(t-t')c(t')dt',
\]

where \( h(t) \) is the impulse response of the medium. Next the correlation \( \Gamma(t) \) between the received response \( y(t) \) and chirp-coded excitation \( c(t) \) is computed during the same time period \( \Delta t \) with

\[
\Gamma(t) = \int_{\Delta t} y(t-t')c(t')dt' \simeq h(t) * c(t) * c(T-t),
\]
called the pseudo-impulse response (Fig.4) which is proportional to the impulse response \( h(t) \). After time reversal and delayed with duration \( T \) and rebroadcasted into the same medium one obtain

\[
y_{TR}(t) = \Gamma(T - t) * h(t) \sim \delta(t - T/2),
\]

which is the TR-NEWS focused signal under receiving transducer where the focusing takes place at time \( T/2 = t_f = 0.64\text{ms} \) in Fig 4.

5. Calibration procedure for nonlinear NDT

The calibration procedure of standards ultrasonic methods comprises determination of appropriate transducers placement and excitation frequencies with respect to geometry and attenuation of the structure, and frequency bands of used transducers [37]. For nonlinear NDT, procedure should be realized by frequency wobbling or by the chirp pulse transmission in order to increase acoustic energy. The best practice is parallel calibration on an intact part, or to a calibrated notch (Fig.4) supposed to describe a defect in a medium under test (Fig.3). No other specific measurement conditions are needed except of ultrasonic and/or electric noise-free environment. The calibration method can be used as global with a pragmatic approach, covering the whole tested structure, and damaged zone localization is more straightforward than in the case of NEWS procedure. The V3 calibration block (IT Nardon, Brescia, Italy) are surface slit for surface and sub-surface indication needed for TR-NEWS experiments (Figs 1 and 2). For crack localization in standard UT techniques (Fig. 4), transducers should be placed at positions surrounding tested area (if possible in a quasi-symmetric way). As known for all experimental characterization of nonlinear signature coming from ultrasonic evaluation, calibration of measurements are necessary since nonlinear effects are amplitude dependant of the excitation.

The first idea of such calibration process was presented in [6] where the same measurements were performed with both the Artann TRA and the commercialized NI-PXI devices. Due to its ability to include nonlinear and memory based properties[38-41], it was conjectured to include memristors and a reverberating chaotic cavity in order to improve Nonlinear Time Reversal processes used for NDT and biomedical ultrasonic imaging [37]. For this instrumentation, packaged chips are presented with 8 discrete memristors in 16 Pin Ceramic DIP (Dual Inline Package) with wafer batch (DM8-16DIP-BS-AF 1403272-9 226,DM8-16DIP-BSAF 1403272-9 230 Tier 3, Knowm Inc, Santa Fe, USA). Consequently, several preliminary tests associated to the TR-NEWS device have been conducted in order to optimize the array of memristors chosen for the experiment (Fig.1), involving the V3 calibration block. Introducing a perfectly calibrated nonclassical nonlinearity in the TR-NEWS excitation device, nonclassical nonlinearity coming from the symmetry breaking of butterfly lobes [5] in the TR-NEWS focusing (Fig.3), signal can be calibrated and controlled for nonlinear NDT based monitoring of complex samples.
3. Conclusions
As predicted during the last 2006 ECNDT in Berlin, TR-NEWS approaches have conducted to several validations during the last twelve years. TR-NEWS is considered as a promising method for NDT and medical imaging. Since improvement of TR-NEWS sensitivity with chirp-coded excitation was validated by experiments, calibration of the nonlinearity signature is suggested using ESAM based advanced signal processing methods. This open the creation of the intelligent agent based reporting multiscale Nonlinear Time Reversal based experiments that produces the ground truth necessary for data fusion to calibrate the multiscale memristive properties of skin. This reporting experimental process is a crucial first step in the construction of a wide big data system to produce a data fusion support tool for evaluating the aging of the skin.

References


