



Ultrasonic transducers self-calibration of nonlinear time reversal based experiments using memristor

Serge Dos Santos and Ali Masood

INSA Centre Val de Loire, Blois Campus; UMR 1253, Imaging and Brain : iBrain,
Université de Tours, Inserm, 3 rue de la Chocolaterie, CS23410, 41034 Blois, France,
serge.dossantos@insa-cvl.fr

Abstract

A calibration process of a nonlinear time reversal based ultrasonic device which is associated to the development of a phenomenological characterization of material local elastic properties is proposed. The experimental device is tested with the V3 calibration block, improved and specially scaled in order to access to a wide range of parameters: mechanical properties, ultrasonic parameters (celerity and attenuation) and local geometric data. The experimental set-up is completed by using modern ultrasonic memosducer components aim at describing memristive properties of damaged media.

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]. The nonlinearity of materials results in nonlinear effects, which arise from defects in the materials. Applications include nonlinear nondestructive testing (NDT), harmonic medical ultrasound imaging and development of new materials such as nanocomposite and memory based materials[5]. One of the strategic plan of the international NDT community is to define standards for developing nonlinear NDT for automated set-up in mass production. 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], several experiments have shown a massive interest in TR-NEWS methods for local nonlinear imaging of complex materials. As demonstrated before[7-10], NEWS methods have been shown to improve crack detection and might, therefore, be also advantageous in studying complex structures. However, to achieve an accurate prediction of ultrasonic propagation, NEWS methods require an adequate knowledge of the initial excitation and the precise geometry of the complex structure. As soon as the linear tomography uses the invariant properties of amplitude dependence, nonlinear tomography should exploit the invariance properties (or symmetry properties) of the complex system. 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 [16-17] like Pulse Inversion (PI).

The need for competent researchers and engineers to perform NDT tasks is now paramount in all laboratories since the methods have been considered as a priority in the strategic plans of most of international (ICNDT) and national (COFREND) NDT societies. In order to determine competency, instrumentation have been devised to ensure that nonlinear NDT could have a proper training with practical aspects. They should have enough experience to properly perform nonlinear NDT measurements using the applicable standard nonlinear NDT method or technique. It is now necessary that engineers that have met all these requirements are said to be “qualified”, and once

qualified they can be certified, as defined in several different ways under the various “classical linear NDT” systems. The nonlinear NDT standards should require that any engineer demonstrates familiarity with the necessary nonlinear NDT equipment and to record and analyse the resultant information to the degree required. Several different checkpoints requiring an understanding of the specificity of nonlinear instrumentation should be included in a “nonlinear NDT” guideline. The amount of experience-time required for nonlinear based NDT methods and/or techniques varies depending upon the complexity of the inspection process and the difficulty in extracting nonlinear signatures. This induce an accurate representation of this noisy “big data” information, and interpreting test results. The TR-NEWS based growing technology described in this paper is suggested to be taken as a first step that should be investigate in order to propose new NDT standards for nonlinear UT. Starting from the signal processing aspects, describing classical nonlinear measurements conducted for NEWS, the new TR-NEWS concept is presented as a way to achieve the definition of a new standard for nonlinear UT. The introduction of the electronic memristor is suggested as a specific electronic component that should be added to any nonlinear NDT instrumentation aim at measuring quantitatively and pragmatically the usefulness or serviceability of a damaged structure.

2. 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.1) to the time reversed emitted pseudo-impulse excitation (chirp-coded TR-NEWS coda).

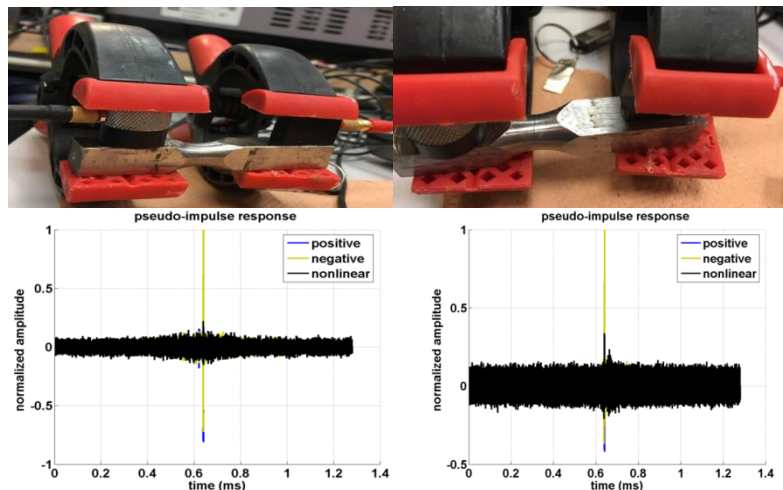


Figure 1. (Top) In-situ protocol for TR-NEWS calibration of nonlinear signature with pseudo-impulse responses. TR-NEWS generate a focusing which is independent of the complexity of propagation. (Bottom) Nonlinear signature extracted with PI process without (left) and with crack (right). Normalized signal processing show an increase of global (nonlinear) noise coming from the presence of crack, and a significant signature (in the time domain) of a nonlinear scattering area due to 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 [20-22], 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 :

$$y(t) = h(t) * c(t) = \int_{\mathbb{R}} h(t-t')c(t')dt', \quad (1)$$

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 Δt with

$$\Gamma(t) = \int_{\Delta t} y(t-t')c(t')dt' \simeq h(t) * c(t) * c(T-t), \quad (2)$$

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

$$y_{TR}(t) = \Gamma(T-t) * h(t) \sim \delta(t - T/2), \quad (3)$$

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 figure 1.

2.1 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 [23]. For nonlinear NDT, procedure should be realized by frequency wobbling or by the chirp pulse transmission in order to increase acoustic energy. Excitation amplitude range and steps of amplitude growth must be also properly determined, since any nonlinear measurement is amplitude dependent. The best practice is parallel calibration on an intact part, or to a calibrated notch (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.

Local nonlinearity evaluation was originally observed experimentally using the TR explorer system developed by Artann Laboratories, which exploits reciprocity and PI signal processing. Imaging based on TR-NEWS continues to develop, with new systems being designed to obtain better focus and optimal images. Using symbioses of these systems, the fundamental experimental 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 [24].

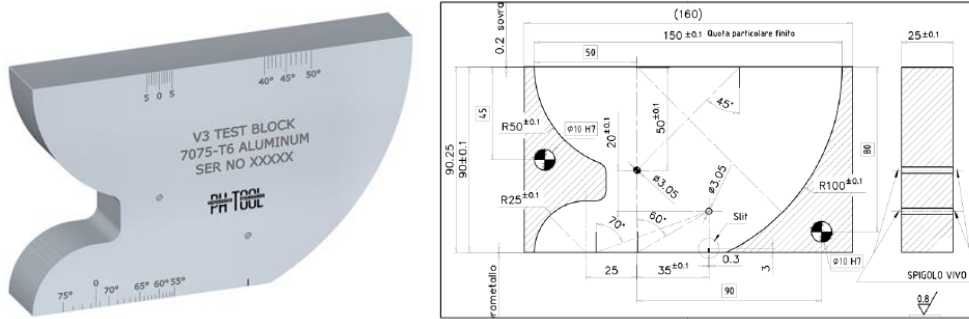


Figure 2. V3 calibration block proposed for nonlinear NDT standards. Instead of using V1 calibration block known for its regular geometry, V3 is preferred because complex propagation increases the reverberant properties needed for TR-NEWS focusing.

The V3 calibration block is used for onsite checking of miniature shear wave probe index, time base, beam angle and gain. It includes a 25mm, 75mm and 100mm radius, 3mm hole. All the V3 test blocks are made with 7075-T6 Aluminium (Metric Version) and geometry is 25mm, 50mm, and 100mm radii, 3.0mm diameter through holes, engraved reference mark scales, and a 0.4mm wide x 2.5mm deep slot. Dimensions are 150mm x 90mm tall x 25mm wide. The main functions of V3 calibration blocks (IT Nardoni, Brescia, Italy) are surface slit for surface and sub-surface indication needed for TR-NEWS experiments (Figs 1 and 2).

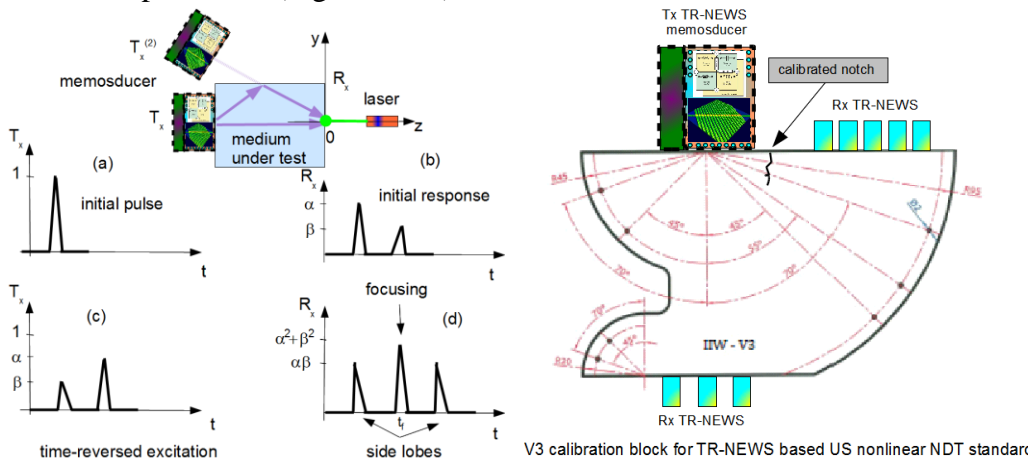


Figure 3. Self-calibration of the TR-NEWS set-up using V3 calibration block and memristor

2.3 Self calibration of crack/notch

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). Four or higher number of transmitting/receiving transducers are necessary to cover relatively large structures, for an increase of excitation power. Laser interferometer scanning can be often used instead of receivers multiplexing in simpler situations when tested part is not completely hidden (Fig.3a). Higher number of transducers gives better results and more accurate defect location (Fig.3b). All transducers must be well mounted on the structure surface. Important factors in performing nonlinear NDT standard guideline are proper selection of primary excitation pulse frequency (or frequency band), signal

waveform, and amplitude range. Most suitable frequencies can be determined with a pre-calibration procedure (chirp pulse or frequency sweeping).

2.4 Nonlinear NDT standardization with V3 calibration blocks

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 step consist in calibrating the real acoustic excitation applied in the material under test by the transducer in contact. This can be done with reciprocity properties which allow the extraction of the absolute velocity in mm/s[11]. The second step is to calibrate all the steps between the real particle velocity in the material and the different physical variables (the receiver response in Volts, the calculated chirp-coded signature $y_{TR}(t)$) necessary for the normalization of the TR-NEWS signature (Fig.4). 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.

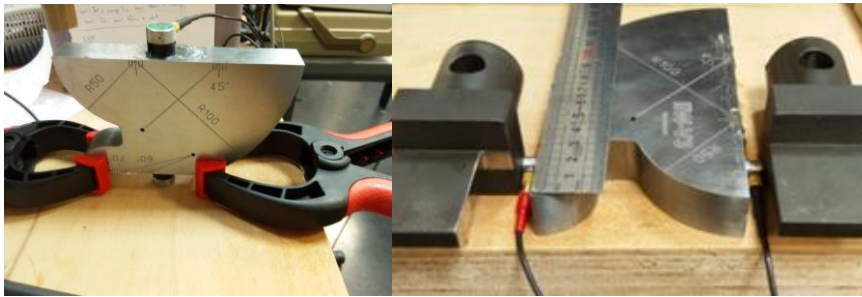


Figure 4. Self-calibration of the TR-NEWS set-up using V3 calibration block under several pragmatic configuration where transducers T_x and R_x are placed arbitrary

Due to its ability to include nonlinear and memory based properties[25-27], 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 [23]. As already studied by the ultrasonic community, multiple scattering in experiments or multiple reflections in wave guides or inside chaotic cavities actually improve the focusing properties for any TR based experimental technique. In TR-NEWS experiments, instead of being an hindrance, reverberation properties are an advantage for energy focusing. The interest related to transducers having chaotic properties is a new field of research, were the behaviour of self-sustained electromechanical transducer have been reported. The chaotic behaviour can be induced by the irregular boundary of the cavity and/or by fabricating patterns of small holes as it is proposed for the V3 block. Due to their specific memory effects, memristive systems are potentially useful building blocks for innovative implementations of classical techniques of nonlinear analogue signal processing, and of course for the definition of this first standard for nonlinear NDT. 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). The memristor is able of a bi-directional pulsed increment response, which is ideal for synaptic learning applications (Fig. 5). According to the memristor datasheet, maximum ratings are linked to the ion-conducting forward and reverse voltages (resp. 1V and -1.2V clearly compatible with voltage applied to US transducers). 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.6), 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 side lobes in the TR-NEWS focusing, signal can be calibrated and controlled for nonlinear NDT based monitoring of complex samples.

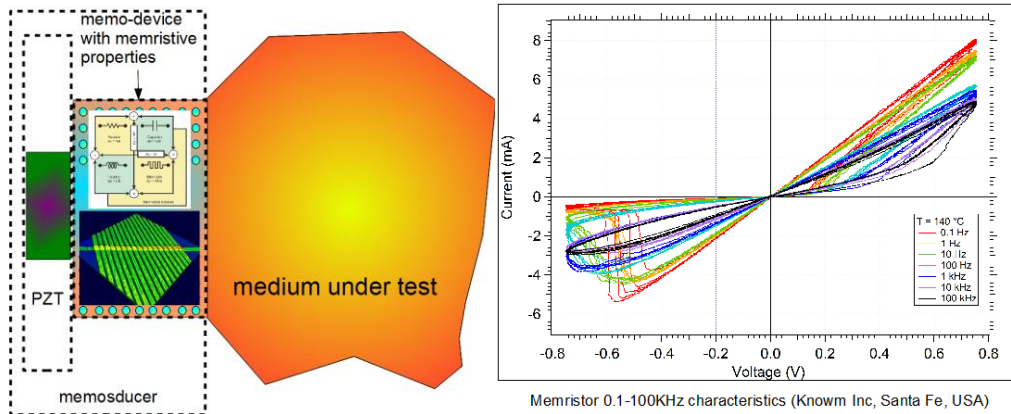


Figure 5. Self-calibration of the TR-NEWS set-up using V3 calibration block and memristor

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 tomography in complex medium. Since improvement of TR-NEWS sensitivity with chirp-coded excitation was validated by experiments, calibration of the nonlinearity signature coming from chip-coded excitation is possible using advanced signal processing methods. It provides to TR-NEWS an advantage for localization of cracks, notches and slits, and also the possibility to apply a surface stress which could be combined with classical tomography for their localization and imaging. The sensitivity and applicability of TR-NEWS methods to damage need to be validated and disseminated with a suitable guideline which will help to compare to the currently used linear technologies. As a perspective, it may be valuable to demonstrate the value of the nonlinear NDT to the profession. The conclusions should be written with this guideline accessible for the general reader. Advances in materials science have led to the physical evidence of self-assembled networks of memristive properties and demonstrations of their computational capability through reservoir computing, for example. A nonlinear dynamical instrumentation, such as the TR-NEWS set-up can be considered as a “reservoir” of a potential huge amount of “nonlinear data” that should be represented accurately (imaging, etc.) when excited with a time-varying optimized signal[33]. Observations of its states will be used to reconstruct a desired output information which will be transmitted, thanks to a suitable artificial intelligence to NDT end-users.

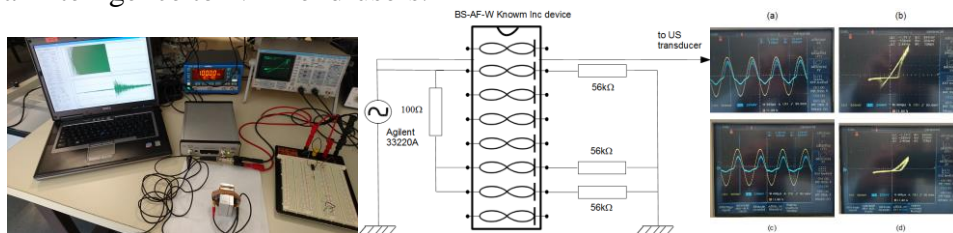


Figure 6. Self-calibration of the TR-NEWS set-up using V3 calibration block and memristor

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