SYMMETRY ANALYSIS SIGNAL PROCESSING FOR LOCAL NONLINEAR SCATTERERS SIGNATURE OF COMPLEX MATERIALS STRUCTURAL INTEGRITY

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Abstract. Over the last few decades, increasing interest has been bestowed on employing nonlinear wave propagation effects (which possess the intrinsic property of enlarging bandwidth frequency of analysis) to detect, at a sub-wavelength scale (below the ultrasonic wavelength), the early damage in the degradation process leading to mechanical fracture. Higher frequencies are used for resolution improvement and lower frequencies for aging monitoring. The NDT community today refers to methods based on analysis of nonlinear effects as Nonlinear Elastic Wave Spectroscopy (NEWS). Recent years have seen considerable development (both in numerical- and experimental aspects) of Time Reversal (TR)-based NEWS methods using TR invariance and reciprocity. The defined TR-NEWS methods 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. The complexity of the experimental set-up has been analyzed with a recent signal processing analysis using symmetry analysis combined with localization methods using the Decomposition of the Time Reversal Operator (DORT), with the objective to detect and localize spatially the nonlinear scatterers responsible of the damaged properties of complex material. Several experimental configurations will be presented in the paper, with materials and medium coming from aeronautic industry (cracked aluminum samples, damaged composites, heated layered materials), from the maritime systems (epoxy adhesive joints), and also from the bio-medical characterization of bio-materials. The specimens under test are analyzed by means of ultrasonic transducers (10 MHz) amplified with a 150W power amplifier. Arbitrary waveform generators and portable acquisitions devices (Artann Laboratories, USA) are joint to high precision Polytec vibrometer measurement devices which insure the calibration of the metrology necessary for nonlinear measurements

1. Introduction

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[1,2,3], several experiments have shown a massive interest in TR-NEWS methods for local nonlinear imaging of complex materials. As demonstrated before[4], NEWS methods have been shown to improve crack detection and might, therefore, be also advantageous in studying complex structures such as bonding properties of secondary barrier of liquefied natural gas (LNG) cargo tanks. However, to achieve an accurate prediction of ultrasonic propagation, the NEWS method requires an adequate knowledge of the initial excitation and the precise geometry of the complex structure. Furthermore, since the previous results were obtained by the Pulse Inversion (PI) technique, complexification of excitations has been generalized using Symmetry Analysis like ESAM[5], which also includes chirp-coded excitation [6] that improves the signal-to-noise ratio essential for harmonic imaging in complex media. Symmetry Analysis is the basic framework of a systemic approach aimed at employing absolute symmetries such as Time Reversal (TR), reciprocity between emitters and receivers, etc, which optimize the determination of nonlinear properties extracted with coded excitations (e.g. pulse-inversion PI or chirp-coded processes, etc.). The objective of combining the features of Time Reversal (TR) and reciprocity invariance with ESAM (in its trivial Pulse-Inversion aspect) in NEWS was vindicated by the experimental results obtained in bubbly liquids[7]. 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, ESAM, chirp-coded ESAM, etc.) and NEWS methods, TR-NEWS [8] were integrated into applications for improving identification of nonlinear scatterers, such as bubbles [7], landmines, cracks in complex aeronautic materials and these techniques are now widely recognized as extremely reliable [9, p.14] for future nonlinear tomography imaging.

2. Advanced Signal processing based on symmetry and invariance properties

As soon as the linear tomography uses the invariant properties of amplitude dependance, 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. For example, in nonlinear physics, stationary properties of soliton (or solitonic) propagation could be associated to stationary properties of dispersion and nonlinearity in the material. Consequently, if degradation process of the material occurs, the disequilibrium between nonlinearity and dispersion can be observed and the quality of soliton propagation could be used as a signature of the degradation of the complex medium with microstructural properties. An other example concerns the TR symmetry. Invariant properties of TR methods were mathematically formulated. The "Décomposition de l'Opérateur Retournement Temporel" (DORT) analysis was developed in order to localize scatterers and acoustic sources in a linear medium[5]. Time invariance is one of the properties of a more general algebraic approach applied in physics and uses intrinsic symmetries for the simplified analysis of complex systems. This framework, known as symmetry analysis, is based on continuous Lie groups and discrete symmetries. Invariance with respect to time is one of the property of a more general algebraic approach that is applied in physics which uses intrinsic symmetries for the simplification, the coding and the analysis of signals coming from complex systems.

a. Coded excitation with the symmetrization of signal processing

Improvement of TR-NEWS is conducted with coded excitation using chirp frequency excitation and the concept was presented and validated in the context of NDE imaging[6]. As detailed in [10], the chirp-coded TR-NEWS method uses TR for the focusing of the broadband acoustic chirp-coded excitation. In order to increase the acoustic energy generated to a complex medium, chirp excitation is associated to correlation process in order to obtain the impulse response of the medium. The chirp-coded coda response $y(t)$ coming from a chirp excitation $c(t)=A\cos(2\pi f(t)t)$ where $f(t)=f_0+at$ is given by :

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

where $h(t)$ is the impulse response of the medium. The correlation $\Gamma(t)$, computed during Δt, given by :

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

and called the pseudo-impulse response is also proportional to the impulse response $h(t)$ if

$$\Gamma_c(t) = c(t) * c(-t) = \delta(t), \qquad (3)$$

which is approximately the case for a chirp excitation like *c(t)* if the bandwidth Δf of time varying *f(t)* frequency is broadband enough.
Under these hypotheses, $\Gamma(t) \sim h(t)$ can be considered to be proportional to the impulse response (referred to the coda) of the medium and used for enhancing the TR-NEWS focusing. If $\Gamma(t)$ is time reversed and used as a new excitation, the response $y_{TR}(t)$ of the medium (called chirp-coded TR-NEWS coda) is then given by

$$y_{TR}(t) = \Gamma(-t) * h(t) = \Gamma_h(t), \tag{4}$$

and provides the linear auto-correlation of the system, independent of the excitation if Eq (3) is verified. All this theory is valid for the linear behavior of the medium represented by its impulse response *h(t)*. If we suppose that the medium is described by the third order response $y_{NL}(t)$

$$y(t) = NL[x(t)] = N_1 x(t) + N_2 x^2(t) + N_3 x^3(t) \tag{5}$$

nonlinearity N_2 and N_3 in the system will induce additional terms in Eq.(1), *i.e.*

$$y_{NL}(t) = y(t) + y_2(t) = \int_{\mathbb{R}} h(t')c(t-t')dt' + \int_{\mathbb{R}}\int_{\mathbb{R}} h_1(t',t'')c(t-t')c(t-t'')dt'dt'' + ... \tag{6}$$

where $h(t')$, $h_1(t',t'')$ are linked to the Volterra kernels. In order to evaluate this source of nonlinearity, we can use the advantage that the linear case is invariant with respect to the change $c(t) \rightarrow -c(t)$ which describes inversion of the PI analysis described previously. This property allows us to extract the nonlinear signature by subtraction of responses coming from *c(t)* and *-c(t)* instead of addition in the case of classical PI method[6].

a. Extraction of nonlinear signature using ESAM signal processing

Excitation Symmetry Analysis Method (ESAM) uses the nonlinear signature originating from the direct acoustic response of scatterers as a pre-processing tool for extraction. If scatterer responses are assumed to follow Eq.(5), ESAM enables parameters N_1 , N_2 and N_3 to be extracted[5] from eigen-responses $y_i(t)$ where the eigen-excitations $x_i(t)$ are given by $x_E(t)=x(t)$; $x_A(t)=-x(t)/2$; $x_{B1}(t)=\sqrt{3}x(t)/2$ and $x_{B2}(t)=-\sqrt{3}x(t)/2$. With a normalization procedure described in [8], N_1 , N_2 and N_3 are linked to eigen-responses thanks to :

$$\begin{pmatrix} s_1(t) = N_1 x(t) \\ s_2(t) = N_2 x^2(t) \\ s_3(t) = N_3 x^3(t) \end{pmatrix} = \frac{1}{3}\begin{pmatrix} -1 & -8 & 2 & 2 \\ 0 & 0 & 2 & 2 \\ 4 & 8 & -4 & -4 \end{pmatrix}\begin{pmatrix} y_E \\ y_A \\ y_{B1} \\ y_{B2} \end{pmatrix} \tag{7}$$

3. TR-NEWS imaging for structural integrity of complex materials

Using the symbiosis of these signal processing concepts (TR, reciprocity, ESAM, chirp-coded excitations, etc.) and NEWS methods, TR-NEWS fundamental experimental demonstrations have been conducted with applications in the improvement of nonlinear scatterers identification within the NDT of complex medium.

a. The generic experimental set-up for TR-NEWS imaging

Lots of experimental configurations have been implemented for TR-NEWS characterization of complex structures and materials. The results presented here use the following equipments:

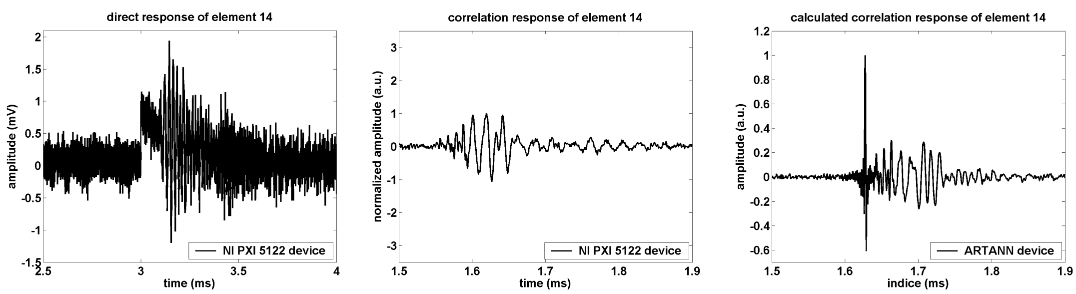
- The TRA Artann device (Artann Laboratories, USA) for the generation of chirp-coded excitation, correlation computing, and acquisition of received signals at 10 MHz sampling frequency
- A high power amplifier (150A100B Scientific Research, 150 Watts)
- A NI-PXI-5122 device for calibration procedures (14 bits)
- A vibrometer (Polytec, 1.5 MHz) for absolute measurements of particle velocity (sensitivity around 20 mm/s/V)
- A 16 elements NDT probe (Vermon 1MHz)
- Various Panametrics NDT contact transducers: 10 MHz V112 (Fig.5), 500 kHz A413S (Fig.2), 1 MHz V102 (Fig.1), 2.25 MHz A104S (Fig.1), V109, V155 5MHz (Fig.7)
- OWIS rotation and displacement stages (Fig.5)

The samples under test are the following :

- bonded assembly of polyurethane foam (300x230x110 mm), rigid triplex and supple triples where artificial air bubbles are manufactured by gluing two discs of vinyl on the both sides of a ring of the same material. It is then inserted into the epoxy layer (Fig.3),
- Third molar human tooth (Fig.5),
- a 100x25x12mm cracked steel sample (N.V. ASCO Industries, Belgium) with E = 18, 5 GPa, ρ_0 = 8000 kg/m^3 and ν=0,3 (Fig.8),
- a 175x180x45mm reinforced fibber composite with 144 plies (Fig.7),
- a steel "Actuator Steering Bracket" (ASB sample No.3 – aircraft landing gear part), containing hair fatigue crack of 2.1 mm length after 123000 loading cycles (Fig.8).

b. Systemic calibration of the nonlinear acoustic parameters signature

As known for all experimental characterization of nonlinear signature coming from ultrasonic evaluation, calibration of measurements are necessary. 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 $\Gamma(t)$) necessary for the construction of the TR-NEWS linear (Fig.4b) and polar (Fig.5a) B-Scan. A step of such calibration process is presented in Fig.1 where the same measurements are performed with both the Artann TRA and the NI-PXI devices.

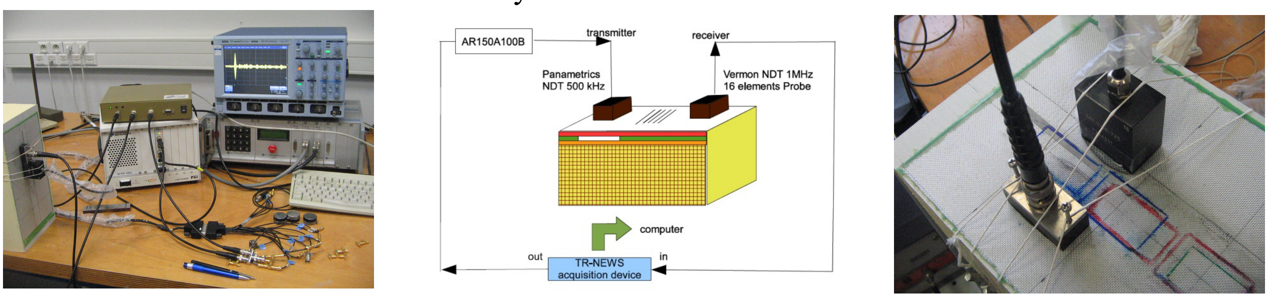


(a) (b) (c)

Fig.1. *Calibration of the TR-NEWS set-up with the NI-PXI-5122 device. (a) : the direct response of element 14 of the NDT probe used for composite epoxy layer characterization (Fig.2). The chirp-coded excitation is a Δf=350-800 kHz bandwidth sweep frequency signal. The correlation response $\Gamma(t)$ is computed (b) with the measured NI response (a) and used for the calibration of the measured one with the TR-NEWS set-up (c). The same measurement is performed with the laser-vibrometer which allow a referenced measurement of the particle velocity (in mm/s) leading to the TR-NEWS referenced polar B-Scan image (Fig.5b) of the acoustic surface velocity (in mm/s)*

C. The TR-NEWS linear B-Scan of epoxy layered samples

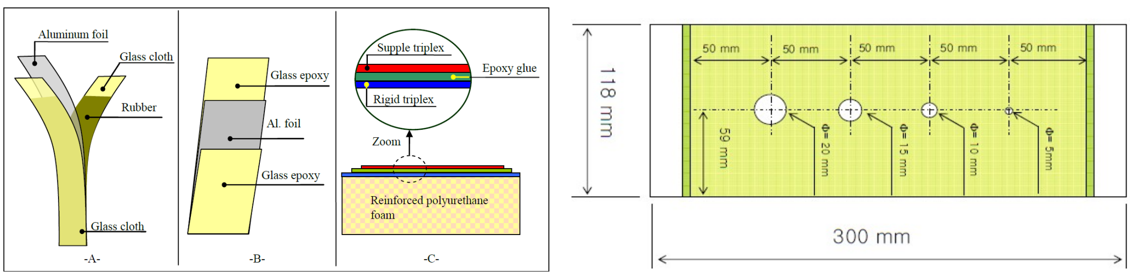
Maritime transport of LNG is carried out using specially designed vessels equipped with a cargo containment system (CCS), composed of large thermally insulated tanks. MIII is a membrane-type CCS consisting of a metallic membrane supported through insulation by the adjacent hull structure. The secondary barrier is the liquid-resisting outer element of the CCS It is designed to afford temporary containment of liquid cargo leakage from the primary barrier and to prevent the lowering of the temperature of the ship structure to an unsafe level below the minimum allowable service temperature[12,13]. It is manufactured using two main components: rigid and supple triplex sheets, which are assembled using epoxy glue. As presented in the figure 4, the supple triplex is composed of three elements: glass cloth/aluminum foil/glass cloth, assembled by rubber-based adhesive layers, whereas the rigid triplex is composed of two thin glass-resin plates and an aluminum foil.
The TR-NEWS method was successfully evaluated through lab-scaled tests to detect bonding defects during construction of the secondary barrier. The used samples were designed to reproduce the behavior of a real insulation structure as close as possible. A sketched in Fig.3, the manufactured specimen (300x230 mm)were cut from a 170 mm thick insulation panel, composed of reinforced polyurethane foam (RPUF) covered with a rigid triplex sheet. A 200x110 mm supple triplex sheet was then glued on the surface of the rigid triplex, using the same epoxy glue used in the manufacture of the secondary barrier of LNG carrier tanks.



(a) (b) (c)

Fig.2: *Experimental set-up for TR-NEWS linear B-Scan imaging (a). The 500 kHz Panametrics NDT contact transducer for the chirp-coded excitation and the 16-element NDT probe (1 MHz) used as the receiver was calibrated and put around the artificially unbounded 20mm diameter defects*

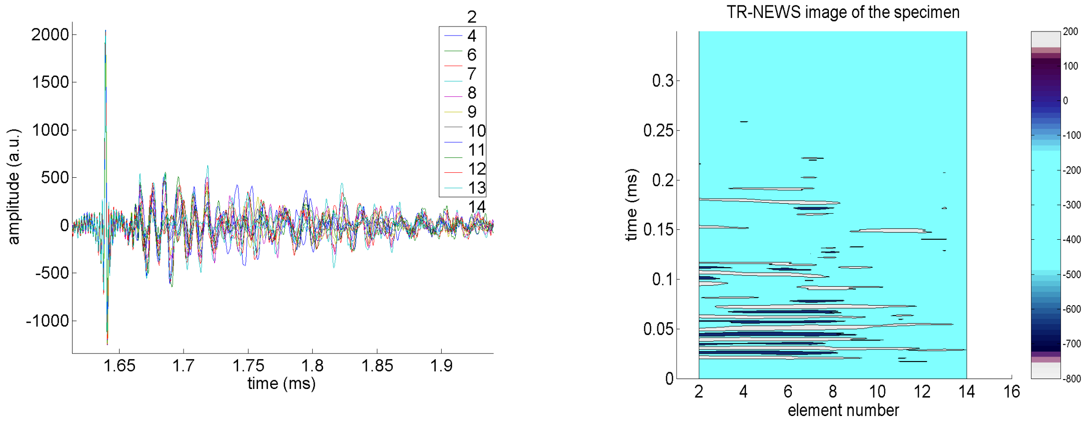
The experimental set-up is presented in Fig.2a. The transducers are glued in contact around the 20 mm diameter artificial unbounded region of the sample (Fig.2c). The TR-NEWS focusing has been conducted for all elements of the NDT probe (Fig. 4a).



(a) (b) (c) (d)

Fig.3: *Sample manufacturing: (a): Supple triplex composition; (b): Rigid triplex composition; (c): The tested specimen: bonded assembly of polyurethane foam, rigid triplex and supple triples; (d): the artificially unbounded regions (the 4 defects with increasing diameter) are manufactured using vinyl rings and discs of the same diameter*

The focusing time t_f defined in Fig.6 is measured around t_f=1.64 ms and constitutes a reference signal with respect to the position of the NDT element (Fig.4a). After calibration procedure, the TR-NEWS linear B-Scan is presented in Fig.4b showing the signature of the unbounded region. As shown in Fig.4b the artificially unbounded area was successfully detected and localized.

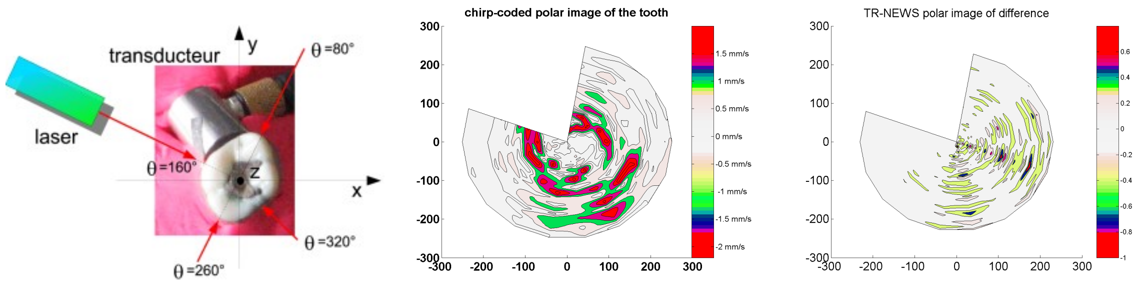


(a) (b)

Fig 4 : *Time evolution of the 11 TR-NEWS focused coda (a) received with the 16-element NDT Vermon probe (5 element where out of order). The normalized (with respect to 2048) focused spot around 1.65 ms is not dependent of the element, but the additional response starting from 1.65 ms to 1.9 ms is dependent of the element number and can be used in order to localized the scattering region. As shown with the B-scan contour plot (b) made with TR-NEWS focused coda during the last 0.35 ms, the artificially unbounded region localized between the transducer and the NDT probe is clearly identified in front of elements 2-10.*

d. TR-NEWS polar B-Scan of complex human tooth : echodentography

Tooth internal structure is known to be characterized by its complex heterogeneous properties like anisotropy and hierarchical structure present in composite or bone. As observed for most composite materials in the NDT community, fatigue and degradation of human tooth needs to be correlated to the presence of cracks and weakening of adhesive bonds in the enamel-dentine interface. A specific TR-NEWS set-up was modified to be applicable to the human tooth imaging (Fig.5).



(a) (b) (c)

Fig.5. *TR-NEWS experimental set-up for ultrasonic imaging of the third molar human tooth. (b) : polar chirp-coded imaging of the tooth. For each angle (160° → 80°), a polar representation (r,θ) of a selected chirp-coded coda is plotted along r coordinate. The maximum amplitude velocity (around 1.5 mm/s) is highly dependent of angle θ. Difference between TR-NEWS images given after and before the focusing (c). Localization of the nonlinear signature is referenced with respect to the surface of the tooth in the border of the image*

The third molar human tooth is excited by an acoustic transducer (Panametrics 10 MHz-V112) which is conditioned in order to apply high level excitations with a 150A100B Scientific Research 150W amplifier. Generated signals are amplified in order to transmit enough ultrasound energy to the tested tooth in order to induce nonlinear behavior[11]. This TR-NEWS set-up is based on local calibrated measurements which are performed using the Polytec PIvibrometer where sensitivity is around 20 mm/s/V. A Δf= 0.5-0.8 MHz frequency range chirp-coded acoustic pulse is generated in the tooth. The laser picks up, at the surface of the tooth, the normal velocity of acoustic vibration for various angles of rotation θ between 160° and 80° along the z-axis of the OWIS micro-displacement set-up. The region where θ covers the angles 80°-160° (the transducer shadow) corresponds to the position of the transducer. After correlation signal processing (extraction of the acoustic coda in the tooth) performing using $\Delta t=3$ms, the pseudo-impulse response $\Gamma(t)$ is normalized in amplitude and constitutes the chirp-coded polar image of the tooth (Fig.5b). Then, in a second step, $\Gamma(t)$ is time reversed, and again amplified by the same amplifier and transmitted into the tooth by the transducer in the same configuration. Signals are then recorded with the same laser at the same position, and gives the TR-NEWS chirp-coded coda. As usual for TR-NEWS, $y_{TR}(t)$ contains additional side lobes (Fig.6d) coming additional artifacts mostly due to reflectivity properties. Time evolution $y_{TR}(t)$ presents a behavior with a single maximum (the focused spot due to the spatial focusing of ultrasound), and additional artifacts (symmetric side lobes around time t_f=1.638ms) which is observed experimentally to be highly dependent of angle θ. Using symmetry properties around the focusing time t_f, and PI technique for extracting the nonlinear signature, a TR-NEWS polar image of the nonlinear signature inside the tooth can be extracted and referenced with respect to the border of the tooth (Fig.5c).

3. Nonlinear imaging with symmetrization : virtual transducers and ESAM-DORT

a. Virtual transducer for optimization of excitation

During experimental TR-NEWS validations in various medium (simple and complex), side-lobes effects leading to "phantom images" have been identified and associated to virtual sources coming for multiple scattering and multiple reflections.

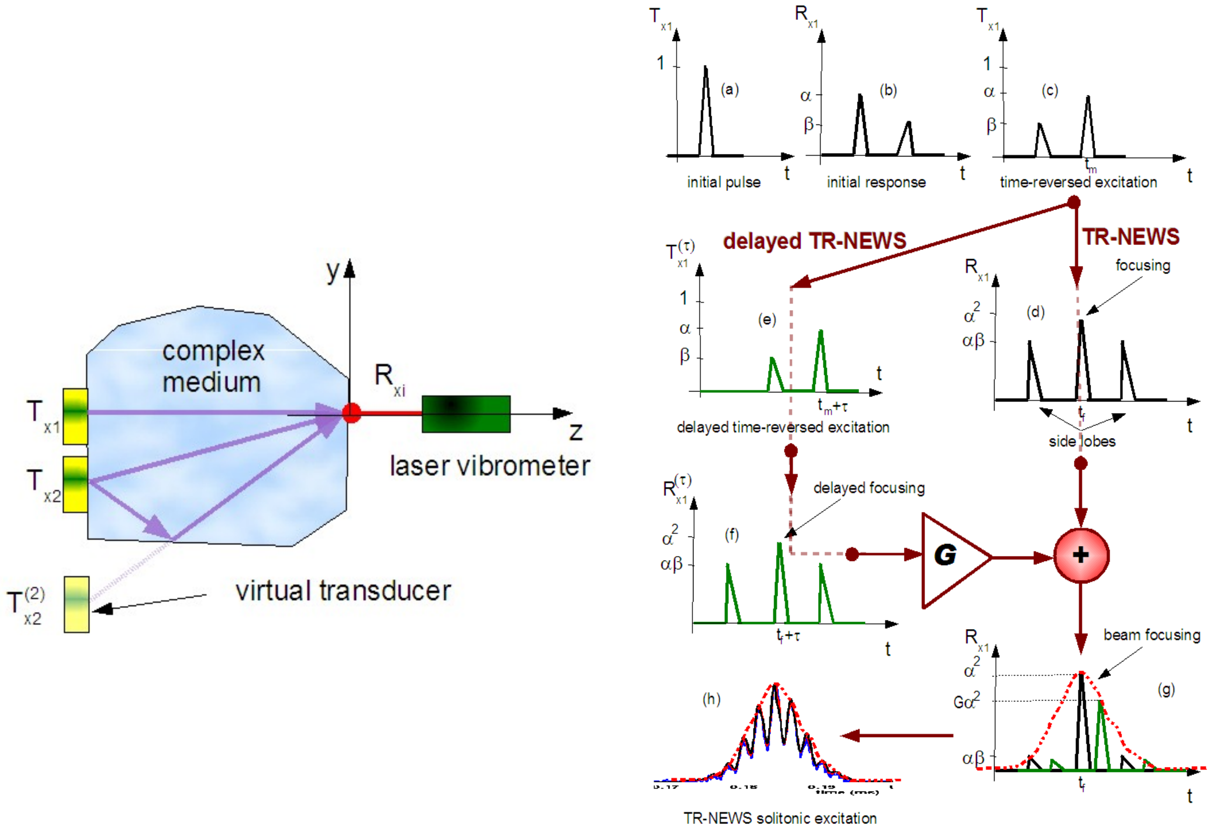
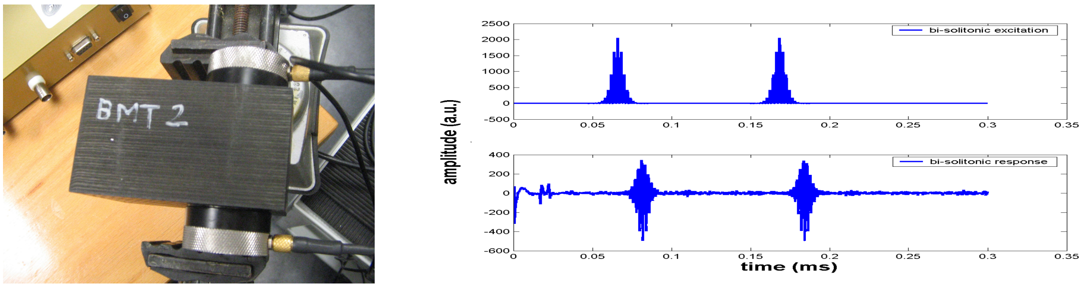


Fig.6 *TR-NEWS schematic process with the virtual transducer concept (left). The initial (a) excitation T_{x1} propagates in a medium. Additional echoes (b) are coming from interfaces. Its response R_{x1} could be associated to a virtual source $T^{(2)}{}_{x1}$. By applying reciprocity and the time reversal process to R_{x1}, the new excitation $T_{x1}(t)=R_{x1}(-t)$ produces the new response R_{x1} with a spatio-temporal focusing at $z=0$; $y=0$, $t=t_f$ and symmetric side lobes (d). The delayed TR-NEWS optimization consist in applying a delay τ before rebroadcasting the reversed signal (e). After applying suitable amplification G, a beam focusing (g) and TR-NEWS based solitonic excitation (h) is done.*

As described schematically for a simple medium (Fig.6 a → d), side lobes could be described and the response R_{x1} presents a symmetry property with respect to the focusing time t_f. The more complex the medium, the lower the side-lobes effect. A new approach of optimization of excitation has been tested with the concept of delayed TR-NEWS (Fig.6 e → h). The idea is to use delayed TR excitations $T_{x1}(t-\tau)$ in order to focus after the main focusing time t_f (Fig.6g). The amplitude of the focusing is controlled with an adaptive gain G and combined to the classical TR-NEWS response in order to built a given beam profile.

Such optimization of excitation, analog to the beam forming approach, can be used to focus spatially a TR-NEWS solitonic excitation for a nonlinear and dispersive complex medium. Such solitonic (and bi-solitonic) excitation using TR-NEWS focusing has been used for the characterization of nonlinear and dispersive properties of a 144 plies composite sample (Fig.7)



(a) (b)

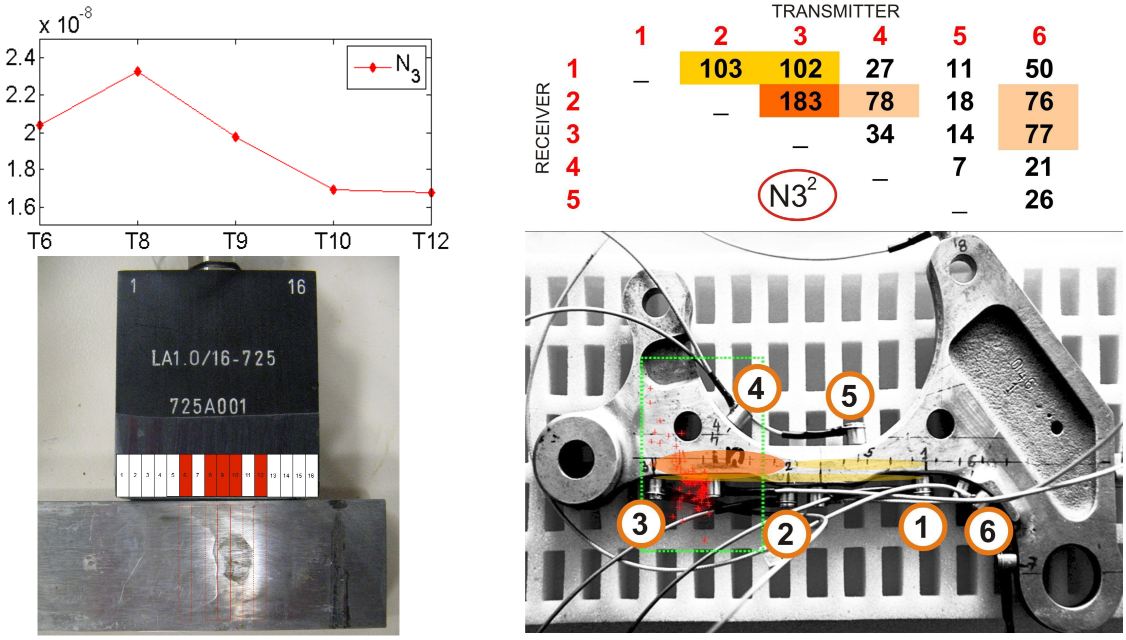
Fig.7 *Bi-solitonic excitation and bi-solitonic responses after ultrasonic propagation in the 144 plies composite sample of 43 mm width.*

b. Nonlinear pseudo-tomography with ESAM-DORT

The ESAM-DORT localization method of nonlinear scatterers consist in using signal pre-processing analysis ESAM (Excitation Symmetry Analysis Method) and the decomposition of the time reversal operator (DORT) method[8]. The third order nonlinear responses (Eq.5) are extracted from ESAM eigen-excitations and constitute the multistatic data matrix associated with the singular value decomposition. The symbiosis of ESAM-DORT provides a normalization process of singular values associated to scatterers. Extraction of nonlinear parameters is sensitive to the presence of scatterers throughout the propagation path and results confirms the dependence between scatterers reflective properties, singular values and nonlinear signatures

The validation of ESAM-DORT imaging has been conducted using a 10x25x120mm cracked steel sample with the 16-elements NDT probe (a) and tested on the bracket sample using 6 AE sensors working both in emitter and in receiver mode (Fig.8). Corresponding responses were measured (assumed composed of linear, quadratic, and cubic terms): at each transducer, and ESAM - DORT method was applied to extract 3rd order nonlinearity parameter. Pseudotomography imaging of extracted nonlinear parameter N_3 matrix (normalized and symmetrized) is illustrated in Fig.8b. Transducers are numbered 1-6 and corresponding transmitter/receiver matrix of N_3 values is shown.

There is a correlation between damaged zones detected by Acoustic Emission (In red near the sensors 3) and the greatest values of N_3 obtained with sensors 2, 3 and 4. It confirms high sensitivity of proposed nonlinear methodology. Advantage of tomography-like nonlinear methods is in their potentiality to acquire very complex information about the tested structure. Extraction of nonlinear parameters is sensitive to the presence of scatterers throughout the propagation path and results confirms the dependence between scatterers reflective properties, singular values and nonlinear signatures



(a) (b)

Fig 8 : *ESAM-DORT imaging. The N3 parameter extracted with ESAM-DORT shows an optimal value for sensors near the expected damaged region : (a) the crack is located in front of the T8 element of the NDT probe showing the higher value of N3 nonlinear parameter; (b) potentially zone with arising defect is signalized already by acoustic emission (in red) near the AE sensor number 3 showing the higher N_3 nonlinear parameter.*

Conclusion

As predicted during the last 2006 ECNDT in Berlin, TR-NEWS approaches have conducted to several validations during the last four years. TR-NEWS is considered as a promising method for NDT and tomography in complex medium. Improvement of TR-NEWS sensitivity with chirp-coded excitation is validated by experiments. Calibration of the nonlinearity signature coming from chip-coded excitation is possible using ESAM signal processing method. It provides to TR-NEWS an advantage for localization of cracks and also the possibility to apply a surfacic stress which could be combined with ESAM-DORT for their localization and imaging. Improvement of chirp-coded TR-NEWS focusing with amplitude coded excitation (in order to obtain for example a calibrated bi-soliton excitation) is proposed and the "delayed TR-NEWS" method is investigate as a future for TR-NEWS. The sensitivity and applicability of TR-NEWS methods to damage need to be validated by the currently used linear technologies.

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