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MECHANICS

Nonlinear signal processing for ultrasonic imaging of material complexity

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Abstract. Ultrasonic imaging of material complexity is investigated theoretically and experimentally using the concept of symmetry analysis based signal processing in symbiosis with nonlinear elastic wave spectroscopy. These concepts were tested experimentally on several complex media with an advanced electronic system. This system exploits TR invariance, reciprocity, and coded excitation for an accurate extraction of the nonlinear signature of the medium under ultrasonic monitoring. Tested both in the context of the medical imaging of a tooth and in those of nondestructive testing of aeronautic composites, the basis of a new tomographic imaging of material complexity is presented with the help of algebraic concepts describing the TR operators.

Key words: nonlinear signal processing, TR-NEWS, symmetry analysis, DORT, echodentography, nonlinear acoustics, coded excitation, complex imaging, solitonic waves.

1. INTRODUCTION

Ultrasonic imaging methods based on the analysis of nonlinear effects of ultrasound propagation are today referred to nonlinear elastic wave spectroscopy (NEWS). Their advantages reside in their capacity for detecting smaller defects below the wavelength limit, so their sensitivity is much greater than that of traditional imaging methods based on measurements of wave velocity and attenuation [1]. Associated to the advanced NEWS techniques, enhanced signal processing should be chosen for the extraction of the nonlinear signature. The pulse-inversion (PI) technique is one of the most applied nonlinear signal processing tools in second harmonic imaging because of its ability to separate second-order harmonic components regardless of the transmitted bandwidth [2]. The framework of symmetry analysis (SA) constitutes the basis [3] of a systemic approach aimed at using absolute invariants such as time reversal (TR), reciprocity between emitters and receivers, and other nonlinear properties so as to optimize coded excitations (e.g., pulse-inversion PI or chirp-coded processes, etc.). Invariance with respect to TR and reciprocity between sources and receivers combined with PI was fully elaborated as the TR-NEWS techniques [4], which supplement and improve classical NEWS methodology. The concept of TR-NEWS symbiosis has a large potential of application in ultrasonic imaging, particularly in nondestructive testing (NDT), and it has been the subject of several investigations for the last five years, both from an experimental and a numerical point of view [4–7]. These TR-NEWS methods can be implemented in a scanning system for adequate localization of

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microdamage. The first step in the procedure is an analogue of classical linear TR for elastic waves [8]: by measuring the response signals arriving from a single or different sources using a laser vibrometer at a fixed point and returning the received signals from the original transducers in time-reversed mode, a high level of energy can be focused locally in time and space on the surface. In the second step, the nonlinear content in the retrofocused signal is analysed: if a nonlinear scatterer is located at the laser position close to the surface, the harmonic content will be substantial. Using symbiosis of these concepts, TR-NEWS fundamental experimental results [6] have led to applications in the improvement of the identification of nonlinear scatterers, such as bubbles [5], cracks in complex aeronautic materials [9,10], and are now highly recognized as extremely reliable [11, p. 14].

The main objective of this paper is to describe the nonlinear signal processing for the improvement of the ultrasonic imaging of complex media. The concepts will be described in Section 2, where the TR-NEWS based methods (focusing, optimized excitations, symmetry properties) will be described. Then, Section 3 will be devoted to the experimental set-up used in order to validate these concepts. The objectives are clearly devoted to the ultrasonic imaging in the medical context but some preliminary results with materials coming from the aeronautic industry will be presented. Finally, Section 4 will contain some ideas about the localization procedure dealing with tomography in complex media.

2. CONCEPTS

Much recent work has proven that NEWS techniques are superior to linear acoustic techniques in diagnosing early stage damage processes in various materials, and thus provide excellent potential for high quality nonlinear imaging [1]. Several NEWS techniques have been developed to probe the existence of damage induced nonlinearity (e.g., delaminations, microcracks, or weak adhesive bonds) by investigating the generation of harmonics and intermodulation of frequency components, the amplitude dependent shift in resonance frequencies, and the nonlinear contribution to attenuation properties. The success of NEWS-based NDT methods is that the internal damage can be measured directly with the instantaneous detection of an increase in the nonlinear signature.

2.1. Local tomography with a nonlinear signature of cracks

Media with tiny cracks generally show an enhanced third-order nonlinearity, which could be extracted using the advanced signal processing approach that, in turn, uses optimized excitations. In addition to being a diagnostic technique, macroscopically observed signatures of nonlinearity have been introduced in innovative approaches for new and sensitive imaging techniques. Classical ultrasonic tomography generally uses source signals of constant amplitude. In fact, this is not compatible with nonlinear processes highly dependent on the excitation amplitude. Tomography is the method of image reconstruction from many projections. The combination of classical TR acoustics and nonlinear spectroscopy brings about a significant enhancement of imaging localized areas of microdamage and is one of the only techniques known today to discriminate between a linear (void) and a nonlinear scatterer (crack). Improvement of NEWS methods for local nonlinear imaging (tomography) requires inclusion of localization signal processing, which could be achieved by multiple mode analysis or by adapting the symmetry of TR methodologies for the nonlinear wave process.

2.2. Advanced signal processing based on symmetry and invariance properties

Since linear tomography uses the invariant properties of amplitude dependence, nonlinear tomography should exploit the invariance properties (or symmetry properties) of a 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, stationarity properties of soliton (or solitonic) propagation could be associated to stationarity properties of dispersion and nonlinearity. Consequently, if a degradation process of a 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. Another example concerns the TR symmetry. Invariant properties of TR methods were mathematically formulated, and the "décomposition de l'opérateur retournement temporel" (DORT) analysis was developed in order to localize scatterers and acoustic sources in a linear medium using the concept of the time-reversal operator (TRO) and Green's functions.

2.3. Time reversal based NEWS methods: TR-NEWS

The basic premise of the traditional TR is the following: if a wavefield is known as a function of time on some boundary surrounding a given complex region, then it can also be reconstructed at every point inside that region at previous times by sending back the wave signals in reversed time. The TR-NEWS methods are defined in such a way that the main signal processing is concentrated on the nonlinear signature of the signals. The difference between classical and nonlinearly based TR can be described as follows: in fact, the scatterer is modelled by a zone with a nonlinear hysteretic stress–strain behaviour. If all signals at the boundaries of the medium are received, time reversed (what comes out last goes in first), and sent back into the medium, the energy focuses spatially and temporally back to the source.

3. ADVANCED SIGNAL PROCESSING FOR COMPLEX IMAGING: NONLINEAR SIGNAL PROCESSING

As nonlinear signature is one or two orders of magnitude below the linear response, advanced signal processing could be proposed for optimizing detection. For example, an alternative filtering procedure for the use in the TR-NEWS methodology 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. Furthermore, there is an increase in the use of SA for nonlinear systems due to its ability to simplify and sometimes completely solve the nonlinear problem under investigation. The main advantage of these algebraic approaches is the possibility of extracting absolute invariants associated to invariance properties.

Let us consider the scatterer as a second-order nonlinear system ($\mathscr{S}$) excited with $x(t)$, and where the response $y_{NL}(t)$ is given by $y_{NL}(t) = NL[x(t)] = N_1 x(t) + N_2 x^2(t)$, where N_1 and N_2 are respectively linear and second-order coefficients. If the direct excitation $X_E = x(t)$ and 180° phase shifted excitation $X_I = -x(t)$ are applied separately to ($\mathscr{S}$), one can extract N_1 and N_2 using the respective nonlinear response $Y_E(t)$ and $Y_I(t)$ with $N_1 = \frac{Y_E(t)-Y_I(t)}{2x(t)}$ and $N_2 = \frac{Y_E(t)+Y_I(t)}{2x^2(t)}$. In terms of symmetry properties [12], excitations X_E and X_I can be associated to the neutral element E and the inversion element I of the C_2 group of inversion. In fact, if we define $\Phi_{A_u} = Y_E(t) - Y_I(t)$ and $\Phi_{A_g} = Y_E(t) + Y_I(t)$, one can see that the linear signature N_1 and the nonlinear signature N_2 are completely isolated and extracted due to these functions. On the other hand, $\Phi_{A_g} = 2N_2 x^2(t)$ and $\Phi_{A_u} = 2N_1 x(t)$ can be seen as eigen-response of the system with respect to linear and nonlinear parts. The signatures N_1 and N_2 can be extracted from Φ_{A_g} and Φ_{A_u}, assuming a normalization by the input $x(t)$ for Φ_{A_u} and $x^2(t)$ for Φ_{A_g}. It is important to note that this calculation is not dependent on the spectral content of the excitation $x(t)$. This means that every kind of coded excitation (chirp-coded, solitonic, and other virtual excitation) could be used for the separation of the nonlinear signature.

3.1. Chirp-coded excitation

Improvement of TR-NEWS is conducted with coded excitation using chirp frequency excitation presented and validated in the context of nondestructive evaluation (NDE) imaging [9]. The chirp-coded coda response

$y(t)$ coming from a chirp excitation $c(t) = A\cos(2\pi f(t)t)$, where $f(t) = At + f_0$ is given by

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

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

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

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

$$\Gamma_c(t) = c(t) * c(-t) = \delta(t), \tag{3}$$

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 given by

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

and provides the linear autocorrelation of the system, independent of the excitation if Eq. (3) is verified. All this theory is valid for the linear behaviour of the medium represented by its impulse response $h(t)$. Any source of nonlinearity in the system ($\mathscr{S}$) will lead to a perturbation of this method, and will induce additional terms in Eqs (1–4), i.e.

$$y_{NL}(t) = y(t) + y_2(t) = \int_{\mathbb{R}} h(t')c(t-t')dt' + \int_{\mathbb{R}}\int_{\mathbb{R}} h_1(t',t'')c(t-t')c(t-t'')dt'dt'' + \ldots, \tag{5}$$

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 $c(t) \to -c(t)$ which describes inversion symmetry of the point group C_2 which is the basis of the PI analysis described previously. This property allows us to extract the nonlinear signature $y_2(t)$ by substraction of responses coming from $c(t)$ and $-c(t)$ instead of addition in the case of the classical PI method [9].

3.2. Generalization of the symmetrization of excitation with ESAM

Let us extend the previous analysis in order to consider the scatterer as a third-order nonlinear system ($\mathscr{S}$), i.e. $y(t) = NL[x(t)] = N_1x(t) + N_2x^2(t) + N_3x^3(t)$, where N_3 is the third-order coefficient [13]. Generalization of the previous method can be made using the transformation operator U_g associated to the group element g, acting on the initial excitation $x(t)$ in order to build the additional excitation X_g: $X_E = U_E(x(t)) = x(t)$, $X_\varepsilon = U_\varepsilon(x(t)) = x(t)e^{\frac{2i\pi}{3}}$, $X_{\varepsilon^*} = U_{\varepsilon^*}(x(t)) = x(t)e^{-\frac{2i\pi}{3}}$. As done previously for PI, the second step is to define the eigen-responses Φ_m using the C_3 group properties, which can be associated to the basic functions of irreducible representations m: $\Phi_{A_1} = \sum_{g\in C_3}\chi_{A_1}(g)Y_g$, $\Phi_{A_2} = \sum_{g\in C_3}\chi_{A_2}(g)Y_g$, $\Phi_E = \sum_{g\in C_3}\chi_E(g)Y_g$, where $\chi_m(g)$ is the character associated to the group element g of the mth irreducible representation, and $Y_g = NL[X_g]$ is the nonlinear response of $\mathscr{S}$ related to the excitation X_g. The eigen-responses Φ_m are then given by $\Phi_{A_1} = 1Y_E + 1Y_\varepsilon + 1Y_{\varepsilon^*}$, $\Phi_{A_2} = 1Y_E + 1Y_\varepsilon - 1Y_{\varepsilon^*}$, and $\Phi_E = 2Y_E - 1Y_\varepsilon$. After simplifications, one finally obtains $\Phi_{A_1} = 3N_3x^3(t)$, $\Phi_{A_2} = N_3x^3(t) - 2\varepsilon\left[N_2x^2(t) + \varepsilon N_1x(t)\right]$, and $\Phi_E = N_3x^3(t) + (2-\varepsilon^*)N_2x^2(t) + (2-\varepsilon)N_1x(t)$. The most interesting application of this method is obtained using Φ_{A_1}, related to the completely symmetric irreducible representation A_1, and which yields the extraction of the third harmonic component N_3 without any perturbation of N_1 and N_2 components. Irreducible representation and character tables properties of the C_3 point group of rotation are on the heart of the excitation symmetry analysis method (ESAM).

The ESAM-responses Y_E, Y_ε, Y_{ε^*} corresponding to the eigen-excitations $X_E = x(t)$, $X_\varepsilon = x(t)e^{\frac{2i\pi}{3}}$, $X_{\varepsilon^*} = x(t)e^{-\frac{2i\pi}{3}}$ allow the third-order nonlinear parameter N_3 to be extracted. Responses corresponding to the excitations can be obtained through the linear combination of y_E, y_ε, y_{ε^*}. As the excitations required by the third-order ESAM are complex rather than real signals, the amplitude variation and post-treatment of real signal excitation is preferred in practice. Taking into account that real excitations are used, it can be shown [14] that the corresponding nonlinear coefficients N_2 and N_3 are picked out with

$$\begin{pmatrix} s_1(t) = N_1 x(t) \\ s_2(t) = N_2 x^2(t) \\ s_3(t) = N_3 x^3(t) \end{pmatrix} = \frac{1}{3}\begin{pmatrix} -1 & -8 & 2 & 2 \\ 0 & 0 & 2 & 2 \\ 4 & 8 & -4 & -4 \end{pmatrix} \begin{pmatrix} y_E \\ y_A \\ y_{B1} \\ y_{B2} \end{pmatrix}, \tag{6}$$

where y_E, y_A, y_{B1} and y_{B2} are $y_i(t) = NL[x_i(t)]$ responses with $x_E(t) = x(t)$, $x_A(t) = -\frac{1}{2}x(t)$, $x_{B1}(t) = \frac{\sqrt{3}}{2}x(t)$, $x_{B2}(t) = -\frac{\sqrt{3}}{2}x(t)$. Thus, the ESAM enables the terms N_1, N_2 and N_3 to be extracted, which corresponds to the nonlinear behaviour caused by the scatterers.

3.3. Bi-solitonic excitation using virtual transducers

As shown previously, TR-NEWS allows the possibility of spatio-temporal focusing of acoustic energy at the position of measurement. The focusing time t_f is defined at the maximum of $\Gamma_c(t)$. The temporal shape of the focused spot is linked to the autocorrelation function $\Gamma_c(t)$ of the excitation (Eq. 3) filtered by the measurement system (laser vibrometer or transducer). An arbitrary waveform of the temporal shape can be constructed using amplitude modulation of $\Gamma_c(t)$ or by a simple delay $\sum_i \Gamma(-(t+\tau_i))$ in order to construct, using the "virtual transducer" concept [14], optimized shapes such as solitonic ones. The main idea of the "virtual transducer" is in the generation of a single excitation signal, which replaces many separate excitations. This signal is created by a sum of the excitations of all the "transducers", which are time-shifted according to the positions of the "transducers" (Fig. 1). The presence of side lobes comes from the geometric symmetry of the medium intrinsically linked to its modal properties. By solitonic excitation, it means an aperiodic signal whose profile is nonzero on a finite rather narrow time interval. This excitation with such profiles is similar to solitonic waves known from other divisions of physics. In this paper, the bi-solitonic excitation is created with the linear superposition of two TR pseudo-impulse responses $\Gamma(-t)$ with a time delay τ_0 defined by

$$y_{TR}^{(2)} = (\Gamma(-t) + \Gamma(-t+\tau_0)) * h(t) = \Gamma_h(t) + \Gamma_h(t-\tau_0), \tag{7}$$

giving also a bi-solitonic excitation localized at the position of the measurement. The first solitonic focused pulse is localized in time at $t = t_f$ (see Fig. 1), and the second solitonic focused spot at $t = t_f + \tau_0$ if the duration between the side lobes is smaller than τ_0. Again, the bi-solitonic excitation created with TR-NEWS is perfectly localized in space (at the position of the emitter transducer T_x) and in time, in view of the use of adapted time delays necessary for each single soliton. In order to evaluate nonlinearity and dispersion parameters necessary for solitonic propagation, preliminary tests were conducted (Fig. 2b) with a bi-solitonic 250 kHz central frequency sech-shape bi-solitonic excitation (with delay $\tau_0 = 1$ ms), which propagates in the composite sample. The bi-solitonic response was studied versus amplitude, and normalized responses (with respect to the max) were compared versus amplitude showing a shock-wave behaviour. The objective was to use the virtual transducer concept in order to find the optimized duration τ_0 between solitonic pulses of the bi-solitonic excitation in order to extract a signature of the sample degradation (through the variation of τ_0) after the nonlinear wave propagation in the medium. The bi-solitonic time interval generated by this "delayed TR-NEWS" could be also used as an invariant of the medium.

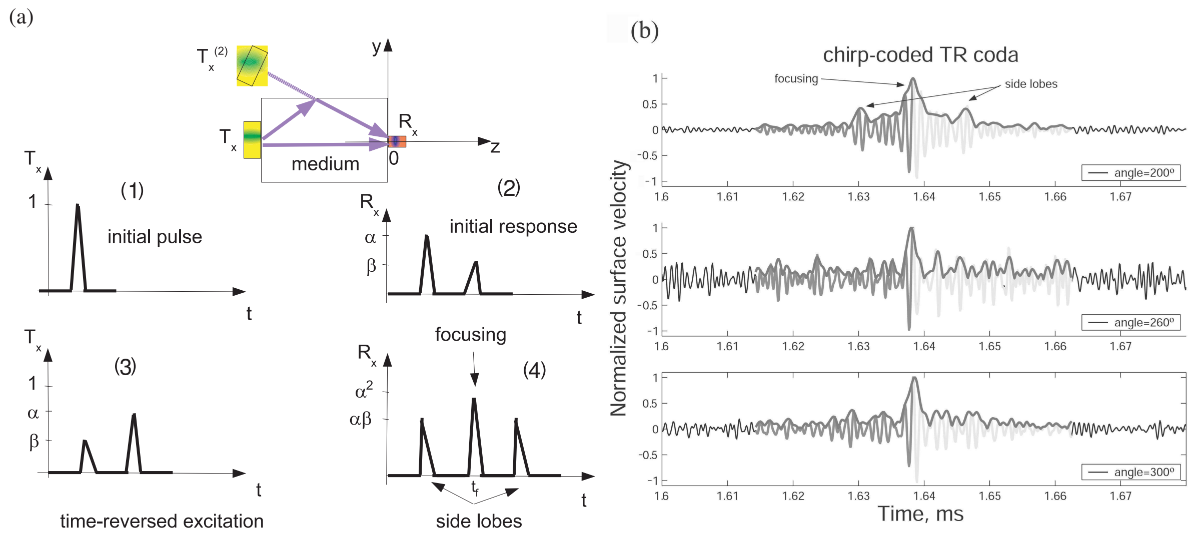

Fig. 1. (a) Schematic process of TR-NEWS with the virtual transducer concept. The initial (1) broadband excitation $T_x(t)$ propagates in a medium where additional echoes coming from interfaces and scatterers in its response R_x could be associated to a virtual source $T_x^{(2)}$. By applying reciprocity and the TR process to R_x, the time reversed new excitation $T_x(t) = R_x(-t)$ produces the new response R_x (the TR-NEWS coda $y_{TR}(t)$) with a spatio-temporal focusing at $z = 0$; $y = 0$, $t = t_f$ and symmetric side lobes (4) with respect to the focusing. (b) Selected chirp-coded TR-NEWS coda $y_{TR}(t)$ (normalized to its maximum) from $t = 1.617$ µs to $t = 1.659$ µs used for the construction of the chirp-coded polar image. The envelope (dark grey line) is extracted with Hilbert transform and constitutes a line ($\theta = 180°$) of the 3D TR-NEWS polar image (r, θ, surface velocity).

4. ULTRASONIC IMAGING OF THE COMPLEXITY WITH NONLINEARITY: EXPERIMENTAL SET-UP

The complexity of the concepts is intrinsically associated to the increase of the complexity of the experimental set-up. The necessity to reach and acquire what was called in the past "hidden information" in the noise has led to think about calibrated advanced electronic systems especially devoted to the extraction of the amplitude-dependent nonlinear signature. Techniques of complex imaging have evolved greatly due to recent advances in microelectronics and signal processing. Among the commercial advanced systems, one can cite the portable electronic TRA device developed by Artann Laboratories (http://www.artannlabs.com/tra-electronic.html), which has been successfully applied to biological bubble (contrast agent) characterization in complex media [5,15].

A specific TR-NEWS set-up (Fig. 3) was modified to be applicable for the human tooth imaging [16]. This TR-NEWS set-up is based on local calibrated measurements, which are performed with the Polytec PI vibrometer where sensitivity is around 20 mm s^{-1} V^{-1}. The third molar is put on the centre of an OWIS rotation stage, which rotates the tooth in the xy plane along the z-axis with the angle between $\theta = 160°$ and $\theta = 80°$. The particle velocity is measured at the tooth surface with the laser scanning the plane based 5 mm below the top of the tooth. The chirp-coded ultrasonic excitation $c(t) = \Pi_{\Delta t}(t)\cos(2\pi f(t)t)$ is applied at the 10 MHz central frequency transducer glued to the tooth. The time varying frequency $f(t)$ covers the bandwidth $\Delta f = [0.5 - 0.8]$ MHz with a time-window $\Pi_{\Delta t}(t)$ duration around Δt = 3 ms. The chirp-coded TR-NEWS method consists in the following successive steps: (i) emission of a linear frequency sweep signal (the chirp-coded excitation), (ii) recording of the response to the emitted signal (the chirp-coded coda), (iii) computation of the pseudo-impulse response, which is the correlation between the chirp-coded excitation and its response, and (iv) recording of the response to the time-reversed emitted pseudo-impulse excitation (chirp-coded TR-NEWS coda). The first two steps, which allow the determination of $y(t)$ versus θ, give the polar chirp-coded imaging of the tooth (Fig. 3b).

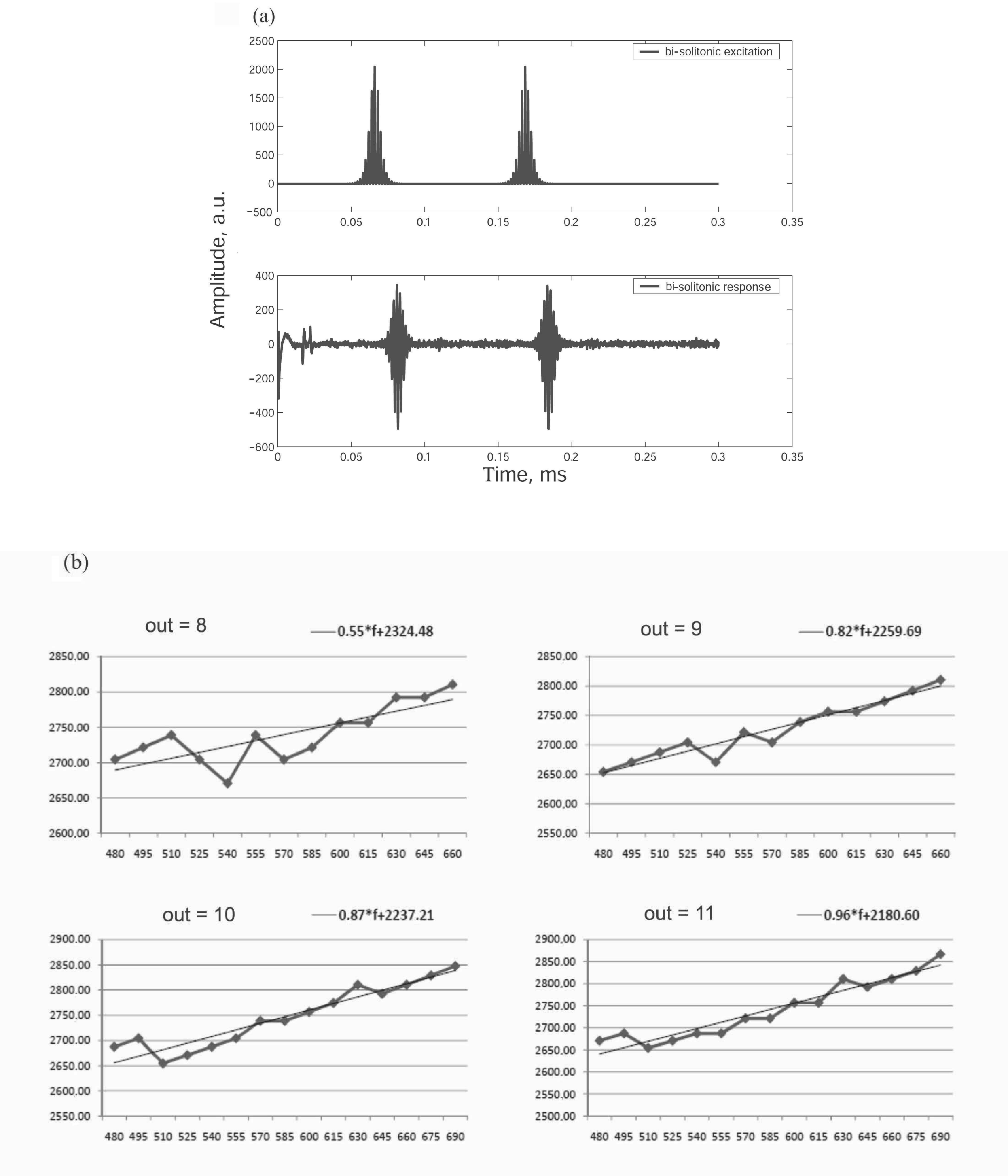

Fig. 2. (a) Bi-solitonic excitation and its bi-solitonic response after propagation in the 144 plies composite sample of 43 mm width. (b) Chirp-pulsed analysis at 400–900 kHz bandwidth optimized excitation for dispersion analysis of the 144 plies composite sample. The chirp-pulsed response allows the extraction of the dispersion properties versus the amplitude (out: 1 → 20) of the initial excitation controlled by a 150A100B power amplifier. The slope of the celerity (around 2200 m s^{-1}) versus frequency (in kHz) is amplitude dependent.

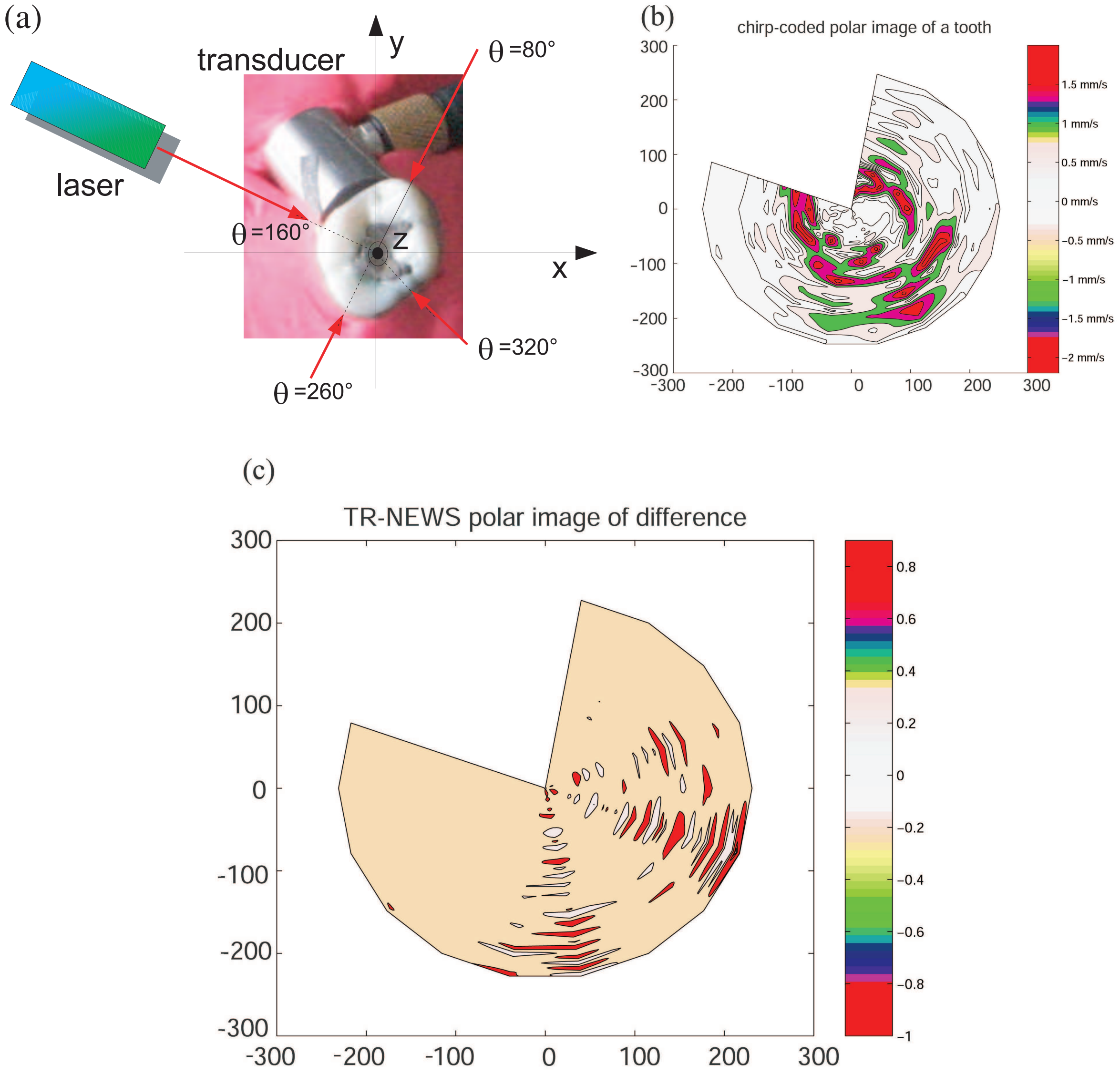

Fig. 3. TR-NEWS experimental set-up for ultrasonic imaging of the third human molar. A 10 MHz Panametrics transducer is glued on the tooth and, initially, a $\Delta f = 0.5$–0.8 MHz frequency range chirp-coded acoustic pulse is generated in the tooth. The laser (a) picks up, at the surface of the tooth, the normal velocity of acoustic vibration for various angles of rotation θ (between 160° and 80° along the z-axis. The region where θ covers the angles 80°–160° (the transducer shadow) corresponds to the position of the transducer. (b) Polar chirp-coded imaging of a tooth. For each angle (160° $\rightarrow$ 80°), a polar representation (r, θ) of a selected chirp-coded coda is plotted along the r coordinate. The maximum amplitude velocity (around 1.5 mm s^{-1}) is highly dependent of the angle θ. The region (transducer shadow) where θ covers the angles 80° $\rightarrow$ 160° corresponds to the position of the transducer (see Fig. 3a). (c) Difference between TR-NEWS images given after and before the focusing. Localization of the nonlinear signature is referenced with respect to the surface of the tooth at the border of the image.

4.1. Signature of the dispersion for "delayed TR-NEWS" based solitonic propagation

The theory of an inhomogeneous medium with microstructures can be used to model the behaviour of acoustic waves propagating in granular materials, polycrystalline solids, ceramic composites, and materials with microdefects. One of the main advantages of this approach is the possibility of taking into account intrinsic space scales, namely, the size of the grains or the distance between microcracks. It has been proved numerically [17] that in such a medium dispersion and nonlinearity could be combined in the way that solitonic propagation could be observed experimentally [18]. Preliminary experiments have been conducted on a 144 plies composite sample with a complex geometry coming from the aeronautical industry. Acoustic properties of the composite sample (43 mm width) were evaluated with an experimental set-up built with a pulse-echo ultrasonic device running at a frequency between 400 and 900 kHz. The power amplifier allows the propagation of nonlinear acoustic waves emitted with a Panametrics 1 MHz NDE transducer with a complex shape (Gaussian broadband solitonic excitation, chirp-coded, pulse inverted, and time reversed). An accurate position and preprocessing, using arbitrary waveform generating devices allowing the possibility of performing TR-NEWS analysis in the composite sample, led to the measurement of dispersion effects of the longitudinal bulk celerity (around 2200 m s^{-1}) versus the amplitude of acoustic waves emitted in the composite sample at frequencies between 400 and 900 kHz (Fig. 2).

4.2. TR-NEWS B-scan for echodentography

Ultrasonic evaluation of the human tooth known as echodentography is the subject of increased interest due to the potential of 35 MHz high frequency imaging. As described previously, the strength of the TR-NEWS approach comes from its signal pre- and postprocessing based on symmetry and invariance properties. The expected time of arrivals is also between $t_{\min} = 2.3$ µs and $t_{\max} = 3$ µs, which is observed experimentally in Fig. 3b. After correlation signal processing (extraction of the acoustic coda in the tooth) performed using $\Delta t = 3$ ms, the pseudo-impulse response $\Gamma(t)$ is time reversed ($\Gamma(-t)$), 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 give the chirp-coded coda $y_{TR}(t)$ (Fig. 3b). After the TR process, the focused spot has a duration of about 10 µs, is localized at the same time $t_f = 1.638$ ms, and localized in space at the tooth surface where the laser picks up surface velocity. As usual for TR-NEWS, $y_{TR}(t)$ contains additional side lobes (Fig. 1) coming as additional artifacts mostly due to reflectivity properties (interfaces, etc.). Time evolution $y_{TR}(t)$ presents a behaviour with a single maximum (the focused spot due to the spatial focusing of ultrasound), and additional artifacts (symmetric side lobes around time $t_f = 1.638$ ms), which were observed experimentally to be highly dependent on the angle θ. The focusing is independent of the distance between the transducer and the laser receiver. However, the most important advantage of chirp-coded TR-NEWS, which was used previously with another complex medium in the context of NDT [9], is the fact that the focusing of ultrasound is generated exactly at the position where laser surface velocity measurements are performed, and provides TR-NEWS with an advantage for localization of cracks and also the possibility of applying a surfacic stress, which could be combined to fractography [19], and with ESAM-DORT [14] for their localization and imaging.

5. CONCLUSION

A systemic approach of ultrasonic imaging of material complexity was described and tested experimentally on the nonlinear elastic wave spectroscopy of a human tooth and complex shape composites from the aeronautical industry. The associate symmetrized nonlinear signal processing using TR invariance, reciprocity, and optimized excitations such as pulse-inverted, chirp-coded, or bi-solitonic signals were included to a standard tomographic analysis elaborated with the “décomposition de l’opérateur retournement temporel”. Several experimental tests conducted on solid samples open new perspectives in the context of medical imaging of complex media such as a human tooth, the skin, or the brain.

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Mittelineaarne signaalitöötlus materjali keerukuse kirjeldamiseks ultraheliga

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Teoreetiliselt ja katseliselt on uuritud materjali keerukuse kirjeldamist ultraheliga, kasutades sümmeetrilise analüüsi mõistel baseeruvat signaalitöötlust sümbioosis mittelineaarse elastse laine spektroskoopiaga. Neid mõisteid kontrolliti katseliselt tänapäevase elektroonse süsteemiga mitmel keerukal keskkonnal. See süsteem kasutab kodeeritud häiritust keskkonna täpse mittelineaarse autogrammi esiletoomiseks ultraheli abil, lähtudes nähtuste muutumatusest ajas pööramisel ja vastastikusest vahetatavusest. Ajas pööratavuse operaatoreid kirjeldavate algebraliste mõistete abil on esitatud materjali keerukuse tomograafilise kirjeldamise uue meetodi alused, mida on kontrollitud nii hamba meditsiinilise kirjeldamise kontekstis kui ka aeronautiliste komposiitide mittepurustava katsetusega.