Nonlinear Time Reversal for Non Destructive Testing of complex medium : a review based on multi-physics experiments and signal processing strategies

Serge Dos Santos[1], Martin Lints[1,2], Nathalie Poirot[3], Zuzana Farova[1,4], Andrus Salupere[2], Michael Caliez[5] and Zdenek Prevorovsky[4]

[1] INSA Centre Val de Loire, Unité Mixte de Recherche "Imagerie et Cerveau", Inserm U930, 3 Rue de la Chocolaterie, CS 23410, 41034 Blois cedex, France, serge.dossantos@insa-cvl.fr

[2] CENS, Institute of Cybernetics at Tallinn University of Technology, Akadeemia tee 21, 12618 Tallinn, Estonia

[3] GREMAN CNRS, IUT de Blois, 15 rue de la chocolaterie 41000 Blois, France

[4] Institute of Thermomechanics AS CR, v.v.i., Dolejskova 5, CZ-18200, Prague 8, Czech Republic

[5] INSA Centre Val de Loire, Blois Campus; Laboratoire de Mécanique et Rhéologie, 3 rue de la Chocolaterie, CS23410, 41034 Blois, France

Abstract The interaction between an acoustic wave and a complex media has an increase interest for nondestructive testing (NDT) applications. For specific applications using nonlinear imaging, inversion procedure needs specific signal processing techniques and new coding schemes. This paper tends to show how symmetry analysis can help us to define new methodologies and new experimental set-up involving modern nonlinear signal processing tools. Generalized TR (Time Reversal) based NEWS (Nonlinear Elastic Wave Spectroscopy) methods and their associate symmetry skeleton will be taken as an example with some new spatio-temporal signal processing tools. The purpose of this paper is to present the extension of TR-NEWS for skin ageing characterization. Hysteresis behavior coming from the complex loading of the skin has been identified with PM-space statistical approach, usually associate to aging process in NDT. Phenomenological hysteretic parameters extracted will be presented and associated to standard parameters used for skin characterization. As another application of mixing properties in a wide frequency range, new broadband techniques are needed in the domain of the preservation of cultural heritage. The use of TR-NEWS based analysis (10 MHz) combined with a FTIR-based system (wavenumber range from 3650-650 cm-1) has shown a specific property of the tuffeau limestone which is a mix of calcite, SiO2 and CaSO4,2H2O whereas other damaged sample is calcite.

Key words: Ultrasonic Testing (UT), Other Methods, signal processing, TR-NEWS, nonlinear ultrasonic imaging, nonlinear acoustic testing, nonlinear time reversal

1 Introduction

Nondestructive Testing (NDT) of complex media is of increasing importance, not only in aeronautic industry, but also in various areas of industry also including modern biomedical media. A general definition of NDT is a examination, test, or evaluation performed on any type of test object without changing or altering that object in any way, in order to determine the absence or presence of conditions or defects that may have an effect on the usefulness or serviceability of that object[1].

Nondestructive tests are usually conducted in order to measure various characteristics such as size, dimension, configuration or structure, including alloy content, hardness and grain size. NDT, as a technology, has seen significant growth over the past 30 years and is considered today to be one of the fastest growing technologies from the standpoint of uniqueness and innovation.

With the increase of modern signal processing tools observed during the last 20 years, the area of interest of NDT based innovations can be explored in such domain like old or new materials for biomedical, or within the increasing demand of inspection of ancient materials in the domain of cultural heritage. Among these modern signal processing tools, nonlinear signal processing is a new field of research with the aim to optimize the excitation of information coming from nonlinear effects[2, 3]. Within the wide range of possibilities of signal processing methods, those using symmetry properties seems to be more efficient for extraction of a specific information. Various nonlinear methods have been investigated in recent years for the detection of faults and fatigue in carbon-fibre reinforced composite materials and structures. However, there is no universally-agreed rationale for which technique is best suited to the detection of which type of defect. Furthermore, even if such a rationale were to exist, real-world samples potentially contain a variety of defects (e.g. micro-cracking, delamination and disbonding) induced by various damage mechanisms (stress, impact, heat) such that no single nonlinear testing technique can offer the optimum inspection choice in all circumstances[4, 5].

Various nonlinear methods have been developed in recent years for defect detection in complex materials[6, 7]. The most common include harmonic and overtone generation, inter-modulation product generation and resonant frequency shift, also known as Nonlinear Elastic Wave Spectroscopy (NEWS) methods. Consequently, new optimized excitations are needed and, thanks to the analysis of symmetry properties of the system such as reciprocity, nonlinear time reversal[8] and other pulse-inverted (PI) techniques, a wide range of innovation can be proposed[9]. This is the case of TR-NEWS methods that use pulse-inversion and chirp-coded coding schemes[10, 11]. The interaction between an acoustic wave and a complex media has an increase interest for NDT applications, but also for biomedical ultrasound. For specific applications using nonlinear imaging, inversion procedure needs specific signal processing techniques and new coding schemes[12]. Nonlinear techniques use the fact that microcracks and delaminations generate harmonic and/or subharmonic tones of the frequency at which they are excited. As an example, intermodulation product generation which is based on the monitoring of nonlinear wave mixing in the material[7] is an alternative and a potentially more sensitive nonlinear method for defect detection in composites. In order to confirm these results, this paper tends to show how symmetry analysis can help us to define new methodologies and new experimental set-up involving modern nonlinear signal processing tools[13].

There is, however, still a need for applying NEWS in a complex medium where an adequate knowledge of the initial excitation and the geometry of the medium should be known precisely in order to predict the ultrasonic propagation with high efficiency. Consequently, using symmetry invariance, TR-NEWS methods are supplemented and improved by new excitations having the intrinsic property of enlarging frequency analysis bandwidth and time domain scales, with now both medical

acoustics and electromagnetic applications[12]. Among the family of pulse coded excitation, solitonic coding constitutes a new scheme in the sense that solitary waves are the best candidates for pulse propagation in nonlinear and dispersive media[14]. Such spatio-temporal focusing may enable efficient delivery of solitonic optimized excitations to a specific target location within a complex enclosure. This method has the potential to be applied in many real-word contexts where the wish to focus acoustic energy at a location is impractical or impossible. Their robustness during propagation could inform aeronautic end-users during monitoring process of layered; granular, lightweight or functionally graded materials.

The purpose of this paper is also to present the extension of TR-NEWS for skin aging characterization using the nonlinear time reversal signal processing tool known to localize, in a complex medium, sources of nonlinearity potentially responsible of complex material aging. One other aspect related to the problem of complex medium aging is the multiscale aspect of the nonlinear signature which can be studied using PM-space. Since the validation of nonlinear time reversal methods within the NDT community[15], another fields of applications have been investigated recently. One can cite landmine detection, composite and echodentography[16]. The NEWS methods have been shown to improve cracks detection and might, therefore, also be advantageous in medical diagnostic ultrasound applied to echodentography. All of theses applications concern aging characterization or degradation in a complex medium. Linear and nonlinear behavior of skin elasticity is measured locally thanks to an acousto-mechanical loading of the skin conducted with INSTRON loading machines specifically optimized for biomaterials. Hysteretic behavior coming from the complex loading of the skin is identified with PM-space statistical approach, usually associate to ageing process in NDT. Phenomenological hysteretic parameters extracted is presented and associated to standard parameters used for skin characterization.

Finally as another application of mixing properties in a wide frequency range, new broadband techniques are needed in the domain of the preservation of cultural heritage. This is an interdisciplinary challenge which needs the expertise of many scientific disciplines as well as chemistry, physic, optics, etc. Advanced signal and image processing for art and cultural heritage investigation is a topic of major interest in order to provide a quantitative source of information to art historians. The Loire Valley in France has a diversified cultural heritage, including monuments where the mainly construction units is stone. Most castles were built with two French highly porous limestone called Richemont and tuffeau limestones. The objective of this paper is to investigate TR-NEWS for skin aging[17] and for tuffeau limestone characterization (Fig.3) which are both subjected to a growing area of research.

2 The Strategy of Symmetry Analysis

Invariance with respect to time is one of the properties of a more general algebraic approach that is applied in physics which uses intrinsic symmetries for the simplification and the analysis of complex systems. Symmetry analysis is a framework of the bases of a systemic approach aimed at using absolute symmetries like Time Re-

versal (TR), reciprocity between emitters and receivers, and others. These methods are highly strategic in the sense that they conduct improvement of the measurements so as to optimize the determination of nonlinear properties extracted with coded excitations (e.g. pulse-inversion PI or chirp-coded processes, etc.) with the virtual increase of the effective bandwidth of the excitation. Coded excitations and signal processing is now considered as an efficient way for imaging the complexity in bio-materials with hierarchical properties[18]. Accurate analysis of nonlinear time reversal systems needs the use of new methods of signal processing[19]. Most of systems used in engineering presents a level of nonlinearity that was considered negligible and included in the small stochastic part of the noise. Modern engineering is developed now by considering this stochastic part of the nonlinear signature as a new vector of information coming from the complex system under study[9]. The huge variety of information extracted from this small stochastic part of the response coming from a complex system induces an increase of uncertainty associate to the linear part. This linear part, with its underlying hypothesis of stationarity and determinism, should be consequently associated to a grater uncertainty if the system under study presents intrinsically a complex structure with mesoscopic properties, memory effects, preconditioning, and aging. Of course, these properties are breaking now the stationarity hypothesis implicitly assumed in any linear signal processing, since linear systems theory dominates the field of engineering. This consequence completely justifies this strategy to use nonlinear signal processing tools.

3 Generalized TR based NEWS multimodal instrumentation

Recent years there has been a considerable development of TR based NEWS methods using invariance with respect to TR and reciprocity, both in numerical and experimental aspects. These methods were practically elaborated as the well-known TR-NEWS methods[20]. Chirp-coded pulse excitation[10, 11] is proposed for improving the SNR of ultrasound imaging. Nevertheless, the chirp-coded pulse elongated that the axial resolution of an ultrasound image. Thus, pulse compression technique is utilized to improve the axial resolution of the images. However, it is still lacking the information about the effects of chirp-coded pulse, which was modulated with different window functions, in conjunction with different strain analysis algorithms upon the qualities of imaging. The aim of this study is development of advanced TR-NEWS methods with chirp-coded excitation for assessing biomechanical properties of porcine skin and for NDT of limestones studied within cultural heritage applications. Improvement of TR-NEWS has been conducted with coded excitation using chirp frequency excitation and the concept was presented and validated in the context of NDE imaging[9]. The chirp-coded TR-NEWS method uses TR for the focusing of the broadband acoustic chirp-coded excitation. The method consist in the successive steps :

- emission of a linear frequency sweep signal (the chirp-coded excitation)
- recording of the response to the emitted signal (the chirp-coded coda)
- computation of the pseudo-impulse response which is the correlation between the chirp-coded excitation and its response

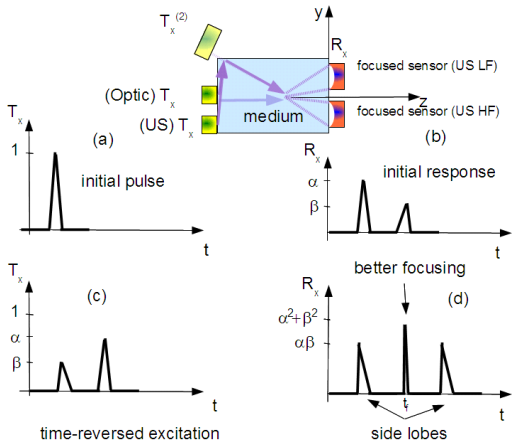


Figure 1: *The four elementary steps of the multi-modal TR-NEWS method : (a) after the excitation of a broadband initial excitation (a short pulse here), the recorded initial response (b) is averaged, filtered, time reversed (c) and rebroadcasted as a time-reversed excitation with the same experimental conditions. The optimized excitation based on this TR-NEWS approach is used for extraction of the local nonlinear signature located in the time domain with respect to the maximun and the side lobes of the crosscorrelation function given by the focused signal (d). The multimodal property come from the fact that the focusing is increase thanks to the use of a broadband multi-physics modality (US LF and HF, optics, etc.).*

- recording of the response to the time-revered emitted pseudo-impulse excitation (chirp-coded TR-NEWS coda)

In order to describe chirp-coded TR-NEWS process in terms of a time-invariant system, we consider a chirp excitation $c(t)$ send in a medium with impulse response $h_{21}(t)$. As described schematically for a simple medium (Fig.1), side lobes could be interpreted with cross-correlations functions and present a symmetry property with respect to the focusing time t_f. The chirp-coded TR-NEWS method uses TR for the focusing of the broadband acoustic chirp-coded excitation. In order to describe chirp-coded TR-NEWS process in terms of a time-invariant system, we consider a chirp excitation $c(t) = A\cos(2\pi f(t)t)$ where $f(t) = At + f_0$ send in a medium with impulse response $h_{21}(t)$. The chirp-coded coda response $y(t,T)$ recorded for a finite time duration T is given by $y(t,T) = h_{21}(t) * c(t) = \int_{\mathbb{R}} h(t-t',T)c(t')dt'$, where $h(t-t',T)$ is an approximation of the (linear) Green's function that satisfy the linear wave equation. The correlation $\Gamma(t)$, computed during Δt, is given by

$$\Gamma(t) = \int_{\Delta t} y(t-t',T)c(t')dt' \simeq h(t) * c(t) * c(T-t,T), \tag{1}$$

and is called the pseudo-impulse response. $\Gamma(t)$ is also proportional to the impulse response $h(t)$ if $\Gamma_c(t) = c(t) * c(-t) = \delta(t)$. Under these hypothesis, $\Gamma(t)$ can be considered proportional to the impulse response (referred as 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

$$y_{TR}(t,T) = \Gamma(T-t) * h_{21}(t) = \Gamma_h(T-t,T), \tag{2}$$

and provides the linear autocorrelation of the system which peaks at $t = T$ and induces a spatial focusing at the receiver. All this theory is valid under linear behavior of the medium represented by its impulse response $h_{21}(t)$. Any source of nonlinearity in the system will result to a perturbation of this method, and will induce additional terms in Eqs.(1-2). When focusing is performed inside a reverberating medium, like the skin or the Tuffeau limestone, the effective aperture of the TR-NEWS process becomes virtually infinite. Indeed, the impulse response computed using previous equations become sharp. This corresponds to an infinite aperture (sources surrounding the focus) producing a focal area used for analyzing the medium.

4 TR-NEWS for skin imaging monitoring

The measurement of skin's mechanical properties (nonlinearity, anisotropy, and viscoelasticity) is important in several fields, including medicine and cosmetics, and present a huge dispersion depending on age, gender, physical size of individual and location on the body (forearms, face, etc). Small changes in the mechanical properties are very sensitively reflecting many diseases. Their influence on the appearance of aging, and their role indicating disease and pathologies is also a societal goal of biomechanical research[17, and ref. therein]. Hysteresis is a phenomenon that occurs in ferromagnetic and ferroelectric materials, as well as in the deformation of some mesoscopic materials, which are flexible or compressible. For example, sand rock[21], which is one of the example of nonclassical nonlinear materials, for which hysteresis behavior is one of the key properties. In electronics, hysteresis is produced by positive feedback to avoid an oscillation. Today hysteresis and memory based modeling is one of the most interesting and challenging fields of innovation in many engineering applications such as actuators. It seems to be a promising way to understand mesoscopic properties of biomechanical materials. Like porous materials characterized by anisotropy, nonlinearity, hysteresis and susceptibility to fluid sorption, we propose in this paper to study human skin with a multiscale model where each state is defined by a set of internal parameters acting on the element. The other consequence is a pragmatic analysis swarming by phenomenological approaches in the family of PM models. The accurate extracted information coming from such systems needs to be associated to the symmetry hypothesis of the underlying mesoscopic structure with respect to scaling effects responses.

The behavior of PM space responses with respect to the optimized various types of signals with the PM space theory was studied. The PM space model has a prominent future in the modeling of viscoelastic behavior of complex materials. It has been recently proposed for understanding physical mechanism including porosity, amorphous or crystalline bonding material and pre-existing cracks, magnetics, magnetostrictive and shape memory, and smart structure components. With this representation and its identification and classification, the physical response (electrical for electromagnetic relays, or acousto-mechanical biomaterial like the skin) can

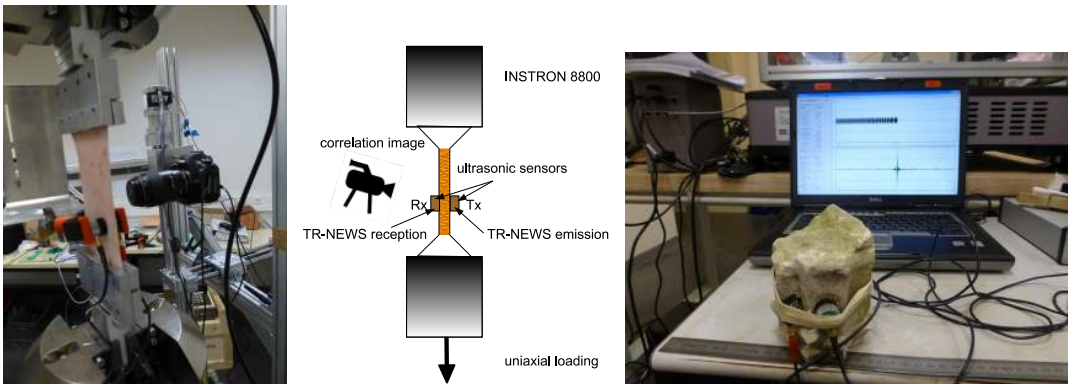


Figure 2: *TR-NEWS experimental set-up for acousto-mechanical imaging of the porcine skin aging (a,b) and for the aging characterization of Tuffeau limestones*

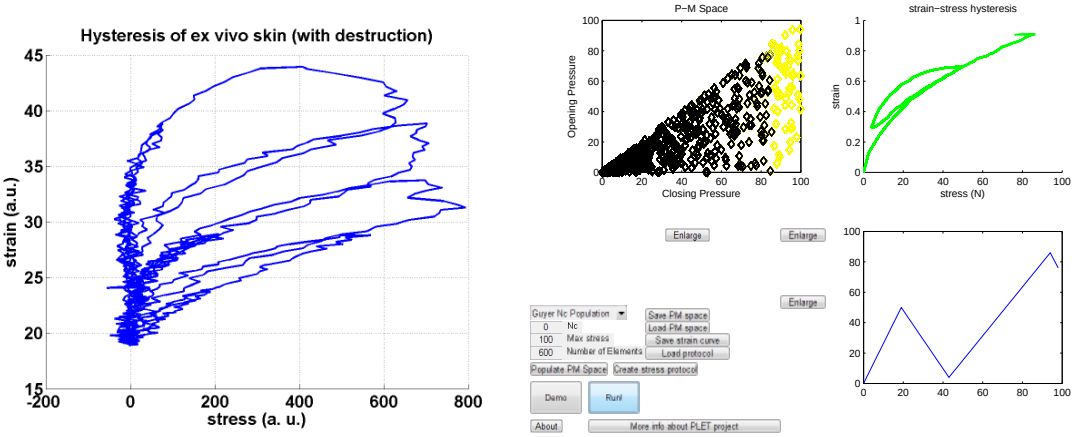
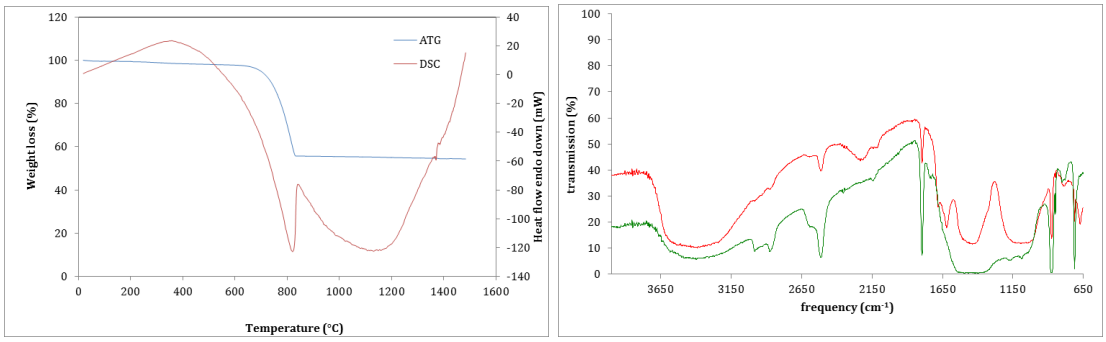


Figure 3: *Skin PM space for memory analysis extracted from hysteretic strain-stress measurements conducted on ex vivo porcine skin. Optimization of the strain-stress curve induces a PM space with 600 hysterons distributed along a Guyer distribution[17]. This original result constitutes the first PM-space identification of viscoelastic and/or hysteretic properties of the skin under uniaxial loading.*

be predicted. Since the strain-stress characteristic of porcine skin under increasing loading is characterized by hysteretic behavior, the preconditonning signature will be investigated with the objective of extracting the memory of the skin[18].

5 Cultural heritage and new NDT multimodal imaging

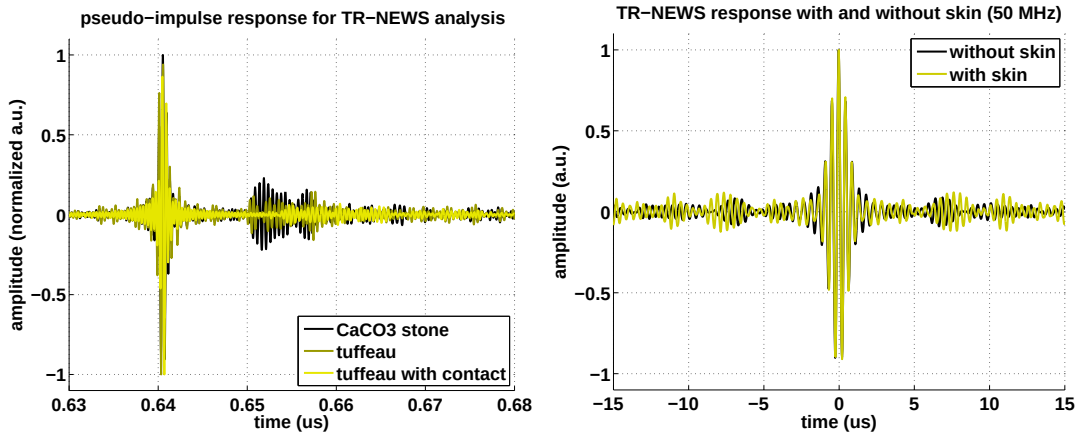
Electromagnetic waves with Terahertz (THz) frequencies or corresponding sub-millimeter wavelenght are associated to the range between infrared and microwaves. These properties give to the THz frequency range an interesting future for new applications in NDT. Besides security applications, THz technologies for NDT are about to enter markets as pharmaceutics and the composite industries[22], but also for studying NDT on historical heritage. Structural maintenance of historical buildings requires knowledge based strategies to keep under control all parameters governing the structural integrity of these historical buildings, and particularly a robust mon-



(a) (b)

Figure 4: *(a): ATD/DSC analysis of the Tuffeau limestone. The slope temperature was chosen to 10°C/mn. The transition observed at 800°C corresponds to the CaCO3 decomposition. (b): FTIR analysis performed in the frequency range [3650:650]cm^{-1} where CaCO3 vibration modes are identified.*

itoring. In order to test TR-NEWS approach for NDT of the fine art objects and the cultural and historical heritage, some preliminary tests have been conducted on Tuffeau limestones. The objective is to confirm the interest of using multi-physics laser based imaging methods for low-cost ultrasound sensor for the detection of defects[23].



(a) Tuffeau limestone (b) Porcine skin

Figure 5: *TR-NEWS pseudo impulse response (a) and cross correlation function (b). The skin signature is located near the maximun of the crosscorrelation function.*

As seen in Fig.5, the chirp-coded excitation $c(t)$ with $\Delta f \in [0.1 : 1.5]$ MHz is plotted in the time domain with $\Delta t = \frac{N}{f_e} = \frac{64000}{50e6} = 1.28$ ms. The pseudo-impulse response given by Eq.1 is plotted in the time domain after filtering with a 20.75 MHz low-pass filter and $N_a = 148$ averages. The pseudo-impulse properties has been compared in the time and the frequency domains. The reverberant properties (in the time domain) of the skin and the Tuffeau limestone have been reached as observed in (a).

6 Conclusions and perspectives

The use of TR-NEWS based analysis (50 MHz) combined with a FTIR-based system (wavenumber range from 2000-800 cm-1) has shown a specific property of the tuffeau limestone which is a mix of calcite, SiO2 and CaSO4,2H2O whereas other damaged sample is calcite. In the future, the ultrasound nonlinear imaging system should be used on human subjects to demonstrate the feasibility of collecting *in vivo* data. The objective to extend this modern approach to skin and human brain, from whose memory effects are currently admitted, gives to this approach a promising future for modern engineering, and medical biomechanical imaging. Concerning cultural heritage applications, we believe that TR-NEWS and its multi-modal aspect including US and FTIR techniques will benefit art collection community as a whole, and further emphasize scientist's contribution to the cultural heritage as well.

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