The acoustical behavior of the skin has been investigated for a number of years, especially for clinical and cosmetic applications. Monotonic tensile tests are one of many techniques used to evaluate mechanical parameters of the skin. We have shown recently that these mechanical properties are strongly influenced by cyclic and stress relaxation loading protocols revealing complex hysteretic multiscale properties of viscoplastic strain, damage, and aging of the skin.

In this paper, we will focus on the ground truth tests associated to modern signal processing tools, coming from Time Reversal (TR) invariance. This modern advanced TR-NEWS methods which constitute one of the most promising trends for nonlinear based metrology is devoted to the nondestructive/noninvasive evaluation of plasticity, fatigue, creep, and aging of complex medium/material coming from the biomedical domain. For example, for skin analysis, an aging evolution model should be used to estimate ground truth data during the acousto-mechanical uniaxial loading test. The TR-NEWS system and data fusion process are used to generate performance curves showing new multiscale memristive properties induced by memory effects activated by the loading protocol.

Keywords: skin, acoustomechanical testing, hysteresis, nonlinearity

1. Introduction

Most biological tissues have significant nonlinear elastic behavior, and the apparent stress-strain relationship is nonlinear in an extended range of strain, for a wide variety of materials as well as for
biological tissues. The nonlinear behavior of the skin is associated with the interaction of the collagen fibers with the proteoglycan matrix. The features of the viscoelasticity of materials are the hysteresis which is the signature of memristive systems, stress relaxation, and creep[1, 2, 3]. The nonlinear behavior of the skin samples in mechanical experiments was currently manifested by hysteresis loops. This phenomenon can be related to one or several effects. It is known that the internal structure of the tissue (i.e. change of collagen molecular structure and the fibrine distribution) changes with the cyclic mechanical loading and called this phenomenon the preconditioning[4]. Overall, it seems that the nonlinear elasticity of the skin varies with many external parameters and hence it makes the skin elasticity hard to evaluate. Nonlinearity is a property of a medium (e.g., water, biological tissues) by which the shape and amplitude of response signal are, in contrary to the linear case, disproportional to the input excitation. Nonlinear effects of such materials can be studied in almost all acoustic measurements beyond a certain excitation level. Relative amount of nonlinearity in biological soft tissues (e.g., skin, fat) is only slightly higher than in water. One possibility how to assess tissue nonlinearity is to gradually increase acoustic amplitude and to investigate the evolution of corresponding responses at the fundamental frequency and the higher harmonics which are generated upon dynamical wave propagation due to cumulative wave distortion. Significant dependence of healthy or damaged tissue state on the acoustic nonlinearity parameter has been observed. Moreover, it has been reported that the diseased and pathological tissues have larger nonlinear response than corresponding normal tissues, and the methods of nonlinearity measurements were further extensively investigated in many works, including fractional modelling of multiscale viscoelasticity[5, 6, 7].

In order to achieve this goal, the paper presents some modifications of the Nonlinear Time Reversal (TR) based Elastic Wave Spectroscopy (NEWS) device which is associated to the development of a phenomenological characterization of skin local elastic properties[8, 4]. Developed for the Non Destructive Testing (NDT) research, the TR-NEWS ultrasonic based device allow to measure locally the degradation and ageing of complex structures and biological medium[9, 10, 11, 12]. The experimental device was improved and specially scaled in order to access to a wide range of skin parameters: mechanical properties, ultrasonic parameters (celerity and attenuation) and local geometric data. The well-known complexity of the skin constitutes a strong advantage for the efficiency of TR-NEWS methods which uses focusing of ultrasonic waves in a chaotic medium for the local characterization of the skin elasticity. This paper focuses on the creation of the intelligent agent based reporting multiscale experiments that produces the ground truth necessary for data fusion to analyze the multiscale memristive properties of skin. This reporting experimental process is a crucial first step in the construction of a wide big data system to produce a data fusion support tool for evaluating the aging of the skin.

2. Memory effects, aging and viscoelastic multiscale behavior

One of the most difficult property in biomaterial to measure, evaluate and model is the multiscale viscoelastic effect. Several authors tried to extract some local properties using specific experimental set-up: uniaxial loadings, biaxial protocols, 1D, 2D, 3D modeling. Furthermore, several effects such as Mulling effects or relaxation were identified in all the communities and seems to be connected all together. For example, in [2], the viscous property of the skin is shown to be influenced by the stress relaxation process. In our approach, all these viscoelastic effects could be associated to multiscale pragmatic and phenomenologic parameters that could be modeled by fractional models where viscoelasticity appears naturally as a direct consequence of the multiscale property of the skin[13, 14]. A basic consequence of viscoelasticity is the energy losses which is difficult to evaluate in biological medium not only the real value, but also the nature of energy (mechanical, thermal, chemical, etc.). Since the multiscale properties is assumed in our approach, energy transfer flux should also be present at all scales, and should induce physical phenomenon at all scales, from the mechanical domain (at low frequency) to the acoustical domain (at 20 MHz, involving solid-solid, solid-fluid and fluid-fluid interaction at the mesoscopic scale). Energy losses appears also in all medium showing hysteresis...
effects[15, 16]. Losses are usually associated to the hysteresis area describing the excitation-response curve of the the material. The analogy between the memory effects of the memristor[17] and hysteresis effects in the skin allow us to suggest the same physical origin of aging[18, 19, 20, 21]. In [22], we consider memristors as a plausible solution for the realization of transducers as an autonomous linear time variant system for TR-NEWS applications, especially for measuring nonclassical nonlinearities. Such highly nonlinear behavior produces strongly nonlinear frequency spectrum broadening inducing low frequency effects equivalent to long time like reverberation and slow dynamics. This consequence induce naturally the problem of duration of any experiment showing this phenomenon. This phenomenon could explain the high number of relaxation parameters present in any uniaxial loading. In our approach, by including memory effects (or memristive effects) in our multiscale phenomenological model, it is naturally assumed that long time behavior could be naturally evaluated by assuming a statistical distribution of parameters[9]. It consider all slow dynamic phenomenon even if their measurements cannot be practically conducted in experiments.

3. Experimental setup and theory

The acousto-mechanical set-up consists of the following parts:

- **Camera** IDS, 1:2.8 50mm ⊗ 30.5 TAMRON lens,
- **Electromechanical Load Frame** MTS Criterion model C43,
- **Load cell** MTS model LPB.502, max 500N, sensitivity 2.055 mV/V,
- **TR-NEWS DAQ** Juvitek TRA-02 (0.02 - 5 MHz)
- **Amplifier** ENI model A150 (55 dB at 0.3-35 MHz),
- **Pulse generator** GPG-8018G as pulse extender,
- **Shear wave transducer** Technisonic ABFP-0202-70 (2.25 MHz),
- **Longitudinal wave transducer** Panametrics V155 (5 MHz),
- **Skin sample** 40x120x2.2mm porcine skin, 72mm length between the clamps.

![Figure 1: Principle diagram for coupling the mechanical and acoustical measurements of a test object](image1)

![Figure 2: Skin sample under test with clamped transducers](image2)

4. The Preisach-Mayergoyz model for hysteresis in skin

The main task in the field of PM space elasticity modelling is the identification of probability density function \( \mu(P_c, P_o) \) that generate the multiscale nonlinear response of a complex medium[10, 23]. The primary goal is to determine a density of hysterons in PM space only from the knowledge of hysteresis curve and the input signal. In order to extract skin multiscale properties, both the fundamental statistical distributions (e.g. exponential, gaussian, uniform, Weibull) and also two distributions originated from Guyer et al [24] are used. To identify the corresponding PM space of the porcine skin under study only from the knowledge of the input signal and the experimentally obtained hysteresis
5. Results

Figure 6 compares the strain calculated from extension, strain from image processing, and the loading. The test sample is excited with sinusoidal excitation with increasing amplitude and base value. In random times during the test, the extension is stopped for 8 seconds to conduct the TR-NEWS measurement. These measurement points are shown by the plateaus in extension data.
Figure 5: Geometrical interpretation of the phenomenological PM space model: during the loading protocol, the macroscopic stress contribution is obtained with the integration (area) of macroscopic phenomenological states. During the complex loading protocol, memory effects are taken into account and can be measured with the properties of the memory line.

Each measurement, a precise and discrete time moment is captured also by acoustic and mechanical test setups which is later used to synchronize the measurement data. The strain calculated from the video follows closely the features in the load frame extension data and matches well with load frame loading data. Moreover, the strain from the image correlation show physical features of the test sample which the load frame extension cannot capture, such as viscoelasticity and relaxation under load. At around 500 seconds of the testing time (Fig. 6), the skin reaches its elastic limit and starts to slip out of the load frame clamps.

Figure 6: Strain calculated from load frame extension versus the strain from the video digital image correlation and loading of the material

Figure 7: Strain and load at a selection of measurement points

The test setup allows to successfully compute the true strain and the actual hysteresis curves. Fig. 11 shows the hysteresis curves computed with the strain calculated from the load frame extension versus strain calculated from the video by digital image correlation. It is apparent that while the true strain, calculated from the video, contains noise, but makes more physical sense. The TR-NEWS measurement points, where extension is stopped, show the relaxation effects in the true strain (from video), while the load frame strain cannot show that (Fig. 12). This results in smaller true hysteresis curve area. Additionally, when the loading is resumed, the true strain hysteresis curves continue along the old path. Therefore the true strain is what should be mainly for hysteresis analysis. The noise of the true strain can be optimized by better lightning conditions and camera setup and by taking care in selecting the region of interest in the video file to be analysed. Additionally, a low pass filter could be experimented with for smoothing the noise in the digital image correlation data. For parameter fitting with PM space theory, the true area of the hysteresis curve is very important. Additionally, the nonclassical nonlinearity can be improved to take into account the viscoelastic effects, such as the relaxation shown in these results. The TR-NEWS measurement points are shown by round markers in Fig. 12. These markers indicate at which load and strain values the multiscale measurements (Section 4) are conducted.
5.1 TR-NEWS measurements of nonlinearity

In order to improve statistical analysis, a set of 73 TR-NEWS measurements were captured, at various strains and stresses. Fig. 7 shows a selection of these points (from 18 to 48). Comparing some TR-NEWS measurements taken at approximately the same strain levels (18, 20, 34, 41 and 48), it can be seen from their TR-NEWS focusing sidelobes in Fig. 13 that as the cycle count of the skin sample goes up, the sidelobe part of the TR-NEWS signal increases, which can indicate damage in the material. Although previous measurements were taken at the same strain, their stresses were different (Fig. 7). Nevertheless the changing stress at constant strain is not what changes the sidelobe amplitude: to compare the TR-NEWS measurements for approximately constant stress, points 25, 31, 33, 38, 40 and 47 are chosen and again, as time goes on and damage increases, the amplitude of the sidelobe part of the TR-NEWS measurements rise (Fig. 14), indicating the increase of nonlinearities. The increase of sidelobe amplitude with increasing damage to the skin sample is small but sure. In the future experiments, larger sample size needs to be analysed and the nonlinearity linked to some measure of hysteresis in the loops, showing the memory effects in the skin. It would also be possible to use different methods of investigating the nonlinearity using advanced optimization techniques of TR-NEWS signal processing, such as pulse inversion or delayed TR-NEWS [25], or taking into account signal-to-noise analysis[26].

6. Conclusion

The acousto-mechanical TR-NEWS based approach allows for the creation of a myriad of experimental data to be generated for input to a data fusion "nonlinear" module. This type of multiscale experimental acousto-mechanical set-up with data fusion is a first step toward the objective of creat-
ing fast, accurate, understandable and trustworthy estimates necessary to understand and to evaluate the aging of the skin described with complex multiscale memristive properties.

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