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FULLY SYNCHRONIZED ACOUSTOMECHANICAL TESTING OF SKIN: BIOMECHANICAL MEASUREMENTS OF NONCLASSICAL NONLINEAR PARAMETERS

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An accurate description of soft biomechanical tissues is an open problem in many fields, with applications ranging from medical imaging and characterisation of tissue aging to medical simulations. Skin is one of these highly complex tissues which is difficult to model due to its nonclassically nonlinear effects such as hysteresis, memory effects and viscoelasticity. A promising model for describing the mechanical behaviour of skin is the Preisach–Mayergoyz model.

The goal of this paper is to present a fully synchronised acoustomechanical method for finding the elasticity and hysteresis parameters of an *ex vivo* skin sample. The coupled test equipment enables to measure nonclassical nonlinearity of porcine skin using a novel setup for mechanically loading a test object and conducting ultrasonic measurements in a synchronised fashion. The skin sample is uniaxially loaded into quasistatic tension with a sinusoidal load path of increasing amplitude and offset. Ultrasonic tests up to 5 MHz range are conducted perpendicularly, through the thickness of the sample. The mechanical extension forms the hysteresis loops in the strain-stress plane while the ultrasonic testing equipment with the Time Reversal – Nonlinear Elastic Wave Spectroscopy signal processing method focuses the high intensity acoustic energy to measure the hysteresis and elasticity parameters of skin under various mechanical loadings. The multiscale properties of the skin are revealed from the hysteresis measurements from both synchronised data sets. This test setup could also used for other kinds of nonclassically nonlinear materials.
Keywords: skin, acoustomechanical testing, hysteresis, nonlinearity

1. Introduction

A novel testing method is developed for measuring the parameters for a mechanical model for the skin using modern ultrasonic Non-Destructive Testing (NDT) methods coupled with mechanical excitations. Skin is a multiscale material with complex properties, including memory effects, hysteresis, creep, and nonlinearity [1, 2]. Its mechanical behaviour is here modelled by Preisach–Mayergoyz

(PM) hysteresis model [3], for which finding parameters can be difficult due to the number of model parameters and large variance between material samples [4].

Accurate characterization of the properties of the skin tissue could be valuable for surgery simulation, medical ultrasonic imaging, disease diagnostics, research on skin aging and skin damage and many other problems in medicine and cosmetics. Skin properties can have large variance between people or even location on the body of a person and in time, making measurements complex [5].

Several approaches have been used to measure the biomechanical properties of the skin and its accurate description remains to be an open research problem. In previous studies it has been found that using computer optimization routines, it is possible to find good parameter estimates for the PM hysteresis model to describe the mechanical parameters of skin under tension test. The works preceding this paper have discussed biomechanical properties, memory and aging effects of skin and statistical determination of PM parameters for various statistical distributions [6, 7].

In this paper a novel testing apparatus is presented which can be used to measure the nonlinear and hysteresis properties of the skin tissue *ex vivo*. The mechanical and acoustical excitations of a skin sample are coupled to probe the nonlinear mechanical effects of skin. The synchronization of different measurement devices allows an even further optimization of the mechanical parameter search. The automatic coupling between the different devices enables to speed up the testing process, to have finer control over complex relaxation and viscoelasticity effects. The automation of the measuring process allows to measure statistical distribution of the mechanical properties of the test objects, which can additionally depend on the loading, extension, their history or time properties. The acoustical measurement of the test object for this setup prototype utilizes the Time Reversal – Nonlinear Elastic Wave Spectroscopy (TR-NEWS) ultrasonic testing method [8, 9].

2. Experimental setup and theory

The acoustomechanical test setup (Fig. 1) consists of Camera IDS, 1:2.8 50mm ⌀ 30.5 TAMRON lens and an Electromechanical Load Frame MTS Criterion model C43, with a load cell MTS model LPB.502, max 500N, sensitivity 2.055 mV/V. The TR-NEWS Data Aquisition (DAQ) system is designed by Juvitek TRA-02 (0.02 – 5 MHz). For synchronization and amplification, amplifier ENI model A150 (55 dB at 0.3–35 MHz), pulse generator GPG-8018G as pulse extender. Chosen sensors were shear wave transducer Technisonic ABFP-0202-70 (2.25 MHz) for emission and longitudinal wave transducer Panametrics V155 (5 MHz) for reception. The transducers are attached to the skin sample by a hand clamp visible in Fig. 2. The porcine skin sample dimensions are 120 x 40 mm with average thickness of 2.2 mm. It is fixed between the load frame clamps with initial gap 73 mm.

In the test setup prototype, the timestamps of the ultrasonic tests are used as synchronization points. The load frame, camera and load cell are controlled by one computer, the TRA-2 DAQ by another. Amplifier is used to amplify the signals from the TRA-2 to the transmitting shear wave transducer. For the synchronization, the TRA-2 emits a short sync pulse whenever it is in transmission, which is extended and amplified by a signal generator and then fed into the load frame digital input. The software controlling the load frame reads this input signal to write the synchronization points (as date time group and time vector point) into the experiment file. On the TRA-2 side (acoustic measurement), the synchronization is conducted similarly: the experiment output files have the current date time group in the filename. In post-processing, the strain from video is calculated and all the signals, including acoustic measurement points, are synchronized.

Since the TR-NEWS procedure relies on two transmissions for one measurement, then two synchronization pulses are sent by TRA-2 per one full TR-NEWS measurement, which is counted accordingly by the load frame controlling software. In future, a more optimal solution would be to control all of the experiment by a single computer and solve the synchronization purely in software or establish a two-way communication between the controlling computers. For the prototype, the TRA-2 controlling computer is acting as the master and the one controlling the load frame acts as the slave. The prototype setup has room for improvement on procedural aspects, but this does not affect the outcome of the experiments.

To start the experiment, the extension load path is imported into the load frame controller. Arbitrary load paths, within physical limits, are possible. The load frame starts moving when the first full TR-NEWS test is completed. After that it follows the prescribed path, stopping for the duration of each new TR-NEWS test. Since the TR-NEWS test is automated and can be conducted fully by a single click of a button, then this results in only short (~ 8 s) plateaus in the extension for the duration of ultrasonic test. The possibility of arbitrary load path enables to investigate the influence of loading speed, which can be important in analysing the energy dissipation mechanism of skin [7]. In this study, a quasistatic loading is used.

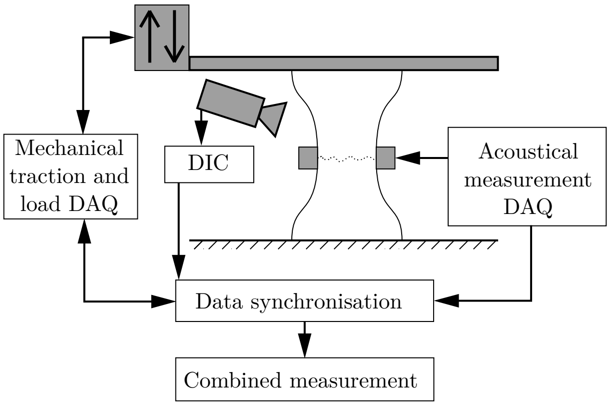

Figure 1: Coupling of the mechanical and acoustical measurements (DIC – Digital Image Correlation)

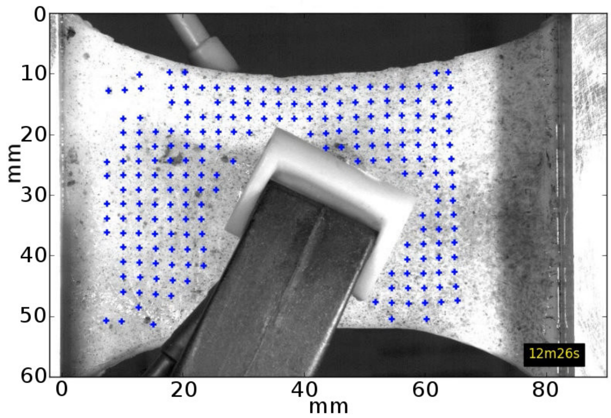

Figure 2: DIC frame with displacement markers added in post-processing. Markers are omitted on the transducer clamp region in foreground. The extension is toward right (video available at [10]).

2.1 Digital image correlation

It is difficult to extend the skin sample in the load frame to result in uniform strain in the sample. This is because skin is not homogeneous, it has varying mechanical properties and the clamps used to grip the skin can damage it near the clamp or it can slip out. For these reasons, a more accurate way of measuring the displacement field is needed. Here the Digital Image Correlation (DIC) method is used [11]. Therefore, the extension is filmed, and the images are processed to reveal the displacement field of the region of interest, frame by frame. Although commercial and open-source solutions exist for DIC, a new prototype code was developed in Python for flexibility reasons, making use of packages scipy [12] and scikit-image [13] for the data and image processing (Fig. 2). Video is available at [10].

2.2 Preisach–Mayergoyz model for hysteresis in skin

The PM hysteresis model was originally developed for ferromagnetic and ferroelectric materials, but later found use in nonequilibrium dynamics of mesoscopic materials [6, 14, 15] and from there to various applications concerning distributed microdamage in materials [16]. In addition to hysteresis, this model allows to describe the elasticity and nonlinearity of the material [17]. When microdamage is present in biological materials, high levels of nonlinearity, including hysteresis, is found.

The PM hysteresis model assumes that the material is composed of a large number of small elastic particles (units, cracks, elementary cells etc.). These elementary cells, or hysterions, are Preisach's operators $\hat{\gamma}_{P_c,P_o}$. The hysterions can be in closed or open state and parameters P_c and P_o represent the hysterions' closing and opening values ($P_o \leq P_c$). The hysterion can be expressed as follows:

$$\hat{\gamma}_{P_c,P_o}(u(t)) = \begin{cases} -1, & u(t) \leq P_o, \\ 1, & u(t) \geq P_o, \\ k, & u(t) \in (P_o, P_c), \end{cases} \tag{1}$$

where $u(t)$ is an input signal and

$$k = \begin{cases} 1, & \text{if} \quad \exists t^* : u(t^*) > P_c \quad \text{and} \quad \forall \tau \in (t^*, t), \quad u(\tau) \in (P_o, P_c), \\ -1, & \text{if} \quad \exists t^* : u(t^*) < P_c \quad \text{and} \quad \forall \tau \in (t^*, t), \quad u(\tau) \in (P_o, P_c). \end{cases} \tag{2}$$

Applying the input signal $u(t)$, the PM space output $y(t)$ is described and results the integrated stress contribution from the skin, which is composed of a large number of hysterons, which is then expressed as a linear combination of final number of hysterons in the discrete case, $y(t) = \sum_{i=1}^{N} \mu(P_{c_i}, P_{o_i})\hat{\gamma}_{P_{c_i},P_{o_i}}(u(t))$, or in the continuous case $y(t) = \int\int_{P_o \leq P_c} \mu(P_c, P_o)\hat{\gamma}_{P_c,P_o}(u(t))dP_c dP_o$, where $\mu(P_c, P_o)$ is probability function and $u(t)$ is the input signal, and N is the number of hysterons of the PM space. The distribution μ of PM space could be one of the following: random distribution, normal random, Guyer distribution used for PM space characterisation of rocks [18] , or von Mises distribution of fibers [7]. Main task in elasticity PM space modeling is to identify the probability density function $\mu(P_c, P_o)$. The primary goal is to determine the density of hysterons in PM space only from the knowledge of hysteresis curve and the input signal corresponding to the loading protocol.

For the purposes of this study, PM space model can be used to describe the multiscale properties of the porcine skin test object: i) large amplitude, quasistatic deformation is induced by the load frame; and ii) small amplitude, high-frequency wideband deformation is induced by the TR-NEWS ultrasonic testing. In the simplest theory, the hysteresis loops should be self-similar regardless of their amplitude. Supposing that an ultrasonic testing is conducted inside the large-scale quasistatic hysteresis loop, then the corresponding hysteresis loops should look like in Fig. 3. The small scale hysteresis (from ultrasonic measurement) should indicate the density of hysterions near that particular small region (region inside the small hysteresis loop) of the current quasistatic strain and stress.

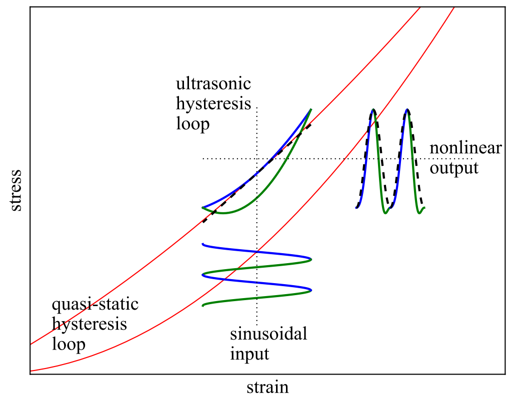

Figure 3: Illustration of acoustomechanical measurement of multiscale hysteresis properties. The material nonlinearity and hysteresis is measured using ultrasonic small amplitude input at the stress and strain level reached with quasistatic large amplitude excitation.

2.3 TR-NEWS signal processing

There has been recent active research on modeling nonclassically nonlinear effects in biomaterials using memory-based phenomenological approaches. Nonclassically nonlinear effects can show aging and degradation in mesoscopic materials and biomaterials (such as teeth [19], skin and bone). TR-NEWS testing method can take advantage of multimodal ultrasonic imaging to study the mechanical properties of materials under the PM model. Nonlinear time reversal methods provide the means to detect, localize and image the structural damage in a complex medium, thanks to the use of advanced signal processing techniques based on multiscale analysis and multimodal imaging. In TR-NEWS the reverberant properties of a test object are advantageous for the signal-processing induced ultrasonic focusing, due to the method relying on internal reflections for the wave focusing process (this is also the reason for shear wave emitting and plane wave receiving transducers). Consequently it is suitable for use in multiscale skin mechanical properties' characterisation.

The first step of the TR-NEWS signal processing is the transmission and reception of a chirp (or broadband) signal in the test object. In this work, the chirp signal span from 0 to 5 MHz linearly. The cross-correlation function between the sent and received signals contains the information of the internal reflections, due to orthogonality of the changing harmonic component of the chirp signal. Thereafter the cross-correlation is time-reversed and resent in the same direction as the chirp. The time-reversal of the cross-correlation (information of internal reflections) produces a wave focusing at the receiving transducer, containing the main signal and its sidelobes. Additional optimization possibilities of the TR-NEWS method are available using delayed TR-NEWS method [9].

In presence of nonlinear effects in the test object, the symmetry breaking of TR-NEWS signal could be measured by the "loss of symmetries". In other words, the sidelobes of the TR-NEWS focused signal could contain the information about the nonlinearities, including hysteresis, in the material properties.

3. Results

Figure 4 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 and also by points in Fig. 5. During each measurement, a precise and discrete time moment is captured 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 shows 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. 4), the skin reaches its elastic limit and starts to slip out of the load frame clamps.

3.1 Hysteresis curves

The test setup allows to compute successfully the true strain and the actual hysteresis curves. Fig. 6 shows the hysteresis curves computed with the strain calculated from the load frame extension versus strain calculated from the video by DIC. It is apparent that 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. 7). This results in smaller true hysteresis curve area, accuracy of which is very important for parameter fitting with PM space theory. 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 used 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 DIC data. The nonclassically nonlinear model can be improved to take into account the viscoelastic effects, such as the relaxation visible in these results. The TR-NEWS measurement points are shown

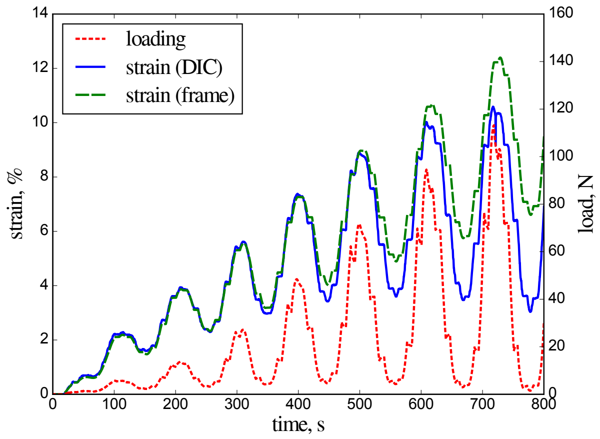

Figure 4: Strain calculated from load frame extension versus strain from DIC and loading of the material

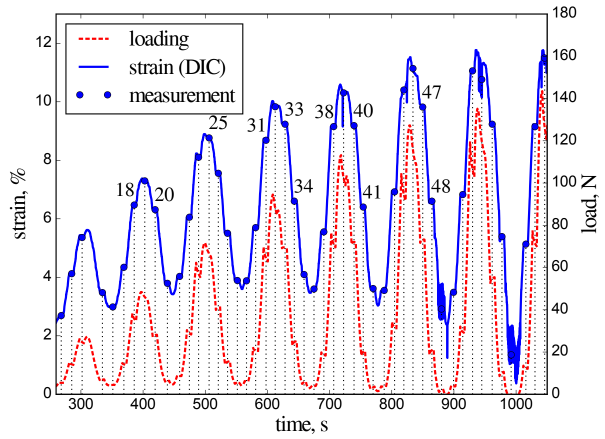

Figure 5: Strain and load at a selection of measurement points

by round markers in Fig. 7. These markers indicate at which load and strain values the multiscale measurements (Section 2.2) are conducted.

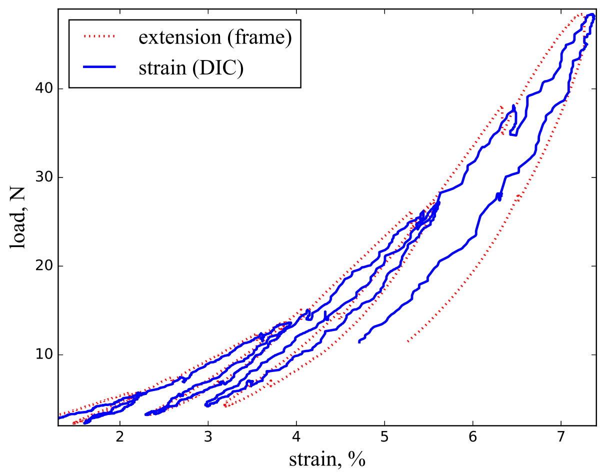

Figure 6: Hysteresis loops using the true strain calculated by DIC, compared with hysteresis from load frame data

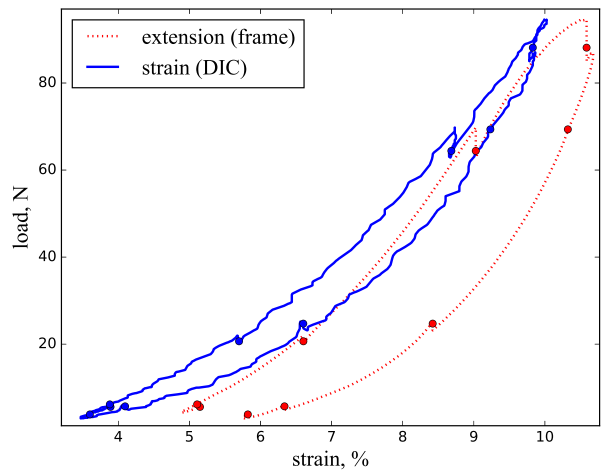

Figure 7: A single hysteresis loop in the test in the timespan from 550 s until 675 s, with round markers showing the synchronization points of TR-NEWS measurements

3.2 TR-NEWS measurements of nonlinearity

In the experiment shown here, 73 TR-NEWS measurements were captured, at various strains and stresses. Fig. 5 shows a selection of these points. Comparing some TR-NEWS measurements taken at approximately the same strain levels (points 18, 20, 34, 41 and 48 in Fig. 5), it can be seen from their TR-NEWS focusing sidelobes in Fig. 8 that as the cycle count of the skin sample increases, 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. 5). Nevertheless the changing stress at constant strain is not what changes the sidelobe amplitude: comparing the TR-NEWS measurements for approximately constant stress (points 25, 31, 33, 38, 40 and 47 in Fig. 5), then again as time and damage increase, the amplitude of the sidelobe part of the TR-NEWS measurements rise (Fig. 9), 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. 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 [9].

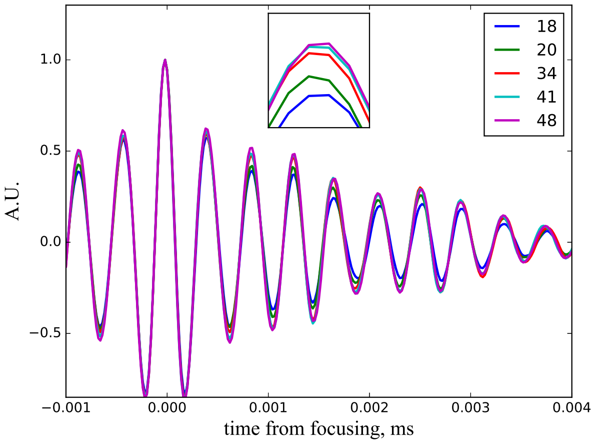

Figure 8: TR-NEWS focusing measurements at roughly the same strain, showing differences

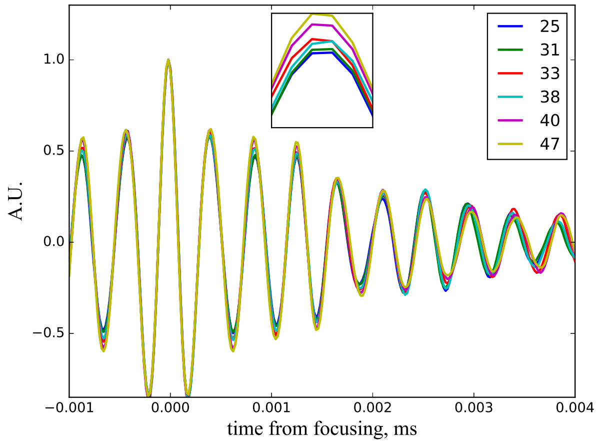

Figure 9: TR-NEWS focusing measurements at roughly the same stress, showing differences

4. Conclusion

A novel fully synchronized acoustomechanical testing setup has been presented here, which links together a load frame with arbitrary extension load path, load measurement, video extension measurement for determining true strain field for the soft test object, and modern ultrasonic nonlinear testing method. This setup allows to measure the nonlinearity, hysteresis, creep and other complex multiscale mechanical properties of the test object in an automated way. The automation of the measurement is useful for the future use of high-speed measurements for determining the statistical distributions of the mechanical properties of the test object. This measurement setup is promising for wide variety of test objects, including skin, and enables to also use other modern ultrasonic testing methods.

The purpose of this work was to present the acoustomechanical measurement system. The full analysis of the measurement results for skin or other complex materials using this system is left for the future. Therefore the results presented here have not yet been optimized and instead serve as demonstration for the multiscale hysteresis experiments which can be conduced on a complex nonclassically nonlinear material, such as skin. Focused experiments are needed to analyse the nonlinearities in the skin sample and characterize the skin tissue fully using statistical PM hysteresis theory.

Possible improvements to the measurement system presented here include controlling all of the measurement equipment by a single computer and solving the synchronization in software, having an option of preselecting the load frame extension or load values at which the TR-NEWS measurements are conducted, and improving the TR-NEWS measurement software to speed up the measurement process to minimize the relaxation effects.

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