Ultrasonic Evaluation of Local Human Skin Anisotropy

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Abstract
Anisotropy level of human skin is typically obtained by multi-axial tensile test, cutometry, elastography, ultrasonic imaging, etc. Most of the methods are time-consuming, expensive, or not suitable for in-vivo measurements. In this paper a new easily-applicable method for immediate evaluation of human skin local anisotropy is described. Results in this area are of great interest in dermatology, plastic surgery, and cosmetics. The method is also utilizable in many industrial applications for anisotropy evaluation of various materials like composites, etc. Proposed system exploits a special flexible multi-directional circular probe with built-in piezoelectric elements (ultrasonic array) for elastic waves propagation measurement. The anisotropy level of the tested structure is determined from directional dependence of elastic wave velocity related with complex elastic modules of the specimen. The method was tested on human skin tissue in-vivo and a composite sample. Comparative tests on isotropic materials were realized to verify the method and system accuracy.

Keywords: Anisotropy, ultrasonic testing, human skin in-vivo, fabric-fiber composite, signal processing

1. Introduction
Anisotropy is a material property describing directional dependence of a physical quantity. Profound knowledge of mechanical properties of human skin, including mechanical and viscoelastic anisotropy, is necessary not only from medical point of view (implants, surgery, diagnostics, etc.), but also for realistic modelling of its behaviour under mechanical stress at various conditions and influences. Quantitative evaluation of complex tissue properties brings better understanding of inter-individual differences, aging processes, cures of diseases, and regenerative therapies [1, 2].

Mechanical behaviour of human skin is derived from elastin and collagen fibres with specific natural orientation. Skin anisotropy is generally described by Langer’s lines, topological lines drawn on the human body, corresponding to the natural orientation of collagen fibres [1, 2]. As the Langer’s lines are well-known, their orientation is not decisive and sometimes it's necessary to determine skin anisotropy for each individual.

Several studies of human skin anisotropy in-vivo and in-vitro were carried out during last decades. The most common method is multi-axial tensile test, mostly combined with elastography or other imaging methods [3, 4]. Other studies are based on characterization of elastic wave parameters [5, 6] or rheological models [7]. Most of the methods are time-consuming, expensive, or not suitable for in-vivo measurements, i.e. don’t respect skin natural tension. Moreover, some of them reflect common anisotropic properties only. For example, cutometry applies a negative pressure to a small area of the skin and measures the directional-dependent elastic displacement of the skin from its initial position and the elastic recovery. Likewise, high-frequency static elastography is performed through-the-thickness of tissue in two different directions to evaluate local mechanical behaviour of the dermis [3].

In this paper a new easily-applicable method for local anisotropy evaluation of biological tissues and various industrial materials (e.g. composites) is presented. The method is based on measurement of ultrasonic wave propagation velocity using a multi-directional flexible probe.
2. Measuring method

Mechanical properties of anisotropic materials are variable in different areas and directions. They can be defined e.g. by Young modulus E or generally by complex elastic modulus, closely related to elastic wave propagation velocity c. Anisotropy level of the material is then determined by measurement of the ultrasonic wave propagation velocity in specific directions. Directional dependence of ultrasonic waves propagation parameters as velocity or attenuation was examined and described in several studies focused on human or porcine skin as well [9].

2.1 Measuring system

A main part of the proposed measuring system is the multi-directional flexible circular ultrasonic probe which enables measurement of the ultrasonic wave propagation velocity in different directions. A relatively small diameter and flexibility of the probe allows measurement of various materials or human body parts. The probe consists of eight ultrasonic PZT (piezoelectric) transducers aligned to the circle of 5 cm diameter as receivers Rx and one transducer in the middle as transmitter Tx. The probe is shown in the figure 1. As the maximum response of the transducers is typically between serial resonant frequency $f_s$ and parallel resonant frequency $f_r$, the sine-train pulse at central frequency $f_c = 300$ kHz were used for ultrasonic waves excitation, according to the impedance-frequency curve (see the figure 2) of the transducers.

Ultrasonic wave propagation velocity is measured in each of all possible directions defined as a path between Tx and Rx. All the signals are sampled using high-speed NI PXIe 8-ch digitizer (60 MSamples/s) and averaged in order to increase signal-to-noise ratio (SNR). The overall scheme of the measuring system is shown in the figure 3.
In order to increase number of the velocity measurement points, the probe was rotated and additional eight points measured completing the resulting anisotropy diagram. The diagrams are then composed of 16 values measured in different paths evident in the figure 3.
2.2 Probe calibration

The velocity of ultrasonic wave propagating along the specific path \( i \in \{1, 16\} \) is given by the equation

\[
c_i = \frac{d_i}{t_i - t_d} \quad \text{(m} \cdot \text{s}^{-1})
\]

where \( d_i \) is the distance between Tx and Rx in the specific path, \( t_i \) is the measured time-delay between sine-train pulse excitation and wave arrival-time, and \( t_d \) is the additional delay given by measuring system, components, and PZT transducers.

The arrival-time of specific wave-propagation-mode is detected in all measured signals using the threshold-value-detection method. As the ultrasound is propagating in layered media (e.g. human skin or composites) as guided or dispersion waves, the first significant mode in the measured signals recognized as longitudinal wave-mode is used for arrival-time detection (see the figure 4).

In order to demonstrate accuracy of the method and the probe, test on isotropic material was performed. We measured anisotropy diagram of polymethylmethacrylate (PMMA) plate of 5 mm thickness in x and y orientation (see the figure 5). The resulting diagram and used PMMA sample are shown in the figure 5 where the green line demonstrates the axis of probe orientation on the sample.

3. Results

The method and multi-directional probe were tested on three volunteers of different gender and age. We measured anisotropy of the forearm skin of all volunteers on both left and right forearms. The resulting diagrams are shown in the figures 6–8 where the green line demonstrates the longitudinal forearm axis.

Measurements on industrial materials were also performed. In the figure 9, the resulting anisotropic diagram for composite sample composed of 10 synthetic layers of carbon-fabric prepreg EP121-C20-45 [0, 90] is shown. Composite sample dimensions: (345 x 345 x 2) mm. The sample was measured in x and y axis orientation, in the figure demonstrated by the green line.
For all the anisotropy diagrams we enumerated the relative anisotropy $A_r$ which is given by the equation

$$A_r = \frac{c_{\text{max}} - c_{\text{min}}}{\bar{c}} \cdot 100 \quad \text{(\%)}$$

where $c_{\text{max}}$, $c_{\text{min}}$, and $\bar{c}$ are the maximal, minimal, and average values of ultrasonic wave propagation velocity obtained in the anisotropy measurement. All the relative anisotropies are summarized in the table 1.

### 3.1 Measurement accuracy

Each measurement was performed three times and the resulting diagrams shown in figures 6–9 represent the values of all measurements and the average. Variation coefficients of wave propagation velocity $v_c$ were also calculated using the equation

$$v_c = \frac{\sum \sigma_i}{\sum \bar{c}_i} \cdot 100 \quad \text{(\%)}$$

where $\sigma_i$ is the standard deviation and $\bar{c}_i$ is the average propagation velocity of three measurements in specific path $i$. Variation coefficients for all anisotropy measurements are summarized in the table 1.

| Table 1. Summary of resulting relative anisotropies and equivalent variation coefficients |
|-----------------------------------------------|----------------|----------------|
| Human skin                                    | Left forearm   | Right forearm  |
|                                               | $A_r$          | $v_c$          | $A_r$          | $v_c$          |
| Man 27 years                                  | 13.6 %         | 0.5 %          | 15.0 %         | 0.4 %          |
| Woman 23 years                                | 15.1 %         | 0.2 %          | 21.3 %         | 0.1 %          |
| Man 69 years                                  | 14.7 %         | 0.3 %          | 9.1 %          | 0.3 %          |
| Composite                                     |                |                |                |
| x axis orientation                            | $A_r$          | $v_c$          | $A_r$          | $v_c$          |
| Carbon-fabric plate                           | 17.8 %         | 0.5 %          | 17.1 %         | 0.4 %          |
Figure 6. Anisotropy diagram of forearm skin: man 27 years, skin thickness 1.9 mm (left diagram ≡ left hand, right diagram ≡ right hand)

Figure 7. Anisotropy diagram of forearm skin: woman 23 years, skin thickness 1.3 mm

Figure 8. Anisotropy diagram of forearm skin: man 69 years, skin thickness 2.4 mm
4. Discussion

On the basis of resulting anisotropy diagrams obtained by measurement using the presented method and multi-directional probe it’s evident that the human skin embodies high anisotropy related to orientation of collagen fibres in the dermis. The anisotropy trend of all the diagrams was the same according to the well-known Langer’s lines but the diagrams are different due to differences in gender, age, skin thickness, and even in comparison of left and right forearms. Asymmetry of some anisotropy diagrams shows that the results obtained are dependent on the exact place where the measurement is performed. The results are supported by fact that the skin structure and mechanical behaviour is rather complicated and still requires further investigation.

It's obvious that the proposed measurement method enables local anisotropy evaluation of various biological or industrial materials with sufficiently accurate results. Composite plate resulting diagrams show clear anisotropic behaviour evoked from typical composition of composite materials. Accuracy of the resulting diagrams could be affected by ultrasonic wave frequency used due to high dispersion of the waves propagating in the layered media as composites and human skin.
Evaluation of anisotropy based on the ultrasonic wave attenuation instead of velocity was also tried out but this technique is highly dependent on sensitivity of the PZT transducers, amount of ultrasonic coupler used and pressure applied on the probe during measurement.

5. Conclusion

A new measurement method for local anisotropy evaluation of various biological or industrial materials was presented in this paper. The method was tested on human skin in-vivo and carbon-fabric-fiber composite sample. Advantage of the method is in its fast, local, easy-to-use application with respect to instantaneous and/or natural states of measured specimen.

Based on the results obtained on the human skin it's obvious that anisotropy of the skin is different for each individual across gender, age, and other conditions. Noninvasive in-vivo measurement of human skin anisotropy provides useful determination of skin changes, e.g. degradation and damages caused by environmental influences.

Presented results of skin tissue anisotropy are promising for further use in medicine, plastic surgery, and also in industrial applications. Further human skin anisotropy investigation should support an explanation of biomechanical and acoustical properties affected e.g. by ageing, diseases, and surgical interventions.

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References
