ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

VIBRATIONAL VISCOELASTOMETRY OF BIOLOGICAL SOFT TISSUES

Evgeny M. Timanin[1], Evgeny V. Eremin[1], and Igor N. Didenkulov*[1]

[1]Institute of Applied Physics, Russian Academy of Sciences
46 Ul'yanov Str., Nizhny Novgorod, 603950, Russia
eugene@appl.sci-nnov.ru

Abstract

Vibrational computer-based technology is presented providing measurement of elasticity and viscosity parameters of soft biological tissue by the hand-held probe on the basis of dynamic stiffness and mechanical impedance registration in experiments on tissue touching by a vibrating disk. A review is made of experimental means developed for this purpose as well as of acoustic models suitable for experiments interpretation.

INTRODUCTION

It is well known that characteristics of shear elasticity of biological soft tissues are very sensitive to their structure and condition [13]. A number of ways of tissues structure visualization are in active development in the last years based on their elasticity mapping [12]. At the same time, traditional measurements of mechanical characteristics of tissue stay to be vital for characterization of its condition affected by various physical, physiological or medical factors. One of the most suitable ways of measuring the mechanical parameters of tissues seem to be a way based on registration of dynamic mechanical characteristics of tissues (dynamic stiffness K and mechanical impedance Z) when touching them by vibrating disk. This approach has a long history [5, 6, 10, 11, 14 and 26] but it is receiving now new impacts for development due to computer-based technologies. First of all computer-based measuring devices allow to perform real-time processing of signals coupled with averaging, that increases greatly the reliability of measurements. Secondly, computer-based post processing of registered data is possible including parameters identification of various models of testing objects. A cycle of theoretical and experimental works related to this approach, named as "vibrational viscoelastometry", was performed during the several last years in the IAP RAS [2, 3, 16-25]. A review of these works is a goal of this report.

MEASURING MEANS

The main section of works is an experimental means development for the measurements of mechanical parameters of soft biological tissues, including alive surface tissues of humans. The first experiments with registration of impedance characteristics of biological tissues [16, 17] were performed on the stationary laboratory setup (*Fig.1*), based on vibration-exciting and vibration-measuring equipment of the Bruel & Kjer company, firstly by the method of single-frequency vibration excitement, then by the method of noise-type vibration excitement and registration of frequency dependencies by the facilities of spectra analyzer. For the expansion of the experimental studies outside of laboratory the portable electronic devices (*Fig.2*) were built subsequently [18], realizing the method of single-frequency measurement of impedance characteristics and their temporal dynamics monitoring in the course of various processes. Else later the PC-based devices were built, realizing such measurements by means of signals processing over the period in specialized programs [19, 20, 22].

Figure.1 - "Vibrostend" Laboratory set

Figure.2 - Vibrational Viscoelastometer

Figure.3 - Myoviscoelastometer

The PC-based device of the first generation (*Fig.3*) used the probe VD-1 (*Fig.4a*), the ISA interface card and operated in the MS DOS. The PC-based device of the second generation (*Fig.5*) used the modified probe VD-2 (*Fig.4b*) and modified algorithms of signals processing, but the same ISA interface card, restricting its operation by the desktops with ISA bus and by Windows 95/98/ME. The probe includes vibration exciter and sensors of force and acceleration, supplying signals to determine dynamic stiffness and mechanical impedance.

On the base of VD-2 signals acquisition through the *Line IN* input of the standard sound card the PC-based device "Spectra Recorder" (*Fig.6*) was built [2, 3, 21, 24]. It realized registration of frequency dependencies of impedance characteristics through noise-type vibrations production and signals spectral processing.

a) *b)* *c)*

Figure 4 – Probes for Vibrational Viscoelastometry:
a) the probe VD-1; b) the probe VD-2; c) the probe VD-3M.

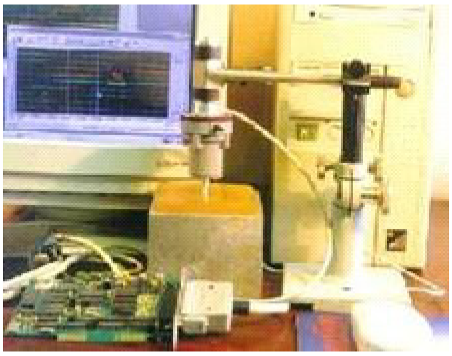

Figure 5 -
Viscoelastograph VEM-2

Figure 6 -
Spectra Recorder

The modern PC-based devices of the third generation for the "Temporal Dynamics Recording of Mechanical Impedance and Dynamic Stiffness" (*Fig.7*) and for the "Spectra Recording of Mechanical Impedance and Dynamic Stiffness" (*Fig.8*) use the probe VD-3M (*Fig.4c*) and USB or Line IN interfaces, providing their operation on portable computers in any Windows. Frequency dependencies of stiffness and impedance are recorded in the range 30 – 300 Hz and temporal dynamics of these parameters is recorded with resolution less then 0.1 of second.

Figure 7 -
Viscoelastograph "TDR MIDS"

Figure 8 -
Spectra Recorder "SpR MIDS"

The measurements by the devices of the first generation were performed when the probe was placed on a tissue surface and the pressure of the probe to tissue was defined by the probe weight. The measurements by the devices of the second generation were performed when the pressure batching was realized by the external mechanical devices – spring-based (*Fig.5.*) or lever-based (*Fig.6.*). The essential advantage of the third generation devices is availability of electronic system for pressure batching of the probe to tissue, providing possibility of the stable measurements by the hand-held probe.

THEORETICAL MODELS

To determine viscoelastic parameters of tissues from the results of mechanical impedance and stiffness registration in experiments on vibrating disk indentation a suitable acoustical model is necessary. Four main approaches to such model development can be found in the literature currently. The first approach [6, 10, 11, 17 and 26] is based on the approximate replacement the impedance of round flat disk, vibrating over a tissue surface, by the equivalent sphere, oscillating inside the boundless medium. The second approach [16] is based on using the expressions for the steady-state indentation of a disk into the uniform half-space and can be approximately correct only in the case of quasi-static disk motion. The third approach [7, 14] is based on the strict formulation of the dynamic contact problem of disk vibration over the tissue surface. The fourth approach [3, 8, 21, 23 – 25, 26] is related to formulation of this dynamic contact problem in the approximation of "a pressure source of vibrations".

Soft tissues are considered as a uniform half-space in the papers [6, 10, 11, 16, 17, 26] and as a uniform layer, bound up with the rigid base and sliding relative to the disk, in the papers [3, 7, 21]. In the paper [8] soft tissues are considered as an uniform layer, sliding relative to the disk and bound up with the hard half-space, deformable but much more stiff then soft tissues (bone). In the paper [14] the models of tissues are built in the form of a layer constructed as a set of sub-layers (one, two or three), bound up with each other, with the rigid base and with the disk. In the papers [21, 24] such models are used within the framework of the approach of "a pressure source of vibrations" at the condition of disk sliding relative to the tissue surface.

The basis of the third and the fourth approaches is developed in the dynamic theory of elasticity [1, 4, 9, 15]. Both they are based on the general solution of the dynamic equations of linear elastic solids in the case of axial symmetry, by means of transition to the scalar and vector potentials and the Hunkel transform using. Distribution of normal stresses (and shear stresses sometimes) is considered unknown within the "strict" approach in the region of the disk contact with the surface. Impedance characteristics are expressed here through the solutions of integral equations. The distinction of the approach of "a pressure source of vibrations" is taking approximate boundary conditions on the medium surface: normal and shear stresses are considered as known on the whole surface, including the region under the disk. Shear stresses are considered equal to zero (the sliding disk). Normal stresses under the disk are taken equal to the external pressure, distributed uniformly or in a more complicated way [7, 15]. The surface displacement under the disk center, or mean value of the surface displacement under the center and under the edges of the disk, or the surface displacement averaged over the disk area are taken as a disk displacement [7, 9, 15].

Comparison of calculations in the model "with a pressure source of vibrations" [9] and in the model of "equivalent oscillating sphere" [6] with the experiments on a tissue phantom from gelatin and with the results of finite-element analysis show [26] that the first-type model is the least accurate. It was also shown in [3, 21] that such models (even when a number of soft tissue layers increases up to three) do not manage to reproduce completely all distinctive features of experimental curves. In particular, they do not reproduce the slope of decline of the stiffness real part with the frequency increase.

To increase accuracy of models “with a pressure source of vibrations” a finite friction between the disk and tissues was taken into account in the paper [25], i.e. the assumption was accepted that the disk creates known distribution of shear stresses in the contact region together with the normal pressure. Shear stresses (σ_{rz}) in this case are taken equal to zero outside of the contact region and are taken proportional to the normal stresses (σ_{zz}) inside this region (in accordance with the Coulomb’s law)

$$\sigma_{rz} = \alpha\sigma_{zz} . \tag{1}$$

Factor α here has a sense of static friction coefficient or even the adhesion factor between the disk and the tissue surface. These models were named as PSVF-models – from “a Pressure Source of Vibrations with Friction”. In the boundary condition sets, corresponding to the PSVF-models, in comparison with the models without friction (PSV-models), the only equation was changed – that for the shear stresses on the surface. This complication of the models is not fundamental because the problem solution will be still reduced to the solution of an algebraic equation set, constituted of the boundary conditions, and to integration of known function, though a bit more complicated. PSVF-models keep thus their advantages over the “strict” models in simplicity and speed of tissue parameters reconstruction from the experimental spectra of impedance characteristics. The expression of complex stiffness of layered tissues K can be found on the basis of general expression for axial displacement of tissue surface (U_z), similarly to expressions for displacements inside the medium in the paper [23]

$$U_z(r,-H_1) = \int_0^\infty W_z^0(k,-H_1)kJ_0(kr)dk . \tag{2}$$

The upper index 0 here corresponds to the order of Hunkel transform; k is a parameter of Hunkel transform; J_0 is the Bessel function of zero order; H_1 is the thickness of the first layer; $z = -H_1$ is the coordinate of tissue surface. The general expression for stiffness obtained from (2) has the following form

$$K = \left(\int_0^\infty [(\mathbf{X}^{-1} \cdot \beta) \cdot \mathbf{Y}] R(k) dk \right)^{-1} . \tag{3}$$

Here $\mathbf{X}^{-1}$ is an inverse matrix of coefficients of boundary condition set; β is a normalized vector of equations right parts (its first element is 1, the second element is α, the rest elements are zeroes); $\mathbf{Y}$ is a coefficients vector, corresponding to the solution for Hunkel image of the surface displacement $W_z^0(k,-H_1)$; $R(k)$ is the known function, determined by the pressure profile under the disk and by a measure of its displacement. In the case of choice the axial surface displacement averaged over the disk area as the measure of disk displacement this function has the form:

$$R(k) = -\frac{2}{\pi a^2 \mu_1} \frac{J_1(ka)^2}{k} \text{ or } R(k) = -\frac{1}{\pi a^2 \mu_1} \frac{J_1(ka)\sin(ka)}{k} , \tag{4}$$

accordingly to the case of uniform or hyperbolic pressure distribution

$$p_z = P/\pi a^2 \quad or \quad p_z = P/\pi a^2 \sqrt{a^2 - r^2}, \quad r \le a. \tag{5}$$

Results of calculations on formulas (3) - (5) in *MathCAD 2000* package for one-layer PSVF-models are shown on *Fig.9*, where the results of calculations in some other models are shown also for comparison. It is seen clearly that taking friction into account in the models “with a pressure source of vibrations” improves greatly their accordance with the experiments.

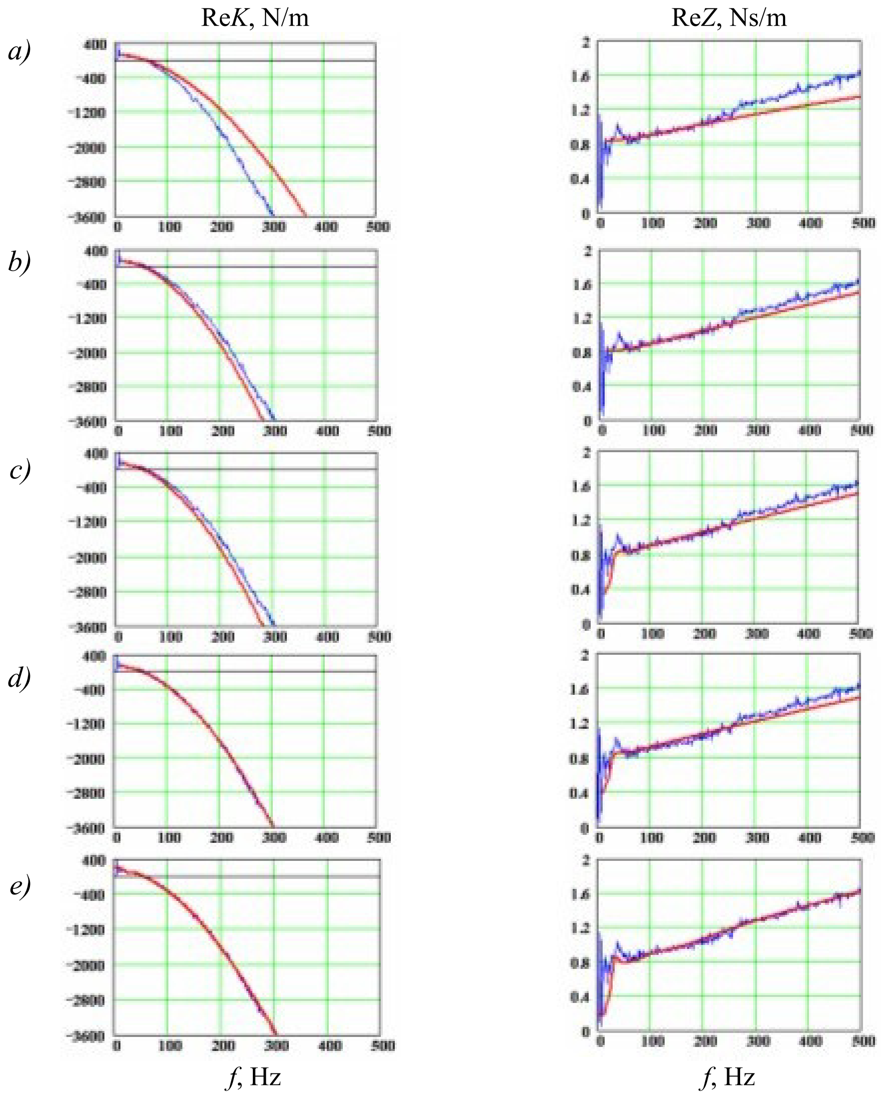

Figure 9 – Frequency dependences of impedance characteristics. Experimental curves on all graphs correspond to the measurements by the disk d = 16 mm on the relaxed forearm. Calculated curves correspond to the following models: (a) – to equivalent oscillating sphere (μ = 1.8 kPa, η = 3.3 Pa·s); (b) – to PSV with uniform pressure profile under the disk on a half-space (μ = 1.8 kPa, η = 3.3 Pa·s); (c) – to PSV with uniform pressure profile under the disk on a layer (μ = 2.2, kPa, η = 4.0 Pa·s, H = 29 mm); (d) – to PSVF with uniform pressure profile under the disk on a layer (μ = 2.2, kPa, η = 4.7 Pa·s, H = 29 mm, α = 0.3); (e) – to PSVF with hyperbolic pressure profile under the disk on a layer (μ = 2.2, kPa, η = 2.0 Pa·s, H = 29 mm, α = 0.2).

SUMMARY

A technology is developed to measure elasticity and viscosity parameters of soft biological tissue on the basis of dynamic stiffness and mechanical impedance registration in experiments on tissue touching by a vibrating disk, including PC-based measuring means and acoustic models for experiments interpretation. The first type of devices developed is based on noise-type vibrations production as well as on signals acquisition through the *LineIN* input of PC sound card and their spectral processing. The second type of devices developed is based on harmonic vibrations production as well as on signals acquisition through the *USB* input of PC and their processing over the period. Acoustical models developed of vibrating disk interaction with tissues are based on the approximate approaches "pressure source of vibrations" and "pressure source of vibrations with friction". They regard testing tissue as a half-space, as a single layer on a rigid base or as a double layer on a rigid base.

REFERENCES

1. B.A. Babeshko, E.V. Glushkov, Zh.F. Zinchenko, *Dynamics of inhomogeneous linear-elastic media*, (Moscow, Nauka, 1989)
2. E.V. Eremin, E.M. Timanin, "Software-hardware complex for spectra registration of mechanical impedance of biological tissues", Nizhny Novgorod Session of Young Scientists V. Abstracts collection, 42-43 (N.Novgorod, 2000).
3. E.V. Eremin, E.M. Timanin "Interpretation of a Layer Mechanical Impedance Measured Using a Hard Round Die", Acoustical Physics, **46**, 421-426 (2000)
4. W.M. Ewing, W.S. Jardetsky, F. Press, *Elastic waves in layered media* (New York, Toronto, London, Mc Graw-Hill book, 1957)
5. E. Franke, "Mechanical impedance of the surface of the human body", J. of Appl. Physiol., **3**, 582-590 (1951)
6. H.E. von Gierke, H.L.Oestreicher, E.K. Franke, H.O. Parrack, W.W. von Wittern, "Physics of vibrations in living tissues", J. Appl. Physiol., **4**, 886-900 (1952)
7. E.V. Glushkov, N.V. Glushkova, E.M. Timanin, "Impedance and waveguide properties of organic tissues", Acoustical Physics, **39**, 551-553 (1993)
8. B.N. Klochkov, A.V. Sokolov, "Waves in a layer of soft tissue overlying a hard-tissue half-space", Acoustical Physics, **40**, 270-274 (1994)
9. G.F. Miller, H. Pursey, "The field and radiation impedance of mechanical radiators on the free surface of a semi-infinite isotropic solid", Proc. R. Soc. Lond. Ser. A, **223**, 521-541 (1954)
10. H. Oestraeicher, "Field and impedance of oscillating sphere in a viscoelastic medium with an application to biophysics", J. Acoust. Soc. Am., **23**, 707-714 (1951)
11. H. Oka, T. Nakamura, "Estimation of internal structure and viscoelasticity from mechanical impedance", Electrical Engineering in Japan, **125**, 31-39 (1998)
12. J. Ophir, S.K. Alam, B. Garra, et al., "Elastography: Ultrasonic estimation and imaging of the elastic properties of tissues", Proc. Inst. Mech. Eng. [H], **213**, 203-233 (1999)
13. A. Sarvazyan, *Elastic Properties of Soft Tissue. In: Handbook of Elastic Properties of Solids, Liquids, and Gases, edited by Levy, Bass, and Stern. V.III: Elastic Properties of Solids: Biological and Organic Materials, Earth and Marine Sciences*, 107-127 (Academic Press, 2001)

14. A.R. Skovoroda, S.R. Aglyamov, “Reconstruction of the elastic properties of layered viscoelastic media using impedance measurements”, Biophysics, **43**, 348-352 (1998)
15. *Theory of contact problems development in USSR*, 326-330 (Moscow, Nauka, 1976)
16. E.M. Timanin, “Prospects for measuring the rheologic characteristics of human soft tissues based on the recording of their transverse rigidity”, Biophysics, **34**, 512-516 (1989)
17. E.M. Timanin, “On contribution of shear waves into a transverse stiffness of soft biological tissues in vibrating indentor investigations”, 13 International Congress on Acoustics, **4**, 215-218 (Belgrade, 1989)
18. E.M. Timanin, V.A. Antonets, A.V.Shishkov, et al. “The device for determination of viscoelastic characteristics of soft tissues”, Patent 2082312 Russia (1997)
19. E.M. Timanin, “Possibilities of myotonography”, Meditsinskaia Tekhnika (Biomedical Engineering), 2, 39-41 (1998)
20. E.M. Timanin, A.M. Reyman, E.V. Eremin, “Software-hardware complexes for studying the impedance characteristics of biological soft tissues”, The Second Congress of Biophysicists of Russia, Abstracts, 626-627 (Moscow, 1999)
21. E.M. Timanin, “On the possibilities of impedance characteristics description of biological soft tissues in the models with the pressure source of vibration”, Pre-print IAP RAS N 488, 1-32 (Nizhny Novgorod, 1999)
22. E.M.Timanin, E.V. Eremin, “Monitoring of Biceps Characteristics in Sustained Isometric Contractions by the Methods of Impedance Mechanomyography and Electromyography”, Acta of Bioengineering and Biomechanics, **4**, Suppl. 1, 616-617 (2002).
23. E.M. Timanin, “Displacement Field Produced by a Surface Source of Vibrations in a Layered Biological Tissue”, Acoustical Physics, **48**, 87-93 (2002)
24. E.M. Timanin, E.V. Eremin, “Interpretation of Mechanical Impedance of Biological Tissues in the Three-Layered Model with the Pressure Source of Vibrations”, Biophysics, **48**, 324-331 (2003)
25. E.M. Timanin, E.V. Eremin, “Interpretation of Impedance Characteristics of Biological Soft Tissues in the Models with a Pressure Source of Vibrations with Friction”, Proceedings of the XIII Session of the Russian Acoustical Society, **V.3**, Speech acoustics. Medical and biological acoustics, 175-179 (Moscow, GEOS, 2003)
26. X. Zhang, T.J. Royston, H.A. Mansy, R.H. Sandler, “Radiation impedance of a finite circular piston on a viscoelastic half-space with application to medical diagnosis”, J. Acoust. Soc. Am., **109**, 795-802 (2001)