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Dynamic interaction of fingertip skin and pin of tactile device

Vytautas Grigas*, Rymantas T. Tolocka, Pranas Ziliukas

Department of Engineering Mechanics, Kaunas University of Technology, A. Mickeviciaus 37, LT-44244 Kaunas, Lithuania

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Abstract

The present paper deals with investigations performed with the aim to study transmitting tactile information into the area of mechanoreceptors of the fingertip skin segment and to estimate the dynamic properties and behavior of the skin by performing numerical analysis. A computational finite element model consisting of four main layers of skin was used for transient analysis of contact dynamic interaction when loading the skin by a moving pin, as well as for modal analysis of skin and analysis of skin stress–strain state under harmonic loading (a plane strain case was studied). Material properties of the skin were assumed as linear elastic because of a very small excitation signal level. The efficiency of the regime of the skin dynamic loading in terms of the tactile signal level was defined on the basis of the strain level in the dermis zone where mechanoreceptors are placed. The possibilities of using vibratory control signal were analyzed.
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1. Introduction

The recent developments in industry and technology have enhanced people's requirements for information availability. One of the challenges is to satisfy the need of information for the blind and visually impaired people in order to integrate them into society. Tactile devices are used for this purpose.

Initially, tactile devices were applied in information transmission for military needs, but later their application expanded to other areas, such as civil aviation training, game industry, medical and scientific research, etc. In the second half of the twentieth century they were successfully introduced to serve the needs of visually impaired people.

Tactile devices excite deformations of finger skin and the information is transmitted by skin mechanoreceptors. Their working frequency range is wide, control and conditioning of the transmitted information is easy. They can be easily connected with additional devices.

Numerous studies have been performed on tactile sensation of human beings and tactile information transmission methods, and a lot of devices have been proposed. However, designing not expensive devices with relevant spatial resolution and operation speed with the simplest possible control systems still remains a considerable challenge to researchers.

*Corresponding author. Tel.: +370 37 323199; fax: +370 37 323876.
E-mail addresses: vytautas.grigas@ktu.lt (V. Grigas), tadas.tolocka@ktu.lt (R.T. Tolocka), pranas.ziliukas@ktu.lt (P. Ziliukas).

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A device introducing a new approach to tactile information transfer systems is presented and the results of its study are described in the present paper.

2. Tactile devices for information transmission

The systems of tactile information transmission (tactile interfaces) are systems aimed at transferring tactile information when a person touches the elements of the moving drive of the system. The first important step in developing such systems of written information transmission was the invention by Braille in 1824, which has been improved and used up to now. Along with quick development of computer technology, the Braille system became the general tool for information exchange and communication of visually impaired and partially sighted people (Fig. 1). At the moment, one of the most widely spread branches of tactile mechanism appliance is the display of Braille on a flat surface. Letters are transformed into Braille code, printed on special paper and then read by blind persons. This is made by a brailler—a device that is aimed to create rises on the sheet of paper. One of the first devices of this kind was Hall brailler. Currently there are a lot of players in the market that intend to make a small, cheap, easily portable device that can be used as a quick note-taker, but retaining the regular Braille keyboard requiring no specialized instruction. One of the latest braillers is Jot-a-dot. With the standard 6 dot Braille keyboard, Jot-a-Dot enables regular Braille writing from the left to the right side of the page, eliminating the major shortcoming of all slate and stylus devices. This device enables users to check what they have just written and to start writing again from exactly the same position where they stopped.

Alternative devices to transmit written information are those using sound. The prevalent software tool for the blind people is JAWS^{TM} [1]. Visually impaired or blind people can easily use the computer without a display and access the internet with only this software. This is available with the software that translates all the text information into the human speech. The process starts when the cursor is placed where text information is written. The information is sent through the text to sound converter and is translated into speech and finally is sent to the computer sound system and from the loudspeaker the user can hear a human voice.

It is a very complicated task to deliver graphic information in a sonic way, and tactile systems are the only practical tools. Graphic information can be transmitted only by tactile displays and mechanisms. Graphic information from a computer can be received by running with a mouse through images which are encoded with appropriate codes and transmitted to the tactile mechanism. Therefore, displays of such kind are installed on the computer mouse.

Nowadays, a lot of investigations and explorations are executed in the area of developing tactile information transmission systems, but still there is no clear, inexpensive and universal method to transmit information of various kinds for the blind and visually impaired.

From the technological point of view, tactile stimulation of the skin may be accomplished in several ways. Solutions based on mechanical needles actuated by electromagnetic technologies (solenoids, voice coils),

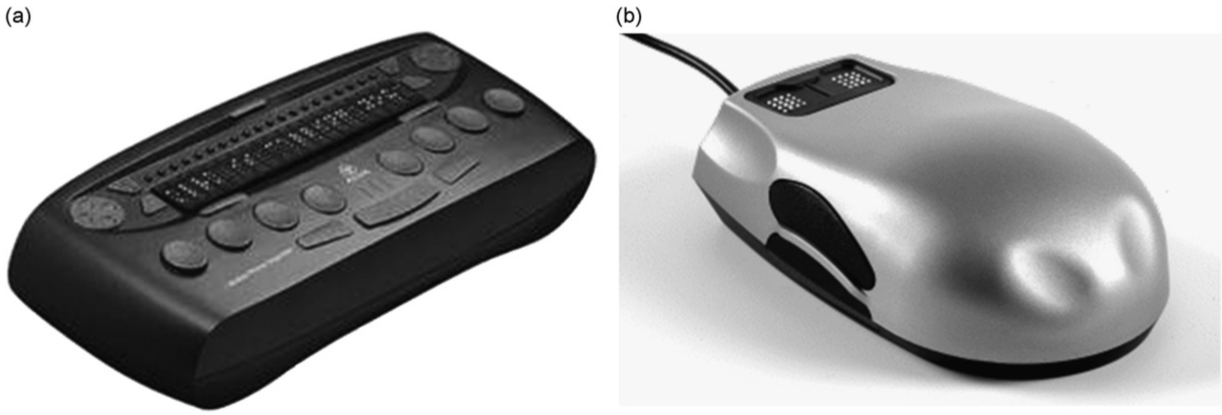

Fig. 1. Modern tactile devices: (a) ALVA MPO mobile phone for blind and visually impaired; and (b) VT Player—multifunctional device for interaction with computer.

piezoelectric crystals, shape memory alloys, pneumatic system, and heat pump systems based on Peltier modules have been proposed [2–4]. However, there exists an obvious need for further development and especially for devices which would be able to access the computer and give blind operators a tactile response to the depicted graphical data.

3. New approach to tactile devices for information transmission

A new method of transmitting written and graphical information in a tactile way and a patented tactile system [5] for its implementation has been developed at Kaunas University of Technology. It is based on the tactile device whose drive is schematically presented in Fig. 2a. The device is installed in the computer mouse 1 and consists of electromagnets 2 with pins 3, which are joined to the mouse body in parallel by springs. The operator moves the mouse with finger 4 placed on the pin protruding from the gap on the top of the mouse. Every electromagnet is magnetized to the metallic plate 6 when current occurs in its winding 5.

The operating principle of the proposed tactile system is described as follows. When the cursor on computer 2 monitor 1 (Fig. 2b) appears in the area which contains any information, signals pass the control block 3 and current occurs in one or several windings of the device electromagnets, thus magnetizing them to the metallic plate 5 on which mouse 4 is placed. The electromagnets then are fixed, but the mouse is moving, and the operator feels the relative motion of the pins with regard to the mouse body. The signals disappear and the electromagnets move with the mouse body, and no tactile signals are transmitted when the cursor moves on the clear area of the monitor.

4. Investigation of the law of motion of the pin of the tactile device drive

The tactile device drive operates according to the given signal from the control unit. When the electromagnet gets a signal, it is attracted to the surface on which it is laid, and it moves freely when there is no control signal. The quantity and accuracy of the transmitted information depend on the law of the pin motion. Investigations of tactile device pin dynamics were carried out to define this law. The goal was to characterize the pin motion of the device as a function of influencing control factors. Experimental methods were used for it because the pin motion is dependent not only on mechanical but also on electric circuit and its control parameters, therefore it is problematic to achieve the goal by theoretical methods.

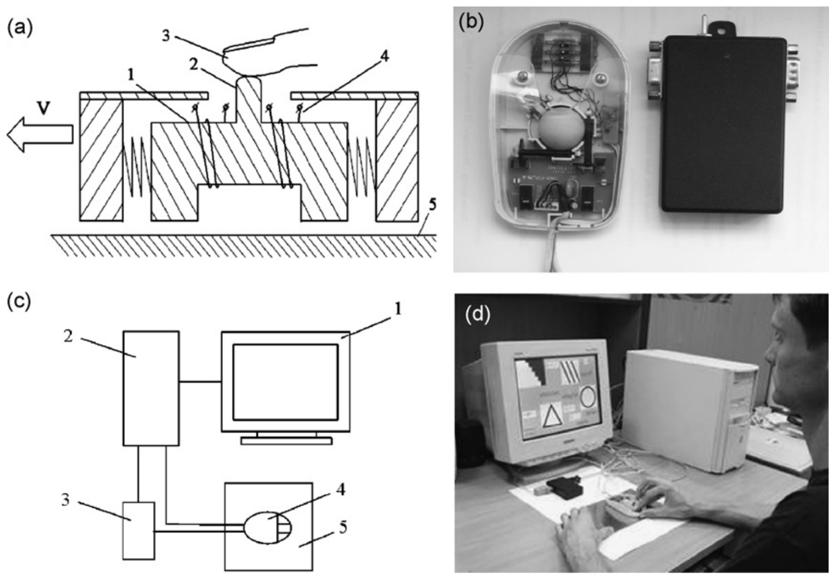

Fig. 2. Tactile information transmission system: (a) scheme of the tactile device drive, (b) mouse with tactile device and control block, (c) block scheme of the tactile system, and (d) system in operation.

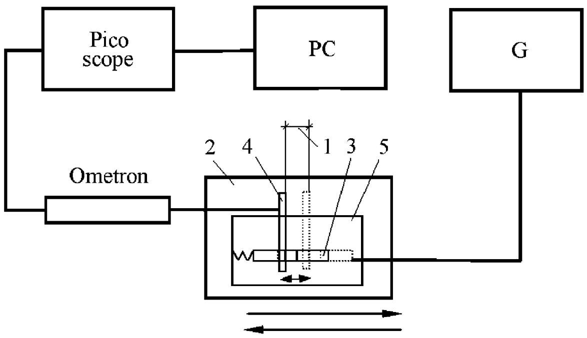

Fig. 3. Scheme of the pin motion investigations.

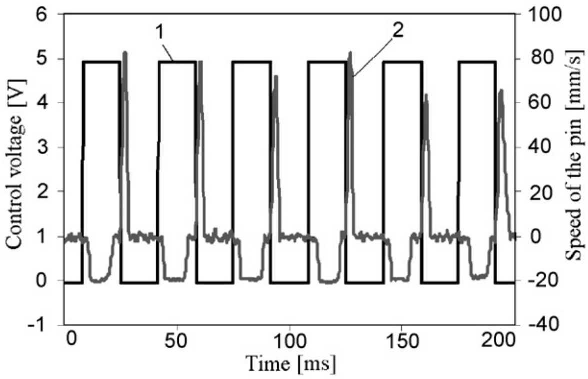

Fig. 4. Law of the pin motion: 1—control signal, 2—pin's law of motion.

The scheme of measurements is shown in Fig. 3. It consists of personal computer PC, data acquisition and processing device *Picoscope* and laser vibrometer *OMETRON VII300*. Mouse 5 with a tactile device in its body was placed on surface 2 moving with constant velocity, thus imitating search motion of an operator. Mirror 4 was secured to electromagnet 3 of the pin. The laser ray signal directed to the mirror was used to measure the velocity of the pin. Periodical signals from generator G were used to control the electromagnet.

The pin's law of motion (Fig. 4) of the experimental device was examined and the measurements were performed at different values of the control signal frequency, voltage, impulse width and shape [6].

It was proved that the tactile device is functioning properly only when the surface on which it is laid is clear and dry and the directions of the drive and movement of the device are strongly parallel. The stroke of the pin of the experimental device was within the range from 0.32 to 5 mm, and the lower value was sufficient to transmit the tactile information. The amplitude would not be less that 1 V, because the electromagnet is not sufficiently magnetized to the surface for proper operation.

The study of the experimental device has shown that the optimal parameters of the control signal are: the frequency range of 15–25 Hz, the voltage from 4 to 5 V, the shape of the control signal—square, the pulse length of the control signal—50 percent. The load has naturally a strong impact on the operating conditions but it can be kept optimal when the operator becomes experienced enough.

5. Dynamics interaction of fingertip skin and pin

The human skin is a multilayered structure consisting of layers of epidermis, dermis and hypodermis, having quite different material properties, with mechanoreceptors reacting to the tactile signals placed in it (mostly—in the dermis layer). The intensity of the tactile signal, which is transmitted to the operator's fingertip skin mechanoreceptors depends on skin deformation, this in turn depending on dynamic properties of the skin and parameters of excitation process. Investigations of the tactile signal transmission are carried out nowadays [7,8], providing general information useful for tactile devices and robots grip design. The proposed original tactile device design requires investigation, which corresponds to its specific needs.

The goal of the study of the biomechanical system consisting of the fingertip skin and the tactile device pin was to estimate the dynamic properties and behavior of the skin and to perform the skin strain–stress analysis in response to the mechanical and the operating regime parameters of the moving pin. Two types of problems were solved during the analysis of the dynamic interaction of the fingertip skin and the pin of the tactile device:

- transient analysis of contact interaction of the skin and a sliding pin;
- modal and harmonic response analyses of the skin segment.

The analyses were performed by the finite element analysis system ANSYS, which is now used not only for solving classical problems of mechanics, but is becoming more and more popular in biomechanics. A simplified plane geometrical model (Fig. 5) of the skin segment (10 mm length and 3 mm height (or thickness), corresponding the longitudinal section of the human finger skin, was created, which included 0.2 mm epidermis layer covered with 0.02 mm thickness stratum corneum (external, tectorial) layer, 2 mm dermis and 1 mm upper, hypodermis (or subcutaneous tissue) layers.

On the basis of the geometrical model two plane computational finite element models were built, each consisting of approximately 8400 PLANE82 type (*2-D 8-Node Structural Solid*) finite elements of 0.05 mm (Fig. 6) where mechanical properties of the appropriate skin layers were defined as listed in Table 1. For both transient and modal and harmonic response analyses, a linear elastic description of the material properties of skin layers was used because of a very small excitation signal level, and the plane strain problem was solved.

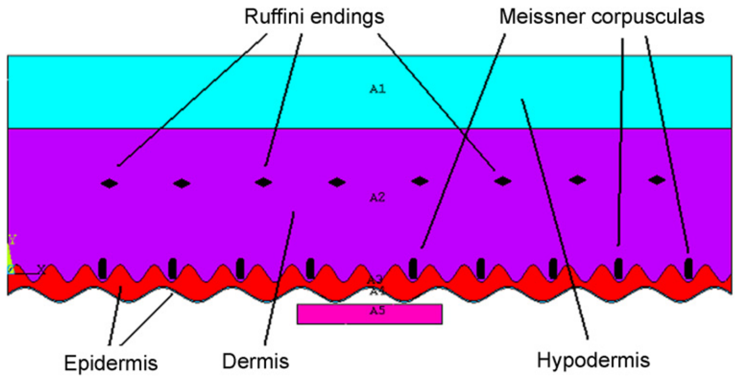

Fig. 5. Geometrical model of the skin segment.

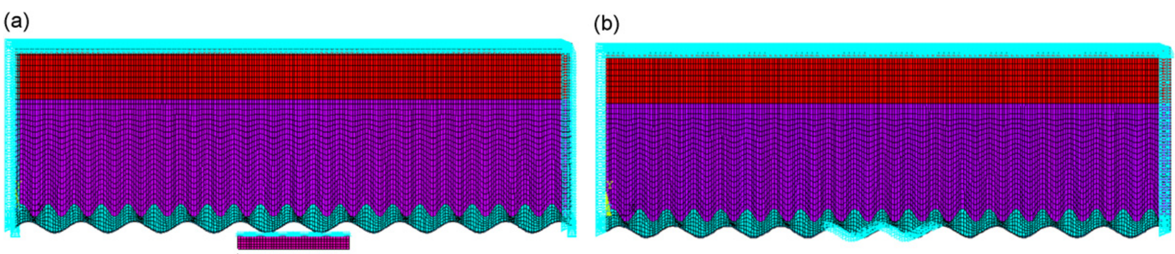

Fig. 6. Computational finite element models: (a) for transient analysis of contact interaction of the skin with a sliding pin, (b) for modal and harmonic response analysis of the skin.

Table 1
Material properties of skin layers

	Stratum corneum (A4)	Epidermis (A3)	Dermis (A2)	Hypodermis (or deep dermis, or subcutaneous tissue (A1)
Young modulus E (MPa)	12	0.05	0.6	0.6
Poison's ratio (v)	0.495	0.495	0.495	0.495
Density ρ (kg/m^3)	1000	1000	1000	1000

The computational model for the transient analysis of contact interaction of the skin with a pin excited kinematically (Fig. 6a) included additionally a 3 mm width rigid rectangle under the middle of the skin segment, imitating the top of the pin interacting with skin. The contact between the pin and skin surface nodal points was modeled by corresponding contact type finite elements CONTA175 + TARGE169. The boundary condition where all degrees of freedom are fixed was used for the upper edge and symmetry conditions for the left and right edges of the model, thus allowing deformations of the whole model in the direction normal to the skin surface.

Transient analysis of contact interaction of the skin and a sliding pin was performed assuming that pin (Fig. 6a) is excited kinematically according to the law of motion obtained experimentally (after 0.1 mm initial indentation in the direction normal to the skin surface) when the skin-pin friction factor was 0.15, 0.3, 0.5 and 0.7. Conclusions on tactile signal transmission effectiveness were made based on the fact that the human being senses 0.1–0.2 mm deformation on the finger surface.

Modal and harmonic response analyses were performed, the latter—by applying 0.1 mm kinematic excitation of 2 mm length piece of the skin surface (Fig. 6b) in the frequency range 800–2600 Hz. In this case displacements and strains of the skin were obtained under harmonic excitation of different frequency. They allowed us to examine possibilities of using a vibratory control signal for tactile signal transmission.

6. Results of computations

While performing the transient dynamic analysis of the fingertip-pin contact when the pin was excited kinematically, computations of the fingertip skin strain–stress state in the contact zone were performed. The character of strain distribution in the skin excited by the moving pin as well as their time histories were defined; the curves representing the movement of the surface skin control points located near the top surface of the pin were obtained (Fig. 7).

It was stated that the process of skin deformation is the following. Firstly, skin strain is enlarging due to the increasing load given by the moving pin, but after some time the strain ceases and the skin comes back to the initial state when the load is the largest. When the pin moves back, the skin strain is of opposite direction and of practically the same value, although the pin's velocity is much larger. There is an evident sharp movement of the skin, when the pin is changing direction of the motion. The displacement of the control point at the surface of the skin depends on the friction between the skin and the pin top and in both directions is varying in the range from 0.05 to 0.1 mm; it is increasing when the friction coefficient is enlarged.

As a result of modal analysis, natural frequencies (Table 2) and modes of skin segment model were obtained (Fig. 8).

It can be seen from Table 2 and Fig. 8 that the lowest natural frequency is quite high for an object consisting of materials having relatively small stiffness like skin. It was also obtained that the global deformation of the skin segment is accompanied by significant local deformations of epidermis, especially external, tectorial layer (stratum corneum).

Harmonic response analysis of the skin segment provided distribution displacements, stresses and strains in the skin loaded by harmonic excitation of different frequency as shown in Figs. 9 and 10. As the most mechanoreceptors are placed in the dermis layer of skin, strains in namely this area were examined more intently, emphasizing dermis zones at the junction with epidermis, where Meissner corpuscles are concentrated, and middle zone of dermis where Ruffini endings are (Fig. 10).

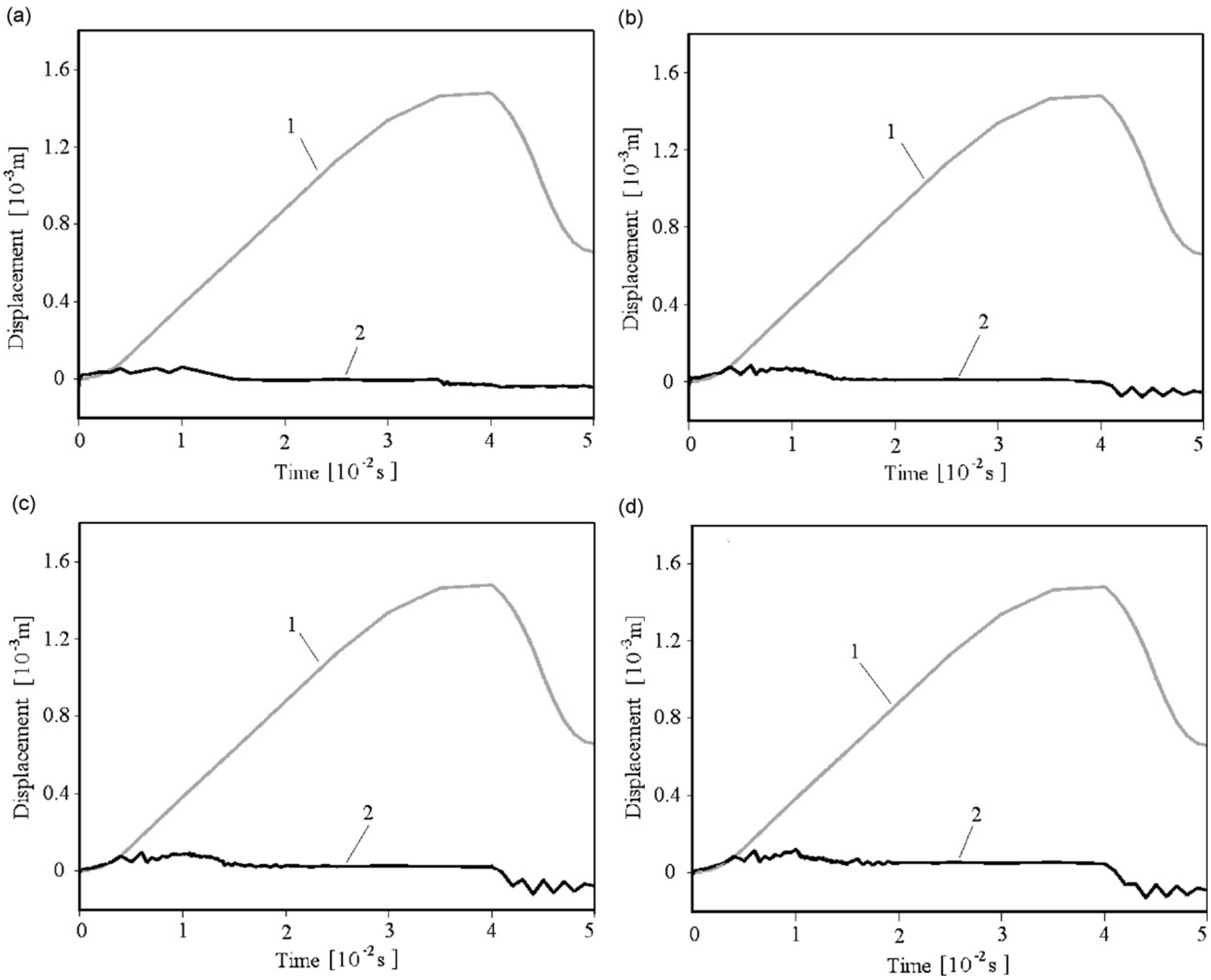

Fig. 7. Displacements of pin (1) and control point of the skin (2) at $\mu = 0.15$ (a), $\mu = 0.30$ (b), $\mu = 0.50$ (c), and $\mu = 0.70$ (d).

Table 2
Natural frequencies of skin segment model

Nr.	Frequency (Hz)	Nr.	Frequency (Hz)
1	2143.9	6	4835.3
2	2915.0	7	5536.1
3	3567.2	8	5780.3
4	4500.8	9	6474.2
5	4695.2	10	6569.4

To evaluate the influence of the harmonic excitation frequency on the level of strain in the zones of skin where Ruffini and Meissner mechanoreceptors are located, average strain dependencies from harmonic excitation (tangential to skin) frequency were built on the basis of the results of stress–strain state computations (Figs. 11–14).

It can be seen from the figures above that the peaks on the curves presented in Figs. 11–14 do not coincide with natural frequencies values obtained during modal analysis (Table 2). Further analysis of skin stress–strain

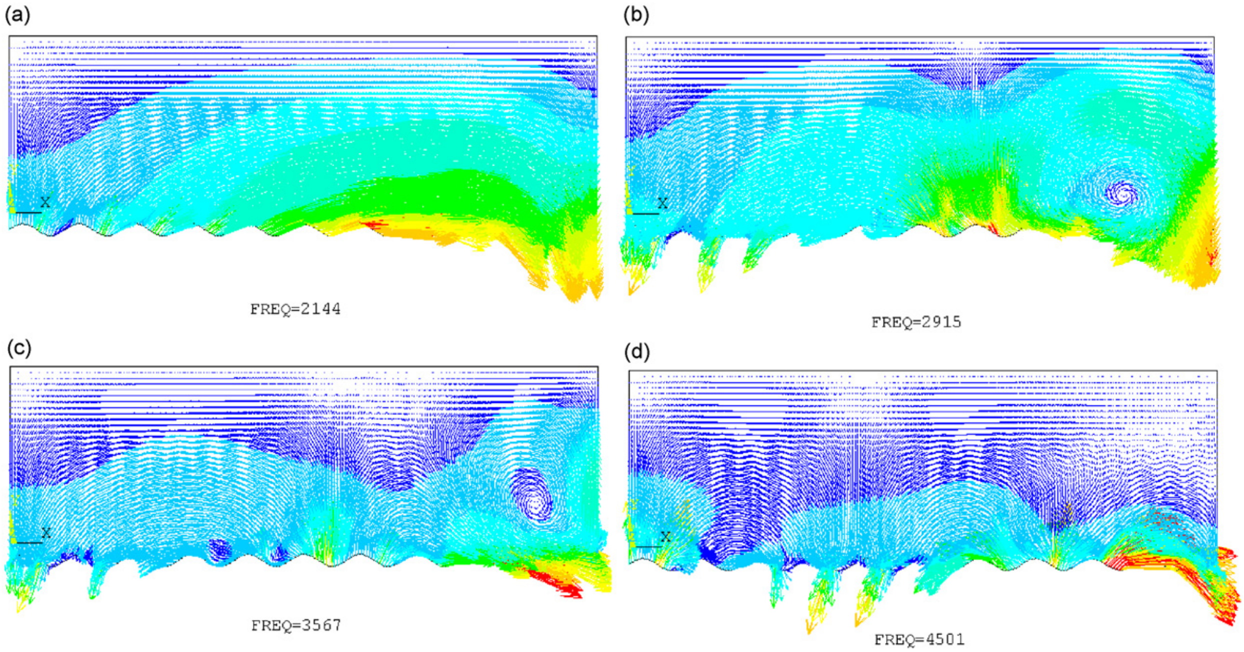

Fig. 8. First (a), second (b), third (c) and fourth (d) natural mode shapes of skin segment model.

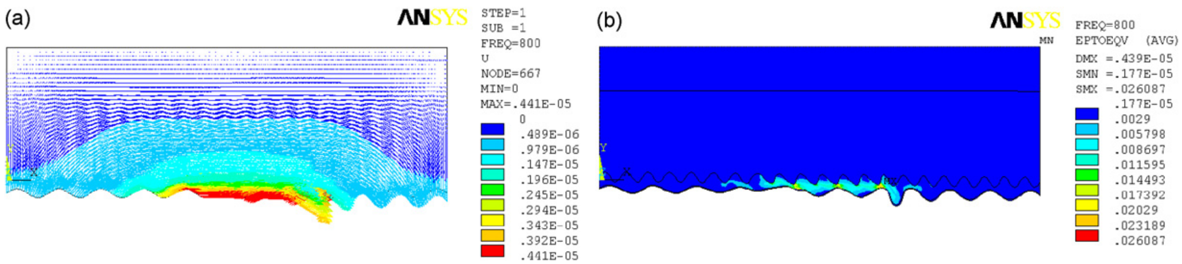

Fig. 9. Displacement vectors (a) and strain distribution (b) in the whole model of skin (loading direction—tangential to skin surface, amplitude 0.1 mm, frequency 800 Hz).

state computation results showed that this significant increase of the strain level is accompanied by a dramatic change in the character of deformation of the model (Fig. 15):

Summarizing the results of modal and harmonic response analysis, it was stated that:

- The character of distribution of the strain (as well as stresses and displacements) in the skin under harmonic excitation varies significantly, depending on the frequency of excitation;
- strain (both components and derivative values) reach their maximum values at the frequency lower than the first natural frequency of the analyzed system (1.7–1.8 kHz against 2.2 kHz);
- significant increase of the strain level is accompanied by a dramatic change in the character of the model deformation;
- frequency at which increase of the strain level occurs depends on global parameters of model—thickness of skin layers, their mechanical properties etc.;
- tangential and normal strain components caused by harmonic excitation in the area where Meissner receptors are located are approximately 100 times higher than in the Ruffini endings location area, while the level of equivalent strain and strain intensity is practically the same.

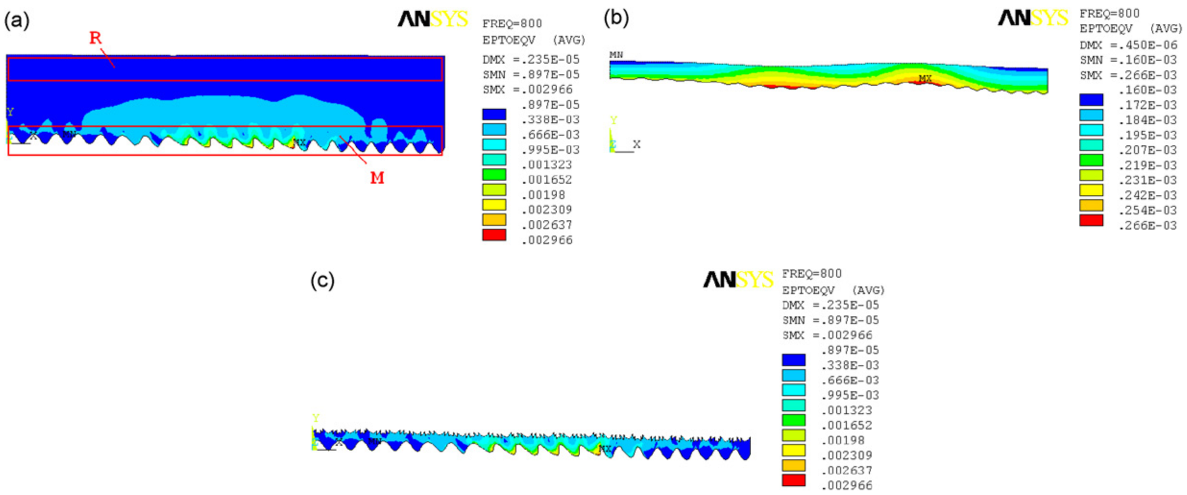

Fig. 10. Strain distribution in the dermis layer of skin (a) and in the zones of location of the Ruffini (b) and Meissner (c) mechanoreceptors (loading direction—tangential to skin surface, amplitude 0.1 mm, frequency 800 Hz).

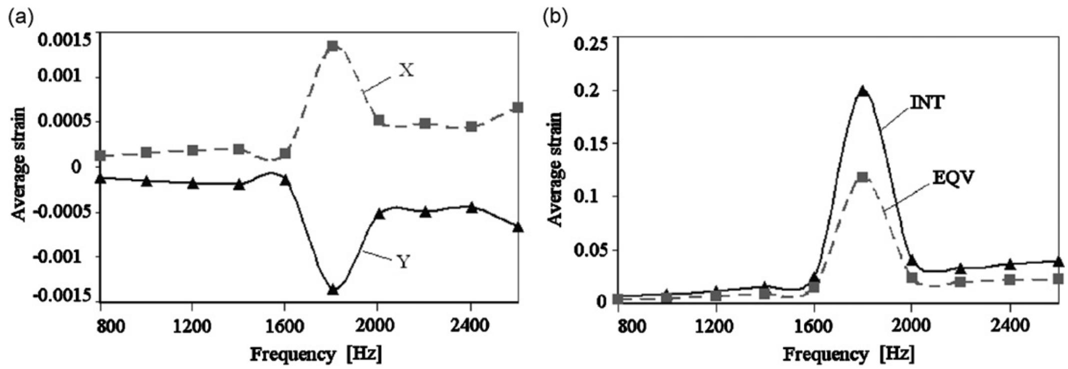

Fig. 11. Dependencies of average strain from harmonic excitation frequency in a whole segment: X and Y components (a) and equivalent strain and strain intensity (b) (X, Y, EQV and INT correspondingly).

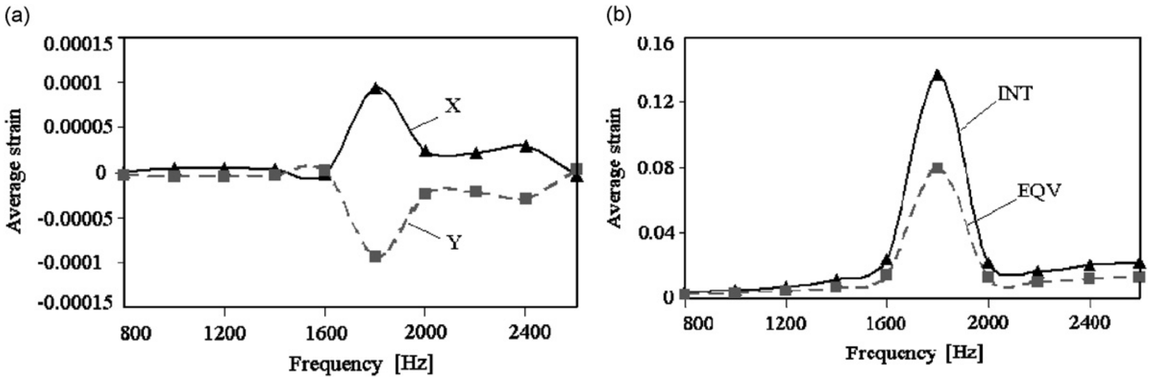

Fig. 12. Dependencies of average strain from harmonic excitation frequency in dermis layer: X and Y components (a) and equivalent strain and strain intensity (b) (X, Y, EQV and INT correspondingly).

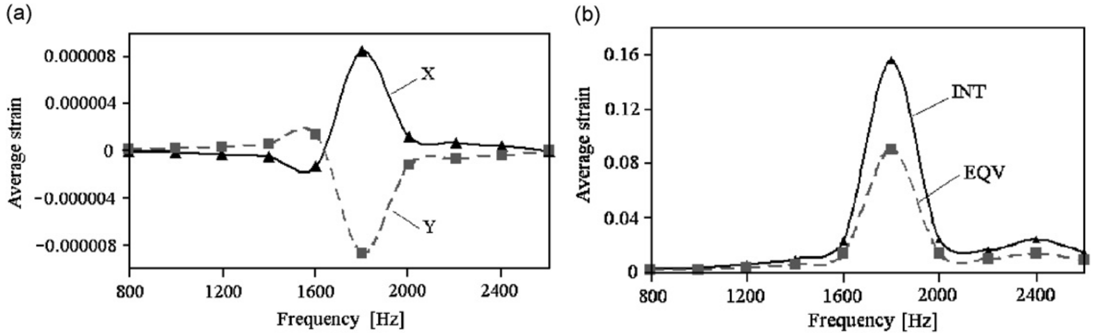

Fig. 13. Dependencies of average strain from harmonic excitation frequency in the zone of location of the Ruffini endings: X and Y components (a) and equivalent strain and strain intensity (b) (X, Y, EQV and INT correspondingly).

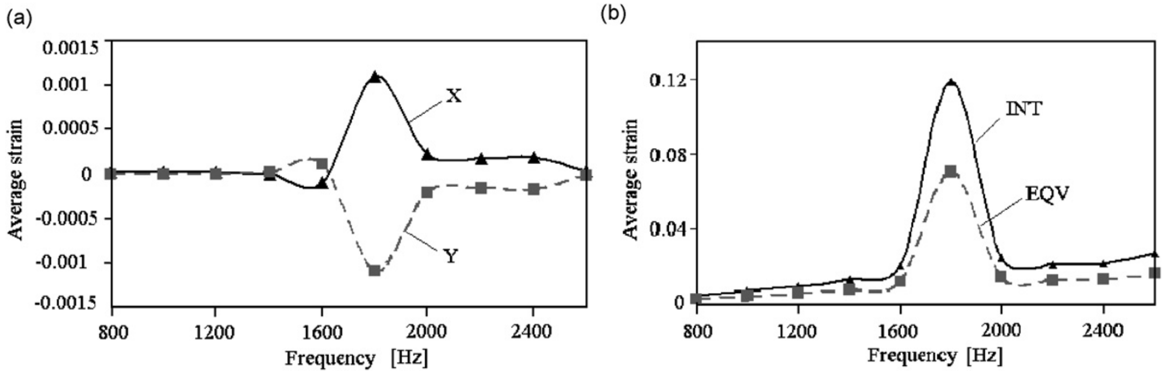

Fig. 14. Dependencies of average strain from harmonic excitation frequency in the zone of location of the Meissner corpuscles: X and Y components (a) and equivalent strain and strain intensity (b) (X, Y, EQV and INT correspondingly).

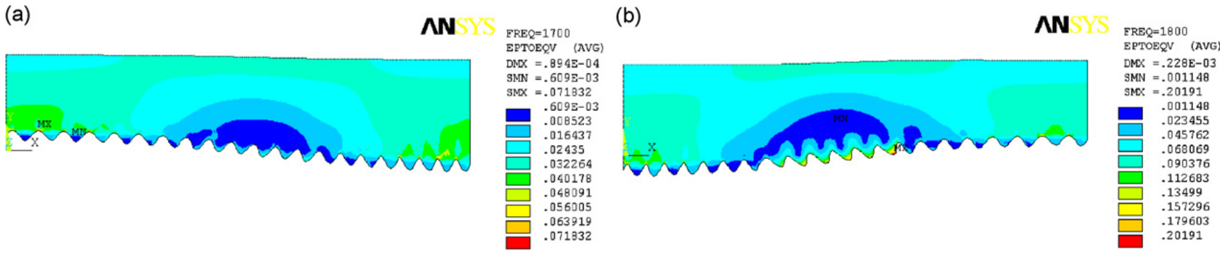

Fig. 15. Strain distribution in the dermis layer of skin under the harmonic loading of frequencies 1700 and 1800 Hz).

7. Conclusions

A new approach of information transmission, where the pin stimulates the operator fingertip skin moving tangentially to it, has been proposed and a tactile device for implementing it has been developed. The possibilities of information transmission by a sliding and vibrating active tactile device element were investigated.

The experimental investigations of the tactile device pin dynamics were performed allowing to determine the law of motion and the stroke of the pin as well as to examine the influence of control signal parameters, such as frequency, voltage, impulse width on the pin motion. It was stated that a stroke of the pin of more than 0.3 mm is sufficient for information transmission in the tactile way.

The fingertip skin–pin contact interaction was investigated by the finite element analysis system ANSYS. The transient analysis of strain–stress state of the skin segment, kinematically excited by a moving pin as well as its modal and harmonic response analysis were performed.

The transient analysis of skin segment was performed when modeling kinematic loading of the system by the experimentally defined law of motion of the pin. Strain distribution in the skin excited by a moving pin and their time histories were defined. The results allowed us to state that the displacement of the control point of the skin segment located near the pin top surface reaches 0.05–0.1 mm under the given kinematical loading and ensures efficiency of the device operation. The strain in the tangential direction to the skin surface is approximately twice larger than in the normal direction. The character of the reaction to the given kinematical loading does not depend on the friction factor between the skin and the pin surfaces, while the maximum skin displacement takes place when the friction factor has the largest value.

The skin segment modal and harmonic response analysis allowed us to examine the possibilities of using the vibratory control signal to transmit tactile information. It has shown that the distribution of the strain (as well as stresses and displacements) in the skin under harmonic excitation varies significantly, depending on the frequency of excitation, and their maximum values do not coincide with at least the first natural frequency of the system under investigation, and a dramatic change in the character of deformation takes place at it. The governing factors of this phenomenon are the global parameters of the model (thickness of skin layers and their mechanical properties). It was stated that the strain caused by harmonic excitation in the area where Meissner receptors are located is approximately 100 times higher than in the Ruffini endings location area, while the level of equivalent strain and strain intensity is practically the same.

References

[1] L. Hamilton, An open letter to federationists, *The Braille Monitor, NFB* 45 (7) (2002) 16–17.

[2] J. Pasquero, Stress: a Tactile Display Using Lateral Skin Stretch, M. Eng. Thesis, McGill University, 2003.

[3] M. Benali Khoudja, M. Hafez, J.M. Alexandre, A. Kheddar, Tactile interfaces: a state of the art survey, *Proceedings of International Sympozium on Robotics*, Paris, March 2004, pp. 23–26.

[4] R. Gouzman, I. Karasin, D. Rozenblium, Mouse-like input-output device with display screen and method for its use, WO 98/31005, PCT, WIPO, 1998.

[5] M. Azubalis, R. Bansevicius, Computer mouse type input–output device. State Patent of Lithuania, No. 5159 B, 2002.

[6] M. Azubalis, R. Bansevicius, R.T. Tolocka, V. Jurenas, Research of the tangential movement of the tactile device. *Ultragarsas* ISSN:1392-2114. Technologija, Kaunas, Vol. 3, No. 52, 2004, pp. 33–37 (in Lithuanian).

[7] T. Maeno, K. Kobayashi, N. Yamazak, Relationship between the structure of human finger tissue and the location of tactile receptors, *Bulletin of JSME International Journal* 41 (1) (1998) 94–100.

[8] T. Maeno, T. Kawai, K. Kobayashi, Analysis and design of a tactile sensor detecting strain distribution inside an elastic finger, *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, 1998, pp. 1658–1663.