Journal of ELECTRICAL ENGINEERING, VOL. 60, NO. 2, 2009, 57–68

WIRELESS MEASUREMENT SYSTEM FOR NON–INVASIVE BIOMEDICAL MONITORING OF PSYCHO–PHYSIOLOGICAL PROCESSES

Libor Majer — Viera Stopjaková — Erik Vavrinský *

This paper presents new portable electronic measurement equipment for non-invasive biomedical monitoring of selected psychosomatic processes. The main goal is monitoring of the psycho-galvanic reflex (PGR) of the human skin that might be very useful for identification of psychical stress, performed in different medical as well as psychological experiments. A portable monitoring system, applicable also in wireless measurement environment, was designed and developed. Comparison to a standard laboratory-like bridge-based measurement system was done in terms of accuracy, sensitivity and other main features. The proposed measurement system employs measurement of the human skin conductivity using the interdigitated array (IDA) microelectrodes. The proposed monitoring equipment utilizes microprocessors with an RF wireless communication module used for data transfer between the measurement modules and a personal computer. A graphical user interface (GUI), developed in C++ under Windows XP platform, is used to provide necessary calibration of the measurement as well as storage, displaying and postprocessing of the measured data (real and imaginary components of the impedance as well as phase of the measured impedance). The measurement method itself and the achieved results are discussed.

K e y w o r d s: biomedical monitoring, IDA microelectrodes, non-invasive monitoring, physiologic processes, psycho-galvanic reflex, skin conductivity measurement

1 INTRODUCTION

The explosive growth in recent wireless communications has caused increased demands for wireless products that would be low-cost, low-power, and compact in size. Moreover, extensive research and development in semiconductor industry in latest years has led towards the novel technologies, and consequently, new products such as smart systems, system-on-chip (SoC), etc. have been widely developed and used. There are modern high-performance microcontrollers with many useful features (A/D converters, several types of interface, RF wireless transceivers, etc.) available and enabling to realize modern compact and low-power portable measurement systems. Similarly, massive expansion in electronic trade has enabled to affiliate electronics to health care that affords new opportunities. Different electronic-medical measurement systems and equipments are indispensable parts of various surgery procedures and help diagnostic a lot of affections. Therefore, biomedical monitoring can be very useful in health care and psychology, and moreover, it can enhance the quality of life in areas of relaxing physiotherapy or professional and leisure sport activities. Even though measurements of the selected physiological parameters *eg* electrical conductivity (impedance) of the human skin surface have a long history, the way how physiological changes in the human tissue are reflected in electrical impedance has not been very cleared up yet [1]. The simple psycho- galvanometer was one of the earliest tools used in psychological research [2]. The psycho-galvanic reflex is the main parameter for reliable detection of stress, excitement stimuli or a shock, and it is characterized with an immediate change of the skin conductivity [3]. Although, technical realization of these measurements might be very simple, in practice, there is a problem with measurement reproducibility and comparison. First, it was assumed that increase in the skin conductivity during a stress stimulus is only caused by the skin perspiration. Later, a very important factor of the potential barrier near the stratum lucidum layer, which thickness changes due to the nervous system, was discovered and proven [4].

In this paper, a new method of biomedical monitoring of psycho-physiological processes, based on the skin conductivity measurement using a dedicated integrated monitoring system with the developed IDA microelectrodes, is presented. The proposed approach offers continuous monitoring and analysis of electrophysiological aspects of human physiology, performed in a completely safe and non-invasive manner. The physiological principle of PGR monitoring is described in [5]. This technique also has no undesired influence on natural physiological processes. The proposed monitoring system employs advanced wireless technologies to control the measurement setup and to transfer data to a personal computer. There are many benefits of the proposed portable solution, such as the wireless monitoring of the tested person, accurate and sensitive measurement, free movement of the person being tested, real life monitoring, no side effects (*eg* additional stress due to the fact that the person is in the labo-

* Slovak University of Technology, Department of Microelectronics, Ilkovičova 3, 812 19 Bratislava, Slovakia, libor.majer@stuba.sk

ISSN 1335-3632

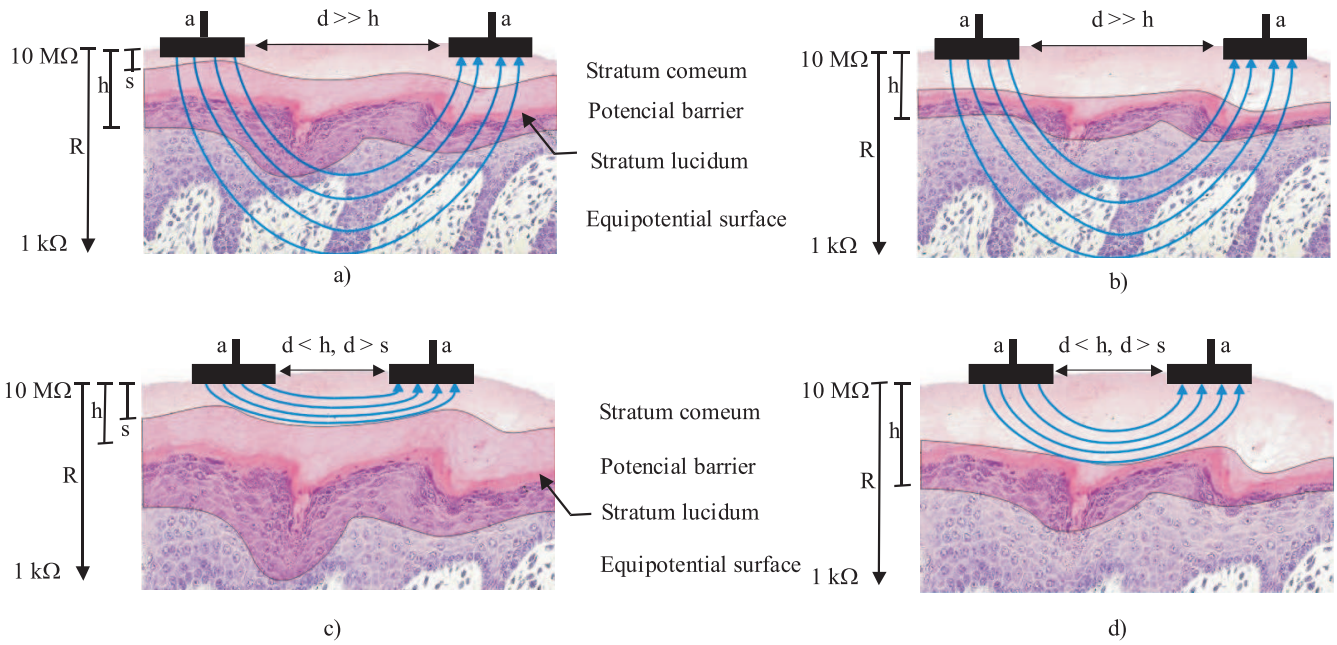

Fig. 1. The vector intensity lines of the electric field in human skin by using: – macroelectrodes: a) in relaxation time b) under stress stimulus – microelectrodes: c) in relaxation time d) under stress stimulus

ratory conditions and become aware of being tested), *etc.* Furthermore, it can help to identify abnormal changes in human physiological and psycho-physiological reactions under certain psychical stress stimuli. This allows reliable diagnostics of stress that might be a very negative factor, influencing not only human performance but causing also serious health problems.

2 STRESS AND PHYSIOLOGICAL PROCESSES

2.1 Stress Phenomena

Stress is a very troublesome and undesired factor dramatically affecting the central neural system and it might invoke significant psychical as well as health problems and inconveniences [6]. From the medical point of view, long-lasting stress conditions could cause an extensive influence on the biological system, interfering in activity of different life-important organs and physiological processes. Thus, monitoring of the some high-risk groups of patients enables the effective prevention and remarkable reduction of possible health risks associated with the chronic consequences of the stress factors' influence. Stress monitoring might be very helpful also in a wide range of psychological applications, such as clinic psychology, treatment of drug-dependent people, monitoring of important and high-reliability jobs (dispatchers, pilots, drivers, *etc*) and others. Thus, measurement of selected physiological variables offers experts a possibility to observe and analyze complex psycho- physiological processes that might considerably contribute to the optimization of diagnostic and therapeutic procedures [7].

2.2 Psycho-Galvanic Reflex

In has been proven that so called psycho-galvanic reflex (a change in the human skin conductivity under stress influence), sensed continuously within a given time period, offers satisfactory information for stress, overwhelmed excitement or a shock identification. From the accuracy and sensitivity points of view, the skin conductivity parameters are best sensed using microelectrodes (as explained bellow).

Several conditions can occur if electrodes are applied on the human skin. In case of using some macroelectrodes, when the distance between the coupled electrodes is greater than the thickness of the stratum corneum (the outermost layer of the skin) with the potential barrier, the electric field intensity vector lines are enclosed across the planar skin structures (Fig. 1 a, b). If microelectrode pairs are utilized, when the distance between the electrodes is less than the electric thickness of the skin (stratum corneum with the potential barrier), then the lines of the electric field are enclosed in longitudinal circuit relative to laminar skin structures of epidermis (in stratum corneum). From inner layers of skin, the electric field intensity lines are embossed to the surface (to the area with a lower conductivity) by the instrumentality of the potential barrier (Fig. 1c). However, under a stress stimulus the potential barrier narrows down, and the electric field can reach inner layers of the human skin with higher conductivity, and therefore, the total conductivity increases (Fig. 1d). Such a configuration is, therefore, ideal for the analysis of electrophysiological processes in the human skin under stress.

The results of analytical analysis also showed that in case of non-symmetric coplanar electrodes the electric

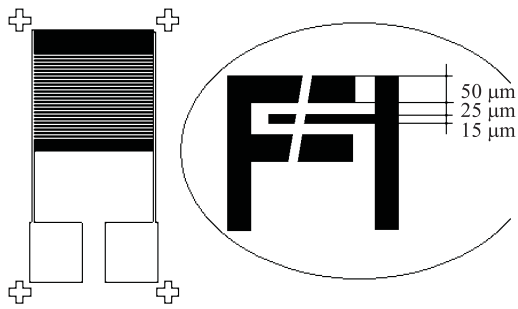

Fig. 2. Layout of the non-symmetric electrode chip

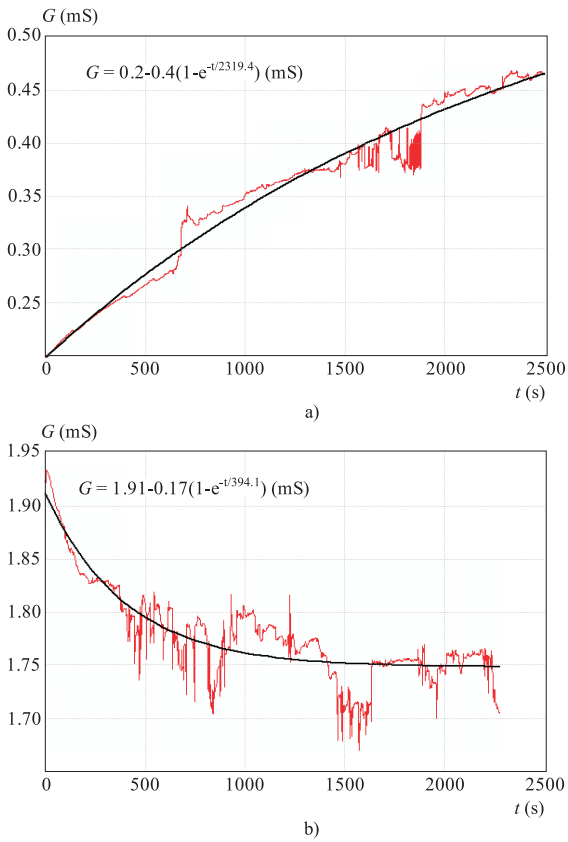

Fig. 3. Electrodermal phenomenon and effect of sweat hydration in time domain, a) dry skin, b) sweat (hydrated) skin

field is more enclosed in the outer layers of the skin laminar structures (stratus corneum). This system consists of the periodical electrode structure with different sizes. In a non-symmetric structure, the density of the electric field intensity lines along the planar structures of the skin is 30 % higher in outer layers [8].

2.3 Developed Microelectrodes

For non-invasive biomedical monitoring of psychophysiological processes based on the skin conductivity measurements, four types of IDA microelectrodes with the following configuration and sizes have been developed, produced and used:

- non-symmetric configuration
  - 15 μm/25 μm/50, μm (finger/gap/finger)
- symmetric configuration
  - 100 μm/100 μm (finger/gap)
  - 200 μm/200 μm
  - 400 μm/400 μm

The total size of the microelectrode chips is 10 mm × 15 mm. The microelectrodes were made from Pt thin film to minimize the polarization effect (Fig. 2). The microelectrodes were fabricated by a standard thin film technology: Pt films (150 nm in thickness) under laid by a Ti film (50 nm) were deposited by RF sputtering on alumina substrates, and microelectrodes were lithographically patterned by lift-off technique.

2.4 Experimental Skin Conductivity Measurements

The electrodermal response (EDR) to a stress stimulus was detected by variations in the skin conductivity ΔG (a relative change of current ΔI at constant input signal amplitude voltage $V = 3$ V and frequency $f = 1$ kHz), sensed by the IDA microelectrodes placed on forefinger of the non-dominant hand (left for right-handers).

During conductivity measurements, a drift of the output signals occurs due to polarization effects in the human skin electrodermal phenomenon (EDF). We investigated the drift of output signals due to EDF and sweat hydration of the skin outer layers (stratus corneum and lucidum) in the time domain. These experiments were done using 200 μm/200 μm microelectrodes for dry skin (Fig. 3a) and for wet (sweaty) skin (Fig. 3b).

Measured curves were interpolated by the exponential function $G(t) = A + B\left(1 - e^{-t/C}\right)$, where G is the skin conductivity, t is time and A, B, C are constants. This function is considered to be very suitable for description of polarization and hydration effects in the human skin. The performed experiments also showed that the signal stabilization (steady state) occurs sooner for hydrated skin (10–40 minutes) than for dry skin (40 minutes and more). For typical macroelectrodes, the increase in the conductivity due to the EDF effect ends in 30-40 minutes [4]. During the several initial seconds, minutes of measurements it is possible to minimize and compensate the undesired output signal drift (caused by EDF, Fig. 4a)) by means of a proper software (Fig. 4b)). The software analysis program for the skin conductance activity was developed in the development environment HP-VEE 6.0.

These experiments led to a very important result: the developed microelectrode probes are able to monitor electrodermal response as well as heart pulse simultaneously (Fig. 4b). The heart pulse was easily read out by derivation of the measured signal (Fig. 4c).

In the next experiments, the influence of microelectrodes size (symmetric: 200 μm/200 μm, 100 μm/100 μm, non-symmetric 15 μm/25 μm/50 μm) on the output signals were investigated. As mentioned above, the different

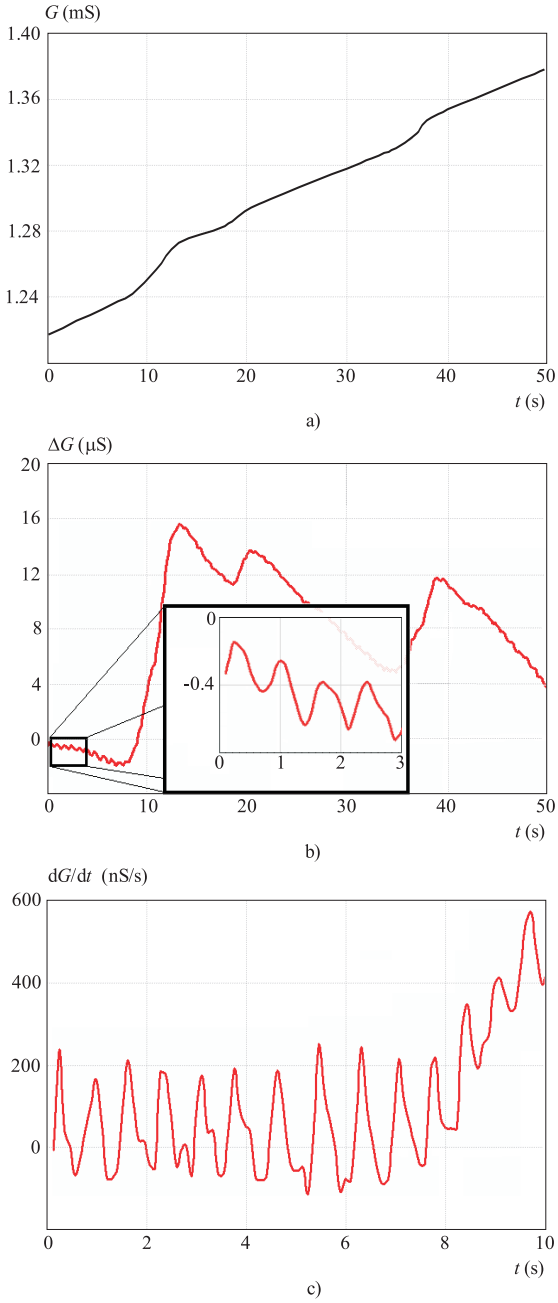

Fig. 4. Typical time dependences of EDR, a) uncorrected, b) corrected EDR and its zoom comprising the pulse of heart, c) derived uncorrected signal comprising the pulse of heart

types of microelectrodes generate the electrical field enclosed in various layers of the skin. Results were obtained using input signal amplitude and frequency of 3 V and 1 kHz, respectively, while employing the EDF correction. It is shown (Fig. 5), that the output signal measured by the non-symmetric IDA electrodes is very low in comparison to the results obtained by the symmetric IDA 100 μm/100 μm and 200 μm/200 μm microelectrode arrangement. It is inflicted by the fact that the penetration depth of the electric field generated by the non-symmetric microelectrodes is insufficient to reach the potential barrier of the skin, which is very sensitive to the detection of psycho-physiological processes like the psychical stress [3, 5]. In case of the non-symmetric microelectrodes, most of the electrical field intensity lines (about 80 %) are enclosed in the depth of 0–25 μm [1], while the most important and sensitive layer of the potential barrier is placed more than 30 μm beneath the surface.

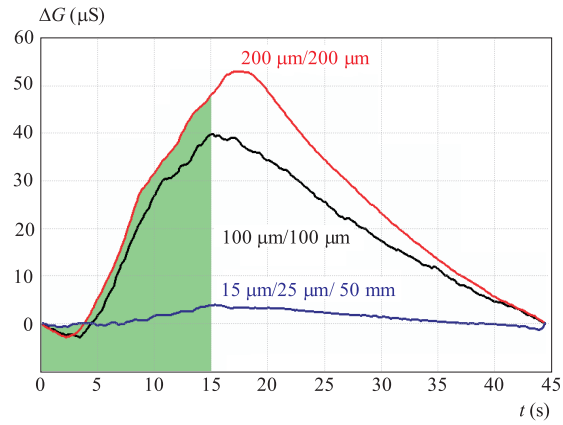

Fig. 5. Influence of size and configuration of microelectrodes on the output signals

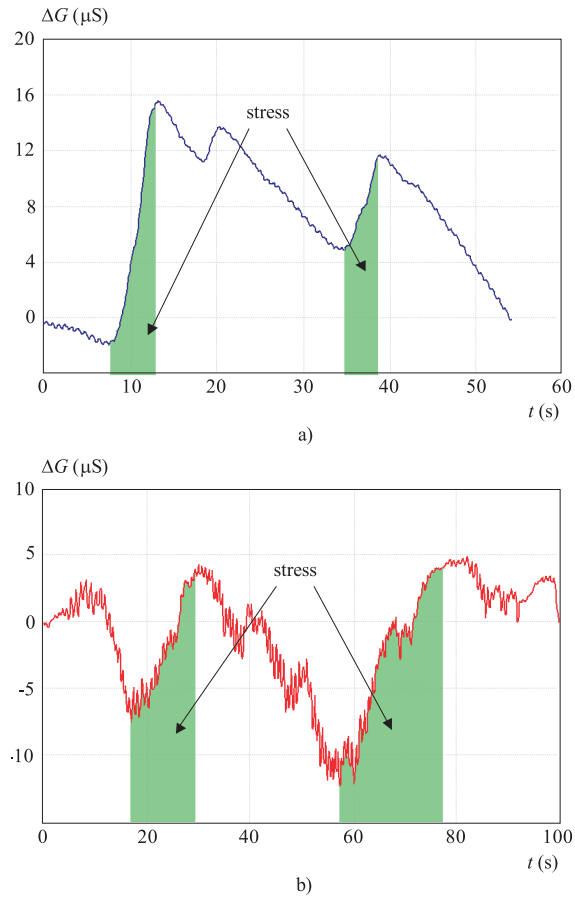

Fig. 6. Influence of sweat hydration on output signal of 200 μm/200 μm IDA microelectrodes: a) dry skin ($G_0 = 1.22$ mS), b) sweaty skin ($G_0 = 2.14$ mS)

We have also analyzed influence of sweat hydration on the output signals. For this purpose, we moistened the skin surface with NaCl solution of concentration, which was several times higher than the normal concentration of human sweat (0.3–0.8 %). The measurements were done using 100 μm/100 μm, 200 μm/200 μm

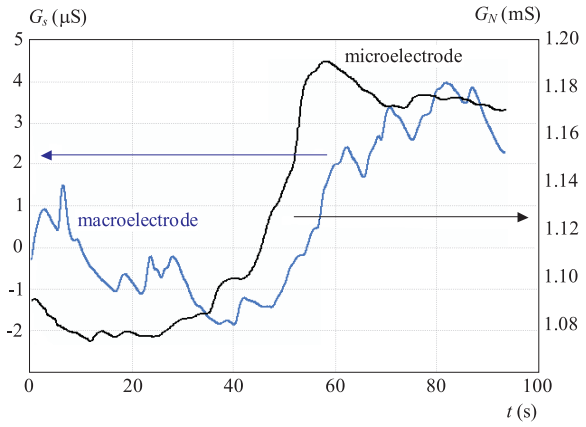

Fig. 7. Comparison of our microelectrode system and classical macroelectrode GSR method

and 400 μm/400 μm microelectrodes. Measured stress response was very small in case of the non-symetric microelectrodes. Measurements showed that sweat hydration causes a noise-like influence on the signal, which gets more observable as the size of microelectrodes is smaller. Therefore, reading out the measured signal becomes more difficult (Fig. 6). Finally, one can say that sweat hydration increases the skin conductivity and brings noise to the output. Based on the experiment results, we can conclude that the skin hydration (sweat) has less influence on the output signal that might by expected, which is in correlation with the theory saying that sweat is not dominant for the current flow across the skin [4].

Finally, a comparison of our microelectrodes-based galvanic skin response (GRS) method to the commercial macroelectrode approach [9], usually used in the laboratory medical or psychological experiments, was carried out. The comparison, performed using standard psychotests, shows that the responses given by both approaches were similar. However, the microelectrode signals are observed to be more stable with a shorter response time (Fig. 7).

After these experiments, the next step in our research was to develop a portable monitoring system offering sensitive and continuous measurement of PGR, with the measured data transfer to a personal computer.

3 PROPOSED COMPLEX MEASUREMENT SYSTEM

3.1 Measurement method

In the preliminary work, a thin film IDA microelectrodes system of different sizes and topologies has been designed, developed and realized [5]. Then, experimental measurements of the electrodermal response (EDR) upon selected stress stimuli (invoked by different mental tasks — standard psychotests) were performed using the developed microelectrode array. The obtained experimental results show that the optimal input signal amplitude should be selected from 1.5 V to 3 V. The input signal frequency is not so critical, however, an optimal value in order of ones kHz has been proved. The most proper IDA microelectrode size is: 200 μm/200 μm (finger/gap ratio).

Several methods applicable to continuous measurement of the human skin impedance were analyzed first. As a result of this analysis, the auto-balancing bridge method was chosen because of few reasons (high accuracy, short time, high repeating rate of measurements, frequency and amplitude signal definition, possibility to measure both real and imaginary impedance components, controllability by a microprocessor, digital processing, *etc*) [10]. Consequently, new measurement methods for both required versions of the proposed measurement equipment: a simple handy "stress-alarm" with limited features, functionality and accuracy as well as a precise laboratory-like monitoring system, have been developed. These methods are properly adjusted and modified in order to match for employing advanced available hardware accessories and peripherals. The stress-alarm method utilizes a microcontroller interface comparators for low-cost and small size. The complex laboratory measurement system is designed using precise A/D converters and with possibility to connect a lot of different integrated or external microsensors.

3.2 Developed Measurement Equipment

The complete measurement environment for continuous and non-invasive monitoring of the skin impedance has been developed. The first proposed measurement system, shown in Fig. 8, consists of the IDA microsensor described above, integrated circuit AD5933, microprocessor ADuC832, and a personal computer.

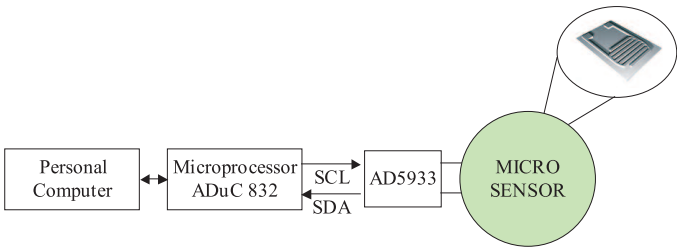

Fig. 8. Block diagram of the monitoring system using the planar IDA microelectrodes

The core of the proposed monitoring system is the integrated circuit AD5933 (Fig. 9) by Analog Devices [11] that provides measurement of the skin impedance sensed by the developed microsensor system. The measurement process is controlled by the microprocessor ADuC832 [12] via I2C interface. Using a serial interface RS232, the microprocessor then sends the measured data to a personal computer providing data storage. Additionally, the microcontroller also provides an initial configuration of the

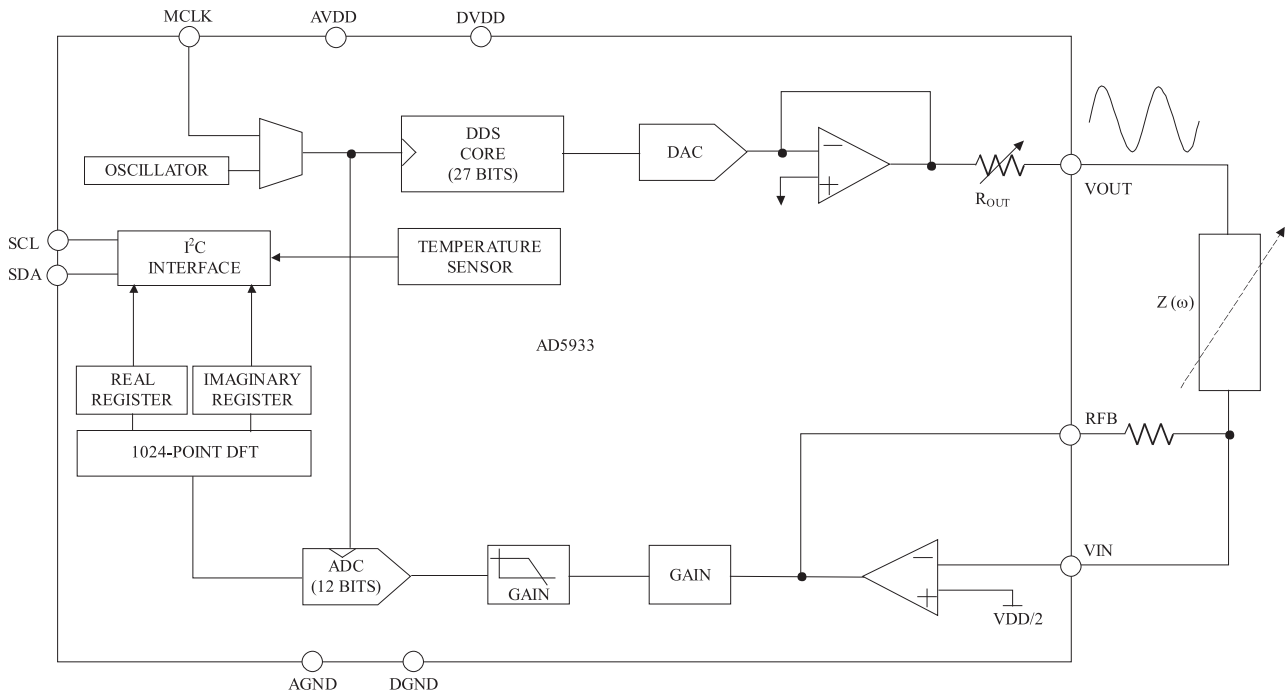

Fig. 9. Integrated circuit AD5933 and its main specifications

integrated circuit AD5933 that is needed at the measurement beginning. The configuration includes mainly setting the frequency and amplitude of the input signal used for measurement of unknown impedance. The microprocessor also controls time slots during which the measurements are performed. After the measurement in the respective time slot is done, the microprocessor reads and sends the measured data from AD5933 circuit to a PC, where data is stored and further processed.

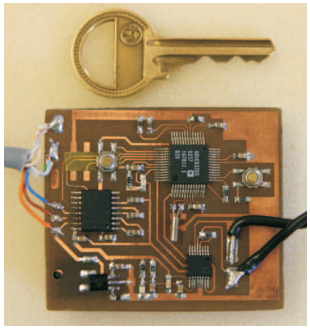

Fig. 10. PCB of the realized monitoring system

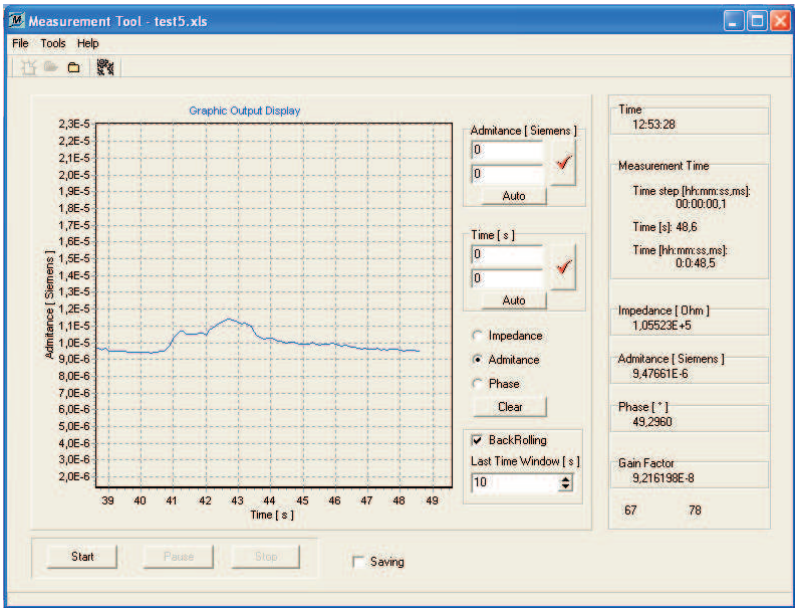

Fig. 11. The GUI main panel

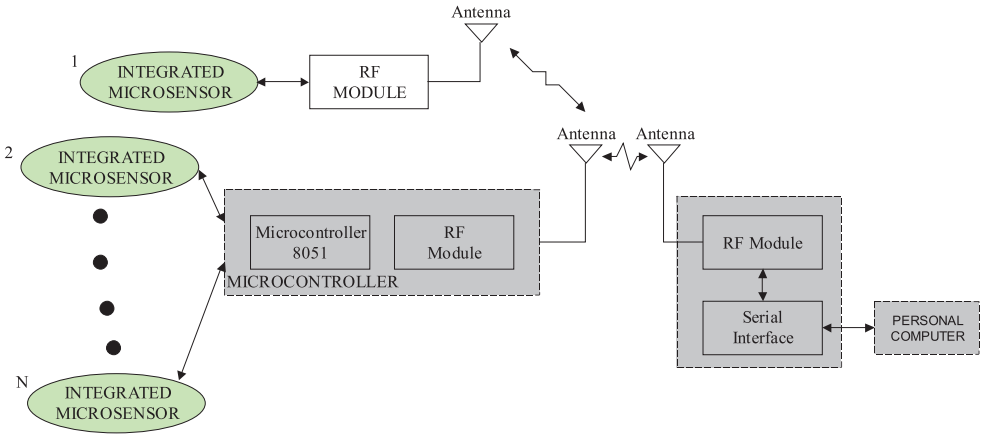

Fig. 12. A complex wireless biomedical monitoring system

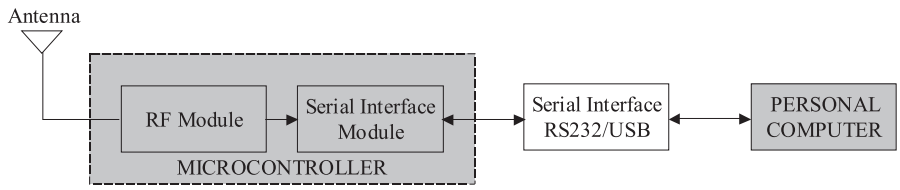

Fig. 13. Block diagram of the RF receiver communication module

The AD5933 circuit is composed of the following parts: an input signal generator, a 12-bit A/D converter, a DFT (Discrete Fourier Transform) circuit, a thermal sensor, and I2C interface. The generator provides a sine wave input signal of certain frequency and amplitude at the output VOUT. Unknown impedance is connected between VOUT and VIN terminals. Thus, the magnitude and phase of the current flowing through a load depend on its impedance. This current is then transformed to voltage that is converted into a digital signal by the D/A converter. Finally, the DFT circuit provides discrete Fourier transform of the converted signal. As a result, values of real and imaginary parts of a loaded admittance are measured. Photograph of the whole printed circuit board (PCB) of the monitoring system is shown in Fig. 10.

The PCB has been realized on FR4 board by SMT technology with minimum strip width of 0.3 mm and minimum clearance width of 0.35 mm. The PCB is functionally divided into four parts: a voltage source, interface RS232, microprocessor ADuC832 and measurement module AD5933, and the power supply part providing two separate supply voltages for analog and digital parts. This is needed for the elimination of unwanted effects (*eg* interference, noise, leakage, disturbance, *etc*). Two SMD buttons ensure the software upload and microprocessor reset. The total size of the designed PCB is 50×60 mm.

3.3 Developed graphical user environment

A graphical user interface (GUI), developed in C++ under Windows XP platform, provides both the necessary calibration of the measurement as well as storage, displaying, and post-processing of the measured data (real and imaginary components of the measured skin impedance). The developed software allows an easy and user-friendly control of the measurement process and data displaying and storage. From the measured data, absolute values of impedance and admittance as well as its phase are computed, and all these parameters can be displayed in several graphical and numeric modes. The main GUI panel is shown in Fig. 11. It is sectioned to the main menu, graphical and numerical parts, and the operating part showing the currently measured data. The easy measurement control is provided only by three buttons (start, pause and stop). The computer port and measurement hardware setup are performed automatically to simplify the measurement process to a user. Besides the measurement control, setup, and calibration, the developed software enables saving of all the measured data, which can be saved to a table format, *eg* MS Excel, for further post-processing, analysis or evaluation.

3.4 Portable version of the Monitoring System

Long term biomedical monitoring plays an important role, especially, in improving diagnosis and therapeutic processes in contemporary medicine. The crucial step towards more exact and precise characterization of psychical stress influence on a monitored respondent in real life conditions is the respondent's free movement (out of a laboratory). This would enable continuous monitoring of the respondent, even during regular daily activities being carried out. From above considerations the demands on the monitoring equipment are as follows [13]:

- compact in size, low weight
- minimization of connecting cables

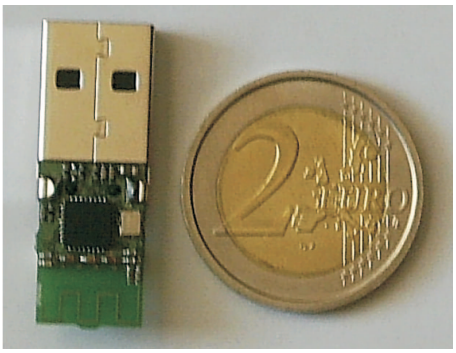

Fig. 14. PCB of a realized wireless/USB receiver module

- suitable sensor placement
- continual measurement ability and data storage
- low-power and battery supply

For these reasons, the developed measurement system should be small, portable and compact in size with possibilities of continuous measurement and wireless data transfer to a personal computer, eventually, storing data in memory. Moreover, this system should be able to measure other parameters (body temperature, heart pulse, *etc*) for complex monitoring different psychophysiological processes in humans. In many cases this measurement is needed to performed in plenty places of human body. The proposed complex system offers these opportunities (Fig. 12). It composed of sensing parts and the core (microcontroller with RF module, A/D, *etc*) ensures measurement control, processing and transmit date. The several sensors are connected using matching circuits or wireless. One of the most important demands on the portable measurement system is the minimization of connecting cables. Therefore, a wireless communication has been considered between the measurement equipment and the personal computer to provide necessary data transfer. The considered RF wireless communication module consists of a transmitter at the side of the measurement unit and a receiver at the PC side.

Receiver module

The block diagram of the proposed receiver module, considered at the PC side, is shown in Fig. 13. There is microprocessor nRF24E1 [14] with an integrated RF transceiver used to provide a simple, small, low-power, versatile solution at the receiver part. The RF module retrieves a signal received by the antenna and sends it to the PC via RS232 or USB interface. Microprocessor ensures control, converting, data transfer and power management.

Photograph of the whole printed circuit board (PCB) of the receiver module is shown in Fig. 14. The PCB has been realized on double layer FR4 board by SMT technology with minimum strip width of 0.2 mm and minimum clearance width of 0.2 mm. The total size of the developed receiver module is 11 mm × 17 mm (excluding the USB connector).

Transmitter module

Several sensing systems with various conception and application way have been proposed. The first complete wireless measurement equipment consists of the planar microsensor, AD5933 circuit, and controlling microprocessor nRF24E1 with the RF communication module (Fig. 15). The core of the proposed portable monitoring system is again the integrated circuit AD5933 that provides measurement of the human skin impedance sensed by the developed microsensor. The measurement process is controlled by the microprocessor nRF24E1 via I2C interface. Using the RF wireless communication interface, the microprocessor then sends the measured data to the receiver part on the PC side. Consequently, the personal computer executes data storage and data post-processing. Additionally, the microcontroller also provides an initial configuration of integrated circuit AD5933 (setting the frequency and amplitude of the input signal, measurement time slots, power management, *etc*).

The next work included mainly design and realization of the miniaturized portable version of the system with RF wireless data transfer. Thus, the integrated circuit AD5933 had to be removed, and its functions have been substituted by a microcontroller with A/D converter and RF transceiver nRF24E1 integrated within. At the same time, research and analysis of novel measurement methods, possibly applicable towards the significant miniaturization of the system and power consumption reduction (battery life time), have been performed. Two small-size monitoring equipments have been designed, applicable in both the stress alarm as well as in a complex precise laboratory measurement system.

The next step in the measurement system developing process will be led towards putting the whole system into a proper chase and making the microelectrode fixing more robust. By completing that, the laboratory or a stress alarm version of the monitoring system will be fully available.

Microcontroller nRF24E1 *with RF transceiver*

To reduce necessary measurement circuitry, and achieve selected features of the monitoring system (low-power, compactness, simplicity, and versatility), a modified solution of the measurement hardware has been proposed. Two microprocessors nRF24E1 [14] with an integrated RF transceiver for the world wide 2.4–2.5 GHz ISM band have been employed. The RF24E1 microcontroller instruction set is compatible with the industrial standard 8051. The RF transceiver consists of a fully integrated frequency synthesizer, a power amplifier, a modulator, and two receiver units. Output power, frequency channels and other RF parameters are easily programmable

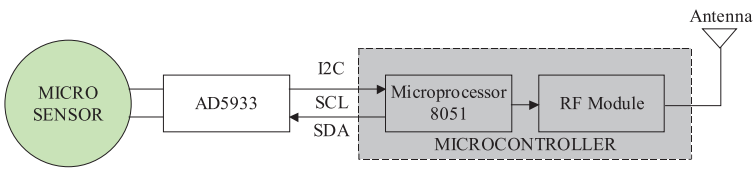

Fig. 15. Block diagram of the portable measurement system with a RF wireless transmitter communication module

by use of the RADIO register. RF current consumption is only 10.5 mA in the transmitting mode (output power −5 dBm) and 18 mA in the receiving mode. The microcontroller clock is derived directly from the crystal oscillator. The nRF24E1 allows be set into a low-power down mode under program control, and also the ADC and RF subsystems can be turned on or off under. The current consumption in this mode is typically $2\,\mu$A. The device can exit the power down mode by an external signal, by the wakeup timer if enabled or by a watchdog reset.

With respect to all the features described above, this microcontroller has been chosen for a miniaturized portable version of the measurement system with RF wireless data transfer. In this case, the whole measurement equipment consists only of several sensors with necessary electronic circuits and microcontroller with the RF transceiver module.

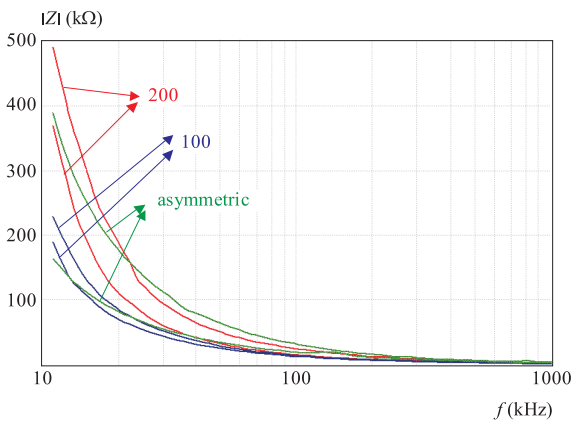

Fig. 16. Skin impedance versus the input signal frequency

A well-designed PCB is necessary to achieve good RF performance. We had to keep in mind that a poor layout may lead to loss of the performance, or even functionality, if due care is not taken. A fully qualified RF-layout for the RF communication module and its surrounding components, including matching networks, has been proposed as the key issue of the proper RF design. A PCB with two layers including a ground plane is needed for the optimum performance. It is designed by surface mount technology (SMT) to achieve the best possible performance. The device sizes 0603 and 0402 have been selected. The nRF24E1 supply voltage is filtered and routed separately from the supply voltages of any digital circuitry. Long power supply lines on the PCB are avoided. All device grounds, VDD connections and VDD bypass capacitors are connected as close as possible to the nRF24E1 circuit. The PCB antenna has been chosen for better miniaturization and compactness. In this configuration, the measurement system has the access range up to several tenths of meters.

Power management

The power management is another crucial issue to be taken into account, since it is the best important parameter determining the operating time, and secondary, also the size of the portable equipment. There are many factors influencing on the power consumption:

1) The input signal — the measured impedance exhibits its own power consumption that depends on the input signal parameters. In Fig. 16, curves of the measured human skin impedance versus the frequency of the input signal for different electrode arrangement are shown.

The impedance value of skin is decreased as the input signal frequency arises. Other parameters influencing the power consumption are: actual value of the measured impedance, the input signal amplitude (possible range 1–3 V), settling time after input signal is applied, sensing time of the measurement, and the frequency of sensing/sampling.

2) Power consumption of the measurement equipment — this portion is reduced by a simple design of the measurement system, and a proper power management of microcontrollers (standby mode, power down mode, *etc*).

The total average power consumption is in order of ones up to tenths mW and it depends on the factors mentioned above.

3 ACHIEVED RESULTS AND DISCUSSION

Finally, experimental measurements and evaluation of the developed monitoring system have been carried out. Comparison of the results obtained by a standard HP 4284A laboratory bridge instrument measurement (G1 - admittance) to the data measured by the developed monitoring system (admittance magnitude G2 and phase Φ, respectively) is shown in Figure 17a. This measurements have been preformed in order verify realized system. The achieved results show that the developed monitoring system is sensitive to same applied stress stimuli. Moreover, the phase of the skin impedance may offer more sensitive

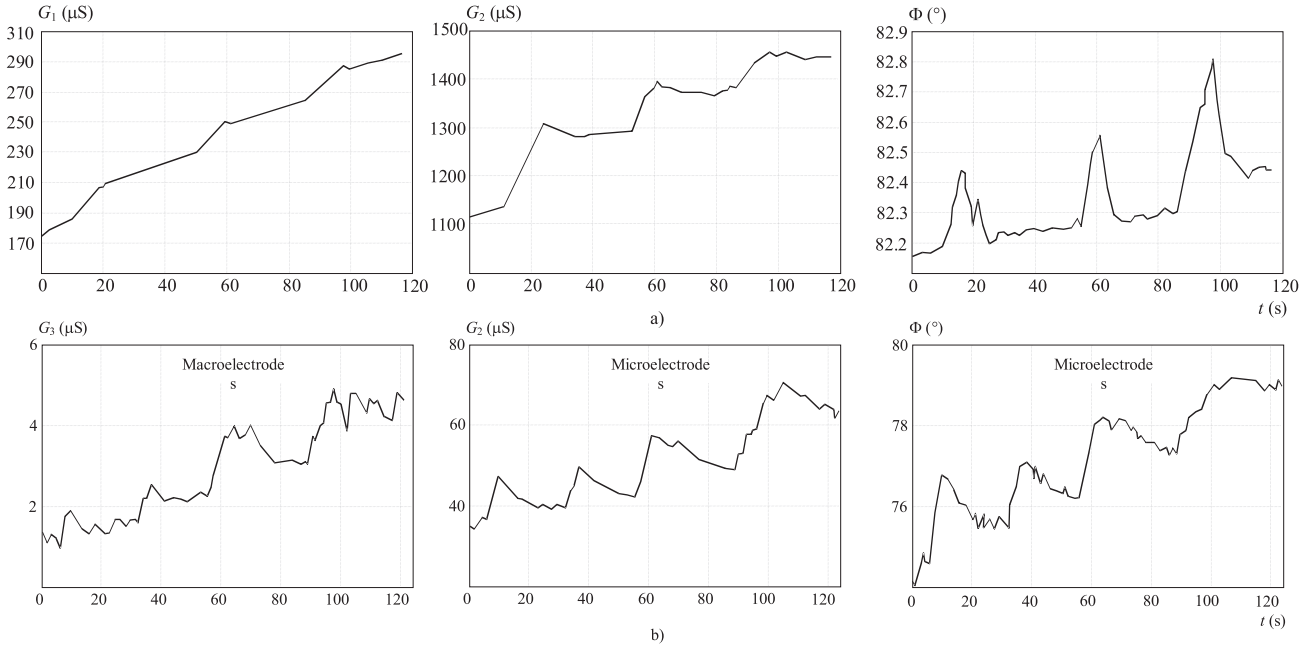

Fig. 17. Comparison of the achieved results, a) standard bridge instrument (G1) versus developed system (G2, Φ), b) macroelectrode (G3) versus microelectrode approach (G2, Φ)

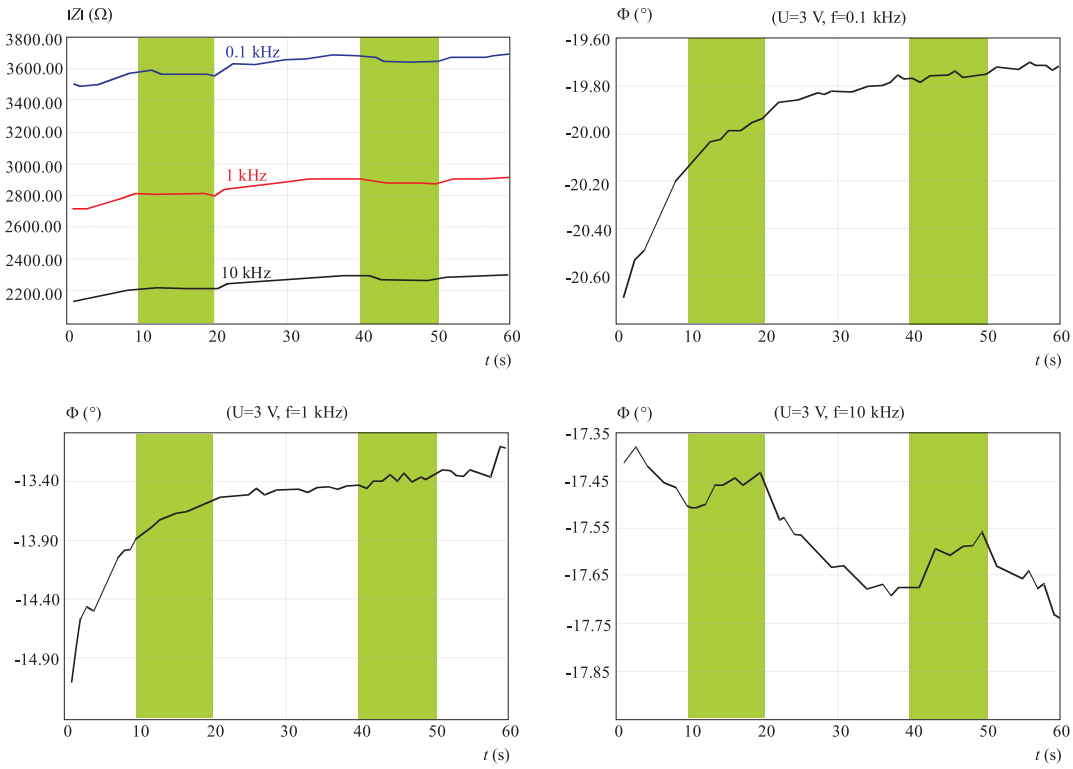

Fig. 18. Skin impedance measurements using different input signals

monitoring of psycho-galvanic response than only a simple impedance amplitude sensing, since the phase reflects the admittance changes in much more significant way (high peaks in the lowest waveform). As the last experiment (Figure 17b), our microelectrode approach was compared to a classical macroelectrodes GSR method [9]. The waveforms are as follows: G3 - skin admittance magnitude obtained by macroelectrodes, G2 admittance magnitude and Φ phase measured by the microelectrode approach). Certainly, for each method the input signal parameters were set in a proper way. In both cases, the physiological response has been evoked by the same stress stimuli. The standard psycho-tests performed have showed that the response signals obtained from both methods match

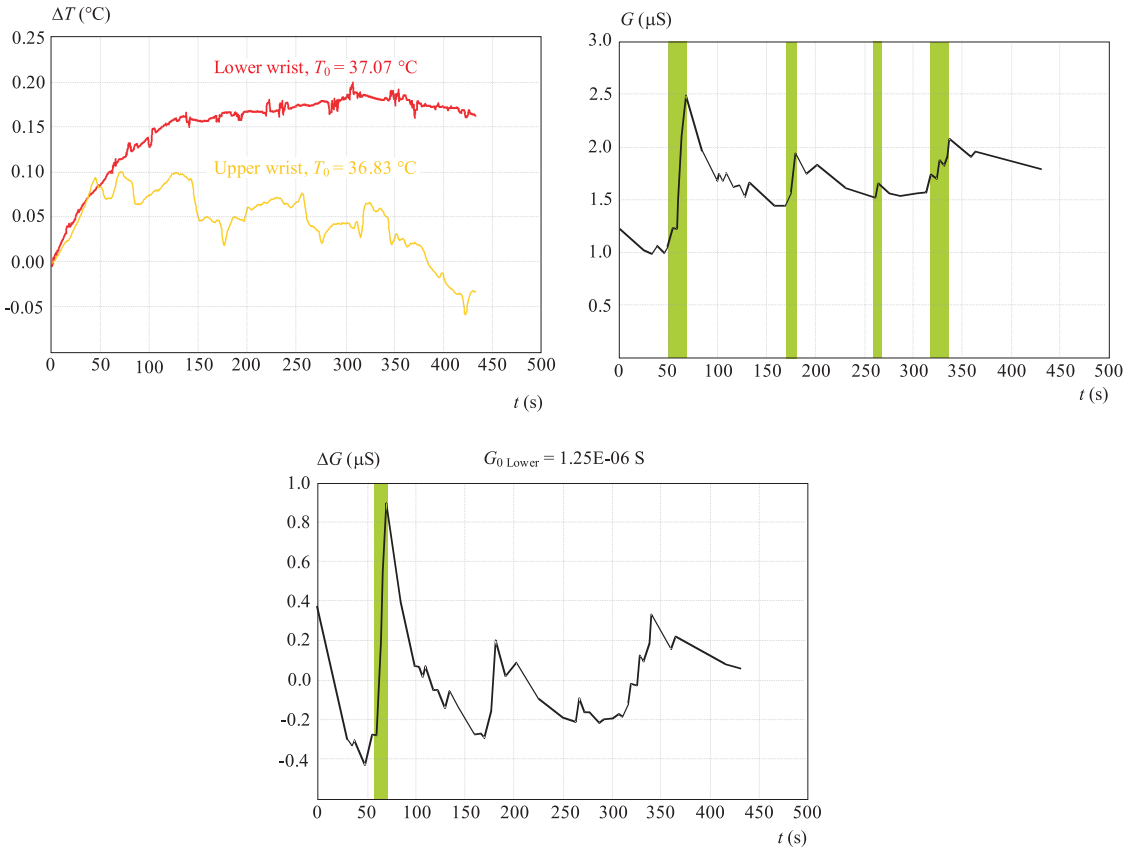

Fig. 19. Multi sensor measurement correlation: a) body temperature, b) skin admittance, c) corrected skin admittance

and the microelectrode signals are more stable, accurate and with shorter time respond. Figure 18 shows curves of the measured skin impedance amplitude and phase as an important factor for definition of the input signal with respect to the power consumption (stress influence periods marked by highlighted areas). It can be observed that the absolute value of the impedance decreases as the input signal frequency gets higher. Therefore, a certain trade-off between those two parameters is necessary. Moreover, the different character of the measured phase at different frequencies of the input signal has been observed, (for higher frequency the phase decreases, for lower frequency the phase has the increasing character).

Additionally, further measurements of several selected physiological parameters, performed on a number of respondents, have been carried out as a next step of our research. The respondents were burdened by tests with various difficulties in order to invoke the proper stress conditions and achieve valuable results. Two IDA microelectrodes for the skin impedance measurement, a temperature sensor and a pressure sensor for heart pulse monitoring have been fixed on their bodies. The pressure detectors did not give valuable results but the temperature and IDA sensors have been working accurately. The sensors were placed on the respondents' wrist (upper as well as lower parts of the wrist). Fig. 19 shows the results obtained by the various tests being applied. During the test, firstly the body temperature increased softly, but after the certain settlement it was decreased under the stress stimulus (Fig. 19a). The behavior of the measured skin admittance was as expected — a remarkable increase due to the stress stimulus (marked with grey areas), as shown in Fig. 19b and Fig. 19c for the absolute value and the relative change, respectively.

4 CONCLUSIONS

The portable measurement system for the reliable and precise stress detection based on the psycho-galvanic reflex monitoring has been designed and developed. The system is based on an auto-balancing bridge measurement method offering digital processing and displaying of the measured data in the developed software operating under Windows XP platform. The measurement equipment uses the dedicated microelectrodes developed for this purpose, and utilizes microcontrollers containing RF wireless communication modules to transfer data between the measurement unit and a personal computer. The complete measurement system has been designed with respect to the system accuracy, sensitivity and power management.

The experimental results show that the microelectrodes are able to sense the electrodermal response in a very precise and fast way. Interesting outcome has been observed — the psycho-galvanic reflex might be much more accurately sensed by the skin admittance phase

since this parameter reflects the human skin conductivity changes significantly. The achieved accuracy, voltage and frequency ranges are suitable not only from human biomedical monitoring point of view but also from the measurement system integration and miniaturization requirements.

Additionally, the proposed system is versatile and flexible, easy to be extended by other sensors' types (integrated or external with wireless communication) or different measurement approaches, which enables measurement of other physiologic parameters (*eg* body temperature, blood pressure, heart beat, *etc*) It is no doubt that the developed measurement equipment offers new opportunities towards non-invasive wireless system for continuous biomedical monitoring, applicable in diverse areas of clinic psychology, medicine or other everyday life areas. All these features and properties make the developed biomedical monitoring system very helpful also from the quality of life enhancement point of view.

Acknowledgements

This work has been done in Center of Excellence CENAMOST (Slovak Research and Development Agency Contract No. VVCE-0049-07) with support of projects AV4/0018/07 and APVV-20-055405.

References

[1] OLMAR, S.: Bioelectrochemistry and Bioenergetics **45** No. 2 (1998), 157–160.

[2] WAKELAM, K.: Biofeedback and the Human Energy Field No. 3 (2000), 7–9.

[3] Qubit Systems – Human Electrophysiology http://www.qubitsystems.com/electro.html/ .

[4] WEIS, M.—DANILLA, T.—MATAY, L.—HRKÚT, P.—KÁKOŠ, J.: Noninvasive Biomedical Sensors on the Biology — Interface of Human Skin, Proceedings of the 7th International IMECO TC-13 Conference on Measurement in Clinical Medicine: Model Based Biomeasurement, Stará Lesná, 1995, pp. 89–91.

[5] VAVRINSKY, E.—TVAROZEK, V.—MARMAN, P.—WEIS, M.: Monitoring of Psychophysiological Processes by Skin Conductivity Measurements using Microelectrode Arrays, European Medical and Biological Engineering Conference, Prague, Czech Republic, 2005.

[6] GERASIMOV, V.: Every Sign of Life, Massachusetts Institute of Technology, USA, 2003.

[7] ANGELOPOULOU, E.: The Reflectance Spectrum of Human Skin, Technical Report MS-CIS-99-29, University of Pennsylvania, USA, 1999, pp. 1–14.

[8] IVANIC, R.—NOVOTNY, I.—REHACEK, V.—TVAROZEK, V.—WEIS, M.: Thin Film Non-Symmetric Microelectrode Array for Impedance Monitoring of Human Skin, Thin Solid Films **433** (2003), 332–336.

[9] SHEPHERDP.: The Galvanic Skin Response Meter, http://www.trans4mind.com/psychotechnics/gsr.html/ .

[10] MAJER, L.—STOPJAKOV, V.—VAVRINSKÝ, E.: Sensitive and Accurate Measurement Environment for Continuous Biomedical Monitoring using Microelectrodes, In: 6th International Conference on Measurement - MEASUREMENT 2007, Smolenice Castle, Slovakia, May 20–24, 2007, pp. 408–412.

[11] AD5933 Datasheet, http://www.analog.com/ .

[12] ADuC832 Datasheet, http://www.analog.com/ .

[13] MAJER, L.—STOPJAKOVÁ, V.: Portable Measurement Equipment for Continuous Biomedical Monitoring using Microelectrodes, In: IEEE Workshop on Design and Diagnostics of Electronic Circuits and Systems - DDECS 2008, Bratislava, Slovakia, April 16-18, 2008, pp. 26–29.

[14] nRF24E1 Datasheet, http://www.nordicsemi.com/ .

Received 1 July 2008

Libor Majer received the MS degree in Electronics from Slovak University of Technology in Bratislava, Slovakia, in 2004. Since 2004 he has been a PhD student at Microelectronics Department of the same university. He has worked in area of RF, analog and mixed IC design and testing, systems on chip, biomedical circuits, application software, and hardware design of the programmable ICs, microcontrollers and signal processing. He participated on several EU projects such as Project REASON, European Social Fund project and many others. He is the author or co-author of more than 15 papers presented at international conferences or published in journals.

Viera Stopjaková received the MS degree, and the PhD degree in Electronics from Slovak University of Technology in Bratislava, Slovakia, in 1992, and 1997, respectively. From October 1997 to September 2003, she was an assistant professor at Microelectronics Department of the Slovak University of Technology in Bratislava, Slovakia. Since October 2003 she has been an associate professor at the same department. She was involved in several EU projects such as Tempus, ESPRIT, Copernicus, Inco-Copernicus, 5th EU Framework Program Project REASON, European Social Fund project and many others. She is the author or co-author of more than 80 papers published in journals or presented at international conferences. Her main research interests include IC design, VLSI & SoC testing, on-chip testing, biomedical circuits, and neural networks.

Erik Vavrinský received the MS and the PhD degree from the Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in 2002 and 2006, respectively. He is currently employed as an assistant professor at the Department of Microelectronics of the same university, working in the field of electronics and microsensors. His current research interests include thin-film microsensors, electrochemical biosensors, MEMS design and electrical measurement methods.