Durable sensors for measurement of foot plantar pressure with piezoelectric polyvinylidene fluoride foil

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ABSTRACT

This paper presents application of polyvinylidene fluoride (PVDF) foil for sensors of foot plantar pressure for measurements in natural conditions (i.e. outside laboratory). The material has been evaluated for this application based on investigation of material resistivity, current and activation energy of electret depolarization process, and relationship between pressure and electrical signal. The investigation shows that PVDF foils can operate at temperatures up to 85 °C, have high activation energy of 5.2 eV and a linear dependence between pressure and piezoelectric signal, which makes them suitable candidates for foot plantar pressure transducers. Influence of foil stretching is eliminated via a design of the shoe insole, which prevents deformations. Design of an input amplifier which eliminates pyroelectric effect is also presented. For applications in measuring foot plantar pressure, sensor calibration can be eliminated by placing several pressure sensors in the shoe insole and expressing pressure as relative values between sensors. The paper also describes a wireless system for measurement of foot plantar pressure, and obtained measurements.

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1. Introduction

Currently existing measuring systems for foot pressure applied to the ground are EMed – SF System with further modifications [1–4] and PEDAR with its further modifications [5–8]. First one is used for measuring forces applied to the measuring surface by a bare foot and the second one is used to measure forces by a measuring insole mounted in the shoe. In first case, conditions during examination are similar to static conditions. The obtained result is the map showing layout of the maximum forces at the points where the foot surface is in contact with the measuring mat. In second case examination is performed in dynamic conditions. The obtained results present similar map of forces but complicated analysis, required frequent calibration of the resistance sensors (every few sessions) and high price make this method inconvenient and difficult for widespread use. Several laboratories over the world are developing the inexpensive and easy to use system which can perform measurements in dynamic conditions, allowing widespread and everyday use. During this research several systems

were developed, e.g. a system based on ceramic sensors with two sensors placed under the heel and two more under the metatarsal [9]. In another solution, sensors are made of elastomer containing metallic fibers where distance between them is reduced during compression which results in decreased resistance proportional to acting force [10].

A system described in this article makes it possible to obtain measurements in natural conditions, i.e. during walking, running, jumping. The main part of our pressure sensors is 110 μm thick polarized PVDF film with printed CuNi electrodes, which was selected among other investigated piezoelectric polymers, like PE, PP [11–13] and PET [14]. PVDF film is characterized by good mechanical durability [15–17]. In our previous work, the PVDF foil (manufactured by Measurement Specialties, Inc.) was studied using scanning microscopy and well crystallized structure was found. Although XRD studies were not performed, the observed very good piezoelectric properties of the foil indicate the beta phase presence since only this phase exhibits piezoelectric properties after polarization.

In this work, film resistivity was measured using alternating polarity method [18] and film depolarization was determined using thermally stimulated discharge current (TSDC) measurements [19]. It is assumed that sensors operating temperature should not exceed

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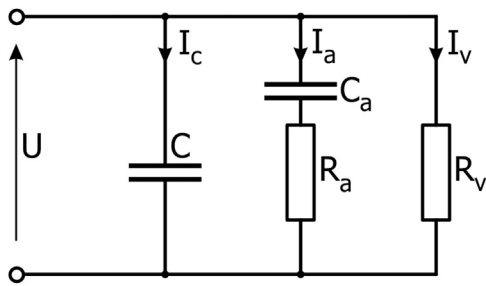E-mail address: eklimiec@ite.waw.pl (E. Klimiec).

Fig. 1. Equivalent circuit of the PVDF foil with applied supply voltage U, I_c – charge current, C – equivalent of the vacuum capacitor with added equivalent of the elastic oscillations of the dipoles, I_a – absorption currents, C_a – dynamic equivalent of dipoles polarization, R_a – relaxation losses, I_v – leakage current, R_v – volume resistivity.

temperature T_m, i.e. the value where the density of discharge current is the highest. Main disadvantage in using PVDF film is pyroelectric effect [16]. Pyroelectric signal disturbs piezoelectric signal. To reduce this effect a resistor-capacitor RC high-pass filter was used in the developed system. From relations between electrical signal and pressure, the voltage d_{33}, d_{31} and charge g_{33}, g_{31} piezoelectric constants were calculated. Measured data are transmitted wirelessly to a personal computer from an electronic circuit fixed to the shoe. Waveforms of the forces applied to the individual sensors are acquired simultaneously.

2. Research method and results

Piezopolymers destined for sensors should be elastic. It means that after releasing pressure from the film, the material recovers to the initial state in a short time. Mechanical durability and elasticity of PVDF represented by Young's modulus and yield strength are ~2000 MPa and 50 MPa, respectively [16,17].

Polarized piezopolymers (electrets) should be good isolators which prevents depolarization. From the practical point of view, lifetime should be over 10 years. According to literature [20] depolarization time of the PVDF film is ca. 50 years. Volume resistance of the polarized PVDF foil was measured using alternating polarity method [18].

Thermal durability of the electrets was evaluated using thermally stimulated discharge current (TSDC) measurements and calculation of activation energy of its depolarization process. Temperature T_m was determined as the point where the electric current magnitude is at maximum [19].

To ensure correct measurement of the foot interaction with the ground, it is necessary to investigate influence of the force direction on the electric signal value.

2.1. Resistivity measurement

The sample of foil under test can be compared to an empty vacuum capacitor with dielectric inside. After applying voltage, a series of transient processes occurs, after which the device reaches steady state. Equivalent circuit of the PVDF foil with applied supply voltage is shown in Fig. 1.

When the foil is polarized by supply voltage U, it conducts a current I(t), which is the result of the superposition of three separate factors: $I(t) = I_c(t) + I_v + I_a(t)$. Charging current $I_c(t)$ decreases rapidly. After measuring the absorption current, and before changing the polarization of the power supply, the electrodes were shorted and resorption current was measured. Current measurements were conducted at electric field of 10 V/μm. Volume resistance measurement was performed using a Keithley 6517

electrometer and a three electrode measuring module. Adsorption, resorption and leakage currents in time are shown in Fig. 2a.

In steady state the foil with volume resistance R_v conducts only the leakage current I_v, and the resistance and resistivity of the PVDF foil can be calculated using the following equations.

$$R_V = \frac{U}{I_V} \quad (1)$$

$$\rho = \frac{R_V A}{h} \quad (2)$$

R_V – volume resistance.
U – supply voltage.
I_V – volume current.
A – effective surface of measuring electrode.
h – sample thickness.

Fig. 2b shows momentary foil resistance in function of time. It was calculated using mean value of $|I_a + I_v|$ measured for opposite polarizations of supply voltage. Fig. 2b shows that $I_a(t)$, which is the effect of polarization of dipoles, disappears after ca. 12 h. Resistivity of the PVDF foil in steady state is 10^{15} Ωm, making it a good insulator.

2.2. Durability of the PVDF electrets – TSDC measurements

The samples were heated at a temperature ranging from 40 °C to 150 °C with gradient of 0.018 C/s (~1C/min), current was measured using a Keithley 6517A electrometer. Approximate value of depolarization process activation energy was calculated using Arrhenius equation (3). During matching straight regression line, temperature taken into consideration was in range from the lowest temperature when TSD current density starts to increase up to the highest temperature corresponding to half of the maximum current density value in accordance with Garlik-Gipson recommendation [18].

$$J(T) \sim const \cdot e^{\frac{E}{kT}} \quad (3)$$

After performing two sided logarithm:

$$\ln(J(T)) = const' + \frac{E}{kT} \quad (4)$$

J – current density.
E – activation energy.
k – Boltzmann constant.
T – temperature in Kelvin.

In case of simple waveforms, where one depolarization process is dominant, ln(J(T)) function is linear vs. reciprocal temperature. Approximate value of activation energy is calculated from the gradient of this straight line.

$$E = k \times tg\alpha \quad (5)$$

where tgα – straight line slope.

Depolarization of PVDF film is associated with a few interacting processes. This is illustrated in Fig. 3 by difficult for interpretation waveform 1 obtained during the first depolarization test. In such case it is impossible to determine one activation energy for complex depolarization process. After depolarization process caused by heating (40–150 °C) the materials typically are damaged. Experiment was repeated on the same sample, because after this first depolarization test, the sample still showed piezoelectric effect, although several times smaller. Upper temperature limit was increased to 150 °C. Waveforms of the thermally stimulated current vs. temperature in both depolarization cases can be seen in Fig. 3. T_m temperature for the first test was ca. 80 °C. For the second test run, temperature T_{m3} was ca. 145 °C.

Approximate activation energy value was calculated from the second depolarization process characterized by a simpler for interpretation waveform. The curve of logarithm of depolarization