Model of a digital device for assessing the state of xylem in tree trunks

N S Kamalova, N Yu Evsikova* and Yu V Krutskikh

Department of General and Applied Physics, Voronezh State University of Forestry and Technologies named after G F Morozov, 8 Timiryazeva Street, 394087, Voronezh, Russian Federation

*E-mail: meetvgltu2@vgltu.vrn.ru

Abstract. For the development of systems for predicting the state of forests and trees, adequate models of the influence of temperature and humidity environment fluctuations on the kinetics of the wood microstructure are needed. Formalized modeling should be based on monitoring data obtained with controlled accuracy in real time. The aim of the work was to substantiate the layout of a device for measuring the potential difference in tree trunks to study their state. For the first time in the article, the recorder layout with the operating principle based on the phenomenon of thermally stimulated polarization of wood has substantiated. In addition, a formalized model has presented for processing the monitoring data of the studied potential difference in the framework of classical thermodynamics, which makes it possible to determine the parameters of the kinetics of the microstructure of wood in tree trunks at fluctuations of external factors. As a result of the research carried out, a model of a digital device for assessing the state of wood of tree trunks was developed. The proposed device for recording the response of the trunk wood on the fluctuations of external factors practically does not violate the unique microstructure of the biocomposite and has a controlled accuracy in real time.

1. Introduction

There is no doubt that forests play an important environmental role and influence the living conditions of people [1-3]. Monitoring the condition of trees in the forest is one of the most important tasks of forestry, the solution of which needs automation and new non-destructive measurement methods [4, 5]. Techniques for monitoring the state of forest stands in real time could make it possible to develop a set of measures for a timely response to the possibility of critical situations [6-8]. In addition, the study of processes occurring in tree trunks is the basis for understanding natural phenomena and the development of nature-like technologies [9]. Automation of operations for determination the quality of wood directly in the xylem of the trunks without significant destruction of its unique structure could be used to solve problems arising in the course of inventory of forests [10, 11].

Recently in the field of specialized instrumentation for determining the vital state of woody plants, it has been actively developed devices that based on gas exchange in leaves (photorespiration) [12-14]. Such devices are significantly limited in employment because they can used only for hardwoods in the spring and summer. Practically, the measurement techniques based on the digital moisture meters using are implemented, its circuit includes a recorder that converts moisture fluctuations into a digital signal.

There are techniques for monitoring the state of trees based on electrical measurements. For example, it is proposed to use tomography of electrical resistance for determining the difference in the concentration of moisture or electrolytes in wood tissue [4, 15]. The article [16] describes the application...
of the resistivity method using an annular array of needle electrodes to visualize the internal electrical structures of the living standing trees trunks. Analysis of the measuring electrical resistance results forms the basis of the plant tissues study [17]. The article [18] describes a procedure for determining the relative vigor of trees based on the interpretation of electrical resistance patterns given by a pulsed-current meter, the Shigometer. These techniques consider the wood of the trunk as a conductor with non-uniform conductivity and are based on the correlation between moisture and resistance. On the other hand, methods for directly measuring the extracellular potential difference are being developed actively. For example, the measurement of the potential difference between the roots and the leaf petiole is proposed to use for monitoring the physiological responses of trees at the moisture content in the soil [19]. Daily fluctuations in the distribution of potential in the tree trunk, which are also associated with sap flow in summer, were studied in [20].

Earlier, we proposed to measure the potential difference along the radius of the woody plants trunks for exposing their vital state [21]. The technique is based on the results of monitoring the dynamics of the potential difference along the trunks radius of different living states trees during daylight hours. The origin of the electric field in wood was described in articles [21-23]. In our opinion, the redistribution of charges in the trunk wood is stimulated by the influence of temperature gradients that appear along the radius when the ambient temperature changes. The presence of temperature gradients in tree trunks is also confirmed by measurements described by other scientists [24]. The results of experiments [24] had shown that the magnitude of such temperature gradients is enough for obtaining energy to power sensors for environmental monitoring using a Peltier cell. Wood is a dielectric biopolymer composite material, the main components of the its cell walls are partially crystalline cellulose and lignin. The redistribution of charges in wood is caused by the piezoelectric and pyroelectric properties of the crystalline part of cellulose and the orientational polarization of the side groups of macromolecules in its amorphous part. This view of the electric field origin in tree trunks differs from that proposed by the authors [20].

The purpose of the work is substantiation of the digital device layout for studying state of trees that based on a digital recorder for measuring the potential difference in tree trunks. The novelty of the proposed approach is in the formulation and substantiation of the tree state measuring principle with controlled accuracy and without irreversible destruction of the trunk structure using digital technologies that allow recording and processing research data using modern information systems. Such a device will be able to measure the potential difference in real time at fluctuations in ambient temperature and humidity and record a digital signal on an electronic carrier for the convenience of its subsequent analysis.

2. Theoretical part
According to our ideas [21-23], arising in the xylem of tree trunks potential difference is the result of non-uniform temperature distribution in the trunk due to the low thermal conductivity of wood. Temperature gradients stimulate the pyroelectric effect in cellulose crystallites. Since the coefficient of thermal expansion of lignin is much higher than that of cellulose, the thermal expansion of lignin leads to a piezoelectric effect in cellulose crystallites. Thus, an electric field arises in the wood, in which the orientation of the side groups of macromolecules of the noncrystalline part of cellulose occurs. That is, the formation of an uncompensated surface charge in wood is a complex effect.

From a thermodynamic point of view, the entropy changes in the process under study is:

\[ dS = k \frac{dW}{W} = \frac{\delta A}{T}, \]

where \( k \) is the Boltzmann constant, \( W = \Delta N/N \) is the thermodynamic probability, defined as the ratio of the change in the number of oriented side groups with a change in temperature to the total number of side groups, \( \delta A \) is the work on orientation, \( T \) is the current value of the absolute temperature in the
wellbore. Since the thermal diffusivity of the trunks wood is very low, it can be assumed that the temperature change occurs very slowly, then from relation (1) it can be obtained that

$$\frac{dN}{\Delta N} = \frac{\delta A}{kT}. \quad (2)$$

The right side of the obtained equality is the ratio of the energy consumption for the orientation of the side groups of noncrystalline cellulose to the value of its kinetic energy per degree of freedom.

It is obvious that the process of ordering the side groups at a change in the ambient temperature is relaxation. Therefore, it is advisable to analyze its speed characteristics. If we introduce the notation

$$\mu = \frac{\delta A}{kT\tau_R} \quad (\tau_R \text{ is transition time to a new more ordered state}),$$

then

$$\frac{dN}{\Delta N} = \mu dt. \quad (3)$$

Any process in a complex composite is accompanied by an inertial response of the system; therefore, the value $\mu = \mu_0 - \varsigma t$ will decrease with an increasing of the number of oriented side groups at a certain rate $\varsigma$. Then relation (3) is transformed to a differential equation of the first kind. Taking into account the initial number of oriented groups $\Delta N = N_0$, the solution of this differential equation is an analytical function

$$\Delta N = \frac{N_0 e^{\mu_0 t}}{1 + \varsigma N_0 / \mu_0} / \mu_0. \quad (4)$$

Since the value of the orientational polarization is $\Delta P_{in} = p_i \Delta N$ ($p_i$ is the dipole moment of the lateral group), the resulting potential difference $U$ can be estimated from the relation

$$U = \frac{U_0 e^{\mu_0 t}}{1 + \chi U_0 / (e^{\mu_0 t} - 1)}, \quad (5)$$

where $\chi = \varsigma R/2\mu_0 p_i$ ($R$ is the trunk radius). Relation (5) illustrates the fact that the value of the potential difference depends on the parameters $N_0$, $\mu_0$ and $\chi$, which characterize the features of the composition and microstructure of the trunks wood. Relation (5) is the basic relation for determining these parameters by the method of formalized modeling, for example, by minimizing the value of the relative deviation of the experimental and theoretical values of the potential difference. In addition, the moisture content of the wood should influence the value of the potential difference, since water has a large dielectric constant.

3. Experimental part

To solve the problem, we used the results of monitoring the potential difference along the trunk radius of individuals of birch (*Betula pendula*) and aspen (*Populus tremula*). The explored trees grew in the same forest growing conditions and were characterized by relatively similar inventory indicators: aged – 55 years, bonitet – III, vital state – 2 and 7. At the first stage, a portable instrument, a MY62 digital multimeter (Precision Mastech Enterprises Co., Ltd., Hong Kong), was used for measuring the potential difference [21-22].

Monitoring of the potential difference along the radius of tree trunks was carried out during daylight hours in natural conditions at changes in the ambient temperature. The measurement scheme is shown in a cross-section in figure 1. To ensure a relatively stable result over time, electrodes were implanted into the wood of the trunk. For this purpose, holes of various depths with a diameter of 4.5 mm were drilled in test samples at a height of 1.3 m from the ground surface. Internal electrodes were implanted
into the wood along the center of the trunk and along the radius of the trunk at distances of 0.25R and 0.5R from the center. An external electrode was inserted into the xylem near the border with the phloem. The electrodes were stainless steel pointed rods insulated up to the contact surface (4-5 mm). The electrodes were connected to a MY62 digital multimeter using a flexible wire.

Since the processing of monitoring data within the framework of the proposed approach is carried out through formalized modeling, it is advisable to use a digital recorder for recording. The next stage of work was the development of a digital device layout for automatic measurement of the potential difference at regular intervals and storing information on a digital medium. The measuring device is developed on the basis of an autonomous recorder - two-channel ECLERK-USB-2mV-G, designed for automatic measurement and archiving of voltage values in the range from 0 to 50 mV at regular specified time intervals with subsequent processing of the accumulated data on a personal computer. In addition, such recorders are used in our conditions in moisture meters and are manufactured by the resident of the Novosibirsk Academpark NPK Relsib, which is the leader in the production of autonomous recorders, portable meters, humidity sensors, thermal relays, microclimate monitoring devices for pharmaceuticals and medicine in the Russian Federation. The device is easily attached to the tree on the connecting wires and records the readings on the recorder carrier. To use the recorder, a matching device was needed that allows measurements in the range from 1 mV to 1 V (figure 2). For digital processing of the measurement data, we used the standard software from the kit of the ECLERK-USB stand-alone recorder, version 1.18.

The diagram of the measurement technique using the developed device is similar to that shown in figure 1. Trial measurements have shown that the main problem is associated with the selection of electrodes and the connection of the device with them. After repeated tests, insulated galvanized nails were chosen as electrodes. To analyze the measurement results, a program was developed that recalculates the data.

4. Results and discussion

The results of measurements carried out in birches and aspens using a MY62 digital multimeter are shown in the form of a histogram in figure 3. In most of the studied individuals, the distribution function of the potential difference value along the trunk radius had a maximum in the middle of the trunk radius. Therefore, further measurements of the potential difference were carried out between the middle of the trunk radius and the outer edge of the xylem. In addition, measurements have shown that the magnitude of the potential difference of the electrostatic field is individual for each tree and each species and, obviously, depends on the vital state of the plant, which is not always possible to determine by visual observation. This result is consistent with the correlation of the results of electrical measurements with...
the moisture content and the vital state of woody plants in the works of other authors. For example, in [18] it was found that the values of electrical resistance differ for different trees. It was shown in [19] that with a decrease in humidity, the voltage between the roots of the tree and the leaf petiole decreased. In [16], an inverse relationship was found between resistivity and moisture content in tissues, and anomalies in resistance are associated with infections. The authors of [4] showed that resistivity tomography can be used for presymptomatic determination of physiological stress in standing trees.

The daily dynamics of the potential difference between the middle of the trunk radius and the outer edge of the xylem in the trunks of birches 1, 2 and aspens 1, 2 is shown in figure 4. The dynamics of this potential difference in the daytime smoothly depends on time. In addition, in aspen trunks the value of this potential difference practically did not change if fluctuations in the ambient temperature during monitoring did not exceed 1-2 °C, and in birch trunks, with a significant change in air temperature in the morning, it stabilized by 16:00. The experimental dependence of the potential difference along the radius of the trunk is of a relaxation nature. It confirms the assumption on the basis of which relation (5) was obtained in the theoretical part of this work, and indirectly confirms the fact that the measured potential difference is determined by the response of the trunk xylem to fluctuations in the ambient temperature.

To carry out formalized modeling according to relation (5) by the method of minimizing the average relative error of the monitoring data from the model curve, an author’s program was developed, which made it possible to determine the parameters $U_0$, $\mu_0$, and $\chi$. The results of comparing the monitoring data of the potential difference between the middle of the trunk radius and the outer edge of the xylem in the trunk of birch 1 and the computational experiment are shown in figure 5.

For the example shown in figure 5, the average relative error for all experimental data does not exceed 4% with the following kinetic parameters: $U_0 = 1$ mV, $\mu_0 = 1.3$ s$^{-1}$ and $\chi = 0.062$ mV$^{-1}$. Since the dynamics of the potential difference for each tree is unique, monitoring makes it possible to determine the parameters of the kinetics of the charge redistribution process along the trunk radius under the influence of the environment for each tree, taking into account the characteristics of growth, moisture content and the unique structure of the trunk biocomposite.

Thus, the monitoring results revealed an unconditional correlation between the potential difference and the model mechanism of the polarization of the tree trunk xylem, stimulated by the temperature gradient. This convincingly substantiates the possibility of studying the kinetics of the charge redistribution process along the trunk radius by measuring the potential difference between the middle of the trunk radius and a point located in the xylem under the phloem.
Figure 5. The results of comparing the monitoring data of the potential difference in the birch trunk and the computational experiment.

Figure 6. Results of monitoring the potential difference in the birch trunk using the developed sensor.

Figure 6 shows the results of monitoring the potential difference in the birch trunk using the developed sensor. It found out that the device makes it possible to record the potential difference between the middle of the radius and the edge of the xylem every second, and the results are stable for a sufficiently long period of time, and the accuracy varies with the capacity of the recorder and does not exceed 0.001 mV. In this case, measurements are carried out using the simplest configuration of electrodes, similar to the method of tomography of electrical resistance [4, 15] without measuring the strength of the current, which is formed by various processes in the wood of the trunks. Consequently, using the developed device, it is possible to observe seasonal changes in the state of a tree caused by fluctuations in temperature and humidity of the environment, in real time with recording the results on an electronic carrier, practically without destroying the unique structure of the trunk and using digital signal processing.

5. Conclusion
Studies have shown the following:

1) fluctuations in ambient temperature stimulate the formation of a potential difference of the electrostatic field along the radius of tree trunk, which reaches its maximum value in the middle of the radius;

2) the magnitude of the potential difference of the electrostatic field is individual for each tree and species and depends on the vital state of woody plants;

3) the proposed mechanism for the formation of a potential difference in tree trunks is based on polarization phenomena in the wood substance under the influence of temperature gradients arising along the trunk radius when the ambient temperature changes due to the low thermal conductivity of wood;

4) within the framework of classical thermodynamics, a formula relation was obtained analytically for a formalized model to determine the kinetics of the parameters of the microstructure of the trunk wood according to the monitoring of the potential difference along the trunk radius;

5) measurement of the potential difference is the registration of the response of the microstructure of the wood to fluctuations in environment temperature and humidity;
6) to automate measurements and record their results on an electronic carrier, a digital sensor model was developed on the basis of an autonomous two-channel recorder ECLERK-USB-2mV-G;
7) a prototype of a digital sensor showed stability of measurements over a sufficiently long period of time with an accuracy of 0.001 mV.

Thus, the result of the research was the justification of a digital device layout for assessing the state of the xylem of tree trunks by measuring the potential difference along the radius of the trunk. The operating according to the stated principle device is proposed for the first time, practically does not disturb the microstructure of wood. Measurements are carried out in real time and have controlled accuracy. The monitoring results are recorded on a digital carrier and processed using formalized modeling, which makes it possible to estimate the parameters of the wood microstructure kinetics.

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