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Measuring systems in technologies of automated humidity control

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Abstract. This paper examines intelligent humidity sensors (transducers) as a component of an automated process control system that converts a controlled physical quantity into a measured signal for further processing in an automatic device, as well as mathematical models of intelligent support for bulk material moisture meters. It is demonstrated that one method for increasing the efficiency of the functioning of quality meters for various bulk materials is the development of conceptual foundations and their practical implementation in the construction of express devices capable of measuring grain and grain materials. The interaction of intelligent support measuring tools in technologies for automated moisture control in technological processes and control is investigated. The microwave method is recommended for monitoring the moisture content of grain and grain materials, as well as their metrological characteristics.

1. Introduction

The automated control system of the technological process is an integrated complex of hardware and software tools that provides automation of the control of technological equipment in the production of grain and the industrial processing of their products. Humidity sensors are widely used when constructing systems for automatic control and management of technological processes [1-3.]. Humidity sensors (transducers), as an element of the automation system, convert the controlled physical quantity into a measured signal for further processing in an automatic device: analysis, comparison, storage, transmission, and registration [4, 5]. After certain processing, an executive signal is generated, which serves to influence the controlled process. Smart sensors define measuring systems with a complex hierarchical structure [6]. To decide the choice of sensor, it is first necessary to study method selection classification, as well as the measuring device. Analysis of all known moisture control devices (moisture meters) of the studied materials (grain and grain bulk materials) [7] based on the electrical method, i.e. the microwave method is classified according to various criteria [8, 9.]:
- According to the informative parameter, moisture meters are divided into amplitude, phase, amplitude-phase, frequency, and resonator;
- according to the schematic solution of the location of the receiver and the emitter of microwave energy relative to the controlled sample, the moisture meters can be for transmission, or reflection of an electromagnetic wave, combined;
- From the method of signal generation, analog and discrete moisture meters are distinguished. According to observations of modern domestic [10-15] and foreign [16-18] literature, technical solutions that used the microwave method are primarily represented by two options:
An informative parameter characterizing the mass ratio of moisture is the amplitude of the wave passing through the material;

Humidity information is presented as a function of two variables (attenuation A, microwave energy, and phase shift φ of the electromagnetic wave).

2. Materials and Methods

The use of the method of drying grain and grain materials showed that due to the low thermal conductivity of grain, it is impossible to obtain a significant reduction in the duration of the analysis, therefore, using the drying method, the problem of express assessment of the mass ratio of moisture content of grain and grain materials cannot be solved. This formulation of the question stimulated the development of indirect methods based on the dependence of the physical and mechanical properties of the material on the mass ratio of grain moisture. The most significant group is represented by electrical methods based on the dielcometric method for measuring the dielectric parameters of a material.

A common feature of the instrumental implementation of methods for estimating the mass ratio of moisture using the dielcometric method is the most optimal microwave method based on microwave frequencies with the use of attenuators and phase shifters operating in the analog mode in the microwave path [19]. A common significant drawback of typical schemes operating according to the first variant is the measurement of the mass ratio of moisture W and density ρ using only one parameter - the magnitude of the microwave energy, i.e. here,

$$A = f(W, \rho) \tag{1}$$

- A -is the attenuation of microwave energy,
- W -is the mass ratio of moisture,
- ρ- is the bulk density of the material under study.

Since the second informative parameter (for example, φ) is absent in the presented equation, it is not possible to get rid of the non-informative parameter (interfering factor ρ.

For this reason, in the considered variant of technical solutions, the mass of the analyzed sample is maintained constant to distort the results of measuring the mass ratio of moisture [20].

3. Results

Moisture meters operating according to the principle of the second option, the so-called amplitude-phase ones do not have the above disadvantage. However, at present, there is no data [21] on the creation of actual designs of moisture meters, which are based on the principle of function transformation.

$$u = f(A, \varphi)$$

Where, u- is the measurement result characterizing the mass ratio of moisture.

The reason hindering their widespread implementation is the complexity of technical solutions and the lack of sufficiently simple and accurate phase shifters operating in the range from 0 to 2π [22]. Nevertheless, the measurement of the mass ratio of moisture according to the two characteristics A and φ of an electromagnetic wave is of interest from the point of view of separating the useful and interfering signals. For this purpose, consider functions of the form $u = f(A, \varphi)$, in which A and φ are also functions of the arguments W and ρ, i.e.

$$
\begin{aligned}
A &= f_1(W, \rho) \\
\varphi &= f_2(W, \rho)
\end{aligned} \tag{2}
$$

In this case, the partial derivatives of the specified function concerning the arguments W and ρ are expressed in terms of the partial derivatives of the function u= $f(A, \varphi)$ as follows [23]:

$$\left.\begin{array}{l}\dfrac{du}{dW}=\dfrac{du}{dA}\dfrac{dA}{dW}+\dfrac{du}{d\varphi}\dfrac{d\varphi}{dW}\\[2mm]\dfrac{du}{d\rho}=\dfrac{du}{dA}\dfrac{dA}{d\rho}+\dfrac{du}{d\varphi}\dfrac{d\varphi}{d\rho}\end{array}\right\} \qquad (3)$$

The increment Δu of the function u= $f(A,\varphi)$ in the case of differentiability at some point M (W,φ) can be reduced to the form

$$\Delta u=\frac{du}{dA}\Delta A+\frac{du}{d\varphi}\Delta\varphi+\alpha_1\Delta A+\alpha_2\Delta\varphi\ \Delta u=\frac{du}{dA}\Delta A+\frac{du}{d\varphi}\Delta\varphi+\alpha_1\Delta A+\alpha_2\Delta\varphi \qquad (4)$$

Here, α_1 and α_2 are constant infinitesimal quantities. Hence, the problem of determining the mass ratio of moisture, taking into account the interfering factor, is reduced to determining the measurement of attenuation A and phase shift φ.

When conducting studies of the considered materials, and the influence of other material parameters, we will not consider their influence on the measurement result. In this case, from [23], we write the transformation equation for the amplitude and phase moisture meters in the form:

$$A=f_1(W,m) \qquad (5)$$

$$\varphi=f_2(W,m) \qquad (6)$$

Where, m is the mass of the material in the control zone W - moisture content of the material.

The influence of W and m on A and φ is expressed from the following relations:

$$dA=\frac{dA}{dW}dW+\frac{dA}{dm}dm \qquad (7)$$

$$d\varphi=\frac{d\varphi}{dW}dW+\frac{d\varphi}{dm}dm \qquad (8)$$

If we express the sensitivity of the amplitude and phase methods to moisture through SA_W and $S\varphi_W$ then:

$$SA_W=\frac{dA}{dW}\ ;S\varphi_W=\frac{d\varphi}{dm}\ ; \qquad (9)$$

$$SA_m=\frac{dA}{dm}\ ;S\varphi_m=\frac{d\varphi}{dm}\ ; \qquad (10)$$

The moisture meter will be calibrated at a constant mass of the materials under study. Then in this case,

$$A=SA_WW \qquad (11)$$

$$\varphi=S\varphi_WW \qquad (12)$$

Humidity measurement by amplitude and phase method with moisture meters will be determined from the ratios

$$WA=\frac{A}{S_{AW}} \qquad (13)$$

$$W\varphi=\frac{\varphi}{S_{\varphi W}} \qquad (14)$$

The attenuation and phase shift will change accordingly if the mass of the controlled material deviates from the value at which the calibration takes place.

$$dA = S_{Am} dm \tag{15}$$

$$d\varphi = S_{\varphi m} dm \tag{16}$$

It is perceived as a measurement of humidity, measured by moisture

$$dW_A = \frac{dA}{SA_W} \tag{17}$$

$$dW_\varphi = \frac{d\varphi}{d\varphi_m} \tag{18}$$

In our case, the errors in moisture measurement by amplitude and phase moisture meters due to fluctuations in the mass of the controlled material will depend on the ratio of the sensitivity of these methods to mass and moisture.

To analyze the above expressions, determine the transformation functions of $F_1 = (W, m)$ and $F_2 = (W, m)$ in the equations $A = F_1(W, m)$, $\varphi = F_2 = (W, m)$ and construct a model of the microwave field's interaction with wet material. In this case, it will be necessary to describe the mathematical model of the interaction of the microwave field with wet material.

To study the possibility of increasing the accuracy of determining the mass-moisture ratio (MMR) by measuring several characteristics of the electromagnetic waves (EW) and expanding the measurement range by clarifying the functional dependence of the EW attenuation on the MMR in the presence of various interfering factors. When processing the experimental data, the regression equation was found by the method of polynomial approximations, the significance of the variance of which, when compared with the Fisher criterion, made it possible to confine ourselves to a polynomial of the third degree of the form

$$W = 6{,}53 \cdot 10^{-4} A^3 - 3{,}74 \cdot 10^{-2} A + 1{,}06 A + 3{,}67 \tag{19}$$

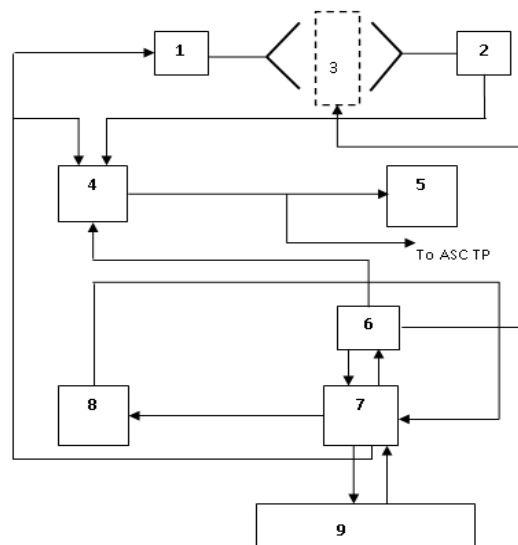**Figure1**. Scheme of the experimental installation for measuring the moisture content of grain and grain materials: 1 - microwave module, 2 - measuring station, 3 - controlled sample, 4 - computing device, 5 - indication unit, 6 - control unit for loading and unloading the sampler, 7 - adjustable suspension with a measuring chamber, 8 - stepper drive for regulation according to height, 9 - belt conveyor

Theoretical and experimental dependences of the EW attenuation on the MMR determined by equation (19) were obtained. The correlation coefficient, in this case, was $K_1 = 0,99$, and the standard deviation of the random error $\sigma_w = 0,237$.

With a graphical dependence of the attenuation of an electromagnetic wave on the mass ratio of moisture, it was found that in the range of 6-30% of the mass ratio of moisture, the nominal conversion function A=(W) is close to linear, and in the range from 5 to 40% it is non-linear. The following influencing factors were established:

-The inhomogeneity of the electromagnetic field in the measurement area is within ±2.1 dB.

- Heterogeneity of the material in terms of properties and composition, the share of the error is in the range from 1.2 to 8.5% rel.

- Material temperature, the error fraction of which is 0.038W for every 10 °C.

The developed algorithm was implemented in the MATLAB environment, and a simulation experiment was performed to determine a feasibility of method. We created an experimental setup, the plan of which is illustrated in Figure 1, to test the moisture characteristics of the materials under investigation.

The microwave moisture measurement method is known [24, 25] to be based on the dependence of the parameters of an electromagnetic wave interacting with the controlled material on its dielectric properties. In this case, the most influencing quantities in the measurement of humidity are the density and temperature of the material under consideration. Density determines the amount of dry material and moisture in a controlled volume, so the dielectric parameters of the sample depend on it.

The effect of material temperature on its dielectric properties is since temperature fluctuations (t_M^o) lead to a change in the binding energy of moisture with the material and the redistribution of moisture between the components of the material. Therefore, the change in dielectric parameters depends on the average binding energy of moisture with the material, i.e. on its humidity (W). In this case, it is also necessary to perform computational operations to determine the optimal dependence of ΔA and $\Delta \varphi$ on W, taking into account (t_M^o).

The analysis of the study [26] confirms that the microwave model provides an increase in the degree of automation of the measurement process and obtains the required accuracy by automatically taking into account the main influencing factors of density (pressure) and temperature of the material. It is achieved by promptly entering these parameters into a computing device and using them in a mathematical model of the measurement process when calculating the moisture content of the material under study. Practice and work experience shows that one hundred modern methods for measuring grain moisture content using express devices are an effective and quick way to determine moisture content in any condition in particular:

- when harvesting;
- In storage facilities (in granaries, grain stores, etc.);
- During transportation;
- Before grinding.

To deal with these issues, it is necessary to develop and synthesize moisture meters for grain, which are distinguished by high accuracy, compact size and maximum ease of use.

The current grain material control systems and instrumentation, as well as the technological process, do not fully meet the requirements for the production of competitive products, particularly in terms of energy saving and energy efficiency [27].

An analysis of several literary sources [28, 29], as well as our research on the choice of method and the development of primary converters for such products as grain and products of their industrial processing, and other crops [30] uses a significant number of primary sources of information. However, often the results of such measurements cannot be applied in process control due to the existing uncorrected error, which is the cause of unreliable information [31].

In this regard, there is a need to correct the latter by eliminating the case and the systematic component of the error [32].

The attenuation and phase shift will change accordingly if the mass of the controlled material deviates from the value at which the calibration takes place. Correction of measurement results by eliminating the systematic component of the error is a complex task that has not yet completed an effective, comprehensive solution. These errors lead to a decrease in the reliability of primary information and the development of incorrect control actions on the technological process, thereby causing a decrease in the efficiency of automated control and management [33-35].

It is advised to implement the instrumentation and hardware of the system using a microwave module with the following metrological properties, according to the findings of the studies conducted on the design of a moisture control system in the process flow of grain and grain materials:

<u>Humidity measurement range</u>: Taking into account that the enterprise receives freshly harvested grain and its moisture content is in the range of 14-17.5%, before processing its moisture content is reduced to 8…12%, then for this case, the measurement range can be selected within 8…18.5%;

Measurement errors:
- for in-line measurements should not exceed 0.8%;
- for discrete measurements up to 1.0%;
- measurement speed. At grain speed and flow, the measurement interval is from 0.5 ... 1.0 s.
- operating temperature range ±5 ... +50 °C
- operating mode: discrete-continuous
- temperature influence compensation. The installed thermistor is designed for temperatures up to 60°C.
- types of output interfaces: (4...20mA, MODBUS RTU) must be connected to ASC systems.

This technology can be successfully adapted to determine the water and wet mass content of grain and other agricultural products.

4. Conclusions

Based on theoretical and experimental studies, a coupled system of mathematical models of the primary converter and moisture content of materials of the agro-industrial complex has been developed, which makes it possible to study their transformation functions and the functions of the influence of various factors on the accuracy of the measurement result. A method for assessing the quality of microwave moisture meters has been developed to solve the problems of optimal design.

The evaluation is based on a comprehensive performance criterion that includes the three dominant individual indicators: accuracy, reliability, and cost.

Summing up, it can be summarized that the use of an automated moistening system using high-precision grain moisture meters based on the electrical dielcometric method, which provides operational control of the grain moisture state, allows stabilizing the output moisture content of the grain, therefore achieving optimal grinding properties of a batch of products, which gives a significant economic effect and a quick return on the money spent.

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