Study of the main parameters of the capacitive converter

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Abstract: Determination of the main parameters of a capacitive humidity transducer with a cylindrical electrode is an urgent task. The article discusses the time characteristics of a capacitive humidity transducer with a cylindrical electrode. Experimental and calculated results show that the reliability of the cylindrical transducer is 0.95. The sensitivity depends on the figure of merit of bulk materials and on the design properties of the cylindrical transducer.

Key words: reliability, sensitivity, polarization effect, design parameter, material quality factor, failure probability, failure rate, average failure rate, microprocessor, dielectric constant, operational amplifier, circuit board, voltages, liquid crystal indicator.

Introduction. Complex automation of production processes, creation of automated control systems widely used in computer technology, often requires the use of measuring transducers for different physical characteristics and the principle of their work. For this reason more stringent requirements are set for measuring systems in terms of their reliability, sensitivity and their elements [1; 6; 10].

The quality features of cylindrical measuring transducers include a wide conversion range, high reliability and sensitivity, low power consumption and function continuity under all conditions [2; 12].

Identification methodology and results obtained

The use of integrated electrical engineering ensures higher reliability of information systems. The problem of increasing reliability remains topical, as the pace of technical progress is constantly increasing. For the efficient operation of these systems and to ensure their normal operation it is necessary to guarantee the operation time (103 - 104 hours) or no-failure rate per one element should be 10-9 - 10-10 [8].

Experimental studies of the design and basic characteristics of cylindrical moisture transducers show that sensitivity and reliability criteria play an important role on the measuring accuracy of the transducer, on the non-linearity of the static characteristic.

Minimization of the polarization effect during operation of the cylindrical transducer, i.e. shifting of the electric charges between the electrodes especially when measuring small humidity values, a reduction (reduction) of the measuring range and a marked decrease in sensitivity are observed.

The sensitivity, accuracy and zero drift of the measuring device depend on the frequency of the sinusoidal HV oscillator and the frequency stability of the AC voltage source [2; 13].

The moisture content of bulk solids is directly dependent on the sensitivity, accuracy of the cylindrical capacitive transducer, the linearity of the characteristic, the linearity of the conversion function and the constructional elements of the transducer.

Absolute and relative sensitivity are the conversion measures for capacitive transducers. Absolute sensitivity is defined as the ratio of the increment of the output signal to the increment of the input signal,

\[ S_1 = \frac{\Delta U}{\Delta U_0} \]  

(1)

The relative sensitivity of a capacitive transducer can be calculated using the following expressions: is the ratio of the increment of the transducer output signal to the relative increment of the input signal

\[ S_2 = \frac{\Delta U}{U_0/\Delta U_0} \]  

(2)
is the ratio of the relative increment of the output signal to the relative increment of the input signal:

$$S_3 = \frac{\Delta U}{U} \cdot \frac{\Delta U_b}{U_b}$$  \hspace{1cm} (3)$$

Experimental studies show that of the three criteria only the third can be used to comprehensively analyse the output signal over a wide range of sensitivity changes of a capacitive cylindrical transducer. For this purpose let's consider a capacitive circuit consisting of two wires connected in parallel, a high frequency pulse generator (quartz resonator) [10].

The output capacitance of the $s$-transducer converts to an equivalent capacitance $S_0$ with sensitivity $S$ and is determined from the following expression:

$$C_{ak} = C_{II} + C_0,$$  \hspace{1cm} (4)

and the sensitivity is expressed as follows:

$$S = \frac{\partial U}{\partial U_0} \cdot \frac{\partial U_b}{U_b}$$  \hspace{1cm} (5)$$

where $s$ is converter capacity; $c_0$ is ballast capacity.

The complex resistance at the output of a cylindrical capacitive converter is determined from the following expression:

$$Z_{ab} = \frac{R_m r_m^2}{R_m + r_m^2} - j \frac{R_m^2 (r_m - r_u)^2}{R_m + r_m^2}.$$  \hspace{1cm} (6)$$

where $R_m$ is the active resistance of the material; $r_m$ is the capacitive (reactive) resistance of the material; $r_u$ is the capacitance of the insulation coating.

Based on the sensitivity analysis of the cylindrical capacitive transducer and according to expression (considering) (6), the differential sensitivity of the capacitive transducer included in the equivalent circuit is expressed as follows:

$$S_R = \left[ \frac{\partial Z}{\partial r_m} \cdot R \right] \rightarrow \min_r,$$  \hspace{1cm} (7)

and

$$S = \left[ \frac{\partial Z_{ab}}{\partial r_m} \cdot r_m \right] \rightarrow \max,$$  \hspace{1cm} (8)$$

By introducing changes to expression (7), the complex resistance can be written in the following form:

$$Z_{ab} = \sqrt{\left( \frac{R_m^2 (r_m + r_u)^2 + r_m^2 r_u^2}{r_m + r_u^2} \right)}.$$  \hspace{1cm} (9)$$

To determine the sensitivity of a cylindrical capacitive transducer, we differentiate (8) by $R_m$:

$$\frac{\partial Z_{ab}}{\partial R_m} = \frac{R_m r_m^2 (r_m + 2r_u r_n)}{\sqrt{(R_m^2 (r_m + r_u)^2 + r_m^2 r_u^2)^2 + r_u^2 (r_m + r_u)^2)}.$$  \hspace{1cm} (10)$$

Thus, the following expression for the sensitivity of a cylindrical capacitive transducer

$$S_R \frac{\partial Z_{ab}}{\partial R_m} \cdot r_m = \frac{R_m r_m^2 (r_m + 2r_u r_n)}{\sqrt{(R_m^2 (r_m + r_u)^2 + r_m^2 r_u^2)^2 + r_u^2 (r_m + r_u)^2)}.$$  \hspace{1cm} (11)$$

This formula (11) shows that the sensitivity of the transducer is a function of three variables, which of course complicates the calculation and therefore by introducing some values, we move to relative values, i.e.

$$\eta = \frac{r_u}{r_m} \quad \beta_m = \frac{r_0}{\sqrt{r_m} / \sqrt{Q_m}} = R_m / r_m = \omega C_m R_m,$$  \hspace{1cm} (12)$$

where $\beta_m$ is the quality factor of the material; $\eta$ is a design value characterizing the structural (feature) properties of a cylindrical capacitive bulk moisture transducer.

From (12) formula it can be seen that sensitivity of capacitive transducer mainly depends on $\beta$ and $\eta$, observations and calculations show that by increasing $\eta$ characterizing design properties (features) of capacitive transducer the sensitivity depending on reactive resistance of bulk material and insulating coating decreases markedly. From the point of view of the theory of physical phenomena (cases) it can be noted that the stated electro physical processes interacting with electric flow in a capacitive transducer of bulk solids lead to a drastic change in the reactive conductivity and quality factor.
From expression (12) we can see that increasing the Q-value, the sensitivity of the cylindrical transducer increases, if we consider this process with consideration of the measuring system, the sensitivity of the transducer directly depends on the Q-factor of the oscillating circuit of the measuring oscillator.

The change in the reactance of the cylindrical transducer with respect to the capacitance of the bulk material is determined experimentally (Fig. 1) and this shows that as the capacitance of the bulk material increases up to 2 pF the value of the reactance decreases sharply. Then it slowly decreases as a function of the material capacitance, i.e. this also means a change in the sensitivity of the transducer.

Figure 1. Change in reactance with respect to the bulk material capacity.

Figure 2. Functional characterization of the $S_m(r_m)$ relation.

Figure 2. shows the functional characteristic of the $S_m(r_m)$ relation.

The graph shows that by increasing the reactance of the cylindrical transducer its sensitivity decreases. Processing of experimental results shows that maximum sensitivity of cylindrical transducer is observed at $r_m=0.5 \times 10^4$ Ohm, this corresponds to maximum change of bulk material capacity.

The reliability of a measuring transducer is evaluated by the probability distribution estimated by the probability distribution of the failure-free operation. For this purpose, several measuring transducers are operated for a long time (long time) and the failure time of each measuring transducer is recorded.

If 100 % measuring transducers are in operation during the first interval, some elements may fail after a certain time has elapsed. Based on numerous measurements, the standardized curve constructed determines the probability density $f(t)$ of failure in time. With the help of the probability density $f(t)$ other characteristics of reliability are defined, for example, probability of failure (out of operation) in the time period from $t_1$ to $t_1+\Delta t$, probability of no-failure operation in the time period $t$, average lifetime of elements, intensity and frequency of element failure are defined. The intensity of failure at time $t$ of failure of elements is determined by the ratio of their numbers.

Experience shows that the probability distribution of failure for random (failure) failures obeys an exponential law. It can be argued that the probability density is related to the failure rate by the following expression [10]:

$$f(t) = \lambda e^{-\lambda t},$$

where $\lambda$ is a parameter which is defined by the number of failures in time (in units of time) and is considered as the reliability parameters of elements. The remaining reliability parameters are determined from the obtained expression.

Average lifetime

$$T_{cp} = \int t f_{cp}(t) dt = 1/\lambda.$$  \hspace{1cm} (14)

Average failure rate:

$$f_{cp}(t) = 1/t \int t e^{-\lambda t} dt = 1/t (1 - e^{-\lambda t}).$$  \hspace{1cm} (15)

If $\lambda t \leq 1$, $e^{-\lambda t} \approx 1 - \lambda t f_{cp}(t) \approx \lambda$
Thus, before the physical ageing (failure) of the device, the average failure rate is equal to the failure rate.

One of the factors determining the overall device reliability is the reliability of the elements included in the device, such as resistors, capacitors, diodes, transformers, integrated circuits, etc. Failure of any elements or changes in parameters within certain limits leads to device failure. For cylindrical converter elements, the graph of variation of $\lambda$ in time as $U$ is shown in Fig.3.

Figure 3. Failure rate curve over time for a cylindrical converter.

The graph shows that in the first initial period of operation (preparatory period), elements with gross defects fail. The failure rate then decreases and remains unchanged, i.e. the normal period of operation begins. The ageing of elements and the failure rate increases again and the ageing (failure) period of elements begins.

The determination of the reliability of the various components of a cylindrical transmitter depends on the time and means required to process the data obtained during operation and verification. In determining the overall reliability of a cylindrical converter, if the failure of any component causes the instrument to become unusable, then all components are considered to be connected in series. In such a case, the probability of failure has an exponential distribution, i.e.

$$\lambda_c = \lambda_1 \cdot S_1 + \lambda_2 \cdot S_2 + ... + \lambda_n \cdot S_n,$$

where $n$ is the number of different components; $\lambda_1, \lambda_2, ... \lambda_n$ - average failure rate (failure); $S_1, S_2, ... S_n$ - number of elements in the given kind of device.

Thus, the failure rate (failure) of a transducer in general reveals (shows) the function in the very elements that make up the transducer, also shows the failure rate of the elements.

In practice, in order to calculate reliability according to element characteristics, a list of applicable elements is compiled and the failure rate of each element is determined. Coefficients are then introduced which take into account the operating mode and the operating condition. In order to take into account the acting factors determining the average operating condition, a factor is usually introduced which takes into account the degree of reduction in the average lifetime of the apparatus from unstable external influences. Then the intensity of failure of elements is summed up and determined necessary, the occurrence of probability of failure in any number of numbers at a certain point in time, the average time of no-failure operation. On fig.4 the diagram of change of reliability in time of the cylindrical converter of loose materials is resulted.
It can be seen from the graph that, over time, the ageing of cylindrical converter elements reduces the reliability of the converter. The measurement of the reliability over time of a cylindrical converter is characterized by the fact that in the initial phase of the converter's operation the noticeable effects of thermal and electrical effects lead to a sharp drop in reliability of up to 0.3.

Thus, the basic parameters of a cylindrical bulk moisture transducer are determined by criteria of sensitivity and reliability of their elements. The time characteristics of a cylindrical bulk moisture transducer are developed and these characteristics lead to ageing of transducer elements over time due to the influence of thermal and electrical effects.

Calculations show that the reliability of the cylindrical moisture transducer is 0.95. The sensitivity of the cylindrical transducer is determined and the sensitivity depends mainly on the quality factor of the bulk solids and on the design factors that characterize the constructional properties of the cylindrical transducer. This of course must be taken into consideration when designing the basic elements of cylindrical transducers.

To improve quality performance, a microprocessor-based measuring device based on a capacitive transducer for bulk moisture has been developed, using high-precision elements of integrated microelectronics.

The principle of operation of microprocessor measuring device based on capacitive converter with cylindrical electrode, the material, the humidity of which is measured placed between the cylindrical electrodes, is based on the change in capacitance of capacitor, dielectric permittivity of material, and is explained by the distribution of electric field flux density along the length of material. This distribution will lead to a change in the complex resistivity and as a result the output of the capacitive transducer gives a signal which depends on the input value of the humidity [5; 7; 11; 12].

The main elements of the structural diagram: 1-capacitive transducer with cylindrical electrode; 2-detector; 3-operating amplifier; 4-microcontroller; 5-measuring generator; 6-liquid-crystal indicator.
Let's analyses the schematics of some of the elements that make up the microprocessor-based moisture measurement device.

Fig. 6 shows a schematic diagram of a measuring oscillator, a symmetrical multivibrator [16].

fig.6. Schematic diagram of a measuring oscillator - symmetrical multivibrator.

The moisture meter with cylindrical electrode, based on an automatic switch circuit, is a symmetrical multivibrator, whereby the generator is characterised by the fact that it consumes a small current (15 mA). The circuit is supplied with voltage (9 V) from an integrated voltage regulator. In the circuit D1.1 and D1.2 are automatic electronic switches. When D1.1 and D1.2 are supplied with voltage, the electronic switches are in open mode. Since capacitor \( C \), is not charged, there is no voltage in the capacitor and the current from the current source flows through the series connected resistors \( R_1 \) and \( R_2 \).

Here \( R_1 \geq R_2 \), so the voltage at \( R_2 \) is not sufficient to trip electronic switch D1.2. As, by decreasing the charge current, this voltage tends to (zero) 0. At the same moment by increasing the capacitor charge the voltage at output 7 of electronic switch D1.1 rises exponentially. This voltage will be sufficient to activate electronic switch D1.1, outputs 6 and 5 will short-circuit and electronic switch D1.2 will start to operate.

After switching on the electronic switches, the bottom electrode of capacitor \( C \), is connected to the positive busbar of the current source.

The accumulated charge does not change immediately, the voltage at output 7 of switch D1.1 changes in steps so that its value exceeds the current source voltage, which is sufficient to operate the electronic switch D1.1.

The voltage at capacitor \( C_i \), then decreases with a constant time \( C_i (R_1/R_1 + R_3) \). This mode of operation of the oscillator is ensured by creating stable pulse oscillations at its output. As a result of changes in humidity, the capacitance of C2-converter by the cylinder electrode changes and a signal is created at the output of oscillator 1.

The oscillator is one of the components of the microcontroller, so they share a common switching point, this ensures their stable operation.

Fig. 7. shows a schematic diagram of the capacitive moisture detector measuring system with a cylindrical electrode.
Figure 7. Schematic diagram of a capacitive moisture transducer measuring system detector with cylindrical electrode.

The DD1 detector is one of the main elements of the capacitive moisture transducer measuring system and is based on a bi-period rectification circuit. The detector has the capability of rectifying the input signal to its maximum value and is designed to rectify the AC voltage coming from the measurement generator into DC voltage. Its 7-4 input can be supplied with DC voltage from 5V to 9V, this voltage is created by a voltage regulator operating in integral mode.

Resistor $R_3$ for DC, capacitor $C_2$ for AC provides 100% negative feedback and this relationship ensures stable detector operation. It is possible to control the sensitivity of the detector with resistor $R_7$.

DD1 is an operational amplifier operating in signal integration mode, so the output of the detector is the RMS value of the signals. Resistor $R_2$ and capacitor $C_1$ at the detector input determines the integration time of the signals, i.e. $\tau = R_2 \cdot C_1$.

It should be noted that the input and output resistances of all components of the measuring system match each other, and this ensures the constancy of the useful signal over the entire cycle range. All the more reason to match the input and output resistances is a basic requirement of integrated microelectronics.

As a result of changes in humidity of the material located between the cylindrical electrodes, its electrical capacitance changes and a variable signal is generated according to the humidity at the output 5 of the measuring generator. The alternating signal (Fig. 5.) is fed to the integral detector 2, then this signal is rectified by a two half-period circuit and at the output of the detector the RMS value of the processed signal is obtained, subsequently this signal is reached to the maximum value [9].

The load of the detector is an operational amplifier 3, in which the signal is amplified and after processing the signal is transmitted to a microcontroller 4 of type AT mega 8A. The microcontroller converts the analogue signal into an encoded digital signal and this system operates according to a special programme. The processed signal is fed into the liquid crystal display 6 and the measured humidity value appears on its screen.

Figure 8 shows the appearance of the capacitive moisture meter for grain and grain products. The microprocessor measuring device based on the capacitive transducer with a cylindrical electrode is designed to measure the humidity of grain and grain products consists of a measuring cell in the form of a quadrilateral, in which four capacitive electrodes of cylindrical transducer are fixed vertically to the side walls [16; 17].
The capacitor electrodes fixed in parallel to the opposite side walls of the measuring cell are included in the oscillating circuit of the measuring generator. The geometrical dimensions of the measuring unit are 20x15x13 mm³, the size of one electrode of the measuring transducer is 10x6 mm². In order to stabilise the density of the product enclosed in the measuring cell there is a cover, the moving lower part is led to the back side by the holder of the measuring device, and it moves along the perimeter by specially made traces of the measuring device.

This way, the holder is the mechanism for releasing a kind of cell from the grain product after the measurement practice. In the lower part of the measuring device of the capacitive moisture transducer there is a special carriage for receiving the grain product after measuring its moisture content.

On the front projection of the measuring device of humidity of grain-products is located with the horizontal plane at an angle of 30° in its front part the liquid crystal indicator 3 (Fig. 10), the electronic circuit board (Fig. 9) fixed in the front wall of the measuring cell and components of the moisture measuring system - measuring generator, detector, op-amp, analog-digital converter and microprocessor [3; 4].
Technical and metrological characteristics of the moisture meter for grain and grain products are given in the table (Table 1).

Table 1.

| №  | Title                  | Value and unit           |
|----|------------------------|--------------------------|
| 1. | Measuring range        | 9÷25%                    |
| 2. | Measurement error      | 0,2÷0,6%                 |
| 3. | Measuring duration time| 1 min                    |
| 4. | Ambient temperature    | 15÷45 °C                 |
| 5. | Relative humidity      | up to 80%                |
| 6. | Sensitivity            | Maximum sensitivity is observed at $r_m=0.5\times10^4$ Om               |
| 7. | Reliability            | 0,95                     |
| 8. | Device size            | 20x15x13 cm³             |
| 9. | Measuring transducer size | 10x6 cm²               |
| 10.| Unit weight            | 0.5 kg                   |

Now proceed to determine the error of the measurement by experiment and, by determining the errors of several measuring instruments, carry out a comparative analysis.

The capacitive cylindrical primary transducer is the main property of the moisture meter, which provides the reading of the meter, i.e. a change in the moisture content of the controlled material changes through the primary capacitive transducer the reading of the meter.

The defined parameter for moisture meters is an important parameter because it characterises the quality of the meter. Measurement repeatability is checked as follows [14].

- 5 grain samples with moisture content from 10% to 20% are taken and allocated (distributed) according to the measuring range. The moisture content of each sample is determined by the method given in GOST, the value found is considered a reference value, its absolute error must not exceed 0.5 %;
- each sample is inserted into the primary capacitance transducer of the moisture meter and the reading of the device is recorded in the workbook;
- the average moisture value is determined after measuring each sample 10 times;
- the average value and the difference between the measurement results is determined;
- the relative error is calculated using the following formula:

$$\delta = \frac{|W_{cp} - W_u|}{W_{cp}} \times 100\%,$$

where $W_{cri}$ $W_u$ is the average value and the result of the measurement, respectively.

The results are used to determine the errors of each instrument and the results are recorded in a table (Table 2).

Static error data for capacitive transducers of various designs.

Table 2.

| Two electrode capacitive converter |  |  |  |  |  |  |
|-----------------------------------|---|---|---|---|---|---|
| $W_{grain}$, %                    | $\delta_{min}$, % | $\delta_{max}$, % | $\delta_{cp}$, % | $\delta_u<2$, % | $\delta_u>2$, % |
| Up to 11 %                        | 0,26 | 1,7 | 1,5 | 8 | 2 |
| 11-13 %                           | 0,38 | 4,3 | 2,0 | 5 | 5 |
| 13-15 %                           | 0,36 | 6,35 | 2,15 | 4 | 6 |
| 15-17 %                           | 0,36 | 7,35 | 3,8 | 3 | 7 |
| 17-20 %                           | 0,4 | 6,3 | 3,9 | 3 | 7 |

| Infrared analyser (Grandyser)     |  |  |  |  |  |  |
| $W_{grain}$, %                    | $\delta_{min}$, % | $\delta_{max}$, % | $\delta_{cp}$, % | $\delta_u<2$, % | $\delta_u>2$, % |
| Up to 11 %                        | 0,8 | 3,1 | 1,4 | 6 | 4 |
| 11-13 %                           | 1 | 4,12 | 2,1 | 5 | 5 |
| 13-15 %                           | 1,7 | 7,1 | 2,4 | 3 | 7 |
| 15-17 %                           | 1,6 | 6,8 | 2,5 | 4 | 6 |
| 17-20 %                           | 1,5 | 6,3 | 3,5 | 4 | 7 |
The table shows the experimental results by degree of repeatability for the infrared, two-electrode and four-electrode transducers. A coaxial type transducer was used as the two electrode primary capacitive transducer. It can thus be seen from the table that the results from the four electrode transducers are close to the actual values, because increasing the number of electrodes in the four electrode transducers has increased the sensitivity and normalised the position of the moist material.

Table 2 shows: δmin - minimum relative error of the sample; δmax - maximum relative error of the sample; δcp - average value. The columns (δu< 2%) and (δu> 2%) comprise the defined measurement interval.

The results of the experiments show that by increasing the humidity in all measuring transducers in the same samples the dispersion values increase. When measuring with a humidity of up to 11%, the results in all the measuring transducers used are almost identical.

At the same time, the repetition of the results in the various designs changes as the moisture content of the controlled substance increases.

Conclusion: It can thus be stated that the basic parameters of a cylindrical bulk moisture transducer are determined by the sensitivity and reliability criteria of these elements. The time response of the cylindrical transducer depends on thermal and electrical effects. The reliability of the cylindrical transducer is 0.95.

Based on experimental results for various transducer designs and analysis, it is shown that the results in four electrode transducers are close to the actual values, as with increasing the number of electrodes, the sensitivity increases.

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