GRAIN MOISTURE MEASUREMENT SYSTEM WITH ROBUST TRANSFER FUNCTION, INVARIANT TO THE CHANGE OF A PHYSICO-CHEMICAL GRAIN COMPOSITION
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СИСТЕМА ВИМІРЮВАННЯ ВМІСТУ ВОЛОГИ ЗЕРНА З РОБАСТНОЮ ФУНКЦІЄЮ ПЕРЕТВОРЕННЯ, ІНВАРІАНТНОЮ ДО ЗМІНИ ФІЗИКО-ХІМІЧНОГО СКЛАДУ ЗЕРНА

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ABSTRACT

The main task was to receive a robust transfer function for the capacitive grain moisture measurement system. It was estimated how the new transfer function compensates for the type uncertainty and how close it is to the nominal values of moisture content. Dispersions of adequacy and repeatability of the new transfer function, which describe possible variation in the measured moisture values and the correspondence of the new transfer function with the nominal linear transfer function of a moisture meter respectively, were calculated for five chosen substances. It was proved that the new transfer function has lower sensitivity to grain type and better adequacy to the ideal transfer function than the closest analog.

АНОТАЦІЯ

Головним завданням був синтез робастної функції перетворення для ємнісної системи вимірювання вмісту вологи зерна. Було оцінено здатність запропонованої функції перетворення компенсувати сортову невизначеність і ступінь її наближеності до номінальних значень вмісту вологи. Для запропонованої функції перетворення було обчислено дисперсії адекватності і відтворюваності для п'яти обраних речовин, які описують можливу варіацію результатів вимірювання вмісту вологи і відповідність нової функції перетворення з номінальною лінійною функцією перетворення вологоміра. Було доведено, що нова функція перетворення має нижчу чутливість до типу зерна і кращу адекватність із ідеальною функцією перетворення у порівнянні з найближчим аналогом.

INTRODUCTION

It is necessary to emphasize that Ukraine is among the top 10 world grain producers, according to FAOSTAT. Ukrainian grain belongs to a relatively short list of products that benefit the internal market and can be competitive abroad. Local grain farming produces approximately 25 million tons of grain and demonstrates stable growth of the grain production index. The structure of local grain production is relatively stable: the most significant part traditionally belongs to the hard, red variant of winter wheat used in bread making (up to 90 %). On the other hand, modern performance indexes of grain are regulated with national and international standards. It is mentioned that grain moisture content should not be more than 14,5…15,5 % (in general) to provide its long-term storage. Grain moisture is one of the main factors affecting the duration of storage without possible damage and loss (*Jones and Shelton, 1994; Tahir et al., 2007; Pathaveerat and Pruengam, 2020; Beficadu, 2014; Mhiko, 2012; Hassoon and Dziki, 2018*).

The excess or absence of moisture in food products is reflected in physical-chemical, physical-mechanical, and functional properties, as well as natural quality indicators (Nielsen, 2010). The grain drying process is one of the most energy-intensive and responsible for the entire grain storage and processing cycle (*Rolle et al., 2015; Amit et al, 2017*).

It is reasonable that grain producers always try to use its food potential most fully, especially peripheral components and fetuses, as a source of valuable nutrients. The grain processing industry implements a list of technologies for that purpose. Among them, we have long-term hydrothermal grain treatment with further sprouting and its usage as basic foodstuffs *(Lupu et al., 2016; Morishita et al., 2020; Hassoon et al., 2021)*. It is possible to use one or two times humidification with further binning, steaming with humid saturated steam for 20 – 30 sec, and 44 – 46 °C temperature control for 20 minutes for grain with weak gluten to improve its bakery properties. *(Jung et al., 2018; Probst et al., 2013; Dabbour et al., 2015)*.

Most European countries have already changed their local standards for moisture meters following international recommendation OIML R59 "Moisture Meters for Cereal Grain and Oilseeds" (*OIML R59*), which restricts the maximal permissible value of moisture content uncertainty to not more than 3% of relative full-scale error. However, even the most popular laboratory moisture meters like Kett, AgraTronix, Isoelectric, and Next Instruments series have a significant accuracy decrease when determining moisture in different kinds of grains of the same type, for example, in different kinds of wheat. An extensive list of factors influences the accuracy of current moisture meters in different bulk substances *(Wu et al., 2018; Wanga and Wang, 2012)*. In addition, it can be said that grain products' physical and chemical composition depends not only on the grains' type but the origin and ways of cultivation, storage, and processing – factors that can hardly be predicted *(Thakur et al., 2015)*.

Currently, a significant part of the means of measurement, which control substances' properties and composition, is occupied with measuring instruments that use capacitive sensors *(Zambrano et al., 2019; Flor et al., 2022)*. It is pretty evident that the widespread introduction of versatile and accurate grain moisture meters and their proper operation will have a tangible technical and economic effect *(Casada and Armstrong, 2009; Song et al., 2020; Li et al., 2021; Klomklao et al., 2017)*. 'Successful' modifications of capacitive sensors appeared years ago *(Hegg and Mamishev, 2004)*. The main idea was to fulfil capacitive measurements using two or several positions for one of the capacitor plates with further direct comparison method application. It helps to eliminate parasitic capacitances, compensate leakage currents and reduce the influence of fringe electric fields. However, for the process of moisture measurement in different types of bulks, 'type uncertainty' error can strongly influence the moisture measurement result *(Shi et al., 2015)*. Its value depends explicitly on the dielectric permittivity of a substance, which is under research (grain type, for example), and needs to be compensated *(Wanga and Wang, 2012; Bessa et al., 2013)*. This compensation is traditionally performed in a secondary measuring transducer using complementary reference capacitors, particular analytic calculations, reference calibration curves stored in the secondary measuring transducers' memory, etc. *(Wu et al., 2018; Jafari et al., 2020)*. Traditional ways of 'type uncertainty' compensation can be used only when it is possible to get an analytic forecast of chemical composition and different features of all the materials, which list is usually limited to a few grain types. The main task of the research is to receive a grain moisture measurement system with robust transfer function, invariant to the change of a physico-chemical grain composition, as described in *(Zabolotnyi and Koshevoi, 2020)*.

MATERIALS AND METHODS

The suggested design of the grain moisture measurement system is described below (Fig. 1). Both of its' sensors consist of a system of flat plates 1, where two pairs of flat plates belong to measuring capacitors C_1 and C_4, and the rest of flat plates create another pair of measuring capacitors C_2 and C_3. All flat plates of equal length l are assembled inside two fluoroplastic rings 2 at an equal gap, designated as *Z*.

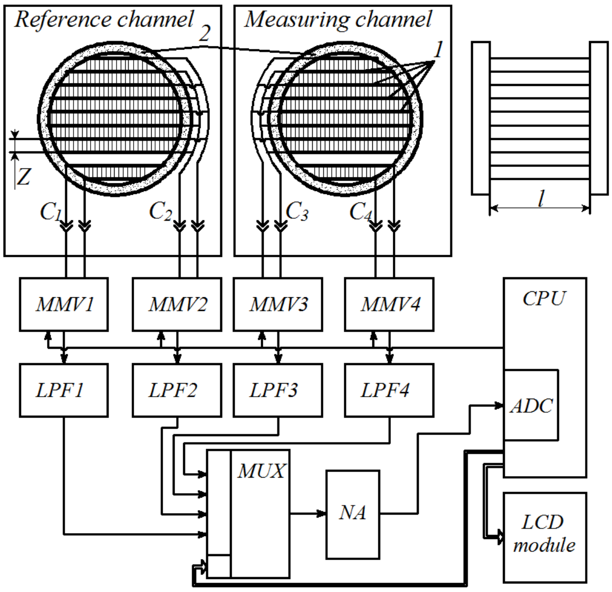


Fig. 1 - Functional electrical circuit of the moisture measurement system

MO1…MO4 – monostable oscillators; LPF1…LPF4 – low-pass filters; MUX – multiplexer; NA – normalizing amplifier; ADC – analog to digital converter

The process of moisture measurement can be performed as described below. The instrument measuring transducer of the moisture measurement system consists of four capacitive sensors C_1, C_2, C_3, and C_4. Two of them (C_3 and C_4) should be filled with a probe of bulk substance in which moisture is going to be measured. Another two (C_1 and C_2) should be filled with a similar probe but previously dehydrated. After the values of C_1, C_2, C_3, and C_4 were measured, we should calculate the relation $(C_3 – C_4)/(C_2 – C_1)$.

A structure of the moisture measurement system is given in Fig.1. Four capacitive sensors C_1, C_2, C_3, and C_4 are connected to the inputs of corresponding monostable oscillators $MO_1…MO_4$. They act as capacitance into pulse duration secondary transducers. The duration of the sequence of rectangular pulses, taken from the corresponding monostable oscillators' output, is proportional to the capacitance value. Central processing unit *CPU* launches monostable oscillators $MO_1…MO_4$ and controls their work by sending the sequence of rectangular pulses of a stable frequency to their corresponding inputs. Low-pass filters convert pulse duration into DC voltage with an amplitude proportional to the pulse duration. Multiplexer *MUX*, controlled by *CPU*, connects the low-pass filters *LPF1…LPF4* outputs with the input of normalizing amplifier *NA*, which, in turn, provides DC voltage levels compatible with measuring range of embedded in *CPU* analog-to-digital converter *ADC*. As soon as four capacitance values are converted into four DC voltage values and passed to the *ADC* input, *CPU* can calculate the value of moisture content and displays it on the *LCD* screen.

As mentioned, moisture content of a substance can be calculated using formula:

$$W = K \cdot \left(\frac{C_3 - C_4}{C_2 - C_1} \right), \tag{1}$$

where *K* is a normalizing coefficient.

If the values of electric capacitances are considered (not filled with a substance), equal to 15 pF for C_1, C_4 and 50 pF for C_2, C_3, normalized equation (2) of a moisture meter transfer function is obtained.

$$W = 28.599 \cdot \left(\frac{C_3 - C_4}{C_2 - C_1} \right). \tag{2}$$

To conduct experimental research it was necessary to get reference samples for chosen grain types with different dielectric permittivity values and prepare necessary laboratory setup.

Unfortunately, the local industry produces stable polymer-based reference samples with controlled values of moisture equal to 12 % and 13 % only. So, necessary grain samples were prepared by grain drying (dehydration) following international standards (*Diane Lee and Harris, 2016; ISO 712:2009*), and subsequent addition of water into dehydrated samples *(ISO 835:2007)*.

A list of grain types to be examined includes: wheat cereals ($\varepsilon = 2.55$), pea ($\varepsilon = 2.97$), millet ($\varepsilon = 3.17$), poppy ($\varepsilon = 3.56$), pearl barley ($\varepsilon = 3,68$), and, following the standards for grain samples dehydration, 20 g weights are necessary. They should be placed in a drying oven with 130°C temperature for 120 minutes (Fig. 2) *(Zabolotnyi and Koshevoi, 2020; Zabolotnyi, 2019)*.

Fig. 2 - Preparation of 30 aluminium containers with 20 g weights of poppy seed, further drying and cooling in desiccators

After drying, moistening and holding in desiccators for an hour, such grain moisture samples can be used to verify any capacitive grain moisture meter.

The connection scheme of the laboratory setup used in the process of moisture measurement is given in Fig.3. It includes four capacitive sensors C_1, C_2, C_3, and C_4, one channeled capacitance into a DC-voltage transducer which performs the sequence of transformations ‘capacitance – pulse duration – DC voltage’, variable air capacitor (reference capacitor), oscilloscope, digital voltmeter and RLC meter.

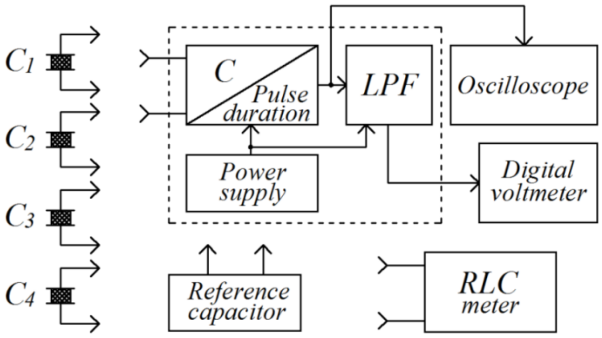
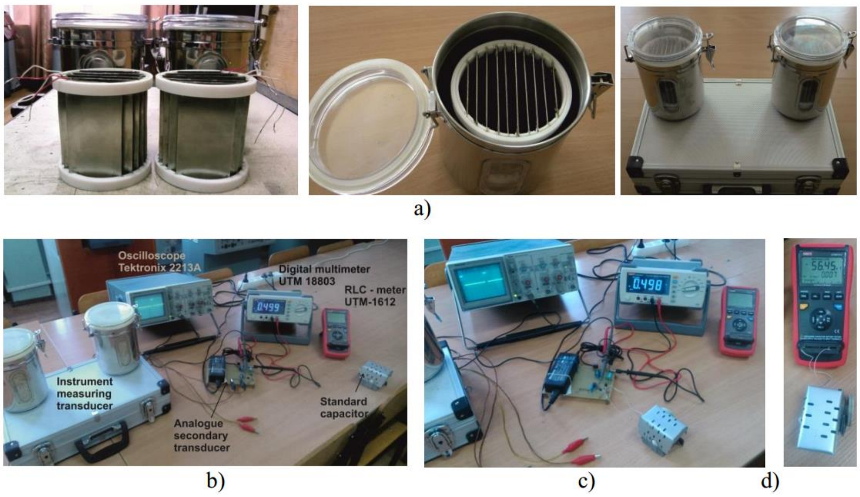


Fig. 3 - Connection scheme of the laboratory setup

Measurement procedure consisted of several steps. Firstly, capacitive sensors of the reference channel were filled with dehydrated sample of grain. Both of C_1 and C_2 capacitive sensors were one by one connected to the input of *C*/*Pulse duration*/DC voltage secondary transducer. Corresponding values of DC voltages were taken from the screen of a digital voltmeter and remembered.

After that, the appropriate capacitive sensor (let it be C_1) was disconnected from the secondary transducers’ input, and the variable air capacitor (reference capacitor) was connected to its input. The capacitance of a variable reference capacitor had been slowly increased until the voltage value on the digital voltmeters’ screen reached the value previously remembered by the operator. As soon as it happened, the reference capacitor was disconnected from the input of a secondary transducer, and the value of its capacitance was measured with the help of an accurate RLC meter at a 10 kHz frequency. The same substitution measurement procedure was applied to C_2, C_3, and C_4 capacitive sensors ten times each. As a result, ten measurements of electric capacitance were received from each capacitive sensor and the value of capacitance was calculated as an arithmetic mean value for ten separate measurements.

The sensors of an instrument measuring transducer were assembled from four identical rings with slots to insert flat stainless steel plates carved out from fluoroplast-4. Stainless steel plates were glued to the internal surface of appropriate pair of fluoroplastic rings with the help of superglue gel and soldered with wires to create four capacitive sensors. Both halves of an instrument measuring transducer (first pair with sensors C_1 and C_2 and second pair with sensors C_3 and C_4) consist of two capacitors with capacitance values of 47 pF for C_2 and C_3 and 15 pF for C_1 and C_4 in the empty state (Fig. 4, a).



a)

b) c) d)

Fig. 4 - Experimental setup for moisture measurement

a – components of the moisture content instrument measuring transducer; b – one of capacitive sensors is connected to secondary transducer; c – standard variable capacitor is connected instead of capacitive sensor; d – capacitance of standard variable capacitor is measured with high accuracy

Each pair with two sensors was placed in its personal container, which, in its turn, was assembled on the front panel of the aluminium case. Images of the moisture measurement process and experimental setup can be found in Fig 4, b, c, and d. To check the ability of equation (2) to retain invariance when working with different types of grain, we took four imaginary values of dielectric permittivity (to simulate different types of grain matrix): $\varepsilon_n = 2.0$; $\varepsilon_n = 2.5$; $\varepsilon_n = 3.0$; $\varepsilon_n = 3.5$. Besides, we set four different values of moisture content for that purpose (W = 0 %; W = 10 %; W = 20 %; W = 30 %). Dielectric permittivity of moist grain samples was calculated with application of universal Wiener equation *(Zabolotnyi et al., 2022)*. The values of C_1, C_2, C_3, and C_4 together with the values of theoretical moisture content are given in Table 1.

Table 1

Calculated values of sensors' capacitances and moisture content for the transfer function (1)

***W*, %**	***ε***	**2.0**	**2.5**	**3.0**	**3.5**	***W*, %**	**ε_n**	**2.614**	**3.252**	**3.885**	**4.512**
0	**C_1, pF**	30	37.5	45	52.5	**10**	**C_1, pF**	30	37.5	45	52.5
	C_2, pF	100	125	150	175		**C_2, pF**	100	125	150	175
	C_3, pF	100	125	150	175		**C_3, pF**	130.7	162.6	194.25	225.6
	C_4, pF	30	37.5	45	52.5		**C_4, pF**	39.21	48.78	58.28	67.68
	W_{calc}	0	0	0	0		**W_{calc}**	8.78	8.60	8.44	8.23
20	**ε_n**	**3.368**	**4.317**	**4.963**	**5.741**	**30**	**ε_n**	**4.317**	**5.324**	**6.305**	**7.262**
	C_1, pF	30	37.5	45	52.5		**C_1, pF**	30	37.5	45	52.5
	C_2, pF	100	125	150	175		**C_2, pF**	100	125	150	175
	C_3, pF	168.4	215.85	248.15	287.05		**C_3, pF**	215.85	266.2	315.25	363.1
	C_4, pF	50.52	64.76	74.45	86.12		**C_4, pF**	64.76	79.86	94.58	108.93
	W_{calc}	19.56	20.78	18.71	18.31		**W_{calc}**	33.13	32.31	31.51	30.74

As can be seen, theoretical values of moisture content do not correspond with nominal in all points, except for W = 0 %. It can be concluded that the transfer function (2) should be close to linear.

To receive the near linear function for moisture content W and $(C_3 - C_4)/(C_2 - C_1)$ relation, the method of Least Squares was used:

$$a + b \cdot W = (C_3 - C_4)/(C_2 - C_1), \tag{3}$$

where a and b – coefficients needed to be calculated.

For the system of equations (4) average values were taken for $(C_3 - C_4)/(C_2 - C_1)$ relation (table 2).

Table 2

Average values for the relation $(C_3 - C_4)/(C_2 - C_1)$

***W*, %**	**$(C_3 - C_4)/(C_2 - C_1)$**				
	ε_n = 2.0	**ε_n = 2.5**	**ε_n = 3.0**	**ε_n = 3.5**	**Average**
0	1	1	1	1	1
10	1.307	1.301	1.295	1.289	1.298
20	1.684	1.669	1.654	1.640	1.662
30	2.158	2.130	2.102	2.075	2.116

$$\begin{cases} a + b \cdot 0 = 1, \\ a + b \cdot 10 = 1.298, \\ a + b \cdot 20 = 1.662, \\ a + b \cdot 30 = 2.116. \end{cases} \tag{4}$$

Solution for the system (4) was obtained in a traditional way:

$$[XX] = 4,\ [XY] = [YX] = 60,\ [YY] = 1400,\ [XL] = 6.076,\ [YL] = 109.7$$

$$Q = \begin{vmatrix} [XX] & [XY] \\ [YX] & [YY] \end{vmatrix} = \begin{vmatrix} 4 & 60 \\ 60 & 1400 \end{vmatrix} = 2000,\ Q_a = \begin{vmatrix} [XL] & [XY] \\ [YL] & [YY] \end{vmatrix} = \begin{vmatrix} 6.076 & 60 \\ 109.7 & 1400 \end{vmatrix} = 1924.4$$

$$Q_b = \begin{vmatrix} [XX] & [XL] \\ [YX] & [YL] \end{vmatrix} = \begin{vmatrix} 4 & 6.076 \\ 60 & 109.7 \end{vmatrix} = 74.24,\ a = \frac{Q_a}{Q} = \frac{1924.4}{2000} = 0.9622,\ b = \frac{Q_b}{Q} = \frac{74.24}{2000} = 0.0371$$

Calculated values of moisture content W', received from the equation (3), can be found in Table 3:

$$0.9622 + 0.0371 \cdot W' = (C_3 - C_4)/(C_2 - C_1),\quad W' = \frac{\left((C_3 - C_4)/(C_2 - C_1)\right) - 0.9622}{0.0371}$$

Table 3

Values of moisture content *W* ’

***W*, %**	**εn = 2.0**	**εn = 2.5**	**εn = 3.0 (*W′*)**	**εn = 3.5**	**Δ*W***	**Δ*W’***
	Values of *W’*, received from a first-order polynomial (2)					
1	2	3	4	5	6	7
0	1.019	1.019	**1.019**	1.019	1.019	1.019
10	9.294	9.132	**8.970**	8.809	-1.030	-1.030
20	19.456	19.051	**18.647**	18.270	-1.353	-1.353
30	32.232	31.477	**30.722**	29.995	0.722	0.722
	Values of W_m, calculated with the help of transfer function (6)					
0	0.268	0.268	0.268	0.268		
10	10.230	10.045	9.859	9.674		
20	20.850	20.470	20.085	19.723		
30	30.658	30.211	29.476	29.280		

Analysing the data in table 3, we can see that LS method happened to be not as effective as it was expected because of poor linearity of the moisture meters’ transfer function. A step forward was to calculate discrepancies Δ*W* between nominal points of moisture content and values of the equation (3), and approximate Δ*W* values by applying instruments of general linear regression *(Zabolotnyi, 2021)*. Discrepancies $\Delta W = W' - W_{\text{nominal}}$ between nominal points of moisture content (Table 3, column 1) and moisture values, taken for $\varepsilon_n = 3.0$ (Table 3, column 4, bold), are given in column 6 of Table 3. To approximate the values of Δ*W*, a sum of four functions (1, *W*, W^2, and W^3) was taken with appropriate coefficients, defined with the help of Mathcad software (function linfit(x, y, Y)).

$$\Delta W' = 1.019 - 0.269\cdot W + 0.00527\cdot W^2 + 0.000112\cdot W^3$$

$$\Delta W' = 1.019 - 0.269\cdot\frac{\left(\dfrac{C_3-C_4}{C_2-C_1}-a\right)}{b} + 0.00527\cdot\frac{\left(\dfrac{C_3-C_4}{C_2-C_1}-a\right)^2}{b^2} + 0.000112\cdot\frac{\left(\dfrac{C_3-C_4}{C_2-C_1}-a\right)^3}{b^3} \tag{5}$$

Formula (5) provides an ideal approximation of the discrepancies Δ*W*, as can be seen from table 3, columns 6 and 7. Taking formula (5) into account, a new transfer function for a moisture meter can be built:

$$W_m = W' - \Delta W' = \frac{\left(\dfrac{C_3-C_4}{C_2-C_1}-a\right)}{b} - 1.019 + 0.269\cdot\frac{\left(\dfrac{C_3-C_4}{C_2-C_1}-a\right)}{b} - 0.00527\cdot\frac{\left(\dfrac{C_3-C_4}{C_2-C_1}-a\right)^2}{b^2} - 0.000112\cdot\frac{\left(\dfrac{C_3-C_4}{C_2-C_1}-a\right)^3}{b^3}$$

$$W_m = -1.019 + 1.269\cdot\frac{\left(\dfrac{C_3-C_4}{C_2-C_1}-a\right)}{b} - 0.00527\cdot\frac{\left(\dfrac{C_3-C_4}{C_2-C_1}-a\right)^2}{b^2} - 0.000112\cdot\frac{\left(\dfrac{C_3-C_4}{C_2-C_1}-a\right)^3}{b^3} \tag{6}$$

Near linear values of moisture content, calculated with the help of formula (6), are given in table 3. If we compare the values of moisture content *W* ’, received from a first-order polynomial (2) and modified transfer function (6), it can be concluded that the transfer function (6) is far more close to linear than the initial transfer function (2) and transfer function received from a first-order polynomial (3).

RESULTS

The results of multiple measurements for capacitive sensors C_1, C_2, C_3 and C_4 are given in table 4. After having these results, the robustness of a static function (6) can be checked with mean values or medians. Calculated values of moisture content with mean and median values of sensors’ capacitances can be found in tables 5 and 6.

Table 4

Multiple measurements of sensors’ capacitance

№	***W* = 0 %**		***W* = 10 %**		***W* = 20 %**		***W* = 30 %**	
	C_1, pF	**C_2, pF**	**C_3, pF**	**C_4, pF**	**C_3, pF**	**C_4, pF**	**C_3, pF**	**C_4, pF**
	Pearl barley							
1	57.05	189.95	250.99	76.38	322.60	104.27	418.46	136.46
2	56.74	189.70	251.64	77.21	323.03	103.50	419.37	135.64
3	56.78	189.42	251.56	76.82	322.30	103.93	418.75	136.12
4	56.45	189.92	251.05	76.61	322.45	104.04	418.93	135.72

5	56.63	189.56	251.27	76.78	322.61	104.30	419.44	135.51
6	57.00	189.43	251.41	76.84	323.10	104.23	419.45	135.98
7	56.94	189.44	251.44	76.59	322.50	103.74	418.88	136.14
8	56.49	189.56	251.55	77.01	322.65	103.86	418.96	136.21
9	56.52	189.58	251.14	77.54	322.80	104.15	419.10	135.84
10	56.69	189.51	251.31	77.12	322.98	103.88	419.29	135.89
	Mean values (Pearl barley)							
	56.73	189.58	251.34	76.87	322.70	103.99	419.16	135.95
	Values of median (Pearl barley)							
	56.72	189.56	251.36	76.83	322.63	103.99	419.03	135.94
	Mean values (Poppy)							
	53.42	178.40	230.20	69.32	293.69	88.35	370.47	112.74
	Values of median (Poppy)							
	53.42	178.47	230.23	69.46	293.62	88.42	370.55	112.77
	Mean values (Millet)							
	47.46	158.90	210.34	64.95	266.48	79.93	335.26	103.12
	Values of median (Millet)							
	47.46	158.92	210.31	64.97	266.44	79.93	335.30	103.13
	Mean values (Pea)							
	44.51	150.05	195.19	58.54	249.81	75.49	316.96	96.61
	Values of median (Pea)							
	44.57	150.06	195.22	58.58	249.81	75.44	316.89	96.66
	Mean values (Wheat cereals)							
	38.10	127.85	166.47	48.26	217.29	67.13	274.44	84.51
	Values of median (Wheat cereals)							
	38.02	127.86	166.38	48.26	217.31	67.12	274.49	84.48

Table 5

Calculated values of a transfer function (6) with mean values

$W_{nominal}$, %	$W_{calculated}$, %				
	Pearl barley	**Poppy**	**Millet**	**Pea**	**Wheat cereals**
0	0.268	0.268	0.268	0.268	0.268
10	10.423	9.575	10.157	9.852	10.540
20	19.886	19.678	20.597	20.026	20.574
30	30.240	29.013	29.422	29.504	29.984

Table 6

Calculated values of a transfer function (6) with median values

$W_{nominal}$, %	$W_{calculated}$, %				
	Pearl barley	**Poppy**	**Millet**	**Pea**	**Wheat cereals**
0	0.268	0.268	0.268	0.268	0.268
10	10.440	9.570	10.136	9.868	10.469
20	19.876	19.748	20.580	20.058	20.540
30	30.228	29.040	29.420	29.501	29.964

For the initial transfer function (2) calculated values of moisture content for the same mean and median capacitance values can be found in tables 7 and 8.

Table 7

Calculated values of a transfer function (2) with mean values

$W_{nominal}$, %	$W_{calculated}$, %				
	Pearl barley	**Poppy**	**Millet**	**Pea**	**Wheat cereals**
0	0.268	0.268	0.268	0.268	0.268
10	8.960	8.215	8.708	8.430	9.069
20	18.483	18.389	19.276	18.638	19.250
30	32.368	30.377	30.975	31.111	32.878

Table 8

Calculated values of a transfer function (2) with median values

$W_{nominal}$, %	$W_{calculated}$, %				
	Pearl barley	**Poppy**	**Millet**	**Pea**	**Wheat cereals**
0	0.268	0.268	0.268	0.268	0.268
10	8.975	8.169	8.693	8.445	9.002
20	18.472	18.330	19.257	18.674	19.211
30	32.347	30.355	30.972	31.107	31.887

To compare the robustness of the data, given in tables 5 – 8 we used the instruments of dispersion analysis. At first, four dispersions of repeatability and four dispersions of adequacy (for data in tables 5 – 8) were calculated. Dispersions of adequacy were compared with the dispersions of repeatability by using F-test. All calculations for the results, given in tables 5 – 8 can be found in table 9.

Table 9

Results of robustness verification for the transfer functions (6) and (2)

Data source	S^2_{rep}	S^2_{ad}	F
Table 5	0.09344	0.0161	0.172
Table 6	0.10775	0.0162	0.150
Table 7	0.29244	0.3750	1.282
Table 8	0.30436	0.3401	1.117

Possible accuracy of moisture measurements can be estimated by using the method of mathematical programming. If some function $f(x)$ is continuous, it's possible to find maximal and minimal values of $f(x)$ inside the limit value of the function's argument error. Absolute uncertainty of moisture measurement can be calculated as a half difference $\Delta f = (f_{max}(x) - f_{min}(x))/2$. Maximal and minimal capacitance values were taken from the results of ten random measurements in pearl barley with 30 % of moisture content (table 10).

Table 10

Maximal and minimal values of electric capacitance

Pearl barley		**Electric capacitance value, pF**			
***W*, %**		C_1	C_2	C_3	C_4
30	max	57.05	189.95	419.45	136.46
	min	56.45	189.42	418.46	135.51

After substituting the values from table 10 into the transfer function (6), maximal and minimal values of moisture content are obtained: $W_{\max}$ = 30.45 %, $W_{\min}$ = 29.92 %. The value of an absolute moisture measurement extended uncertainty would be equal to $U(W_m)$ = (30.45 – 29.92)/2 = 0,27 %, which is very good for a capacitive grain moisture meter. The same operations had been done for the initial transfer function (2): $W_{\max}$ = 32.75 %, $W_{\min}$ = 31.81 %, $U(W_m)$ = (32.75 – 31.81)/2 = 0,47 %. As it can be seen, moisture measurement extended uncertainty of the modified transfer function (6) is approximately two times smaller in comparison with the uncertainty of initial transfer function (2).

CONCLUSIONS

After checking the workability of the equation (6) for different moist substances, it was possible to say that it happened to be far more robust to grain type variation than the initial transfer function, suggested in *(Zabolotnyi and Koshevoi, 2020)* and equation (3), received from a first-order polynomial after LS method implementation.

During the meter's transfer functions (2) and (6) comparative analysis, it was necessary to estimate how both of them compensated for the type uncertainty, and how close both of them were to the nominal linear transfer function. Dispersions of repeatability, calculated for transfer function (2) and transfer function (6) with mean and median values, describe a possible variation in the measured moisture values for five chosen substances (wheat cereals, pea, millet, poppy, and pearl barley).

It was demonstrated that the values of the dispersions of repeatability of S^2_{rep1} and S^2_{rep2} are approximately 3 times smaller compared with S^2_{rep3} and S^2_{rep4}.

This means that the transfer function (6) is not as sensitive to grain type as an equation (2). Dispersions of adequacy describe the correspondence of experimental transfer functions (6) and (2) (taken for different grain types as dielectric substances with a significant difference in relative permittivity) with the nominal linear transfer function of a moisture meter. Again, we can see that the dispersions of adequacy calculated for the transfer function (6) give values that are much smaller in comparison with the dispersions of transfer function (2). This means that transfer function (6) provides better adequacy to the ideal than transfer function (2). As a general result, it can be concluded that it would be rational to apply transfer function (6) with median values of moisture content as a nominal transfer function of the grain moisture measurement system.

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