DESIGN OF A LOW-COST CAPACITIVE-TYPE MOISTURE MEASUREMENT SYSTEM EMBEDDED IN COMBINE: CONSTRUCTION AND ELETRICAL CHARACTERISTICS

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Abstract. *Brazil has been highlighted internationally as a great producer and exporter of grains. That position has been firmed each passing year by the high competitiveness of the country in that area, attracting great seed research companies and promoting the formation of national research companies. The need of such companies of a moisture meter embedded on a combine, the lack of an appropriate system in the country and its high acquisition cost abroad motivated the development of a low cost moiture measurement system (M.M.S.) with own characteristics to be embedded on a combine in order to automate the data aquisition of plot seeds. Some requirements for installation in a combine were proposed so that the developed system would be capable to work in the own grain combine conditions. A capacitive moisture sensor has been built obeying such requirements. This paper aims at showing the current state of sensor development, its electric characteristics and the procedures used for its frequency determination. The eletrical circuit tranfer function was used to simulate the possible answers according to a range of frequencies. An experimental setup was run and compared with that simulation. The frequency that offers the best sensitiveness to a future calibration is 10kHz with divisor voltage resistor R_1 equal to 100$k\Omega$. The experimental setup showed to be possible the calibration of the system proposed to corn in a range from 11 to 27% moisture.*

Keywords: *moisture sensor, capacitive sensor, grain, seed, combine*

1. INTRODUCTION

Brazil has been highlighted internationally as great producer and exporter of grains. That position has been firmed every each paasing year by the high competitiveness of the country in this area. All those advantages allied to the good potential for agricultural growth (mainly for the availability of arable lands) have attracted great seed research multinationals.

All those companies accomplish research on development of new corn hybrid, improvements of soy varieties and other great cultures. During the research process (that can last several years), great quantity of equipments and agricultural implements especially developed for this branch of activity is employed, for instance, seed accountants, breeders for plot planting, special grain treshers and plot combines.

Plot is a small area planted (in general from three to five meters long) containing one, two or four lines of plants (soy, corn, sorghum and others) spaced in the width. Hundreds and even thousands of portions are planted, each with a different genetic material destined for studies. The research companies need, at the time of crop, to extract information from each one of these plots in a fast and reliable way to develop new hybrid or improve certain characteristics of a seed.

At first, the portions were harvested manually and taken to the laboratory for analysis. With increasing research programs (that elevated the landing of planting from hundreds to thousands of plots), the manual work became practically unviable. The solution goes by task automation through instruments installed in own combine. Pieces of information are obtained during the crop of each plot and stored in digital memory (through Programmable Logical Controller - P.L.C), rationalizing the laboratory work.

This system already exists for commercial application, however it has to be imported. The cost of these equipments is high, what turns prohibitive an acquisition by smaller research companies. Without access to this technology, such companies have limitations in the new seed development process.

The lack of appropriate system in the country and its high acquisition cost are the factors that motivated the accomplishment of this paper and denote its importance. The objective here is the development of a capacitive moisture sensor. That sensor is part of a larger project which is the complete development of a low cost Moisture Measurement System (M.M.S) with own characteristics to be embedded in a combine, in order to automate plot acquisition data. In this paper, the current state of sensor development and its electrical characteristics of construction will be discussed.

2. CONSTRUCTION REQUIREMENTS

As the M.M.S. that was developed will be embedded in a combine, it was necessary previous establishment of some requirements to be observed. This way, it is tried to guarantee that M.M.S. will have conditions of working in the unfavorable environment present during the crop. Such requirements, as well as the aspects of mechanical construction of capacitive sensor (Fig. 1) were described by Lagares and Sousa (2006), as it is metioned bellow:

1. Robustness (capacity to resist to mechanical vibrations and eventual mechanical shocks);
2. acquire speed (around 30 seconds in order to become commercially viable);
3. Resistance to the bad weather (high temperatures, high humidity of the air on rainy days and exposition to the dust);
4. Easy operation (operated by the own combine driver);
5. Compatibility with a Programmable Logical Controller (responsible for the automation of whole process);
6. Imput voltage 12 V (only source of imput voltage in a combine);
7. Low cost (seeking for smaller companies).

Figure 1. Moisture Sensor final mechanical conception(Lagares and Sousa, 2006)

3. MOISTURE SENSOR ELECTRICAL CHARACTERISTICS

The employed electrical circuit in the sensor of Fig. 1 is similar to the one described by Pinto (1997). It was used successfuly in the development of a moisture soil system. It is very simple and could be built with passive electric elements and integrated circuits of low cost available on the market. Therefore, it has conditions to fill the Construction Requirements above defined.

It is constituted of an alternate voltage U_e, a divisor voltage resistor R_1 and a capacitor. In this model, the sensor is represented by the association of a resistance R_2 (capacitive sensor internal eletric resistance) and a capacitance value C, in parallel. Figure 2 illustrates the electric outline used.

Its transfer function is given by:

$$R_1 C\dot{U}_s + \frac{(R_1 + R_2)}{R_2} U_s = U_e \qquad (1)$$

Any instrument like that

$$a_1 \dot{q_0} + a_0 q_0 = b_0 q_i$$

where:

- a_0, a_1 e b_0 are constants
- q_i is a value in an
- q_0 is a value out

is, by definition, a first order-instrument (Doeblin, 1990).

This way, the eq. 1 denotes that the eletric circuit chosen configures an instrument of first order.

Substituting the differential operator that is applied in U_s by D, dividing Eq. 1 by the constant a_0 and putting U_s in evidence, follows:

$$\left(\frac{R_1 R_2 C}{R_1 + R_2} D + 1\right) U_s = \frac{R_2}{R_1 + R_2} U_e \qquad (2)$$

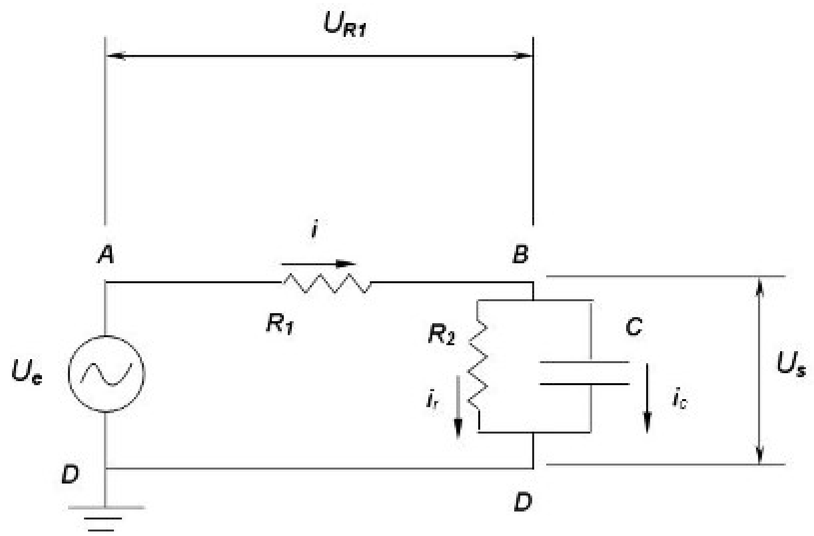


Figure 2. Eletrical circuit used in the moisture measurer

Doebelin (1990) defines the multiplier factor that follows D (eq. 2) as τ and names *time constant*:

$$\tau = \frac{R_1 R_2 C}{R_1 + R_2} \tag{3}$$

The factor that multiplies U_e in 2 is called *sensitiveness static*, being defined by the letter K:

$$K = \frac{R_2}{R_1 + R_2} \tag{5}$$

The relationship between in/out measurement system values is defined with the help of the two previous (3 and 5) parameters as being:

$$\frac{q_0}{q_i}(D) = \frac{U_s}{U_e}(D) = \frac{K}{\tau D + 1} \tag{6}$$

Doebelin (1990) proves that, for sinusoidal transfer functions, D can be substituted by $i\omega$. This way, eq. 6 becomes:

$$\frac{q_0}{q_i}(i\omega) = \frac{U_s}{U_e}(i\omega) = \frac{K}{\tau i\omega + 1} \tag{7}$$

The equation 7 is a complex number in which can be splited in their amplitude ratio ($\frac{q_0}{q_i}$) and phase angle (ϕ):

$$\left|\frac{q_0}{q_i}(i\omega)\right| = \left|\frac{U_s}{U_e}(i\omega)\right| = \frac{K}{\sqrt{\tau^2\omega^2 + 1}} \tag{8}$$

$$\phi = \angle\frac{q_0}{q_i}(i\omega) = \arctan(-\tau\omega) \tag{9}$$

Equations 7 and 8 may be also obtained through the Laplace Transformation, as used in Control Theory (Ogata, 1997). Doebelin (1990) illustrates a nondimensional representation of eq. 8 and 9 like in Fig. 3.

4. MOISTURE SENSOR FREQUENCY DETERMINATION

The literature reveals that the higher the frequency applied, as more linear the behavior of the moisture is, regarding dieletric constant (Berbert and Stenning (1997), Nelson (1992), Berbet et al (2004)). However, the circuit used here shows restrictions to the use of high frequencies (mega or gigahertz). Besides, to assist the Construction Requirements *Robustness* and, mainly, *Cost*, it is necessary that signal generator have low cost (what is not usually observed in systems working in high frequency).

Attempting to fill previous conditions and find out the frequency to be used, it was necessary the rising of the answer curves in frequency for the studied circuit. A simulation was driven and compared with an experimental setup as it follows.

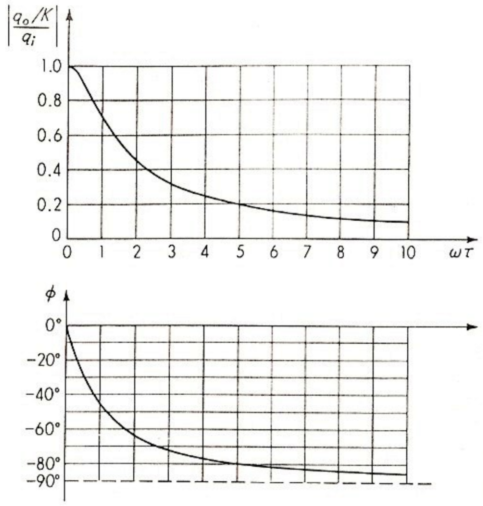


Figure 3. Nondimensional representation of eq. 8 and 9 (Doebelin, 1990)

4.1 Frequency response simulation

The circuit in Fig. 2 denotes an instrument of first-order (Fig. 3).

This behavior is, however, verified in capacitance C constant instruments. In this work, the capacitance varies according to seed moisture that fills the sensor gap. Therefore, there will be one frequency response curve for each moisture to be analyzed. Hence, instrument will work "jumping" curve to curve for a fixed frequency.

A simulation using Matlab has been done. The equations used were the same obtained from transfer function in 3(eq. 8 and 9).

The limits maximum and minimum of the following parameters related to the previous equations, R_1 (divisor voltage resistor), R_2 (intern eletrical resistance) and C (intern capacitance) were defined. The values R_2 and C were obtained with the use of two corn moisture samples (one moist and one dry). The value R_1 was, initially, maintained in $10k\Omega$. A Hewlett Packard HP 3054A Megometer was used to obtain R_2 connecting the probes directly to the sensor plates. A capacimeter was used to obtain C.

It was done two measures of R_2 and C with sensor in three conditions: empty, full of dry corn (11% moisture) and moist corn (27% moisture). Corn moisture 27% was reached by adding water to the grains and staying 24 hours to sorption. A Dickey John moisture measure was used. Table 1 shows the results.

Table 1. R_2 and C values to empty and full (dry and moist corn) sensor

EMPTY		DRY (11%)		MOIST (27%)	
R_2	C	R_2	C	R_2	C
above $1G\Omega$	$29pF$	1GΩ	$88pF$	$380k\Omega$	$6500pF$

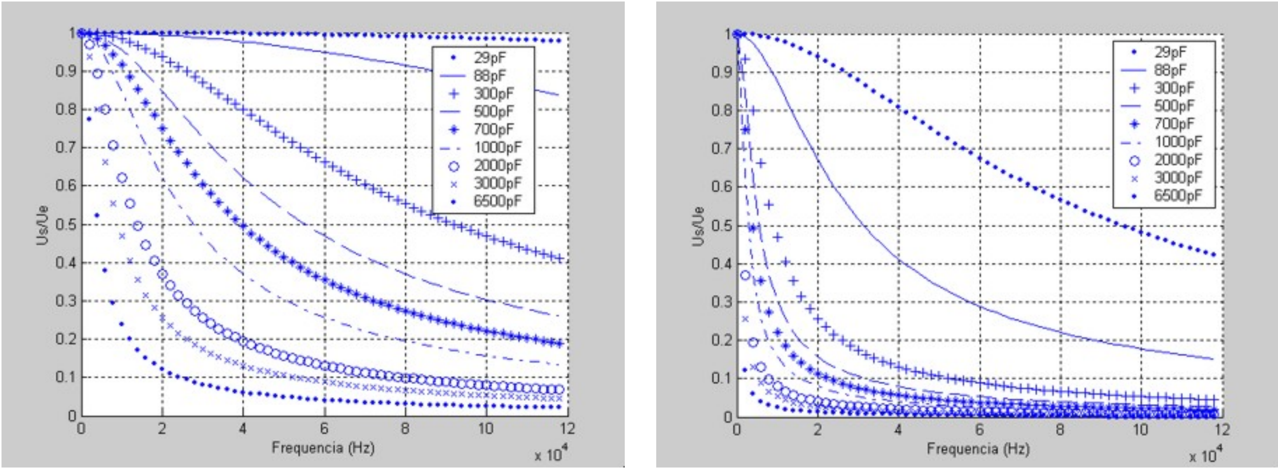
From 11 to 27 % of moisture, R_2 showed changes of order $k\Omega$ and C changes of order of thousands pF. Also when sensor is empty, differences between values kept significant (R_2, for sensor emptiness, extrapolated the maximum limit of Megometer, being attributed to it a value above $1G\Omega$). That shows the proposed model (where the sensor is modeled as being an association in parallel of a resistor R_2 and a capacitor C) is in agreement with the observed data. On the other hand, differential equation solution that represents tranfer function becomes quite complex, and confirms that the instrument is not first-order.

In order to observe model curves behavior towards capacitances, curves were done in function of the following instrument arbitrary values: 29, 88, 300, 500, 700, 1000, 2000, 3000 and 6500 pF. Two groups were studied, a group for R_1 equal to $10k\Omega$ and other for R_1 equal $100k\Omega$. R_2 was kept in $1G\Omega$ and frequency ranges from 0 to $120kHz$ (Fig. 4).

It is observed that, increasing capacitance values C or increasing R_1, an expected decrease of cut frequency f_c happens, given by:

$$f_c = \frac{1}{R_1 C} \quad (10)$$

Then, for each different moisture seed sample put in the sensor, differents curves will work (each one with different cut frequency f_c). As the objective is not obtaining frequency filter, f_c doesn't have practical sense in this work. Aims

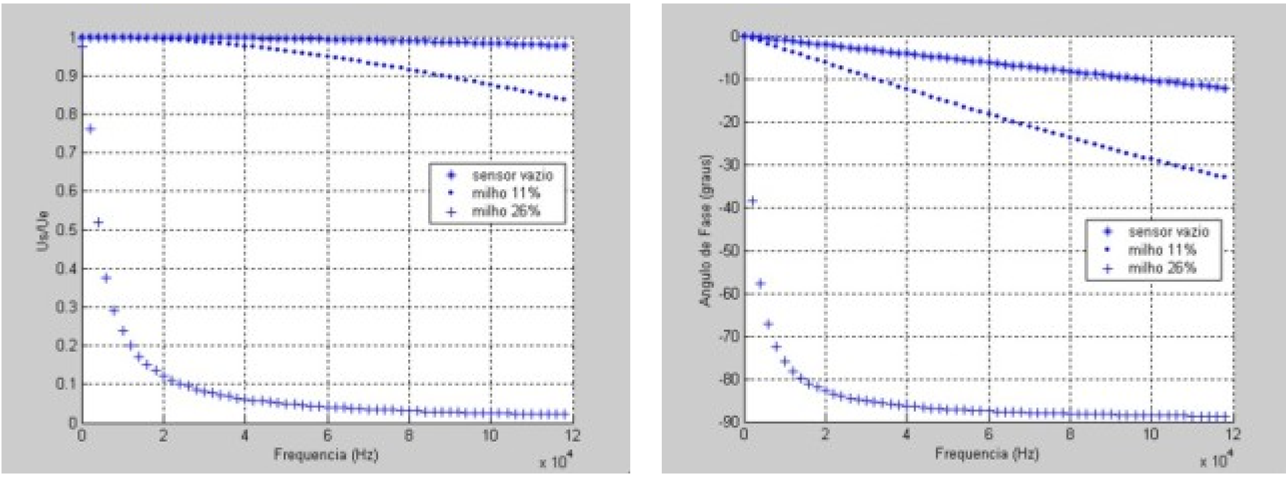


(a) (b)

Figure 4. Amplitude ratio U_s/U_e to: 29, 88, 300, 500, 700, 1000, 2000, 3000 e 6500 pF (R_2 constant equal $1G\Omega$): (a) R_1 = $10k\Omega$ (b) R_1 = $100k\Omega$

reading capability of different U_s values in function of capacitacevalues C.

To reach the objective described previously, another simulation was done using the equations 8 and 9, where R_2 and C given by Tab. 1 and R_1 equal to 10 $k\Omega$. Figure 5 shows results.



(a) (b)

Figure 5. Frequency response simulation for R_1 equal to $10k\Omega$: (a) Amplitude ratio U_s/U_e (b) phase angle U_e/U_s

Figure 5 (a) shows a wide frequency range from wich one can be chosen as a suitable one.

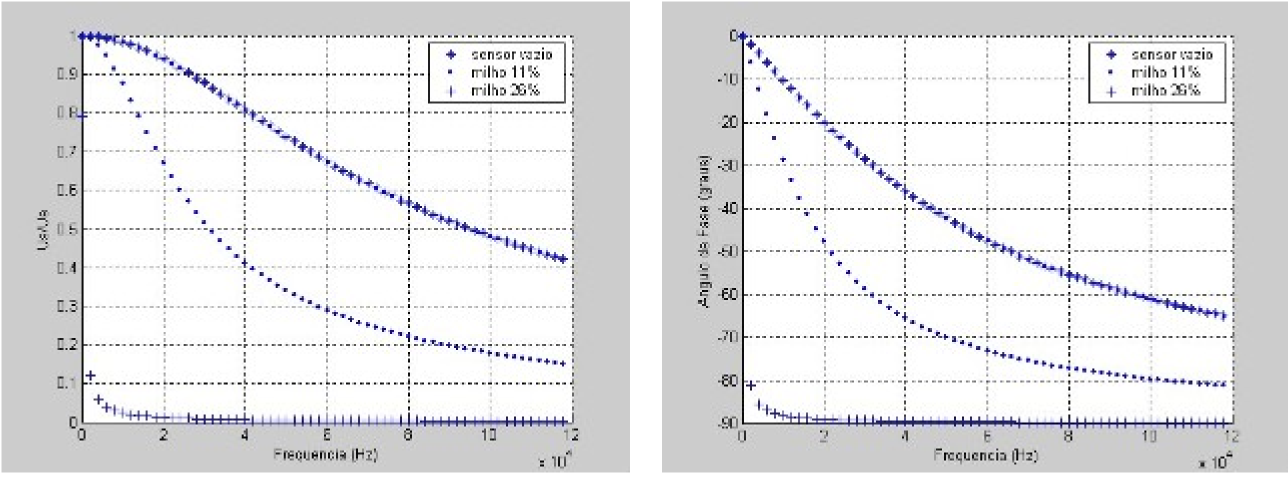
The wider the difference among values U_s/U_e minimum and maximum, regarding the minimum ($88pF$) and maximum ($6500pF$) capacitances, the more sensitive the sensor will be. For low frequencies this difference is each time smaller, achieving zero when f is zero. To find f for intermediate and high values, it is necessary to set up a curve that shows the relationship between frequency and differences between U_s/U_e for dry corn ($88pF$) and U_s/U_e for moist corn ($6500pF$). This same reasoning is applied when R_1 is substituted by $100k\Omega$ (Fig. 6).

Subtracting U_s/U_e for dry corn ($88pF$) from U_s/U_e for moist corn ($6500pF$) one obtains the Fig. 7 ((a) - R_1 = $10k\Omega$ and (b) - R_1 = $100k\Omega$). In that Figure, it is clear that ideal frequencies for greater sensitiveness are: 40 up to $50kHz$ for R_1 equal to $10k\Omega$ and 3 up to $5kHz$ for R_1 equal to $100k\Omega$.

4.2 Experimental determination of frequency response

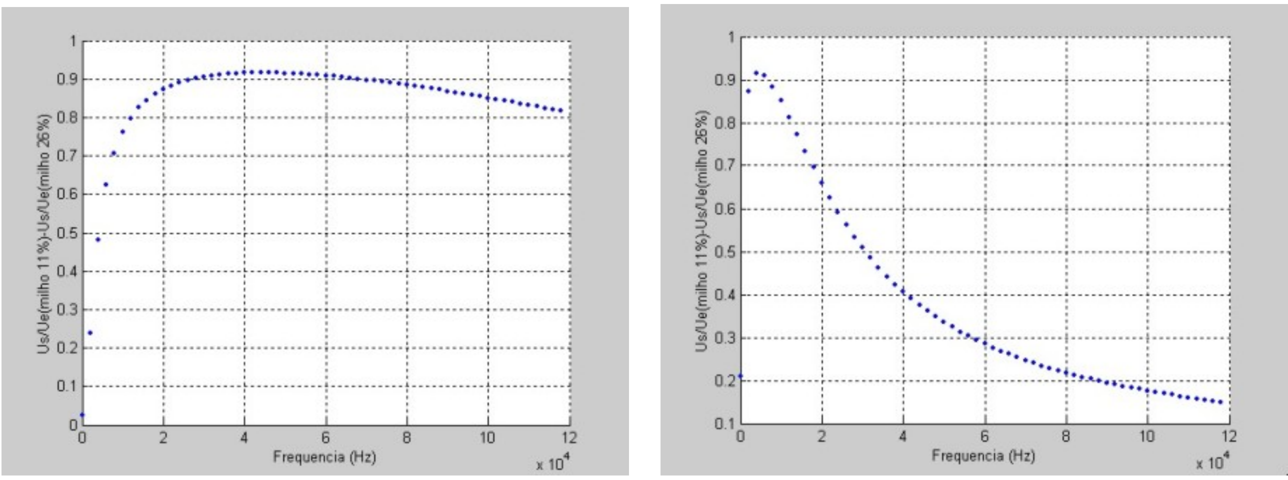
Using the same corn samples described in 4.1 a experimental set up was run with five frequency levels and two levels of R_1.

The experimental bench had a function generator Tektronix TM 503, the moisture sensor (Fig. 1), two resistors of 10 and $100k\Omega$ and an oscilloscope Tektronix TDS 310. U_e was a sinusoidal sign kept on 10,0 V_{pp}. U_s was measured by



(a) (b)

Figure 6. Frequency response simulation for R_1 equal to $100k\Omega$: (a) Amplitude ratio U_s/U_e (b) phase angle U_e/U_s



(a) (b)

Figure 7. Diference simulation between U_s/U_e for dry corn ($88pF$ - 11%) and U_s/U_e for moist corn ($6500pF$ - 27%): (a) R_1 equal to $10k\Omega$ (b) R_1 equal to $100k\Omega$

oscilloscope.

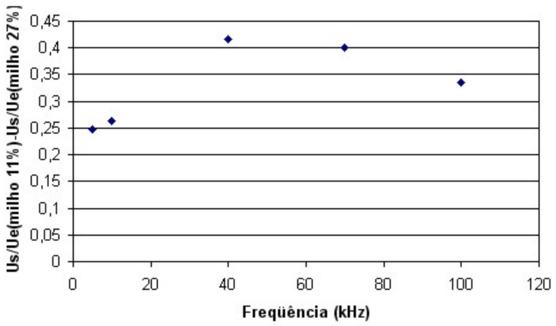
A run was done for three diferent conditions: sensor emptiness, sensor full with dry corn (11 %) and sensor full with moist corn (27%). This procedure was repeated for frequency values from five up to $100kHz$ and for the two values of resistors R_1, according to Tab. 2).

Table 2. Sensibility range determination

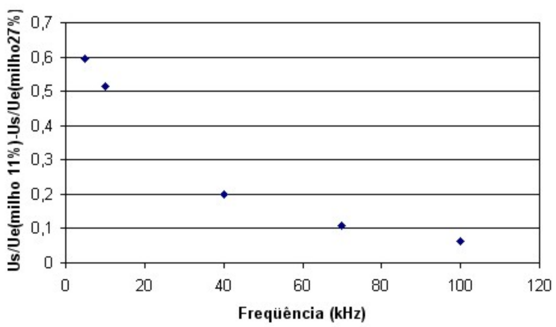
$f(kHz)$	$R_1(k\Omega)$	U_s (V_{pp})			Diferences between U_s for: (V_{pp})		
		Empty	corn 11%	corn 27%	Empty and 11%	11% e 27%	Empty and 27%
10,0	10	9,92	9,85	7,22	0,07	2,63	2,70
	100	7,73	6,81	1,66	0,92	5,15	6,07
40,0	10	9,61	9,30	5,14	0,31	4,16	4,47
	100	3,53	2,88	0,880	0,65	2	2,65
70,0	10	9,15	8,56	4,56	0,59	4	4,59
	100	2,14	1,74	0,672	0,4	1,07	1,47
100,0	10	8,32	7,68	4,32	0,64	3,36	4
	100	1,50	1,24	0,608	0,26	0,63	0,89
5,0	10	9,96	9,86	7,38	0,1	2,48	2,58
	100	8,67	8,00	2,04	0,67	5,96	6,63

In the same Table the values obtained from differences between U_s for: *sensor emptiness* and *sensor full with dry corn*; *sensor full with dry corn* and *full with moist corn* are shown.

Dividing the values of the differences of U_s (shown in Tab. 2) by U_e (equal to 10,0 V_{pp} and organizing them in a graph function of frequency f, it can be compared with the graphs of Fig. 7. This way, it was obtained the graph of Fig. 8.



(a)



(b)

Figure 8. Experimental determination of diference between U_s/U_e for dry corn (11%) and U_s/U_e for moist corn (27%): (a) R_1 equal to $10k\Omega$ (b) R_1 equal to $100k\Omega$

The used simulation (Fig. 7) was shown appropriate for the studied electrical circuit. This can be confirmed comparing it with the graphs of Fig. 8, where an equivalent behavior of the curves is observed.

Experimentation has confirmed the frequency range

- 40 up to $50kHz$ for R_1 equal to $10k\Omega$ and
- 3 up to $5kHz$ for R_1 equal to $100k\Omega$

as being the most appropriate ones to obtain a calibration with larger difference between maximum and minimum U_s values (better sensitiveness).

In a final step, it is necessary to choose a frequency value (and not a range) to be used in the system calibration. Like a parameter choice, the largest difference value of U_s for corn 11% and 27% was taken from data in Tab. 2. That leads to the choice of $5kHz$ for R_1 equal to $100k\Omega$, where U_s is maximum in the value of 5,96 V_{pp}.

However the difference between U_s for empty corn and 11% can not be negligible. If it happens, the calibration process won't be capable to distinguish if the sensor is empty or with a hard dry corn. Hence, it was chosen frequency of $10kHz$ for R_1 equal to $100k\Omega$ because that presents the largest difference among the two mentioned parameters (Fig. 9).

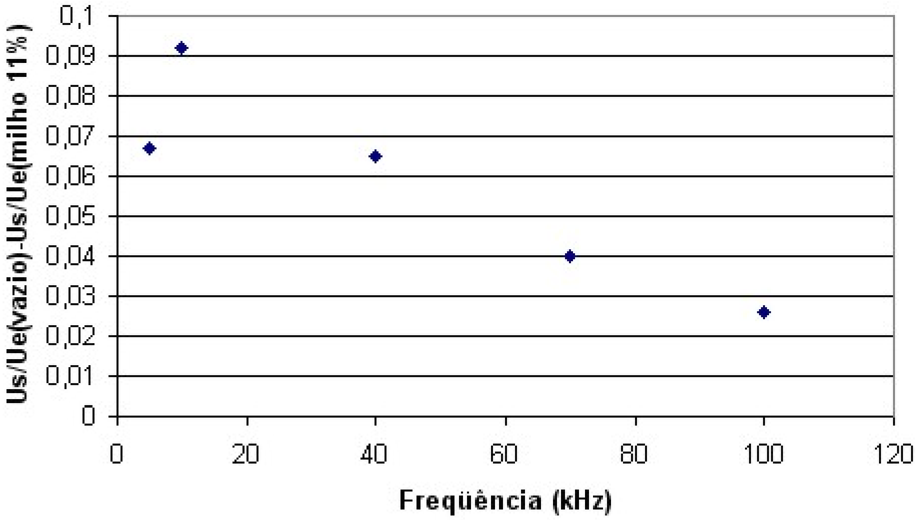


Figure 9. Diference between U_s/U_e for empty sensor and U_s/U_e for dry corn (11%)

5. CONCLUSIONS

Moisture sensor eletrical characteristic were defined. The best frequency that offers best sensitiveness to the measurement system calibration is: $10kHz$ for R_1 equal to $100k\Omega$. the driven experimentation has shown to be possible the system calibration for the corn in a range from 11 up to 27% of moisture. The Construction Requirements 1, 4 and 7 were filled by the development up to now reached.

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