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A grain moisture model based on capacitive sensor

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Abstract. This study starts with the principles of the variable dielectric-type cylindrical capacitive sensor, conducts the theoretical analysis after dielectric is divided into three phases (solid, liquid and gas), determines the relation between dielectric constant and other influence factors through the least squares fitting method, makes compensation for such factors as temperature, grain variety and air void ratio, builds the mathematical model of grain moisture content(GMC) through the variable dielectric-type cylindrical capacitive sensor, and suggests the capacitance measure-ment method based on pulse-width modulation. The experiment result shows that the suggested capacitance measurement method can accurately measure micro-(pF-class) capacitance, and the theoretical value of GMC as produced by this mathematical model falls within an allowable error range when compared to actual value, so this model proves to be rational.

1. Introduction

Measurements of grain moisture content (GMC) is vulnerable to the human factors in the course of agricultural production, but the government has a high requirement for the grain processing, storage and purchase. Therefore, it is of great importance to accurately measure GMC.

Now the accurate measurement methods of GMC include direct drying method, neutron method, nuclear magnetic resonance method and microwave method. Despite their high measurement precision, these methods are troubled by some disadvantages as inefficient measurement, complicated procedure, high cost and large instrument size. In contrast, the capacitive method can indirectly measure GMC through the change in dielectric constant, and have some advantages like high-speed measurement, high reliability, economy and portability, maintain-ability and online detection. However, this method involves quite a few factors (grain variety, temperature and grain compaction) [1].

This study theoretically examines the relation between variable dielectric-type cylindrical capacitive sensor and GMC [2-4], makes compensation for those main influence factors like temperature and grain variety [5-8], builds the mathematical model of GMC [9-12], and proposes the capacitance measurement circuit with pulse-width modulation[13]. This model is of some significance to the design of capacitive GMC measurement system.

2. GMC model of variable dielectric-type cylindrical capacitive sensor

2.1. Structure of capacitance sensor

Capacitance sensors have such advantages as simple structure, high resolution, high measurement rate, high reliability and strong anti-interference performance. The capacitance sensor used in this study is the same-axis metal cylindrical dielectric-type sensor (figure 1). When compared to the one-sided capacitance sensor, this capacitance sensor has the small edge effect. Copper foil is used in the design as the internal and external polar plates in sensor. The internal and external cylinders have a radius of R_1 and R_2, and a height of H. When $H >> R_2 - R_1$, the edge effect can be dismissed. The equation of $R_2 = eR_1$ in design is used to make sensor more sensitive. To reduce the external interference and the adverse effects of parasitic capacitance, the two-layered shield lines are used and the metal screening device is provided outside the cylinder.

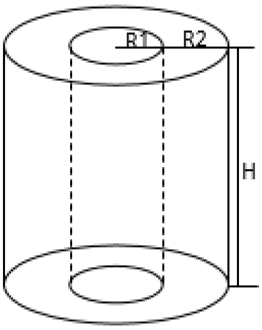


Figure 1. Cylindrical capacitance sensor.

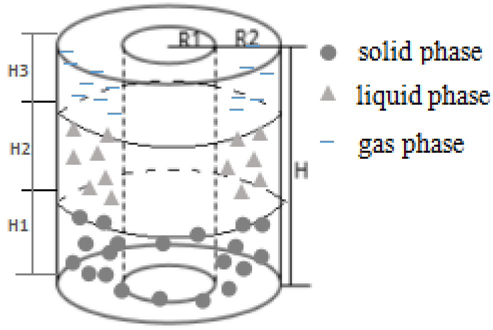


Figure 2. Three-phase diagram.

2.2. Establishment and solution of GMC model

The capacitance between internal and external plates of dielectric-type capacitive sensor is indicated in figure 1(where ε、ε_r、ε_0 are dielectric constant, relative dielectric constant and vacuum dielectric constant respectively):

$$C = \frac{2\pi\varepsilon H}{\ln(R_2/R_1)} = \frac{2\pi\varepsilon_0\varepsilon_r H}{\ln(R_2/R_1)} \tag{1}$$

The matters between the internal and external plates are abstracted into three phases. As indicated in figure 2, three phases include solid phase (grain's dry matter), liquid phase (grain moisture) and gas phase (air in grain gap). Therefore, the capacitances C_1, C_2, C_3 of three-phase matters can be deemed as parallel capacitances. If their relative dielectric constants are ε_1, ε_2, ε_3, their heights are H_1, H_2, H_3, and their matters are m_1, m_2, m_3 separately, the total capacitance between the internal and external plates can be described as follows:

$$C_x = C_1 + C_2 + C_3 = \frac{2\pi\varepsilon_0 H}{\ln(R_2/R_1)}\left(\frac{H_1}{H}\varepsilon_1 + \frac{H_2}{H}\varepsilon_2 + \frac{H_3}{H}\varepsilon_3\right) \tag{2}$$

Allow grain and water density to be ρ and ρ_w respectively, and S to be base area of annulus, so:

$$S = \pi(R_2{}^2 - R_1{}^2) \tag{3}$$

With air quality ignored $(m_3 \approx 0)$, water density $(\rho_w \approx 1000 kg \cdot m^{-3})$, and total weight of three-phase matters as follows:

$$m = m_1 + m_2 + m_3 \approx m_1 + m_2 = \rho S H_1 + \rho_w S H_2 \tag{4}$$

The GMC is shown as below:

$$W = \frac{m_2}{m} \times 100\% = \frac{\rho_w H_2}{\rho H_1 + \rho_w H_2} \tag{5}$$

Suppose grain void rate to be $\gamma = \frac{H_3}{H}$, and substitute $H = H_1 + H_2 + H_3$ into equation (5), the solution is:

$$\begin{cases} H_1 = \dfrac{\rho_w(1-W)(1-\gamma)}{(\rho-\rho_w)\ W+\rho_w} H \\ H_2 = \dfrac{\rho W(1-\gamma)}{\rho_w-(\rho_w-\rho)\ W} H \\ H_3 = \gamma\, H \end{cases} \tag{6}$$

Substitute it into equation(2), the solution is:

$$C_x = \frac{2\pi\varepsilon_0 H}{\ln(R_2/R_1)}\left[\frac{\rho_w(1-W)(1-\gamma)\varepsilon_1}{(\rho-\rho_w)W+\rho_w} + \frac{\rho W(1-\gamma)\varepsilon_2}{\rho_w-(\rho_w-\rho)W} + \gamma\varepsilon_3\right] \tag{7}$$

Based on equation (7), GMC is solved as follows:

$$W = \frac{2\pi\varepsilon_0 H\rho_w[\varepsilon_1(1-\gamma)+\gamma\varepsilon_3] - \rho_w C_x \ln(R_2/R_1)}{C_x(\rho-\rho_w)\ln(R_2/R_1) - 2\pi\varepsilon_0 H[\rho\varepsilon_2(1-\gamma)+\gamma\varepsilon_3(\rho-\rho_w)-(1-\gamma)\rho_w\varepsilon_1]} \tag{8}$$

Because air's relative dielectric constant ε_3 is hardly affected by temperature, it can be considered as a constant. But relative dielectric constant of grain's dry matters ε_1 is related to grain density ρ and temperature T , and water's relative dielectric constant ε_2 is related to temperature T . To determine the specific relation between ε_1、 ε_2 and their influence factors, the first step is to measure relative dielec-tric constants of dry matters in wheat, rice, pearl barley and buckwheat under different temperatures (figure 3). It is found that ε_1 of the same type of grain's dry matters is hardly affected by temperature, and can be considered as a constant, but ε_1 of different grain varieties varies considerably. So this study examines the relation between ε_1 and ρ for different grain varieties and uses least squares to conduct polynomial fitting (figure 4). It is found that a good result is achieved in the case of cubic polynomial fitting. The relation model between ε_1 and ρ is indicated as follows:

$$\varepsilon_1 = 1789.2\rho^3 - 7215.1\rho^2 + 9644.2\rho - 4271.1 \tag{9}$$

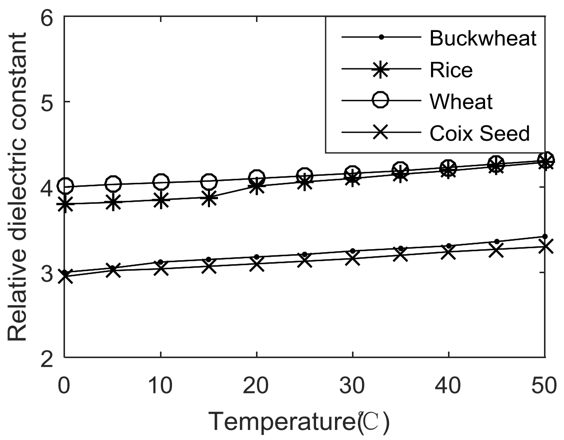


Figure 3. Relation curve between ε_1 and T .

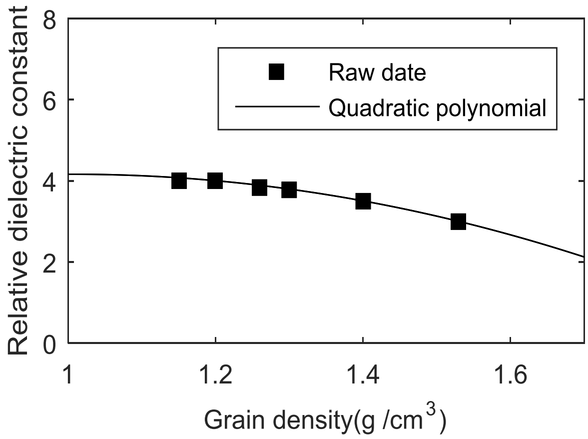
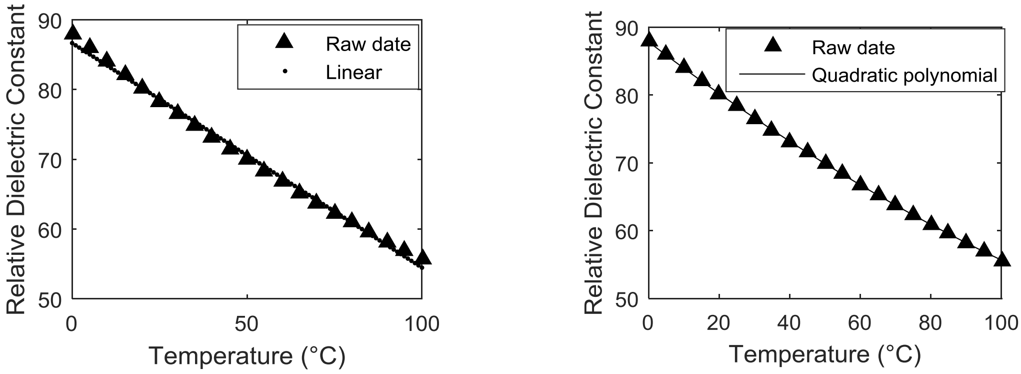


Figure 4. Relation curve between ε_2 and T .

To study the relation between water's relative dielectric constant ε_2 and temperature T , we use the least squares to conduct linear fitting and quadratic polynomial fitting (as indicated in figure 5(a) and figure 5(b)). It is found that the latter has a better fitting result than the former. So the quadratic polynomial model is used to describe the relation between ε_2 and temperature.

$$\varepsilon_2 = 0.0007T^2 - 0.3962T + 87.8339 \tag{10}$$



(a)Linear fitting (b) quadratic polynomial fitting

Figure 5. Fitting curve between water's relative dielectric constant ε_2 and temperature T .

In summary, the GMC model of the variable dielectric-type cylindrical capacitive sensor is shown as follows:

$$\begin{cases} W = \dfrac{2\pi\varepsilon_0 H\rho_w[\varepsilon_1(1-\gamma)+\gamma\varepsilon_3] - \rho_w C_x \ln(R_2/R_1)}{C_x(\rho-\rho_w)\ln(R_2/R_1) - 2\pi\varepsilon_0 H[\rho\varepsilon_2(1-\gamma)+\gamma\varepsilon_3(\rho-\rho_w)-(1-\gamma)\rho_w\varepsilon_1]} \\ \varepsilon_1 = 1789.2\rho^3 - 7215.1\rho^2 + 9644.2\rho - 4271.1 \\ \varepsilon_2 = 0.0007T^2 - 0.3962T + 87.8339 \end{cases} \tag{11}$$

3. Capacitance measurement circuit

The estimation in this design reveals that the capacitance to be measured in capacitance sensor is class pF. The measurement methods of small capacitance mainly include operation amplified circuit method, current bridge method, resonant circuit method, pulse-width-modulation (PWM) control circuit method [14, 15] and DC recharge and discharge detection method. Specifically, the operation amplified circuit method requires steady voltage and sufficient input impedance, and this method's measurement scope is limited by fixed capacitance and amplifier's amplification times. The discharge detection method lacks the function of automatic balance and requires steady voltage and small output voltage amplitude. The resonant circuit method enjoys high precision, but faces an uncertain balance point. The DC recharge and discharge detection method will produce the zero drift. The PWM control circuit method has some advantages including high precision, sound steadiness and high resolution.

After the advantages and disadvantages of these existing methods are examined, the capacitance detection circuit in this study adopts the monostable PWM control circuit method.

This method uses the capacitance's power recharge and discharge to make the width of output pulse change along with the variation of capacitance to be measured, and receives the DC signals from the capacitance change through low-pass filter and then conducts ADC(figure 6) .

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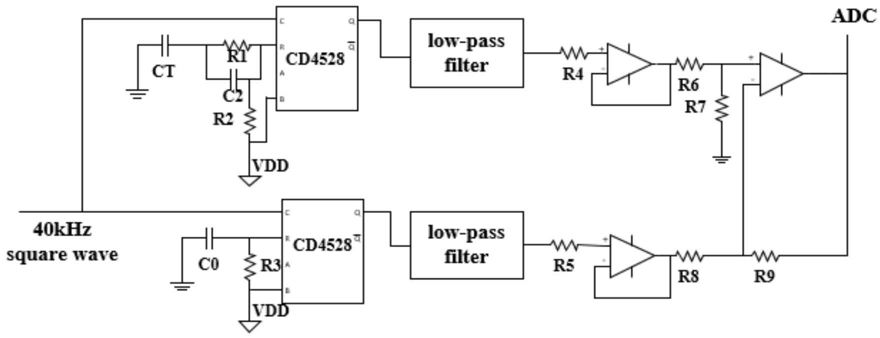

Figure 6. Measurement circuit of capacitance sensor.

This circuit is composed of monostable trigger, low-pass filter, voltage follower, and subtractor. The measurement circuit is divided into upper and lower circuits to remove the effects of temperature on component parameters in circuit, increase circuit stability and expand measurement scope. The upper circuit is the branch to be measured, and C_T is the capacitance to be measured in capacitance sensor. The lower circuit is the compared branch, and C_0 is the fixed capacitance with the same degree as the capacitance to be measured.

This design uses the square wave with integrated dual monostable CD4528 and triggered signal of 40kHz (as generated by microcontroller). The output end of monostable trigger has one stability state and one temporary stability state. When triggered signal becomes the high-level output voltage, the monostable output will change from low-level output voltage to high-level output voltage, but will automatically come back to low-level output voltage over time. Thus, the time (τ) involved in high-level output voltage in monostable output pulse is related to the capacitance to be measured (C_T).

Theoretically, the equation goes as follows (where: C_T's unit is pF and τ 's unit is μs)

$$\tau = 0.0297 C_T + 2.8 \tag{12}$$

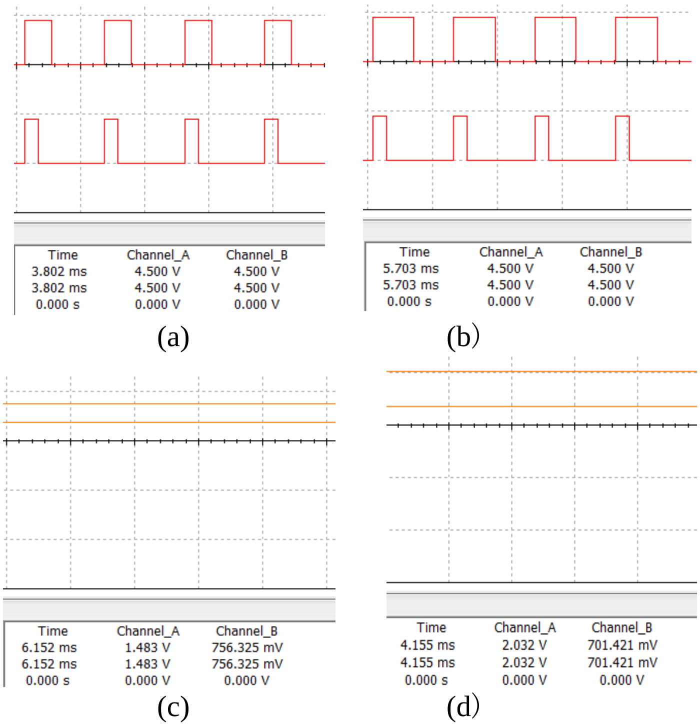

Figure 7. Simulation result of monostable circuit.

Multisim is used to simulate the monostable circuit. The related analysis is made as below. When the capacitance to be measure reaches 12pF and 18pF, the output pulse waves of upper and lower circuits are indicated in figure 7 (a) and figure 7 (b).

When pulse signal becomes DC signal through low-pass filter, higher duty cycle of pulse signal will generate high DC voltage, and then the DC output signal passes voltage follower to enhance the load-bearing ability.

Multisim is used to perform the simulation analysis of wave filtering circuit. When the capacitance to be measured is 12pF and 18pF, the post-signal filtering results in upper and lower circuits are indicated in figure 7 (c) and figure 7(d).

The DC signals from followers in upper and low circuits, which have passed subtractor, are subject to ADC. A higher capacitance to be measured can lead to a high voltage in ADC.

4. Experiment results and error analysis

4.1. Preparation of grain standard

The first step is to sample five portions of grain from the grain with unknown moisture, measure and average the moisture of each sample through 105°C constant weight method [16], and calculate and obtain the necessary mass of water for the preparation of standards with different moistures. Then rice is placed inside a sealed box and a pipette is used to add water into the sealed box. Arrange the sealed box inside a thermostat and leave it untouched until water contents become evenly distributed. Get five portions of grain with the same mass and use them as samples, and measure and average the moisture of each samples through 105°C constant weight method again. The final moisture is the actual moisture of grain standard.

4.2. Measurement of grain void ratio

Grain void ratio can be defined as the ratio of air volume to total dielectric volume in sensor. Drainage method is used to measure its size. Add 20ml water to 50ml graduated cylinder, and then put $0.01m^{-3}$ grain into the graduated cylinder quickly and read the liquid-level calibration at this moment. The difference in liquid-level calibration before and after the addition of rice is the air volume of grain gaps. So grain void ratio can be obtained in this way.

4.3. Experiment results analysis of capacitive measurement circuit

To test the reliability of capacitive measurement circuit, the measurement system is used to measure the fixed capacitance of 1 to 50pF. Actual capacitance value, measurement value and error are shown in figure 8. Since error falls within the scope of -1.35% to 2.10%, it can be concluded that the method is feasible and measurement results are accurate.

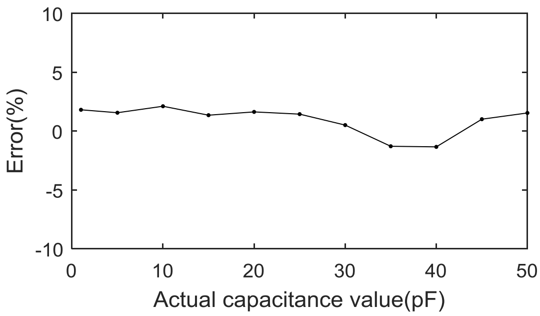

Figure 8. Measurement data and error.

4.4. Experiment results analysis of GMC model

At 25°C, the measurement system is used to measure the capacitance values of rice and wheat standards with the moisture of 0% to 25%, and substitute measurement value into the mathematical model equation (8) of GMC as suggested in this paper to get theoretical moisture value of rice and wheat. Experiment results and errors are indicated in table 1. It is easy to find that there is a very small gap between theoretical and actual moisture of rice and wheat, and the errors fall within the range of $\pm 0.4\%$ .This means that the model completes quite accurate compensation for grain variety and proves rational and reliable.

Table 1. Experiment results and errors of grain standards with different moistures.

Actual moisture (%)	Rice			Wheat		
	Theoretical moisture (%)	Capacitance value (pF)	Error (%)	Theoretical moisture (%)	Capacitance value (pF)	Error (%)
0	10^{-9}	7.2	0	10^{-9}	7.56	0
5	4.98	15.68	-0.4	5.02	15.48	0.4
10	9.99	23.96	-0.1	9.97	23.12	-0.33
15	15.03	32.04	0.2	15.02	30.76	0.13
20	20.03	39.84	0.15	19.98	38.12	-0.1
25	24.91	47.24	-0.36	24.93	45.32	-0.28

At 0 to 50°C, the measurement system is used to measure the capacitance values of rice and wheat standards with the moisture of 15%, and substitute measurement value into the mathematical model equation (8) of GMC as suggested in this paper to get theoretical moisture value of rice and wheat. Experiment results and errors are indicated in table 2. It is easy to find that the errors for theoretical moisture value fall within the range of -0.27% to 0.13% at different temperatures. This means that the model completes good compensation for temperature.

Table 2. Experiment results and errors of grain standards with the moisture of 15% at 0 to 50 ℃.

Temperature (°C)	Rice			Wheat		
	Theoretical moisture (%)	Capacitance value (pF)	Error (%)	Theoretical moisture (%)	Capacitance value (pF)	Error (%)
0	15.01	35.16	0.07	14.98	33.64	-0.13
10	14.99	33.84	-0.07	14.99	32.44	-0.07
20	14.97	32.56	-0.27	15.02	31.32	0.13
30	15.03	31.44	0.27	15.02	30.20	0.13
40	15.02	30.28	0.13	14.99	29.08	-0.07
50	14.99	29.12	-0.07	14.96	28.00	-0.27

5. Conclusions

This study divides dielectric into three phases (solid, liquid and gas), conducts the theoretical analysis of the relation between grain moisture content(GMC) and capacitance, determines the relation between dielectric constant and other influence factors through the least squares fitting method, makes compen-sation for such factors as temperature, grain variety and air void ratio, builds the mathematical model of GMC, and suggests the capacitance measurement method based on pulse-width modulation. The experiment results reveal that the error of capacitance measurement falls within the scope of

-1.35% to 2.10%, the sensor's capacitance can be accurately measured, the theoretical value of GMC as produced by this mathematical model falls within $\pm 0.4\%$ when compared to actual value, and this model makes good preparation for temperature, grain variety and other factors. The model proves to be rational and accurate.

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