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Microwave Mixing Technique for Nondestructive Measurement of Moisture Content of Particulate Agricultural Products

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Abstract. A new method for nondestructive measurement of moisture content of particulate agricultural products is developed using microwave mixing technique. A double horn system with a relative vertical distance of one-fourth wavelengths is designed to measure the reflected microwave signals. The particulate materials are interacted with microwave at a frequency of 10.5 GHz, and the reflected microwave signal is mixed with the launch signal. Corns with different moisture contents are chosen as samples. Calibration models for moisture content are proposed in accordance with the measurement of the differential attenuation of the microwave mixing signal. A moisture content from 6.8% to 30.1% is obtained with a coefficient of determination of 0.98 and a standard error of calibration value of 1.12%.

Keywords: Moisture content; Microwaves; Mixing technique; Nondestructive measuring

1 Introduction

Water is an important component of industrial and agricultural production. Moisture content directly affects the quality of storage and processing conditions of agricultural products. The measurement of moisture content has important scientific significance and application value in agriculture product processing applications.

To achieve automatic processing and production, the moisture measurement process of agricultural products needs to be completed accurately and quickly, and the tested samples are not damaged. The drying weighing method is often used as a calibration method. Each measurement requires very few samples.[1, 2]. The process is destructive and time and energy consuming. Resistance method needs to measure the impedance of samples between probes, with low accuracy and destructive measurement. RF capacitance method is a non-destructive measurement, in which samples are added between capacitor plates and water content is retrieved by measuring capacitance changes. [3, 4]. However, the method

results in bulk density of sample, thereby causing a large number of measurement errors. It is an urgent research topic to realize on-line non-destructive and high-precision detection of moisture content in agricultural products.

In recent decades, microwave measurements have been used in many industrial applications. Microwave moisture content sensing measures the relative insensitivity to ionic conductivity, during which the electromagnetic energy is mainly absorbed by water. This selective absorption is due to the polar characteristic of the water molecules and their high permittivity compared with that of dry matter [5, 6]. Water molecules have very strong polarity, and microwave has a high frequency, so the interaction between the two will lead to energy storage and loss. The dielectric constant critically depends on the moisture content of water-containing materials at constant frequency and temperature [7]. There are many reports on dielectric constant measurement, including resonant cavity method and transmission line method. [8, 9]. The dielectric constant of the sample is calculated by measuring the stationed Bobbi and field strength of the microwave. During the measurement, the sample is strictly confined to the waveguide cavity or coaxial line, which limits the application of on-line measurement [10].

Free-space technology presents great flexibility and does not bound microwaves to specific regions. After the interaction between microwave and sample, the transmission energy and phase will change. The moisture content and bulk density of sample can be measured by measuring the transmission parameters of microwave [11]. The microwave transmitting and receiving antennas are fixed on both sides of the measured sample. The thickness of the sample should be kept constant during the measurement to determine the relative attenuation of microwave energy. Therefore, the dual probe method cannot be applied to the situation where the thickness of the sample changes continuously during the flow. In our previous studies, a free-space microwave reflection measurement system with a single sensor is designed for the nondestructive determination of moisture content and bulk density [12]. The amplitude and phase parameters of traveling-standing wave are measured through the microwave horn antenna of continuous motion. However, for large particles of material, the single probe measurement sensitivity decreases as microwave scattering increases.

In the present study, a double probe microwave reflection measurement system is designed. The reflected microwave signal is mixed with the launch signal. Two radar probes are fixed separately on the position of signal maxima and minima. Measuring sensitivity is increased by differential output. This method is fast, continuous, and nondestructive. The measuring sensor does not directly contact with the grain materials, thereby facilitating its use in the real-time monitoring and controlling processes of moisture content of industrial and agricultural products.

2 Materials and Methods

The microwave moisture measurement system described here is based on a free-space reflection method and possesses the advantages of being nondestructive and not requiring sample preparation and physical contact with the material. Moisture content is determined from the measurement of attenuation and phase shift after the incident wave reflection from the material surface. A transmit and reflection wave mixing method is designed to determine the parameters of attenuation and phase shift.

2.1 Principle of Microwave Mixing Moisture Measurement

The schematic view of this microwaves mixing moisture measurement is shown in Fig. 1. The materials are interacted with microwave, and the reflected microwave signal is mixed with the launch signal in the mixing diode. $U_L(t)$ is the incident wave signal with the frequency ω_L , and $U_S(t)$ is the reflected microwave signal with the frequency ω_S . D_1 is a Schottky mixing diode. The DC offset voltage E_0 is used to make sure the diode working well. Finally, the signals are processed by an amplifier and a low pass filter.

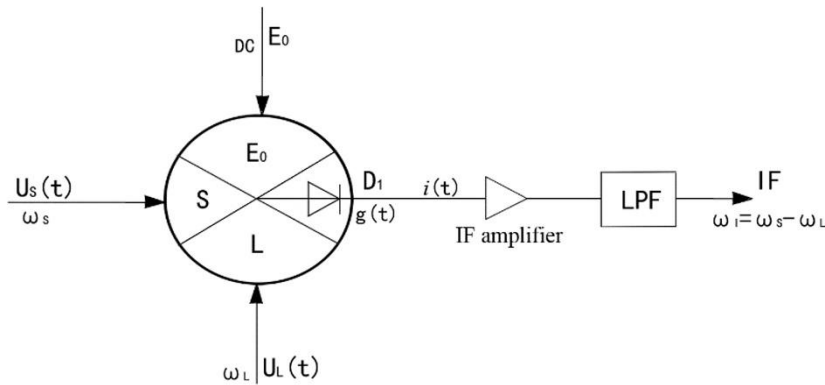


Fig. 1. The schematic view of microwave mixing process

The mixing principle is described as follows. The incident wave signal $U_L(t)$ and the reflected microwave signal $U_S(t)$ can be described as

$$U_L(t) = U_L \cos \omega_L t, \quad (1)$$

$$U_S(t) = U_S \cos(\omega_S t + \varphi). \quad (2)$$

The incident and reflected waves have different amplitudes and phases. After contact with the material, the reflected microwave $U_S(t)$ is a small variation compared with the incident wave. So the current $i(t)$ flowing through the Schottky diode mixer D_1 can be expanded as Taylor series

$$i(t) = f(E_0 + U_L(t) + U_S(t))$$

$$\begin{aligned}
&= f(E_0 + U_L \cos \omega_L t) + f'(E_0 + U_L \cos \omega_L t) U_S \cos(\omega_S t + \varphi) \\
&\quad + \frac{1}{2!} f''(E_0 + U_L \cos \omega_L t) (U_S \cos(\omega_S t + \varphi))^2 + \Lambda \cdot
\end{aligned} \tag{3}$$

The first expansion is a large signal, which contains the DC and local microwave fundamental signals. Other items are small signals. For the second item of Eqs. (3)

$$\begin{aligned}
i(t) &= f'(E_0 + U_L \cos \omega_L t) U_S \cos(\omega_S t + \varphi) \\
&= g_0 U_S \cos(\omega_S t + \varphi) + \sum_{n=1}^{\infty} g_n U_S \cos((n\omega_L + \omega_S)t + \varphi) \\
&\quad + \sum_{n=1}^{\infty} g_n U_S \cos((n\omega_L - \omega_S)t + \varphi) \cdot
\end{aligned} \tag{4}$$

In (4), g_n is the conductance of the diode mixer and it is a constant for the given diode. After the mixing signals passing through the low-pass filter, the differential frequency signal, at the point $n = 1$, can be expressed as follows

$$i(t) = g_1 U_S \cos((\omega_L - \omega_S)t + \varphi). \tag{5}$$

In actual measurement, the relative distance between the microwave probe and the material remains constant. So the frequency of the incident wave is equivalent to the reflected microwave. Then we can get the following equation

$$I_0 = g_1 U_S \cos \varphi. \tag{6}$$

In (6), g_1 is the o conductance constant of the diode. U_S is the amplitude of reflected microwave, which is proportional to the moisture content of tested materials. φ is the relative phase value of the reflection microwave. The value $\cos \varphi$ varies periodically from 1 to -1 with the different relative position of the antenna probe and the material. The mixing signal has the best sensitivity when the microwave antenna is fixed in one of the two phase extreme points ($\cos \varphi = 1$ or -1).

In this study, two microwave antennas are mounted on the maximum and minimum phase positions respectively. In experimental measurement, two mixing signals are opposite to each other. The moisture content of the material is obtained by difference operation of the two signals. Microwave mixing technique has greatly facilitated the high-frequency signal processing and extraction in moisture measurement.

2.2 Microwave Measurement System

The measurement system consists of microwave cavity oscillator, double horn antenna, mixer, sample holder, differential amplifier, and data processing unit. The construction of microwave measurement system is illustrated in Fig. 2. Two microwave horn antennas, which transmit and receive signals independently, are mounted on the same side of the sample holder. The sample container is made of acrylic material, rectangular and filled with

the tested sample. The vertical distance of microwave transceiver probes 1 and 2 is $\lambda/4$, which relates to microwave wavelengths. Prior to the actual measurement, the distance L between probe 2 and the sample surface needs to be adjusted to ensure that the mixing signal is at the limit value. When L is finalized, the phase difference φ between mixing signals A and B is π . Therefore, the mixing current presents opposite changes between signals A and B, as shown in Eq. (6).

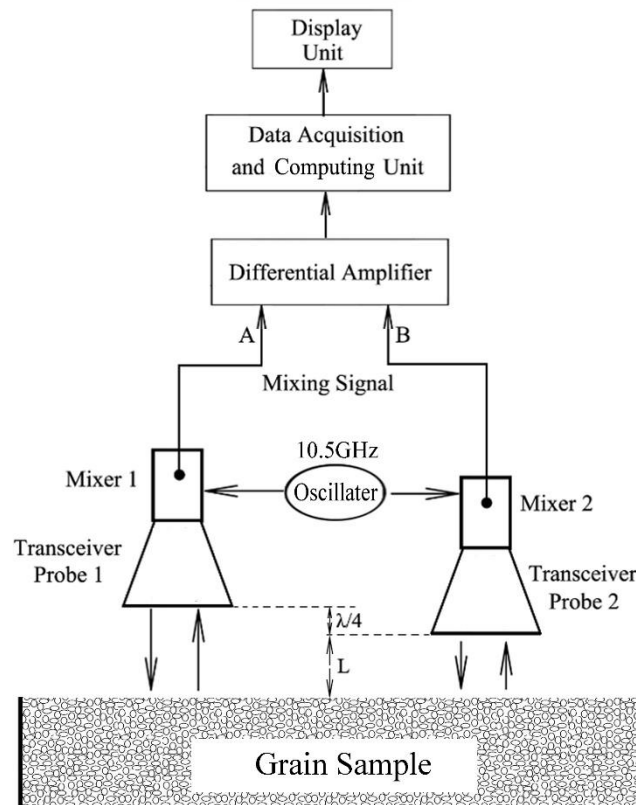


Fig. 2. Schematic diagram of double horn antenna microwave measurement system

The microwave sensors are designed as follows. The continuous microwave signal with a frequency of 10.5 GHz and a power of 20 mW is generated by a Gunn diode. The waveguide cavity is wr90, and the oscillating diode is mounted in the waveguide cavity. The microwave cavity oscillator is connected with the horn antenna. The aperture of the microwave horn antenna is 8.4 cm×6 cm and the output gain at the frequency of 10.5 GHz is 17.2 dBi. The incident and reflected waves are detected by a Schottky mixer diode. Finally, mixing signals A and B are measured by using the differential amplifier.

The output voltage of the differential amplifier is linearly related to the moisture content of the tested materials. In accordance with the fitting equation, a data acquisition and

adjustment unit is designed with different modes to realize the display and control of moisture content.

2.3 Sample Preparation

Corns are used as the experimental sample in this study. Each sample consists of approximately 10 kg of material and is dried by natural drying prior to the experiments. The moisture content of the sample is determined by drying and weighing. A certain amount of the sample is placed in the drying equipment at a temperature of 130°C until the weight is constant. Moisture content is calculated as follows:

$$M(\%) = \frac{m_w}{(m_w + m_d)}, \quad (7)$$

where M is the moisture content of corn, m_w is the mass of water, and m_d is the mass of dry matter.

The initial moisture content of corn sample is 6.8%. The water content of the sample was increased by adding water and stirring evenly. The samples were prepared with the distance of 3% water content. A total of 8 samples with moisture contents from 6.8% to 30.1% for corn are prepared. Samples are placed in a sealed plastic bag for at least 24 h at 4 °C to equilibrate. Before the measurement, the samples were transferred to room temperature for at least 24 hours to achieve a temperature balance.

2.4 Measurement Procedure

The sample container is filled with corn samples and placed on the side of the microwave antenna. The surface of the sample is perpendicular to the direction of microwave radiation. The size of the sample container should be larger than the microwave antenna to reduce the edge scattering interference of the microwave.

The microwave horn antenna is fixed on the sliding orbit, and the position of the antenna can be adjusted freely. The distance between antenna probe 2 and sample surface is L_1 . In measurement, the electric field of space microwave varies periodically with the change of L_1 . The voltage signal B detected by the digital voltmeter changes with the increase in horn antenna distance. The variations in voltage signal B with the antenna distance L for corn with an initial moisture content of 6.8% are illustrated in Fig. 3.

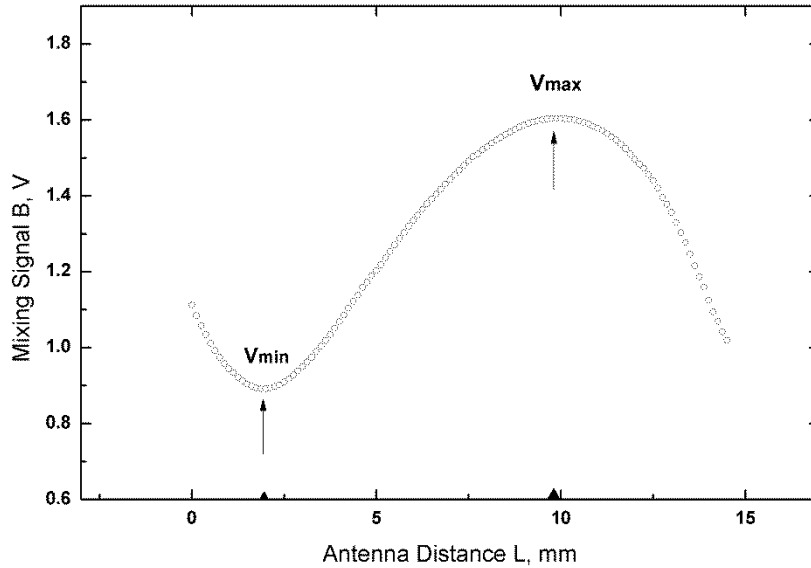


Fig. 3. Variation of voltage signal B with antenna distance L at the moisture content of 6.8%

Two extreme points, V_{min} and V_{max} , appear with the increase in horn antenna distance. The corresponding antenna distances are 2.4 and 9.8 mm. During the experiment, two microwave antenna probes are fixed in the two positions. Extreme position distance is 7.4 mm, which is in good agreement with the theoretical calculations of $\lambda/4$ at 10.5 GHz.

For each corn sample with specific moisture content, measurements are repeated and performed three times. Mixing voltage signals A and B are recorded by using the digital voltmeter, and the differential values are calculated for data fitting.

3 Experimental Results

The relationship between moisture contents and mixing voltage signals of corn samples is shown in Fig. 4. The sample is measured at room temperature (24 °C) with eight different moisture contents in increments of approximately 3%. The moisture contents vary from 6.8% to 30.1%. Each of the samples is repeated for three times, and 48 sets of data are recorded.

Curves A and B represent the output of the two microwave probes. The trends of A and B variation with moisture content are opposite to each other because the phase difference between the mixing signals is π . Curve B presents a greater slope than curve A because of the close measuring distance.

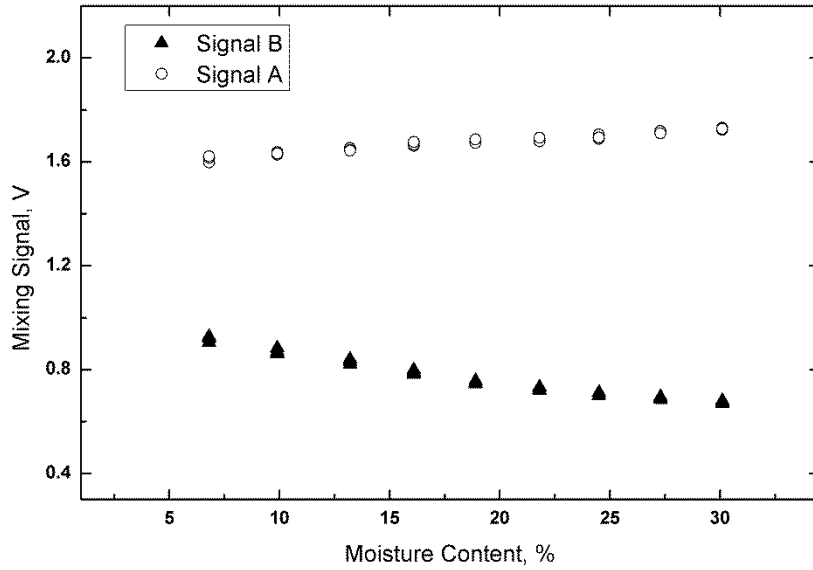


Fig. 4. The variations in the mixing signal with moisture content. The round and triangle data are output of probe 1 and probe 2 respectively.

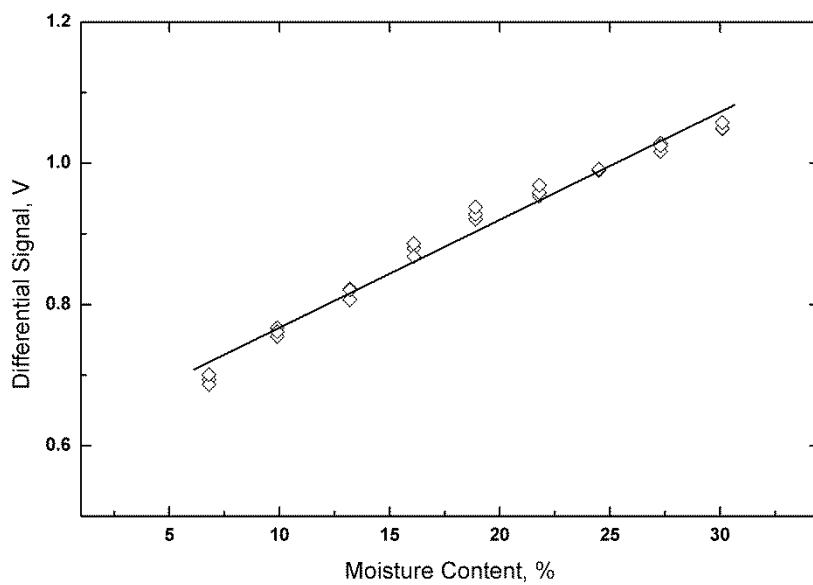


Fig. 5. Differential mixing signal versus the moisture content of corn

The variations in the differential mixing signals with moisture content are illustrated in Fig. 5. The sensitivity of the differential signal is obviously improved compared with that of

a single mixing output probe 1 or probe 2. The differential output is generally linear. Therefore, calibration equation is assumed as follows:

$$M_C(\%) = a_0 U_d + b_0, \quad (8)$$

where a_0 and b_0 are the coefficients, U_d is the differential signal voltage, and M_C is the moisture content of corn. The calibration equation is obtained by statistically analyzing all experimental data to determine the coefficients. The results show that, the coefficients a_0 and b_0 are 63.86 and 38.79, respectively. The moisture content is determined with an R^2 of 0.98, and the standard error of calibration (SEC) is 1.12%.

Particulate material microwave scattering is a major error factor. The main source of microwave scattering is the inhomogeneity of sample distribution, which is affected by the size, shape and water content of the particles. Temperature and bulk density also affect the measurement results. In the experiment, the particle of materials should be stacked compactly and orderly to reduce the irregular scattering of microwaves.

Conclusion

A microwave mixing system is designed for the rapid and nondestructive determination of moisture content of grain materials. The measurement system consists of microwave cavity oscillator, double horn antenna, mixer, sample holder, differential amplifier, and data processing unit. The reflected microwave signal is mixed with the launch signal. Measuring sensitivity is increased by using the double probe microwave reflection measurement system. In accordance with the fitting calibration equation, the moisture content of corn is determined with a coefficient of determination (R^2) of 0.98 and a standard SEC of 1.12%. The proposed measuring method is suitable for the independent moisture measurement of monomers and on-line moisture measurement, and also meets the real-time monitoring needs of agricultural products moisture change in industry.

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