A Review on Frequency Selection in Grain Moisture Content Detection

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Abstract. A brief review on the dielectric properties of grain and their use in sensing moisture content is presented. Dielectric constant and loss factor were defined generally, and their correlation with grain permittivity from historical studies is presented. References are cited on dielectric measurement techniques using various frequency ranges from radio frequency through microwave frequencies. The described techniques including from the past decades until current studies.

1. Introduction

Grains such as wheat and paddy represent the majority of worldwide consumed daily food. However, as the grain is naturally hygroscopic, the grain’s quality post-harvesting revolves around their level of moisture content. Moisture content generally referred to the wet basis, meaning the total weight of the grain including the water (MCwb) expressed in percentage. According to [1][2][3], moisture content is the essential parameter that impacts the quality and longevity of the granular material to be stored without degrading before processing for commercial purpose. It is also a key factor that influences the selling price because the quality of dry grain is more valuable, thus extra drying costs for safe storage must be considered. Even so, for other grain processing such as flour, packaging foods, and animal feeds, achieving desired moisture content is necessary in obtaining high quality products. In short, accurate moisture content sensing is important because different purpose in managing and marketing the grain required different ideal moisture content.

The grain moisture content generally being measured by using primary and secondary method. The primary method [4][5] is sensing the absolute moisture content in grain through oven drying process. The grain is heated over a certain duration under specified temperatures, and the weight loss in grain is used to calculate the moisture content. Weight measurement constantly reliable and high precision; thus, this method is referred as the reference method. Since the reference method involves tedious procedures, time consuming and not suitable for online and on-site measurement, a secondary method which is simpler, low cost, rapid and non-destructive have been developed. This method works on the principle of sensing the clear relationship between moisture content and the dielectric properties of the grain [6][7][8]. Over the past decades, [9–13] presented that the grain dielectric properties is a function of moisture content, applied frequency, temperature of the grain and the material density. Their influence therefore is significant for moisture level-sensing applications in agricultural industry as well as in dielectric heating processes.
In agricultural industry, dielectric properties, or permittivity affect the absorption and dissipation of electromagnetic energy when they are subjected to radio frequency (RF) or microwave (MW) heating and practically expressed as the complex permittivity relative to free space, \( \varepsilon = \varepsilon' - j \varepsilon'' = |\varepsilon|e^{j\delta} \) where \( \delta \) is the loss angle of the dielectric. The real part, \( \varepsilon' \) is the dielectric constant associated with the material’s ability to store the applied electrical energy while the imaginary part, \( \varepsilon'' \) known as dielectric loss factor represents the dissipation of applied electrical energy in the form of heat [14]. The conductivity of the dielectric in S/m is \( \sigma = \omega \varepsilon_0 \varepsilon'' \) where \( \omega = 2\pi f \) is the angular frequency with \( f \) in Hz and \( \varepsilon_0 \) is free space permittivity, \( \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \) [6].

2. Historical Perspective

Appropriate moisture content sensing techniques for any particular application mainly depend on the frequency of interest and the nature of the dielectric material to be measured [15]. Different kinds of instruments have been used for measurement, but any instrument that provides reliable determinations of the required electrical parameters involving unknown material in the interest frequency range should be considered. In this section, previous works on the moisture detection over the past decades in low, medium and high frequency were briefly reviewed.

2.1. Frequency Range 1 – 50 MHz

The first recorded quantitative data about the dielectric properties of grain was reported by [16] using frequency range 1 – 50 MHz. It was presented that permittivity of grain is clearly correlated with the moisture content, as illustrated in Figure 1 and 2, which therefore can be used for moisture sensing. Diverse kinds of grain tested by [16] has shown that the dielectric constant, \( \varepsilon' \) either remains constant or decreases as frequency increased of all moisture content percentage while the loss factor, \( \varepsilon'' \) varies with frequency accordingly. The changes in dielectric properties due to the variations in moisture content are greater at lower frequencies.

![Figure 1. The permittivity of ‘Nebred’ hard red winter wheat at 24°C. Test weight: 768 kg/m³ (59.7 lb/bu) [16].](image1)

![Figure 2. The permittivity of ‘Hawkeye’ soybeans at 24°C. Test weight: 738 kg/m³ (57.3 lb/bu) [16].](image2)
2.2. Frequency Range 50 – 500 MHz
According to [17], a slightly similar method was developed principally for measurement the grain and seed dielectric properties. A coaxial-line sample holder with open-circuit terminations and with sample holders exhibited as transmission-line sections were used for similar measurements with bridges and admittance meter at frequency 50 – 250 MHz and 200 – 500 MHz respectively. By using bridges meter, the loss factor for lossy materials is not determined accurately. [18] has reported that accuracy of permittivity for liquid materials is about 2%, but as the interest frequency increases, the accuracy decreases. However, as the losses of grain and seed samples were high, this method is useful to be used in studying the frequency dependency of the dielectric properties. The measurement is taken on hard red winter wheat sample using admittance meter [19] also gave out the same conclusion. Both techniques in this frequency range were suitable for dielectric sensing on grain.

2.3. Microwave Frequency
In previous work, while measuring the permittivity of static grain samples for moisture detection, the dependency of permittivity on temperature and bulk density must also be thought out. However, later, it was recognized that using microwave frequency, the sensing of grain moisture content had the capability of providing a measurement independent of bulk density by single-frequency measurements of attenuation (decrease in amplitude) and phase shift (delay in phase) or by using density-independent functions of dielectric constant and loss factor [20][21]. This finding provides the possibility for on-line and real-time monitoring for grain moisture content sensing.

At lower frequency, [19] stated that the precision of conductance measurement is about 5%. At 2% alteration in conductivity value, less than 0.1% dielectric constant being changed and about 2% changes in the loss factor. However, [22] reviewed that at frequency higher than 1 GHz, materials’ conductivity would not be affected. Besides that, in [11] which measured moisture content at 16.8 GHz, they concluded that using higher frequency, the characteristic of equipment can be smaller, and the thickness of material layer should be thinner than the required at lower frequencies. Therefore, better sensitivity to moisture variation can be allocated along with the layer of the material.

2.4. Wide Band Frequency, 250 Hz – 10 GHz
In Figure 3, the dependence of hard red winter wheat permittivity on moisture content in the frequency range 250 Hz to 10 GHz is illustrated [12]. The plotted graph determined that the dielectric constant, $\varepsilon'$ continuously decreases as the frequency increased, but for loss factor, $\varepsilon''$ varies differently as the frequency increased while both values constantly depending on the moisture content of the wheat.

![Figure 3. Correlation of dielectric constant and loss factor of hard red winter wheat with frequency from 250 Hz to 10 GHz at 24°C [12]](image-url)
3. Current Frequency Selection
Based on the diverse grain moisture range, and the continuous reliance between grain dielectric properties and frequency from Figure 3, instrument designers and researchers had a wide range of frequency selection in set up the grain moisture meter. Commonly, the frequency was selected based on the tradition, familiarity with the design as well as the components cost. Table 1 briefly reviews the current frequency selected for grain moisture content detection over the past three years.

Table 1. Frequency selection for grain moisture content detection

| No. | Frequency Selection (MHz) | Setup of the system | Description |
|-----|--------------------------|---------------------|-------------|
| 1   | 3000 to 4500             | ![Diagram 1](image1.png) | The system is proposed by [23] to detect the moisture distribution of the grain in silo storage. The beam of far-field microwave was able to scan the whole horizontal plane [24]. The results obtained shows that the moisture distribution can accurately be calculated with 0.5% error. |
| 2   | 78 and 93                | ![Diagram 2](image2.png) | [25] presented a system capable in sensing spoiled grain region inside an industrial-scale grain bin. Both frequencies selected are tested suitable based on the modelling error where the difference between the real scale system and simulated model are reduced. The spoilage region can be clearly distinguished even for the region up to 0.24% of total grain volume. The contrast image and knowledge of the spoiled grain inside the bin later being studied using inversion algorithm [26]. |
| 3   | 5800                     | ![Diagram 3](image3.png) | The microwave meter built by [27] is used for instantaneous shelled peanut kernel moisture content detection. The operated signal on 5800 MHz using free-space transmission measurement principles determined the standard error of performance of 0.53% compared to the oven-drying method, whereas official moisture meter error performance was 0.87%. |
The capacitive measuring device designed by [28] was suitable to test on-line corn grain moisture content. The selected frequency of 433 MHz has ensured the real-time, accurate, and stable data communication between the device and the computer. [29] presented a non-invasive in situ system to measure corn kernel moisture content. At 100 MHz, the effect of conductivity has been reduced. They reviewed that permittivity of dielectric materials under electric field is affected by the ionic polarization, thus conductivity is one of the factors to be considered in measurement moisture content. The results presented that the signal varied less than 1% if the conductivity change less than 1 mS/cm. By using RF frequency (100 MHz), the conductivity effect has been reduced.

All microwave systems mentioned in [30] were able to predict the moisture content in single and bulk rice grain. For granular material, the water molecules polarization is sensitive and showed a significant response when exposed to microwaves. As for moisture sensing in broken rice, the sensor used microwave up to 13.5 GHz because the short wavelength is required to enhance the air gap sensitivity and reduce the penetration energy. The setup shown in [31] is used to measure the dielectric properties of rice grain (RG) and rice flour gel (RFG). At the same value of conductivity for both materials, the penetration depth of 915 MHz is deeper compared to 2450 MHz. It is also reported that, at higher frequency (more than 1000 MHz), microwave measurement is unaffected by conductivity of materials.
The setup shown in [32] is used to establish advanced pasteurization treatments using RF (10-300 MHz) and MW (300-3000 MHz) energy. Based on the results, the detection of almond kernels moisture content within RF ranges showed a significant effect on the frequency-dependent dielectric properties. At higher moisture content, the effect of RF (10-200 MHz) on dielectric properties also was illustrated greater. They also developed quadratic polynomial equations to analyse the relationship between dielectric properties and frequency at 27, 40, 915, and 2450 MHz. The penetration depth at RF ranges was larger compared to those at MW frequencies at similar moisture content and temperatures.

4. Conclusion
Determination of dielectric properties on agricultural products are prominent mainly because of their usefulness in correlation with the material moisture content. Familiarity between the variation of both dielectric constant and loss factor with variables such as moisture content, frequency, temperature, and bulk density is vital in selecting the most suitable techniques for the measurement system. In selecting the most suitable frequency range for the moisture detection system, both radio frequency and microwave offer different advantages depending on the parameters for example moisture content range, temperature, material conductivity and size of the tested system. The ability to monitor online and on-site grain moisture content will provide significant information for better handling and storage management which later improvise the quality of commercial products.

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