

# Research on Frequency Response Characteristics and Parameter Optimization of Soil Moisture Sensors

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**Abstract:** Accurate measurement of soil moisture content is a crucial prerequisite for achieving agricultural irrigation automation and promoting water-saving technologies. This paper designs a soil moisture detection device based on frequency response characteristics, utilizing the principle that changes in soil dielectric constant with varying moisture content induce changes in plate capacitance, which in turn affect the circuit frequency characteristics. To achieve optimal sensitivity, three types of series loads were investigated. Through scanning analysis in the 10~50 MHz frequency band, the optimal operating frequency was determined to be 34.8 MHz, and the optimal series load resistance was found to be 556  $\Omega$ . To address systematic deviations between theoretical and measured values, a proportional coefficient calibration method was proposed, resulting in an average calibration coefficient  $\lambda=1.326$ . Experiments showed that the calibrated theoretical capacitance values fitted well with the measured values, with a determination coefficient  $R^2=0.865$ , meeting the accuracy requirements for soil moisture detection in agricultural irrigation.

**Keywords:** Soil Moisture; Sensor, Frequency Characteristics, Parameter Optimization, Calibration

## 1. Introduction

Real-time and precise measurement of soil moisture is the foundation for developing water-saving irrigation technology and the core component for achieving agricultural irrigation automation. Therefore, the research and development of high-precision and low-cost soil moisture sensors are of great significance for enhancing the level of agricultural modernization and promoting the development of efficient water-saving agriculture [1].

Currently, there are various methods for soil moisture measurement, among which the measurement technology based on dielectric principles is the most widely used [2]. Although most methods exhibit high accuracy, they often suffer from issues such as high cost and complex circuitry. In contrast, the capacitive method has become an important technical means in the field of soil moisture detection due to its advantages of simple structure, low cost, rapid response, and good portability [3].

Research indicates that there is a significant difference in dielectric constant between dry and wet soil (approximately 3 to 30). As soil moisture content increases, its polarization effect intensifies, and dielectric properties change accordingly. Therefore, there is a clear physical basis for inferring moisture content by measuring changes in soil dielectric constant. This paper proposes a measurement method based on frequency response characteristics, utilizing multi-frequency and multi-load testing and optimization strategies [4]. This approach overcomes the limitations of traditional single-frequency detection, which is susceptible to external interference and lacks verification of operating parameters. With the goal of optimizing frequency characteristic changes, key parameters have been designed and verified, achieving good detection results [5].

## 2. Design of Capacitive Soil Moisture Sensor

### 2.1. Detection System Structure

The soil moisture detection system primarily consists of a signal generator, a resistive-capacitive load, a sensor electrode plate probe, and a digital oscilloscope. Its structure is illustrated in Figure 1.

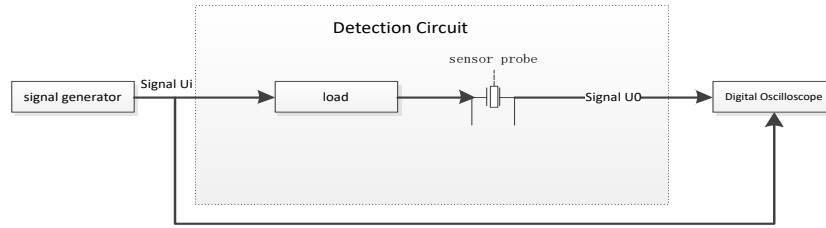


Figure 1: Detection system structure.

## 2.2. Principle of Frequency Characteristic Measurement

The equivalent model of the detection circuit is shown in Figure 2, where capacitor  $C_x$  represents soil capacitance, resistor  $R_x$  represents soil equivalent resistance, and resistors  $R_1$ ,  $R_2$ , and capacitor  $C$  serve as three types of series loads, collectively forming an RC network. Changes in soil moisture content will cause changes in the dielectric constant, which in turn affect the value of  $C_x$ , thereby altering the frequency response characteristics of the entire RC network. By measuring the changes in the frequency characteristics of this network, the soil moisture content can be inferred.

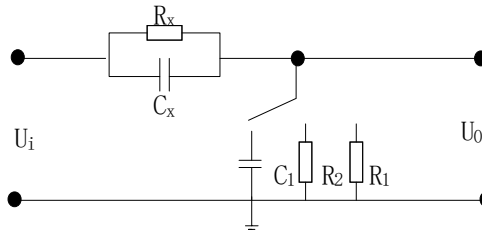


Figure 2: Circuit principle of the measurement part.

The frequency response function of a circuit can be expressed as:

$$A=|G(j\omega)|=\frac{\sqrt{R_1^2+(\omega C_x R_x R_1)^2}}{\sqrt{(R_x+R_1)^2+(\omega C_x R_x R_1)^2}} \quad (1)$$

$$\varphi=\angle G(j\omega)=\arctan\left(\frac{\omega C_x R_x^2}{R_x+R_1+\omega^2 C_x^2 R_x^2 R_1}\right) \quad (2)$$

Where  $A$  represents the amplitude ratio of the AC signals  $U_0$  and  $U_i$ ;  $j$  denotes the imaginary unit;  $R_x$  signifies the soil equivalent resistance ( $\Omega$ );  $C_x$  indicates the measured capacitance of the plate (F);  $R_1$  stands for the series load resistance ( $\Omega$ );  $\varphi$  represents the phase difference between  $U_0$  and  $U_i$ ; and  $\omega$  is the angular frequency. By utilizing the actual measured values of  $U_0$ ,  $U_i$ , and  $\varphi$ , the parameter values in the soil equivalent dielectric model can be calculated.

When the load is capacitive, the frequency characteristic function of the circuit can be expressed as:

$$A=\frac{\omega R_x C}{\sqrt{1+(\omega R_x(C_x+C))^2}}, \varphi=\frac{\pi}{2}-\arctan[\omega R_x(C_x+C)] \quad (3)$$

Where  $A$  represents the amplitude ratio of the output to the input signal,  $\varphi$  denotes the phase difference,  $\omega$  stands for the angular frequency,  $R_x$  is the equivalent soil resistance,  $C_x$  signifies the equivalent soil capacitance, and  $C$  is the series load capacitance.

Based on the measured amplitude ratio  $A$  and phase difference  $\varphi$ , the soil equivalent parameters can be inferred:

$$R_x=\frac{A}{\omega C\sqrt{1-A^2}}, C_x=\frac{\sqrt{1-A^2}}{\omega R_x}-C \quad (4)$$

## 2.3. Detect Sensor Probe Module

The probe structure is shown in Figure 3. The top is sealed with epoxy resin and connected to the signal source through a  $50\Omega$  coaxial cable. The probe is a parallel plate structure, and its capacitance value can be theoretically calculated using equation (5). However, due to the presence of edge effects, the actual capacitance value needs to be obtained through a modified model. To balance insertion

convenience and measurement stability, the plate dimensions are set as follows: length 65mm, width 10mm, and spacing 2.5mm.



*Figure 3: Capacitive digital temperature and humidity sensor module.*

The soil moisture detection is based on the capacitance method within the dielectric method, utilizing a circular non-contact design structure. It primarily consists of a moisture detection circuit and a sensor probe. The probe is needle-type, and the detection circuit is connected to a brass electrode via a metal wire. The output signal from the moisture detection module is an analog signal, with an output voltage ranging from 0 to 2 V.

The measurement principle of capacitive sensors for objects is generally explained using the structure of parallel-plate capacitive sensors. For an ideal parallel-plate capacitor, that is, a flat capacitor with good insulation properties, its capacitance value is calculated using formula (5)

$$C = \epsilon_r \epsilon_0 \frac{s}{d} \quad (5)$$

In the formula,  $s$  represents the facing area of the electrode plates;  $d$  denotes the spacing between the electrode plates;  $\epsilon_r$  signifies the relative soil dielectric constant; and  $\epsilon_0$  stands for the vacuum dielectric constant ( $8.85 \times 10^{-12}$  F/m).

The capacitance value of the head is closely related to the geometric parameters of the plates. An excessively large plate area can lead to a larger overall sensor size, making it difficult to insert into the soil, while an excessively small plate spacing can easily lead to breakdown. Taking into account the actual measurement requirements, the final plate length is determined to be 65mm, width 10mm, and spacing 2.5mm.

### **3. Test Materials and Methods**

#### **3.1. Test Materials**

The materials used in the experiment include: air-dried loam soil, PVC board, 3D printed parts, graduated cylinder, spray bottle, coaxial cable, epoxy resin, constant temperature drying oven, precision electronic scale, high-frequency signal source (SDG6012E), digital oscilloscope (SDS2204X), and high-precision multimeter, etc.

#### **3.2. Test Method**

##### **3.2.1. Preparation of Test Soil Samples**

Construct a test chamber measuring 15 cm × 15 cm × 10 cm using PVC boards, fill it with loam soil, and securely embed the sensor. Use the water dispensing method to prepare soil samples with varying volumetric water contents, injecting 50 mL of water each time. After each water injection, seal the chamber with PVC boards and allow it to stand for 24 hours. Begin measurements once the moisture has been evenly distributed [6].

### 3.2.2. Data Acquisition Process

We set the signal source output voltage to 4 V and output a sine wave signal. We then measure the amplitude and phase difference between  $U_o$  and  $U_i$  using an oscilloscope. Finally, we calculate the phase response at different frequencies, optimize the operating frequency and load parameters, and analyze the difference between the theoretical capacitance value and the measured value [7].

## 4. Test results and Analysis

### 4.1. Selection of Series Load and Operating Frequency

To achieve optimal sensitivity of the RC network to capacitance changes, it is necessary to optimize the operating frequency and load. Considering the increased complexity of the circuit at high frequencies and the influence of soil dielectric relaxation, the frequency range is initially set to 10~50MHz. The capacitive reactance value decreases with increasing frequency and decreases with increasing dielectric constant. To match the equivalent impedance of the soil, the capacitive reactance value at 50MHz is selected as a reference, and 556Ω and 138Ω are determined as the series resistance and series capacitance, respectively.

The calculations indicate that within the frequency range of 10~50MHz, the equivalent capacitive reactance of soil decreases as the dielectric constant increases, primarily concentrating within 800Ω. Using the capacitive reactance values at 50MHz (555.6Ω and 138.2Ω) as a reference, we select similar values of 556Ω and 138Ω as the series resistances.

To compare the testing effects of three types of loads, namely  $R_1$ ,  $R_2$ , and C, experiments were conducted using soils with different volumetric water contents within the optimal operating frequency range. To minimize errors, the average phase difference value within the frequency range was used. Figure 4 illustrates the relationship between soil volumetric water content and phase difference variation under three different loads. It can be seen from the figure that as the volumetric water content increases, the phase difference for each load tends to increase [8].

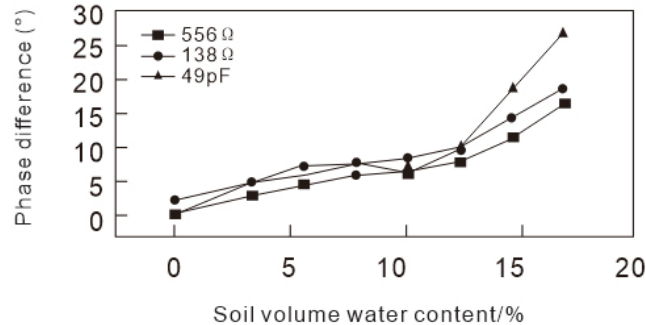


Figure 4: Relationship between soil volumetric water content and phase difference angle variation.

Further analysis revealed that the circuit phase difference changes most significantly at a frequency of 34.8 MHz, thus determining this frequency as the optimal operating frequency. By comparing the capacitive responses of three loads at this frequency, it was found that the capacitance variation trend corresponding to the 556Ω load was closest to the theoretical value, thus being selected as the final load.

### 4.2. Test Analysis and Calculation

#### 4.2.1. Calculation of Soil Theoretical Capacitance Value

According to the Topp empirical formula:

$$\theta_v = 4.3 \times 10^{-6} \epsilon^3 - 5.5 \times 10^{-4} \epsilon^2 + 2.92 \times 10^{-2} \epsilon - 5.3 \times 10^{-2} \quad (6)$$

By fitting the functional relationship between soil dielectric constant  $\epsilon$  and volumetric water content  $\theta_v$  through software, it is found that  $\epsilon$ - $\theta_v$  exhibits an approximate linear relationship within the tested range, which can be expressed as:

$$\epsilon = 50.4873\theta_v + 0.9451 \quad (7)$$

The relationship between soil volumetric moisture content and soil mass moisture content is as follows:

$$\theta_v = \rho \times m \quad (8)$$

In the formula,  $\rho$  represents soil bulk density, and  $m$  denotes soil mass moisture content. Through actual measurement, the soil bulk density used in this experiment is found to be 1.28g/cm<sup>3</sup>. Based on different volume moisture contents, the equivalent dielectric constant of each experimental group is calculated using formula (7), and the theoretical capacitance value can be obtained by combining formula (5). The results are presented in Table 1.

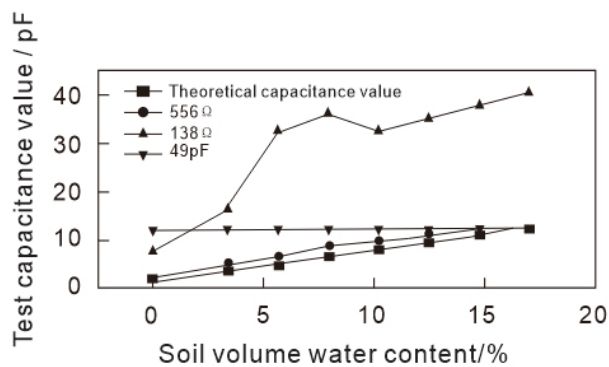
*Table 1 Theoretical capacitance values of soils in each group*

Number of groups	Dry soil/g	Water/g	Volumetric water content $\theta_v$ /%	Theoretical capacitance value C/pF
1	0	0	0	1.32
2	4234.2	113	3.51	3.57
3	4234.2	188	5.54	4.83
4	4234.2	263	7.83	6.39
5	4234.2	338	10.16	7.92
6	4234.2	413	12.39	9.32
7	4234.2	488	14.78	10.81
8	4234.2	563	17.12	12.47

#### 4.2.2. Calculation of Measured Capacitance Value

Measurements were conducted on three types of loads at a frequency of 34.8 MHz, and the average values were taken to reduce errors. The results showed that when the load was 556  $\Omega$ , the measured capacitance values followed the same trend as the theoretical values, but there was a systematic deviation. The analysis suggested that this deviation mainly originated from the contact capacitance between the electrode and the soil, which was difficult to measure directly. Therefore, a proportional coefficient method was introduced for calibration.

At this frequency, the test capacitance values for three different loads were calculated, and a graph was plotted to show the relationship between soil volume water content and test capacitance values. At a frequency of 34.8 MHz, the circuit phase difference changes most significantly, thus it was determined as the optimal operating frequency. Figure 5 shows that when the load is 49pF, the calculated test capacitance values tend to be a straight line; when the load resistance is 138  $\Omega$  and 556  $\Omega$ , the calculated capacitance values gradually increase. However, when the load is 556  $\Omega$ , the trend of change is closer to the theoretical capacitance value. Therefore, the series load of 556  $\Omega$  is selected as the final series load.



*Figure 5: Relationship between soil volumetric water content and test capacitance value.*

To ensure more accurate experimental results, multiple trials were conducted at 34.8 MHz and the average values were taken to reduce errors. The results are shown in Figure 6(a), which illustrates the relationship between soil capacitance and volumetric water content under the condition of 34.8 MHz and 556  $\Omega$ . From the curve trend in the figure, it can be observed that the variation trend of experimental capacitance values and theoretical capacitance values with soil volumetric water content is very close. However, there is a deviation between the experimental capacitance values and the theoretically calculated capacitance values. The main source of this deviation may be the contact capacitance between the electrode plate and the medium. The specific magnitude of the contact capacitance is difficult to

measure directly, so a method using a correction coefficient for calibration is proposed.

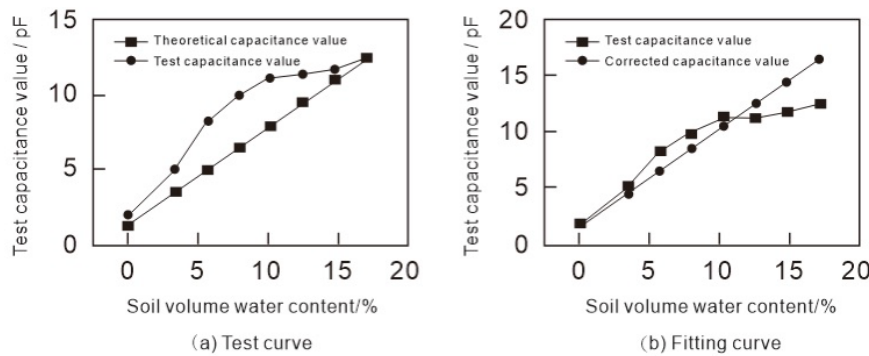


Figure 6: Relationship between soil capacitance and volumetric water content.

The calibration coefficient  $\lambda_i$  is defined as  $\lambda_i = \frac{C_{xi}}{C_i}$ , and the average value  $\bar{\lambda} = 1.326$  is used to correct the theoretical value. The fitting result between the corrected capacitance value and the measured value is shown in Figure 6(b). The determination coefficient  $R^2 = 0.865$  indicates that the model has good predictive ability.

## 5. Conclusion

This paper designs a soil moisture detection device based on frequency response characteristics, establishes a soil equivalent circuit model, and proposes a multi-frequency band and multi-load optimization testing method, effectively avoiding electromagnetic interference and resonance errors that may occur in single-frequency detection. Through experiments, the optimal operating frequency was determined to be 34.8 MHz, and the optimal series load was 556  $\Omega$ . After calibrating the theoretical model using the proportional coefficient method, the measured values fit well with the theoretical values, with a determination coefficient  $R^2 = 0.865$ , which meets the accuracy requirements for soil moisture detection in agricultural irrigation.

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