Measurement of soil moisture by means of resonance control

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Abstract. The article is devoted to the research of innovations in the field of improvement of resonance methods of soil moisture control with the help of capacitive sensors. Soil moisture is one of the most important indicators of the hydrological state of the land, the variability of which is determined by both the soil structure and the impact of atmospheric processes. Study of the state and spatial and temporal dynamics of soil moisture is necessary not only for solving local applied problems of agrotechnical character, but also for conducting fundamental research in the field of ecology, hydrology, meteorology, climatology, including the forecasting of global climate change. In order to increase the accuracy of resonance control devices, it is proposed to use multiparameter methods of measurement and linear frequency modulation of the signal that excites the measuring transducer. Analytical studies of the processes associated with the appearance of additional measurement errors arising from the influence of active losses in the controlled soil and the “drift” of resonance frequency have been carried out, and ways of reducing these errors have been identified.

1. Introduction

Measuring the humidity of various substances and materials is a necessary and important task in scientific, industrial, agrotechnical and other types of activity. A special place in this list is occupied by soil moisture, the exact measurement of which is necessary for conducting meteorological, climatological, ecological, hydrological studies; planning of irrigation activities; increasing agricultural productivity [2, 4, 17, 18, 20, 22].

Three groups of methods are mainly used to measure soil moisture in the field: gravimetric, nuclear and electromagnetic methods [11, 20]. Of these, electromagnetic methods have become the most widespread [2, 8, 10, 15, 16], which is due to their obvious advantages. They allow to carry out fast, safe, non-destructive control of soil moisture content and are easy to automate. Among electromagnetic methods a special place is occupied by high-frequency humidity measurements with the help of capacitive sensors [3, 5, 15, 19, 21]. Such measurements are based on the relationship of soil moisture content and its dielectric permeability [7, 12, 17]. This interrelation can be described by various analytical and empirical models [6, 9, 13, 14, 20, 23], which allow us to estimate the soil moisture with some accuracy based on the results of dielectric constant measurements.

Soil generally refers to complex multi-component heterogeneous media. Such media, when interacting with a high-frequency electromagnetic field, can, depending on the composition and humidity, be in any electrical state from conductor to dielectric. Water as a source of soil moisture can be in a variety of phase states. Accurate measurement of soil moisture in such conditions is difficult due to the influence of many heterogeneous factors. This is the effect of different types of soil active
conductivity, which varies widely [1, 4]. It is the dependence of dielectric permeability on granulometric composition, salinity and soil temperature. This is the influence of frequency dispersion of electrical properties of soil, typical for heterogeneous media [4, 5, 11, 22]. To overcome the above difficulties, it is advisable to use resonance control methods with high sensitivity and significant immunity to interference [12].

When performing resonance control of soil moisture, the capacitive sensor is included in the frequency of the electoral system, which is excited by a high-frequency electrical signal. Changes in the parameters of the capacitive sensor under the influence of soil moisture lead to proportional changes in the amplitude, frequency and phase of the high-frequency signal. In order to obtain information on humidity, it is necessary to measure the increments of the listed HF signal parameters.

The most common method of resonance control is the use of amplitude frequency dependencies of the selection system with a capacitive sensor to measure soil moisture [2, 11, 13, 19]. At sufficiently high quality of the oscillating circuit, one of the elements of which is a capacitive sensor, there is a pronounced peak of the resonance curve at the resonance frequency. This makes it possible to track changes in the resonance frequency with good accuracy, in which humidity information is hidden. The main disadvantage of this method is a sharp decrease in measurement accuracy under conditions of increased active losses in the controlled material.

One of the types of resonance humidity control is parametric modulation of the frequency of the selection system with a capacitive sensor. The method with linear change of frequency of the high-frequency signal exciting the measuring transducer has become the most widely used [12]. This method allows increasing the speed of humidity measurements, expanding the control range and increasing the versatility of resonance control devices. In most practical schemes, we use the amplitude method of determining the resonance frequency by the maximum value of the voltage on the oscillating circuit. At the increased active conductivity of the controlled soil, this method leads to an increase in the error of humidity measurement. In addition, the increase in the frequency change rate of the high-frequency excitation signal leads to additional inaccuracy of the resonance frequency measurement. This is due to the inertia of the high-speed selective system and the resulting phenomenon of "drift" of resonance frequency, which also reduces the accuracy of humidity measurements.

Various technical solutions can be offered to reduce the impact of interfering factors that reduce the accuracy of resonance humidity measurements. These include multiparameter methods of resonance control, two-stroke mode of linear frequency modulation of the frequency of the selective measuring system and the use of a two-circuit circuit transducer, etc.

2. Methods and materials

In order to estimate the error of humidity measurement, arising at resonance control in conditions of increased active soil conductivity, it is proposed to use the model of measuring transducer as a second order system:

\[ A_1(d^2Y/dt^2) + A_2(dY/dt) + A_3Y = X, \]  

where \( A_1 = \Phi_1(X, O, \Xi) \), \( A_2 = \Phi_2(X, O, \Xi) \) and \( A_3 = \Phi_3(X, O, \Xi) \) – the frequency parameters of the electoral system, which generally depend on the input influences \( X \), the characteristics of the measuring system \( O \) and interfering factors \( \Xi \), and the output signal \( Y \) is removed from the capacitive sensor in the measuring transducer.

The normalized transfer function for the system (1) can be as follows:

\[ H(j\omega) = 1 / \left( 1 - (\omega / \omega_r)^2 + j2\delta(\omega / \omega_r) \right), \]  

where \( \omega_r = \sqrt{A_2/A_1} \) – The resonance frequency of the electoral system without taking into account losses; \( \delta = A_2 / 2\sqrt{A_1A_3} \) – attenuation coefficient.

Expressions showing frequency dependencies of amplitude changes were obtained from equation (2) \( V_n \), resonance frequencies \( \omega_r = 2\pi f_r \) and phases \( \varphi_r \) of the high-frequency signal at the output of the measuring transducer if there is a high-frequency signal at the input \( X \):
\[ V_\omega (\omega) = \frac{1}{\sqrt{1 - (\omega/\omega_0)^2}} + 4\delta^2 (\omega/\omega_0)^2 \] ; \quad (3)
\[ \omega_p = \omega_0 \sqrt{1 - 2\delta^2} \] ; \quad (4)
\[ \varphi_\omega (\omega) = -\arctg \left\{ \frac{2\delta (\omega_0/\omega) \left[ 1 - (\omega/\omega_0)^2 \right]}{1 - 4\delta^2 (\omega_0/\omega)^2} \right\} . \quad (5) \]

Analysis of expressions (3), (4) shows that the increase in the attenuation coefficient \( \delta \) causes the frequency of the maximum amplitude response to shift. This means that humidity control with increased active conductivity significantly reduces the measurement accuracy. An additional error occurs due to incorrect determination of the resonance frequency as the maximum abscissa of the resonance curve. This error will increase with increasing losses in the controlled material. At the same time, the phase response (5) is characterized by a constant position of the resonance frequency regardless of the losses. This makes it possible to increase the accuracy of humidity measurement by using all signal parameters – amplitude, frequency and phase.

Linear frequency modulation (LFM) is often used to increase the range of soil moisture measurements. This modulation consists of a linear change in the frequency of the signal that excites the measuring transducer. Methods of resonance control with the deployment of frequency conversion have been described quite a lot. The main differences between these methods are in the ways of determining the frequency of resonance, the value of which contains information about the controlled humidity.

The model of resonance control of soil moisture with the use of LFM will be considered. Measuring transducer with transfer characteristic (2) is influenced by high-frequency \( x(t) \) signal with linearly changing frequency \( \omega(t) \):

\[ \omega(t) = \omega_0 + V_\omega t ; \quad (6) \]
\[ x(t) = X_\omega \cos (\omega_0 t + \frac{V_\omega t^2}{2}) \text{ при } t \geq 0, \quad (7) \]

where \( \omega_0 \) and \( V_\omega \) – the initial value and the frequency change rate.

We need to find the signal \( y(t) \) at the output of the measuring transducer. The amplitude, frequency and phase parameters of this signal will contain information on the controlled soil moisture. The signal (7) is a rather complex function, the spectral analysis of which is difficult. It is expedient to use a time method of analysis, at which the output signal \( y(t) \) of the measuring transducer is defined as a convolution of the input signal (7) and the pulse characteristic of the transducer:

\[ y(t) = \int_0^t x(\tau) g(t - \tau) d\tau , \quad (8) \]

where \( g(t) = e^{-\delta t} \sin \omega_0 t \) – pulse characteristic of the measuring transducer.

The general solution of the integral equation (8) is obtained in the following form:

\[ y(t) = Y(t) \cos \left( \omega_0 t + \frac{V_\omega t^2}{2 + \varphi(t)} \right) , \quad (9) \]

where the envelope amplitude \( Y(t) \), instantaneous frequency \( \omega(t) \) and phase \( \varphi(t) \) do not only depend on the parameters of the measuring transducer, but also on the frequency change rate \( V_\omega \) of the actuating signal.

The analysis of the expression (9) allows us to draw the following conclusions. Firstly, the frequencies at which the envelope amplitude has maximum values vary depending on the attenuation coefficient \( \delta \) and don't match the resonance frequency \( \omega_0 \). This phenomenon is called "demolition" of resonance frequency. The value of this "drift" increases with the quality of the measuring transducer (with the reduction of the active loss factor). \( \delta \) in the controlled soil) and when increasing the speed \( V_\omega \). This means that when measuring soil moisture by means of resonance control, additional errors occur in the LFM and the reliability of the control is reduced.
Secondly, as the speed $V_ω$ increases, the maximum amplitudes $Y(t)$ decrease. At the same time, the sharpness of the maximums decreases and the resonance curves become gentle and asymmetrical. Since the accuracy of the resonance frequency measurement, in which humidity information is hidden, is reduced, this also results in a loss of control reliability.

Since the LFM resonant humidity control method has obvious advantages (extended measuring range, increased control versatility), technical solutions are needed to overcome the identified disadvantages.

3. Results
Expressions (1)–(4) allow to estimate relative changes of amplitude and frequency of signal resonance at the output of the measuring system with increase of active conductivity of the controlled soil. If the attenuation coefficient is within $\delta \in [0, \sqrt{2}]$, amplitude characteristics $V_m(ω)$ has a single maximum at some frequency $ω_0$. The maximum amplitude value is determined by the following ratio:

$$V_m^{max}(ω) = \frac{1}{A_δ} \sqrt{1 - 2 \delta^2}.$$  \hspace{1cm} (10)

The analysis of expressions (10) and (4) leads to the following conclusions. With the increase of active losses in the controlled soil, the attenuation coefficient increases. This results in a reduction of the maximum amplitude of the law (10). In addition, according to expression (4), the frequency of this maximum $ω_0$ also decreases. It is shown that the increase $δ$ from 0.05 till 0.5 leads to a decrease in resonance frequency $ω_0$ by almost 30 % compared to the frequency $ω_0$. The amplitude of the resonance value of the output signal decreases by 17 dB.

The results of the analysis show that the measurement of humidity by resonance method leads to significant errors, if we use only the amplitude parameters of the measuring signal. This is because the evaluation of the resonance frequency of the transducer, in which humidity information is hidden, occurs with a large error. This error increases with the increase in active losses in the soil being monitored. An expression can be written down for the relative value of this methodological error:

$$γ = \frac{Δω}{ω} = \left(\frac{ω - ω_0}{ω_0}\right) = 1 - \sqrt{1 - 2 \delta^2}.$$  \hspace{1cm} (11)

In real life, this error can be quite large and even comparable to the normalized value of controlled soil moisture. To compensate for this, we offer a two-parameter method of resonance control. The proposed method is based on the independence of the frequency of zero value of the phase characteristic of the measuring transducer from the value of active losses in the controlled soil. From the expression (5) it follows that the abscissa of the point of transition of the phase characteristic through zero value coincides with the frequency of true resonance and does not depend on the value of losses. A change in the attenuation coefficient only results in a proportional change in the slope of the phase response in the vicinity of the resonance frequency.

Thus, it is possible to define the essence of the two-parameter method of resonance control of soil moisture. To estimate the frequency of resonance it is proposed to use the first informative parameter – zero value of the phase difference between the output and input signals of the measuring transducer. The second informative parameter – the amplitude of the maximum resonance curve – is used to correct the amplitude of the input high-frequency signal exciting the measuring transducer, depending on the magnitude of losses. Implementation of such an approach will allow to completely exclude the methodological error of humidity measurement in conditions of increased electrical conductivity of the controlled soil [12].

In addition to the implementation of the two-parameter method of resonance humidity control, it is possible to significantly increase the control range and increase the versatility of measuring instruments. For this purpose it is necessary to use the input signal of the measuring transducer with linear frequency modulation. However, the direct application of LFM is connected with the appearance of additional error of measurements due to the “drift” of resonance frequency. Let's consider the mechanism of this phenomenon in more detail, for what we will introduce two limiting
situations – very slow change of frequency of an input signal $\omega(t)$. It is shown that these situations are determined by the sign of inequality $\delta > \sqrt{V_\omega}$ and $\delta < \sqrt{V_\omega}$.

When frequency changes slowly, when inequality is performed $\delta/\sqrt{V_\omega} >> 1$, envelope amplitude $Y(t)$ in expression (9) simply follows the shape of the resonance curve of the transducer and no "drift" of the resonance frequency occurs. Despite the fact that the output signal phase (9) $\varphi(t)$ is time dependent and this should result in a time dependence of the instantaneous frequency, with a slow change $\omega(t)$ the phase change rate is low enough: $d\varphi(t)/dt \approx 0$.

If the speed $V_\omega$ of linear frequency changes increase and inequality is observed $\delta/\sqrt{V_\omega} << 1$, By quickly changing the frequency of the input signal in the resonant measuring system, free vibrations are excited. The peculiarity of these vibrations is that the envelope amplitude $Y(t)$ The output signal of the measuring transducer differs in shape from the standard frequency response of the selection system. The resonance curve becomes asymmetrical, the maximum frequencies increase with a decrease in the ratio $\delta/\sqrt{V_\omega}$ ("demolition" of the resonance frequency increases). In addition, the amplitudes of the maximums decrease with the growth $V_\omega$ and the tops of the resonance curves become flatter. The following factors reduce the accuracy of the resonance frequency measurement and result in the loss of confidence in the resonance control of soil moisture.

The complexity of mathematical description of the processes occurring in a resonant measuring system with the use of LFM does not allow to obtain quantitative estimates of humidity measurement errors directly from the expression (9). However, simulation of the processes occurring in the resonant measuring transducer using the input high-frequency signal with a linear change of frequency allowed to obtain specific results. With increasing frequency conversion rate $V_\omega$ the difference between the frequencies of amplitude and phase resonances is increasing and can be sufficiently large to influence the accuracy of humidity measurement in this way. The value of the additional error of humidity measurement from the "drift" of the resonance frequency can reach several percent, which can be a significant deterioration in the reliability of resonance control.

The technical solution for compensation of such methodical error from "drifting" is offered – use of a two-stroke mode of LFM at realization of the resonant control of humidity of soil. The essence of the two-stroke mode is the following. Humidity measurement cycle $T_{uw}$ is divided into two parts – $T_1$ and $T_2$. In the first part $T_1$ the frequency of the signal at the input of the measuring transducer increases linearly, in the second one $T_2$ – linearly decreases. Deviation signs $\Delta\omega_p = \omega_p - \omega_0$ of the measured resonance frequency $\omega_p$ from the real meaning $\omega_0$ are opposite for parts $T_1$ and $T_2$. Therefore, the opposite will be the signs of humidity measurement errors in each of these two cycles. Averaging the measurement results in a general cycle $T_{uw}$ will allow to compensate the total error from the "drift" of the resonance frequency and increase the reliability of soil moisture control. Depending on the ratio of frequency hopping speeds in the first measure $V_{u1}$ and in the second one $V_{u2}$ two resonance control algorithms are offered.

In the first algorithm, the speed of the linear frequency increase $V_{u1}$ is chosen 10 … 100 times more often in comparison with $V_{u2}$. In the first part $T_1$, signal frequency $\omega(t)$ at the input of the measuring transducer will increase by law $\omega(t) = \omega_0 + V_{u1}t$ and the measured resonance frequency will be equal $\omega_{p1} = \omega_0 + V_{u1}T_1 = \omega_0 + \Delta\omega_{p1}$, where $\Delta\omega_{p1}$ – measurement error from "drift" in the first measure due to high speed $V_{u1}$.

In the second measure, the law of frequency change will change: $\omega(t) = \omega_{p1} - V_{u2}t$, and after a time interval $T_2$ the second resonance frequency will be measured:
\[ \omega_{p2} = \omega_{p1} - V_{w2} T_2 = \omega_b - \Delta \omega_{p2}. \]

According to the ratio \( V_{w2} \ll V_{at} \), the error of resonance frequency measurement in the second measure will be much smaller than in the first measure. Consequently, the measurement error due to "drift" will be determined by \( \Delta \omega_{p2} \ll \Delta \omega_{p1} \), which significantly increases the reliability of resonance humidity control.

In the second algorithm, the frequency conversion rates for both measures are the same, but opposite in: \( V_{at} = -V_{w2} \). If you calculate the resonance frequency from the average value of the two measurements, the drift errors in the two measures are mutually compensated:

\[ \omega_p = 0.5 (\omega_{p1} + \omega_{p2}) = 0.5 (\omega_b + \Delta \omega_{p1} + \omega_b - \Delta \omega_{p2}) = \omega_b \]

the methodological error of humidity measurement from the "drift" of the resonant frequency is completely eliminated.

Thus, the implementation of the considered two-stroke transformation algorithms for soil moisture control with the use of linear frequency modulation of the measuring signal allows to reduce the measurement error from the "drift" of the resonance frequency. In this case, the advantages of this method of resonance control, consisting in the expansion of the measuring range and increasing the versatility of the method, can be implemented with greater completeness and quality. If, in addition to the LFM, the advantages of the two-parameter method (phase response resonance determination) are used, the reliability of soil moisture control will be further increased.

4. Conclusion
The proposed methods of resonance control allow to overcome to a certain extent the contradictions between the requirements of high accuracy of soil moisture measurements in a wide range of control and the inability of existing methods and means to realize these requirements in full. Two-parameter method of assessment of soil moisture with the help of capacitive sensors and the use of resonance phenomena in the measuring system allows to exclude the methodological error of measurements in conditions of increased active conductivity of controlled material. In combination with the use of linear frequency modulation of the signal at the input of the measuring transducer, the two-parameter method gives additional advantages – expansion of the measuring range and increase of versatility of the devices of resonance control of soil moisture.

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