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Forked Finger Electrode Based Acquisition Circuit and Humidity Correlation Model Design

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Abstract. With the continuous development of industry, humidity sensors have long been used in many fields such as industrial and agricultural production, public meteorological services, and medical fields. Humidity is a very important environmental parameter that has an impact on production, health and comfort in many fields. Conventional humidity sensors usually use capacitive or resistive measurement principles, which are not very sensitive and accurate to meet the needs of certain high precision and high sensitivity measurements. In addition, high-precision and high-sensitivity humidity sensors are usually expensive, which limits their use in certain applications. First, this paper designs a humidity acquisition hardware circuit based on forked-finger electrodes by taking advantage of their high sensitivity. Second, the data tested by the constant humidity chamber method and the saturated solution method are compared to select a suitable method for the humidity testing environment. Finally, the humidity correlation model design was carried out based on the least squares method. Thus, the humidity sensor based on the forked finger electrode obtained by the design can test the humidity in the environment easily and quickly, and the correlation model of the relative humidity-forked finger electrode capacitance value is obtained at the same time. By evaluating the model and calculating the error between the theoretical capacitance value and the actual capacitance value, it can be concluded that the model is a more reliable model within the error range without overfitting and underfitting problems. In turn, the problem of low sensitivity and high cost of the current humidity sensor can be well solved, providing a basis for relevant academic research and practical applications.

Keywords. Humidity sensor; Forked finger electrode; Correlation model; Least square.

1. Introduction

Humidity is a basic physical quantity and is one of the most important environmental indicators in production and life. For example, dairy products are best stored in a 50% to 60% relative humidity environment; fruits and vegetables are suitable for storage in a

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50% to 70% relative humidity environment; cotton and wool textiles are best stored in a 40% to 60% relative humidity environment, so it is important to accurately detect the humidity of the environment.

At present, according to the different operating principles of humidity sensors, the common humidity sensors can be divided into three categories: resistive humidity sensors [1-4], thermally conductive humidity sensors[5-7], and capacitive humidity sensors[8-12]. Among them, resistive sensors use the interaction of water molecules with a resistive material to change the resistance value, but their relevance is usually limited, especially at very high and low humidity. Thermal sensors use the effect of water molecules on the thermal conductivity of a sensitive material to detect humidity, but are temperature sensitive and less sensitive. Capacitive sensors detect humidity by changing the capacitance value through the interaction of water molecules with a dielectric material and have high sensitivity. Among them, fork finger electrodes can significantly increase the sensitivity of capacitive humidity sensors.

To solve the above problems. Firstly, the hardware circuit of humidity acquisition based on forked finger electrodes is designed. The acquisition circuit consists of two parts: a main control board with STM32F103C8T6 as the main control chip and an acquisition board with a humidity sensitive unit based on forked finger electrodes. Secondly, the data tested by two methods, constant humidity chamber method and saturated solution method, are compared and a suitable method is selected as the environment for humidity testing. Finally, the humidity correlation model design based on the least squares method is carried out. By understanding the principle of the least squares method, the data collected above were fitted. The correlation model of relative humidity-fork finger electrode capacitance values is fitted, and the model is evaluated and validated for correctness.

The chapters of this paper are organized as follows: Section II introduces the current status of humidity sensor research; Section III discusses the fork finger electrode hardware design; Section IV analyses the data of two test methods, constant humidity chamber method and saturated solution method, and selects one as the humidity test environment, and then designs the humidity model and verifies the model's validity; Section V draws conclusions, summarizes the research work of this paper and discusses future research directions.

2. Status of Research on Humidity Sensors

Humidity is a key environmental parameter and is critical for many applications. Different items require different humidity environments, e.g. dairy products are suitable for 50-60 per cent humidity, fruits and vegetables for 50-70 per cent, and cotton and wool textiles for 40-60 per cent. Therefore, it is important to detect humidity accurately.

In recent years, although the research on humidity sensors has become increasingly mature, more results have been achieved with humidity sensors developed using different materials. In 2008, Sen et al[13] proposed a capacitive humidity sensor combining parallel plate electrodes and fork-finger electrodes, which improved the sensitivity by 1/3 compared to the traditional sandwich structure while providing a faster response time. In 2013, Prof. Sun et al. deposited GO-sensitive membranes on the fork-finger electrodes to create humidity sensors with higher sensitivity in the range of 15% RH-95% RH and response recovery times of 10.5 and 41 seconds, respectively[14]. In

2014, Professor Yang Li's team at Zhejiang University prepared an impedance-based humidity sensor using MWCNTs and QC-P4VP[15]. The sensor was able to detect 1% RH with high sensitivity and fast response. Its impedance change rate was 16%/%RH in the range of 1%RH-30%RH. In 2015, Y. Takei et al. of the University of Tokyo[16] prepared a flexible humidity sensor using EMIMBF4 mixed with PVDF. The sensor can effectively test a humidity range of 40% RH to 80% RH with a sensitivity of about 2.5 × 10^-3Ω/% RH. In 2017, Z.S. Hosseini et al[17] from Sharif University of Technology used polyimide as a flexible substrate and graphene as a moisture-sensitive material to obtain a flexible humidity sensor. The sensor was effectively tested in the full range of relative humidity from 1% RH-100% RH and responded relatively quickly to humidity changes with an absorption time of 12 s and a dehumidification time of 43 s. In 2019, Prof. Huiling Tai et al. of USTI produced a low-cost, environmentally friendly humidity sensor using printing paper and flexible conductive adhesive tape. The sensitivity of this humidity sensor was greater than 3 orders of magnitude and linear response (R2 = 0.9549) in the range of 41.1% RH-91.5% RH [18]. Although, good progress has been made in humidity sensors, there are still some problems: the sensitivity and accuracy of humidity sensors are not high enough to meet the needs of certain high-precision and high-sensitivity measurements. In addition, high-precision and high-sensitivity humidity sensors are usually expensive, which limits their use in certain applications.

3. Hardware Design based on Forked Finger Electrodes

In this paper, the acquisition circuit and humidity related model are designed based on the fork finger electrode, the hardware circuit is shown in figure 1. The acquisition circuit includes the main control board and the fork finger electrode capacitance acquisition board. The main control board is responsible for driving the capacitance measurement of the fork finger electrode, and also communicates with the standard temperature and humidity sensor SHTC3 to achieve the acquisition of temperature, humidity and capacitance. The collected data is transferred to the computer via the on-board USB-to-serial port and interacted with via the on-board LEDs and buttons. The Fork Finger Electrode Capacitance Acquisition Board is specifically designed to measure the tiny capacitance values of the fork finger electrodes, using specific communication methods to interact with the main control board, such as IIC, Single Bus, etc.

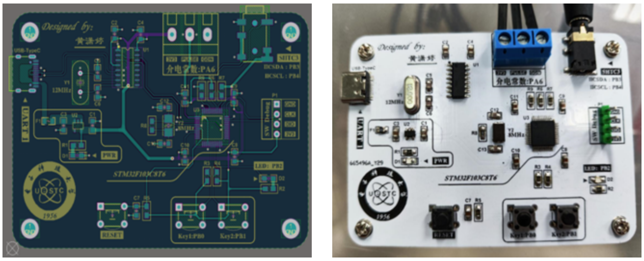

Figure 1. Circuit diagram and physical diagram of hardware circuit.

Since the range of digital capacitance test chip is limited, the fork finger electrode with smaller capacitance value should be selected for testing. Different fork finger electrodes have different fork finger pairs and spacing, and their capacitance values will be different when combined with equations:

$$C = \frac{n\varepsilon l h_{finger}}{W_{gap}} + \frac{n\varepsilon l}{2} \tag{1}$$

In the above equation, W_{gap} is the fork finger electrode spacing, n is the total number of fork finger electrodes, l is the fork finger electrode length, ε is the dielectric constant of the complex (the mixture after moisture absorption in the moisture-sensitive layer), h_{finger} is the fork finger electrode thickness.

After screening, we selected three types of fork finger electrodes, Alumina ceramic (AC), PI, and Polyethylene terephthalate cool (PET), for testing and selecting the most suitable fork finger electrode for subsequent testing by testing the capacitance value.

The following three forked finger electrodes are all 20mm*10mm in shape and 6.3mm in finger length, other parameters are shown in table 1.

Table 1. Arameters Of Different Forked Finger Electrodes

Substrates	Line width(um)	Line spacing(um)	Fork Finger Logarithm(pairs)
AC	100	100	20
PI	50	50	25
PET	200	200	12

The capacitance of the fork finger electrode is tested using an LCR bridge with a frequency of 1000 HZ, a level of 1V and an impedance of 100Ω. Connect the fork finger electrode to the LCR bridge at the same time and the capacitance value is clearly displayed on the screen.

When the ambient humidity is about 60%, the capacitance value of alumina ceramic fork finger electrode is 14.148pF, PI fork finger electrode is 19.028pF and polyethylene PET fork finger electrode is 3.348pF. The capacitance value of PET fork finger electrode remains around 4~5pF, which is still within the range of the digital capacitance test chip.

In summary, the PET fork finger electrode was selected for subsequent testing.

4. Experiment and Analysis

4.1. Construction of Experimental Environment

The constant humidity chamber method is used for testing by means of a humidity-controlled experimental platform that controls humidification and dehumidification, monitors humidity in real time and transmits data to a computer.

As shown in figure 2, The platform uses a cube box in which both humidifier and dehumidifier are placed, the forked finger electrodes and standard humidity sensor are placed as close as possible, and the main control board is placed outside the test box for easy debugging.

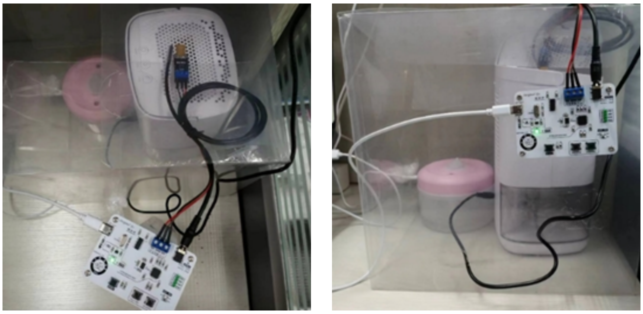

Figure 2. Constant Humidity Chamber Testing Environment.

Fork finger electrode data were collected and transferred to a computer by repeatedly varying the humidity from 0% to 100% and then from 100% to 0% under constant humidity conditions, using a serial assistant to complete the data transfer.

The saturated salt solution method utilizes a stable dynamic equilibrium system and humidity environment that is formed by air, solution and salt crystals in a well-confined environment. Six salts, $LiCl$, $MgCl_2$, K_2CO_3, $NaBr$, $NaCl$, and KCl were chosen to divide the 100 percent humidity into six humidity points and test the capacitance generated by each humidity point separately. It is important to note that the humidity values generated by different salt solutions at different temperatures may vary during the test. Therefore, the temperature of the experimental environment needs to be kept constant as much as possible during the test to ensure the accuracy and reliability of the test data.

Figure 3. Saturated salt solution method testing process.

As shown in figure 3, the forked finger electrode and humidity sensor (SHTC3) are placed above the saturated salt solution, and since SHTC3 can also be used for temperature detection, it will simultaneously monitor the real-time temperature of the test environment. Leave it for a period of time, the test vials are replaced after approximately 2000 data acquisitions and the test is repeated for different humidity environments, including 0% to 100% and 100% to 0%. And transfer capacitance data to computer via serial assistant.

Compared with the constant humidity chamber method, the saturated salt solution method can obtain the capacitance value corresponding to the forked finger electrode at a certain determined humidity, and the forked finger electrode can be tested repeatedly, and the data obtained are all valid data. Therefore, the saturated salt solution method is chosen as the core test method.

4.2. Humidity Capacitance Data Fitting

By placing the test board and standard humidity sensor inside the bottle and replacing the bottle after collecting about 2000 sets of test data, a series of test data under different humidity environments is acquired.

For each reagent bottle, 2000 sets of data were collected and the three quantities of temperature, humidity, and capacitance values were averaged, as shown in table 2.

This set of data was tested at room temperature of 25°C and ambient humidity of about 50%. In order to ensure the accuracy and reliability of the test data, the temperature of the experimental environment needs to be kept constant as much as possible. Observing the above table, we can see that the temperature changes are all around 25°C, which meets the experimental requirements.

Table 2. Capacitance Values Of Different Saturated Salt Solutions Measured At The Corresponding Temperature And Humidity.

Reagent type	Temperature(°C)	Humidity (%)	Capacitance value (pF)
$LiCl$	25.20	13.30	1.67
$MgCl_2$	25.20	36.00	2.74
K_2CO_3	25.80	44.00	2.78
$NaBr$	25.20	59.00	3.02
$NaCl$	25.30	72.00	3.62
KCl	25.40	78.00	4.01

As K_2CO_3 reacts with water, a chemical reaction occurs in which potassium carbonate reacts with water to produce potassium hydroxide and carbon dioxide, accompanied by an exothermic process. This exothermic process will lead to an increase in temperature, so the temperature measured by K_2CO_3 will be somewhat higher than the temperature of the other test bottles, but it is within a reasonable range of temperature error.

In this paper, the relationship between relative humidity and the capacitance of the fork finger electrodes is linearly fitted using the least squares method by importing the test data in MATLAB, see figure 4.

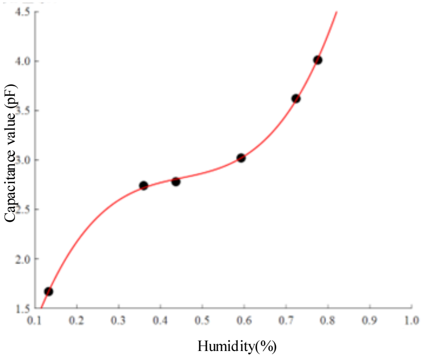

Figure 4. Relative humidity-fork finger electrode capacitance relationship.

A correlation model for the capacitance relationship of the relative humidity-fork finger electrodes can be obtained as follows:

$$Y = 26.83X^3 - 36.33X^2 + 17.28X - 0.0467 \tag{2}$$

where is the relative humidity in the environment and is the capacitance of the forked-finger electrode.

The R-squared value ranges from 0 to 1, with close to 1 indicating a good fit. Typically, calculating the R-squared value involves calculating the sum of squared residuals (SSE) and the sum of total squares (SST).

SSE indicates the difference between the predicted and actual values of the regression model, and SST indicates the difference between the dependent variable and the mean. They are calculated as follows:

$$SSE = \sum (Y_i - \hat{Y}_i)^2 \tag{3}$$

$$SST = \sum (Y_i - Y_{mean})^2 \tag{4}$$

where, Y_i denotes the actual value, $\hat{Y}_i$ denotes the predicted value, and Y_{mean} denotes the average of the actual values.

$$R^2 = 1 - \frac{SSE}{SST} \tag{5}$$

The R-squared value of the obtained correlation model was calculated and obtained R^2 =0.9995, which is closer to 1, and the fit is good.

MSE is the square of the average error between the predicted and true values of the model, while RMSE is the square root of MSE. Typically, smaller values of MSE indicate stronger predictive models, and RMSE is similar to MSE in that smaller values also indicate stronger predictive models.

$$MSE = \frac{\sum (Y_i - \hat{Y}_{\mathrm{i}})^2}{n} \tag{6}$$

where, Y_i denotes the actual value, $\hat{Y}_i$ denotes the predicted value, and n is the sample size.

$$RMSE = \sqrt{MSE} \tag{7}$$

The RMSE of the obtained correlation model was calculated and the RMSE = 0.04047, which is a small value and the predictive power of the correlation model is strong.

To verify the accuracy of the model in question, we randomly tested humidity and capacitance to examine the relative humidity-capacitance model for the fork finger electrode. We performed three sets of tests with different relative humidity and capacitance of the fork finger electrode, substituted these data into the model, calculated the theoretical values, and then calculated the error between the actual and theoretical values (AV&TV). The results are shown in table 3.

Table 3. Errors Of Theoretical And Real Capacitance Values Of Capacitors Under Different Temperatures(T) And Humidity(H)

Group	T(℃)	H(%)	TV(pF)	AV(pF)	Error
Group1	25.2	30.0	2.59	2.63	0.04
Group2	25.3	55.0	2.93	2.99	0.06
Group3	25.5	84.0	4.73	4.81	0.02

The above table shows that the error between the theoretical capacitance value and the actual capacitance value is within 2%~6%, and the error is very small, so we can know that the correlation model obtained in 4.3.2 is more reliable.

5. Conclusion

This paper investigates the application of forked finger electrodes in the field of humidity sensors. Polyethylene terephthalate cool (PET) was chosen as a substrate to design a hardware circuit for humidity acquisition. On its hardware circuit, a large amount of data was collected, data analysis was performed, and the correlation model about the relative humidity - capacitance of the forked-finger electrode was obtained and validated by least squares fitting. The theoretical capacitance value was calculated by randomly testing the humidity in the environment, and the error between the theoretical and actual capacitance values was calculated, and the errors were found to be relatively small. There was no overfitting and underfitting.

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