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Design of capacitance measurement module for determining critical cold temperature of tea leaves

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ABSTRACT

Critical cold temperature is one of the most crucial control factors for crop frost protection. Tea leaf's capacitance has a significant response to cold injury and appears as a peak response to a typical low temperature which is the critical temperature. However, the testing system is complex and inconvenient. In view of these, a tea leaf's critical temperature detector based on capacitance measurement module was designed and developed to measure accurately and conveniently the capacitance. Software was also designed to measure parameters, record data, query data as well as data deletion module. The detector utilized the MSP430F149 MCU as the control core and ILI9320TFT as the display module, and its software was compiled by IAR5.3. Capacitance measurement module was the crucial part in the overall design which was based on the principle of oscillator. Based on hardware debugging and stability analysis of capacitance measurement module, it was found that the output voltage of the capacitance measurement circuit is stable with 0.36% average deviation. The relationship between capacitance and 1/Uc2 was found to be linear distribution with the determination coefficient above 0.99. The result indicated that the output voltage of capacitance measurement module well corresponded to the change in value of the capacitance. The measurement error of the circuit was also within the required range of 0 to 100 pF which meets the requirement of tea leaf's capacitance.

1. Introduction

Tea (*Camellia sinensis*) is a subtropical plant, which is planted on the hilly areas in the central and southern China and its optimum growth temperature is around 20 °C [1]. Freezing injuries happened in the early-spring caused huge damage on tea production and quality, and resulted in enormous economic losses to tea industry. In recent years, kinds of equipment and techniques which are based on airflow disturbance frost prevention have been developed and applied in tea fields and orchards such as anti-frost fans, large wind machines, helicopters and sprinklers [2–5]. The main control strategy of above equipment is to determine the time of plants suffers from critical freezing injury and the critical cold temperature is used as one of the most crucial parameters [6,7].

Plant electrical signal is a sensitive indicator for the early prediction and real-time evaluation on the physiological changes of the plant [8–13]. In the non-destructive determination of moisture content of maize leaves, Guo et al. [14] designed a moisture detector based on leaves' capacitance and tested it to develop a model on the relationship between capacitance and moisture content of maize leaves at the best pressure. The running test indicated that the absolute measurement error of the designed detector for moisture content of maize leaves was 1.2% to 1.7% on wet basis when the moisture content was between 55% and 80%, and the response time was within 3 s at oscillation frequency of 8 MHz. Similarly, Wei et al. [15] employed a pair of electrical-capacity-type electrode to test the effects of test voltage and frequency on physiological capacitances (C_p) and physiological resistances (R_p) of wheat seedling leaves with different water contents, and found that both C_p and R_p were significantly related to the leaf water content. The authors reported that C_p was a better indicator of leaf water content than R_p which could measure water content of wheat seedling leaf quickly and harmlessly. In another work, Bao and Shen [16] established an interesting the relationship between the plant water deficit and the electric property it found that the capacitance of leaves to have changed with the drought degree under the frequency of 100 Hz, providing a useful tool for efficient and precise assessment of plant water lack degree. Luan et al. [17] further investigated the changes in water parameters of wheat leaves by determining the total water content, the ratio of bound water/free water and the capacitance under different PEG stress period. Their study also showed a decreasing trend of the ratio of bound/free water to capacitance with

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increasing drought stress period indicating that physiological capacitance as a potential tool for characterizing the water dependent properties in wheat leaves. Other studies have also proposed new approaches to quantifying moisture properties and their relationship with electrical properties such impedance and capacitance for the leaves of tea and other crops [18,19].

Recent work by Lu [20] established a test system of tea leaf's electrical property to measure the typical temperature of the samples and measured relative electrical conductivity (*REC*) and cell damage rate of two varieties under different cold stress conditions, and found that the capacitance of tea leaves had obvious peak response to a typical temperature where the cells were undergoing serious cold stress and mostly of them had been destroyed, which showed that typical temperature could be used to evaluate the freezing tolerance of different varieties of the tea and indicate critical temperature.

Therefore, this study sought to the utilize capacitance as an essential indicator for nondestructive testing the physiological characteristic of tea plants. A new detector was designed to measure tea leaf's critical cold temperature based its capacitance peak response to a typical low temperatures and its stability verified using the capacitance measurement module.

2. Design principle of capacitance measurement module

Critical cold temperature is a crucial parameter for the control of frost protection equipment and this is clearly as shown in the test principle of the detector in Fig. 1. Capacitance and temperature of tea leaf were measured and the peak of capacitance identified to extract the effective peak. Critical cold temperature was indicated by the corresponding temperature where the effective peak capacitance was utilized. As a result, the critical cold temperature detector based the capacitance peak response to a typical low temperature mainly consisting of microprocessor, signal detecting circuit, power supply module, capacitance measurement module, temperature measurement module, keyboard and display module was built (Fig. 2). Capacitance and temperature measurement module is used to measure the capacitance of tea leaf and ambient temperature around the leaf. Microprocessor is the main part for the control detector and the keyboard is used to select different function, and for LCD display, it is used to display the output parameters and the state of detector. Power supply module is composed of power source, power source circuit and power conversion module, and which applies stability working voltage for microprocessor and functional circuits.

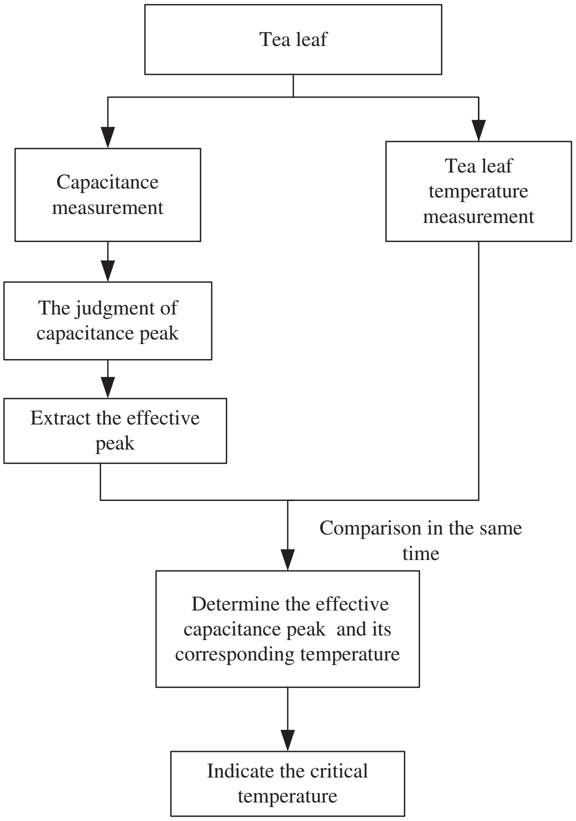

Fig. 1. Approach of the detector design.

The analog signals of capacitance and temperature are collected by capacitance and temperature measurement module. The signal detecting circuit changes analog signal into voltage signal, and then transferred to microprocessor for AD conversion and extracting the effective capacitance peak, and LCD display presents critical cold temperature.

2.1. Design of the detector's hardware

2.1.1. Design of capacitance measurement module

Capacitance measurement module is the crucial part in the overall design which used the method of oscillator type to measure the capacitance of tea leaf. The unknown capacitance C_x (tea leaf) and a size known inductance L_1 are connected in parallel to a voltage controlled oscillator chip which constitutes a LC oscillation circuit. The high frequency sinusoidal wave outputs from the voltage controlled oscillator carried on waveform transformation and frequency division by division circuit, and then transmitted by its frequency signal is converted to voltage signal through the voltage/frequency conversion circuit. Eventually, the MSP430F149 MCU acquires the output voltage signal for further data processing.

LC oscillation circuit uses MC1648 voltage controlled oscillator chip (Motorola, USA) as an oscillator which has a high purity of frequency spectrum and its working frequency is up to 225 MHz (Fig. 3), and its maximum current is 19 mA when the excitation voltage is 5 V [21]. The output signal from MC1648 is a kind of high frequency sine wave which is converted into square wave in order to achieve the input range of voltage/frequency (V/F) converting chip. As shown in Fig. 4, the design adopts two levels frequency division. This is due to the fact that the signal frequency is still above MHz after only one level which is hard for further processing. The first level uses MC12017 (Motorola, USA) which is a dual mode front divider with 63/64 frequency division and it has a good match with MC1648. The second one uses 74HC4040 which is a CMOS asynchronous counter with 12 bit high speed and it achieves 2^1 to 2^{12} times frequency division and converts the sine wave to a square wave. The frequency signal after two levels frequency division is low enough to be converted into DC voltage signal through the V/F convert circuit [22]. As shown in Fig. 5, the design adopts LM331 as voltage-frequency conversion chip which has highly cost effective and the design of peripheral circuit is simple and uses common capacitance and resistance (R_2 is 100 kΩ, R_4 is 5.1 kΩ, C_{11} is 0.01 uf and R_3 is 14 kΩ.

In measuring the capacitance in the circuit, the relationship between capacitance and frequency with an output from the MC1648 oscillation chip could be expressed as,

$$f = \frac{1}{2\pi\sqrt{L(C_1 + C_x)}} \tag{1}$$

where, C_1 is the inherent capacitance in the circuit, C_x is the capacitance to be measured, L_1 is a size known inductance. The F/V conversion equation of LM331 is $U_c = k_2 \cdot f$.where, K_2 is a constant. U_c and C_x can be rewritten as,

$$U_c = k_2 \cdot \frac{1}{2\pi\sqrt{L(C_1 + C_x)}} \tag{2}$$

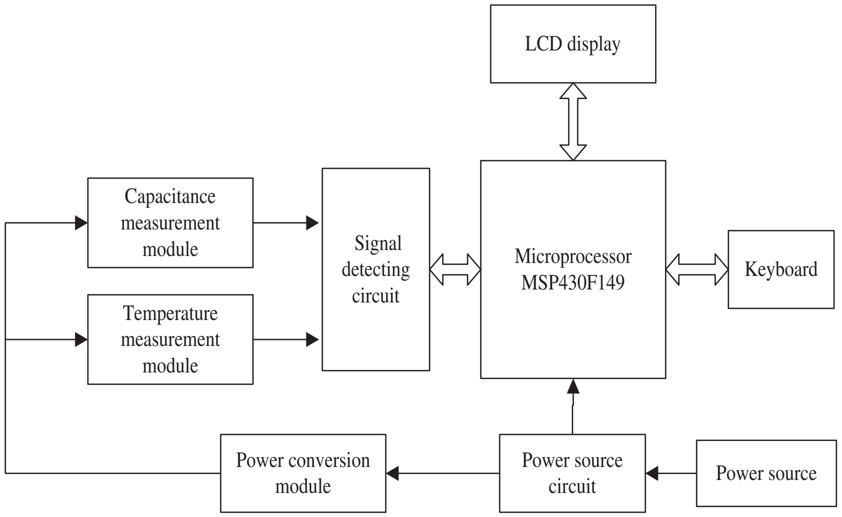

Fig. 2. System block diagram of the detector.

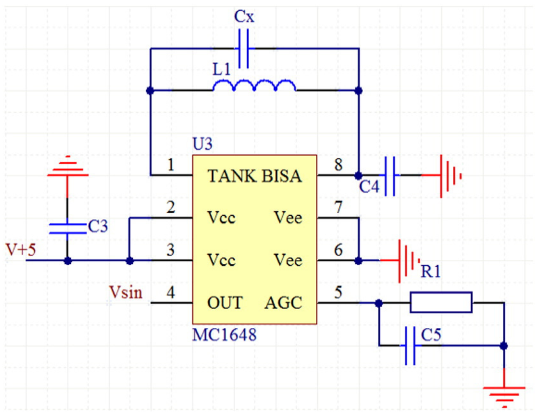

Fig. 3. LC oscillating circuit.

$$C_x = \frac{k_2^2}{4\pi^2 U_c^2 L} - C_1 \tag{3}$$

where, U_c is the output voltage from capacitance measurement circuit.

From the Eq. (1), it shows that the f is inversely proportional to $\sqrt{C}$. From Formula (3), it shows that C_x is proportional to the $1/U_c^2$. So U_c decreased with the increase of C_x.

2.1.2. Design of main control circuit

Microprocessor is MSP430F149 MCU (TI, USA) which is a 16 bit ultra-low power MCU with 87 I/O ports, 256 KB flash memory, 16 KB RAM and 12 bit high-speed A/D converter. It consists of five low power modules to protect battery life and its power supply voltage at 3.3 V [28]. As indicated in Fig. 6, the key module includes P2.0, P2.1, P2.2 and P2.3 and the MSP430F149 MCU receives the voltage signal from signal detecting circuit via P6.0 and P6.1. The display data segment from AD0 to AD7 connects to microprocessor via I/O port from P9.0 to P 9.7 and the other control bits in LCD display connects with the microprocessor via *P*4.1 to *P*4.6, respectively.

2.2. Design of the detector's software

The software was programmed by C programming language and compiled in IAR5.3 workbench. The main program flow chart of detector is shown in Fig. 7, and the design of software included parameter measurement, data record, data query, data delete and other function modules. In the overall design, the program aimed at the estimation of cold critical temperature (Fig. 8) and the program starts with reading the stored capacitance data, and then follows-up with the

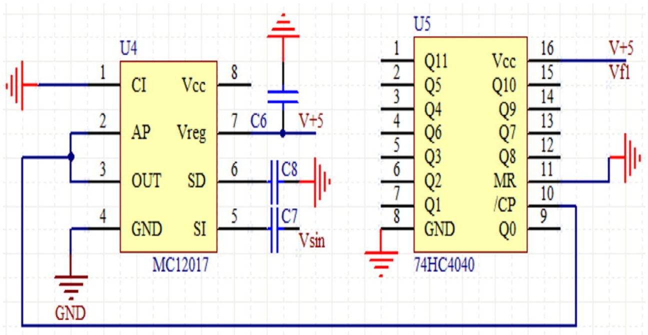

Fig. 4. Fractional frequency circuit.

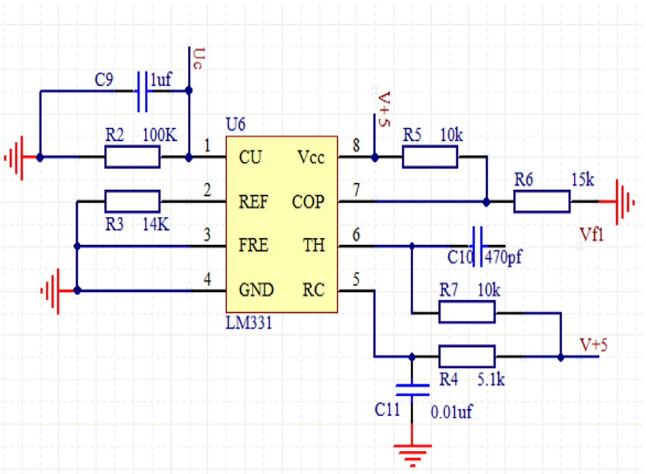

Fig. 5. V/F convert circuit.

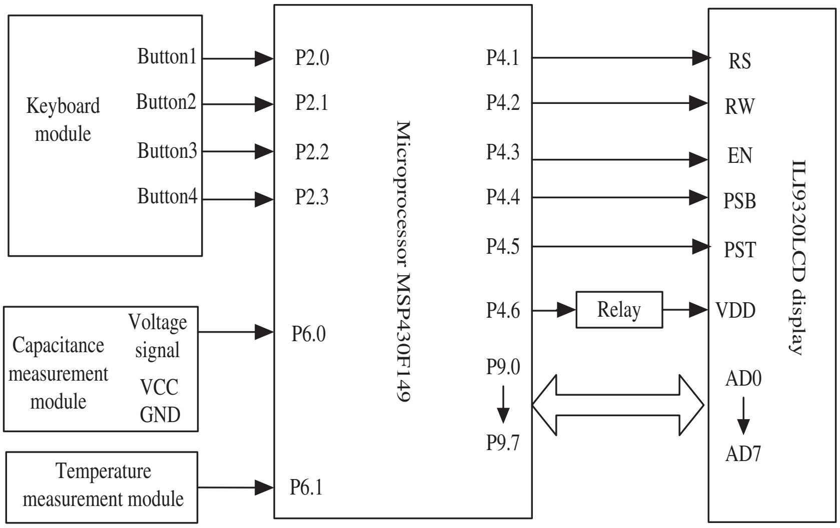

Fig. 6. Block diagram of hardware connection.

establishment of the maximum capacitance and its corresponding temperature. The program indicated a maximum capacitance output of more than 100 nF at the corresponding temperature equivalent to its critical cold temperature; otherwise it will end with “unknown”.

The program of parameter measurement module starts with the signal-acquisition introduction and then collects the voltage of temperature and capacitance which are sent to MSP430F149 MCU for AD conversion and computing (Fig. 9). The design is such that a user can

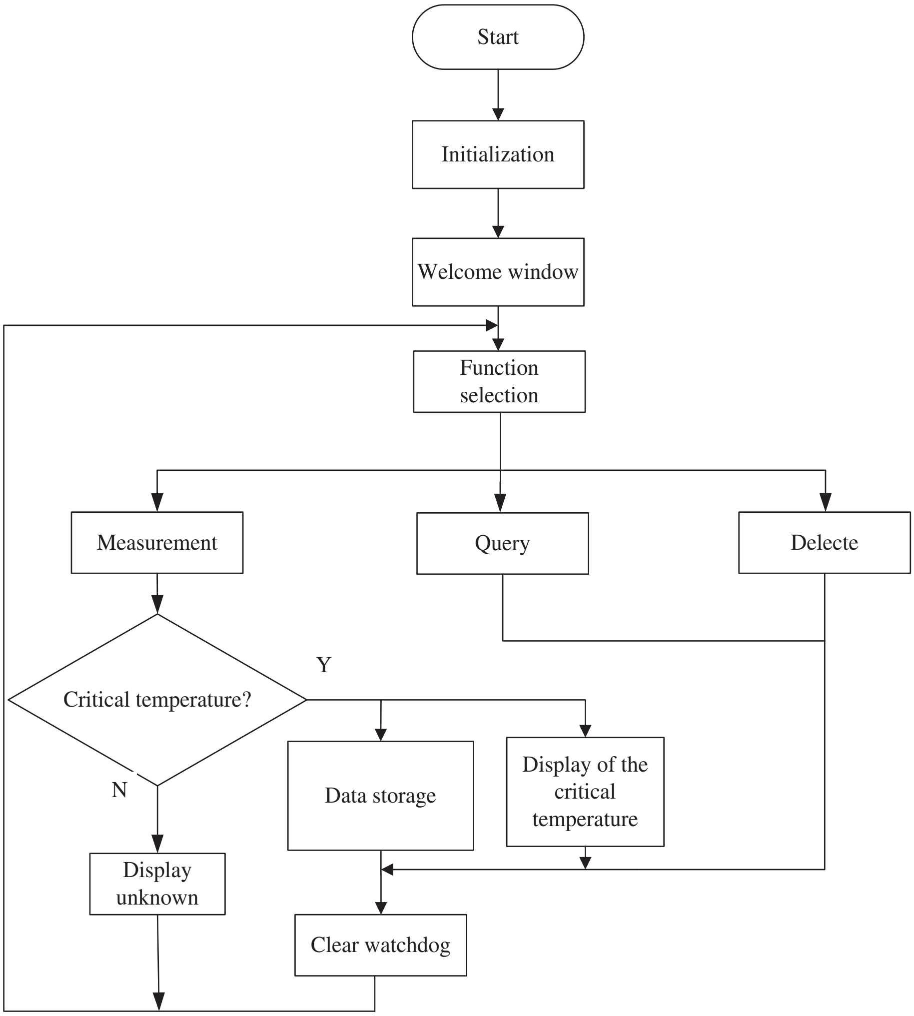

Fig. 7. Main program flow chart of detector.

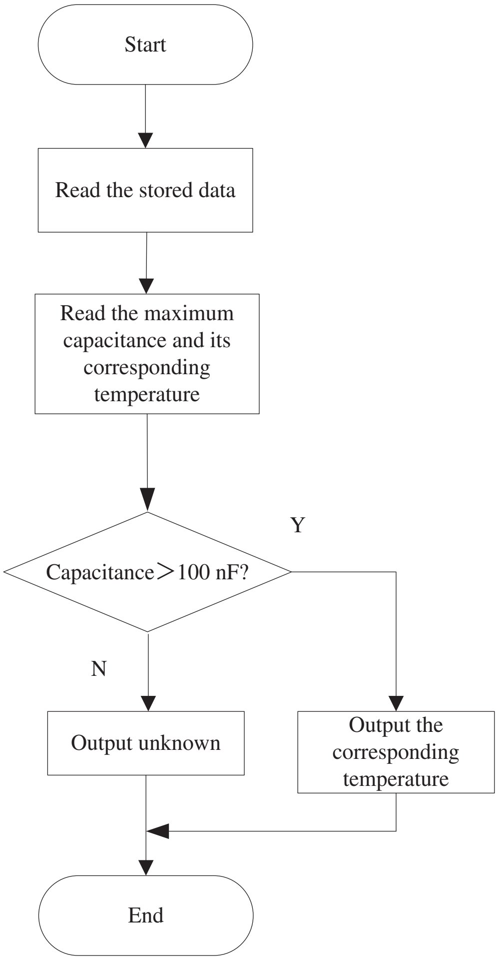

Fig. 8. Program of judging cold critical temperature.

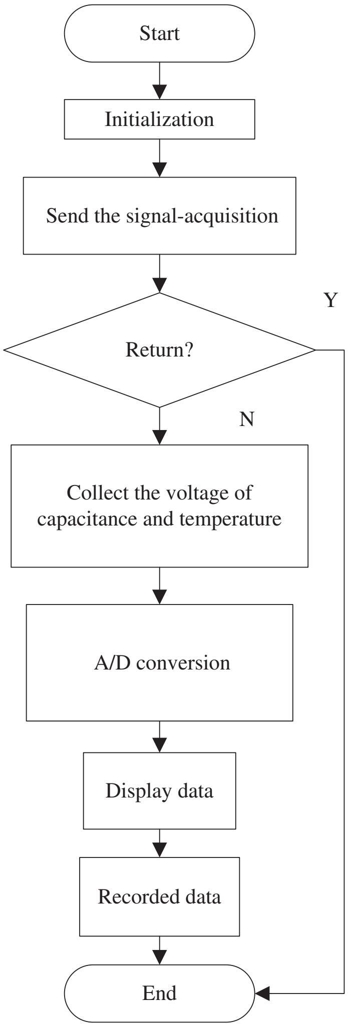

Fig. 9. Main program flow chart of detector.

record data at any time with the continuous mode of as seen in the program flowchart (Fig. 10).

2.3. Debugging of capacitance measurement module

Capacitance measurement module is a crucial part of the detector which is shown in Fig. 11, the circuit is made of PCB and all the chips and components are encapsulated by the patch type in order to make the overall volume of the measurement circuit small enough, and welded one by one along the signal flow according to the circuit diagram.

The hardware debugging has two parts which are power-off test and power-on detection. The power-off test is to confirm that all the chip pins were welded well and the power-on detection is to make sure the power supply voltage of all the chips are +5 V. Because of the processing voltage range of AD conversion is below 2.5 V, it is necessary to ensure the output voltage of measurement circuit is less than 2.5 V with regulation of the output voltage from capacitance measurement module. The values of resistance and capacitance in circuit module are adjusted to make sure the voltage output completely cover the range voltage of AD sampling. In this capacitance measurement circuit module, the output voltage U_c is 0.844 V when capacitance is 0 nF which meets the requirement of MCU AD sampling.

3. Results and discussion

As shown in Fig. 12, in order to analysis the stability of capacitance measurement module, seven standard capacitors including 0, 2, 20, 30, 47, 68 and 100 pF, were tested by the critical cold temperature detector and their output voltage sampled 10 times for per capacitor. Test result showed that the output of capacitance measurement circuit is stable and the average deviation of output voltage is 0.36% which is caused by the change of ambient temperature and electromagnetic interference. The output voltage of capacitance measurement module and its fitting result are shown in Table. 1 and Fig. 13, respectively. This presents a linear distribution relationship between the capacitance and $1/U_c^2$, and the equation is shown as:

$$y = 5.5897 * \left(1/{U_c}^2\right) - 9.0312 \tag{4}$$

The determination coefficient r^2 of Formula (4) is 0.9928 which indicats that output voltage of capacitance measurement circuit is responds suitably to the change in capacitance within the capacitance range of 0 to100 pF.

Tea leaves are easily suffered from freeze injury in the early-spring was focused on in this research, which has caused huge losses for tea production. When they suffer from freeze injury, the plasma membrane is thought to be the primary site of injury and it has the property of capacitance [23,24]. Lu et al. [25,27] put forward a method of testing electrical property of tea leaves under cold stress to indicate critical temperature and established a testing system to measure the capacitance of the samples under different air temperature, air humidity and airflow velocity, and found that the capacitance was rather small

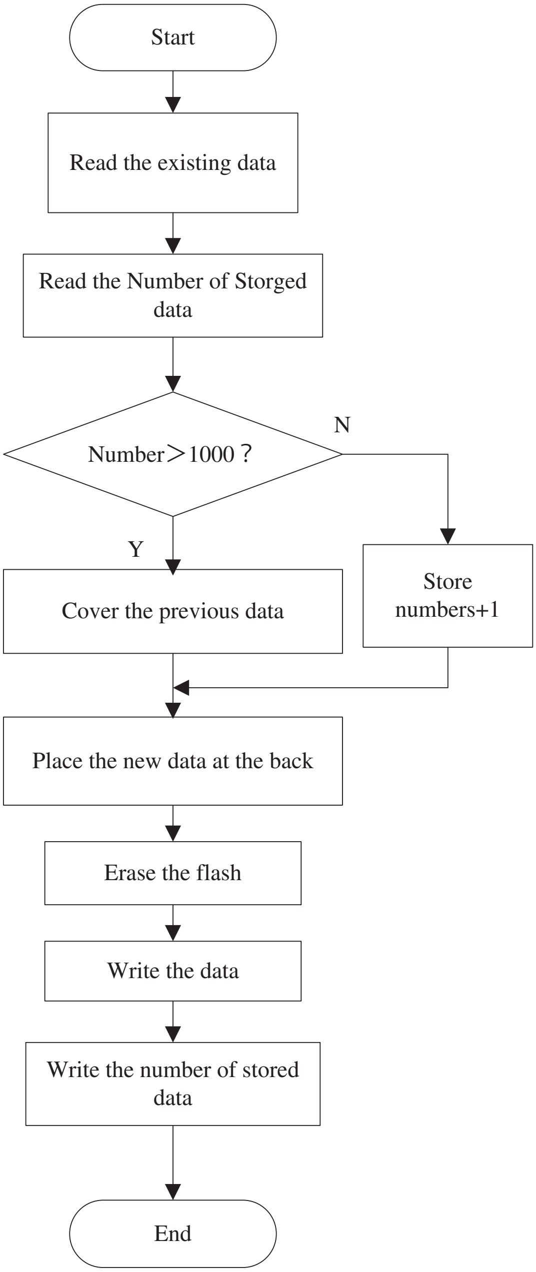

Fig. 10. Program flow of data record.

which was approximately 0 to 100 pF at a room temperature, but the responses had obvious characteristics of a few abrupt peaks at the typical temperature. The results agree with the findings that the capacitance of tea tree leaf is approximately 0 to 100 pF at a room temperature. So the capacitance measurement module basically meets the test requirement of the capacitance of tea leaf at a room temperature.

4. Conclusion

Radiation frost is the most common in early spring frost events and it forms a thermal inversion layer near the ground, and temperature increases with height due to the net energy loses through radiation from the earth surface to the sky. Frost protections based on critical temperature and thermal inversion strength equipment have been applied for frost protection by pushing warmer air aloft downwards to the canopy [26]. As one of the most crucial control factors for frost protection, critical cold temperature of plant could be indicated by the capacitance peak response to a typical low temperature.

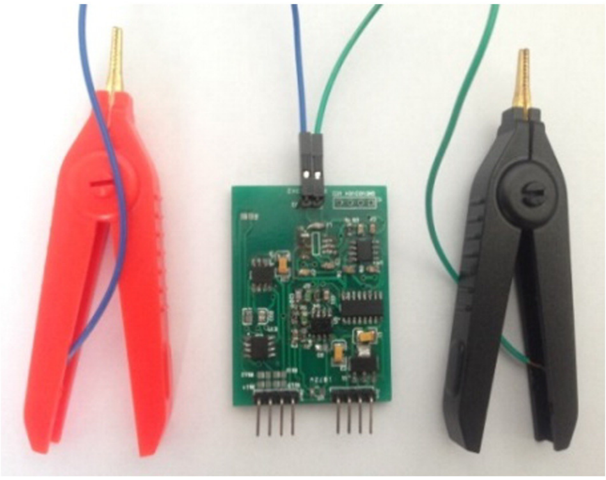

Fig. 11. Main program flow chart of detector.

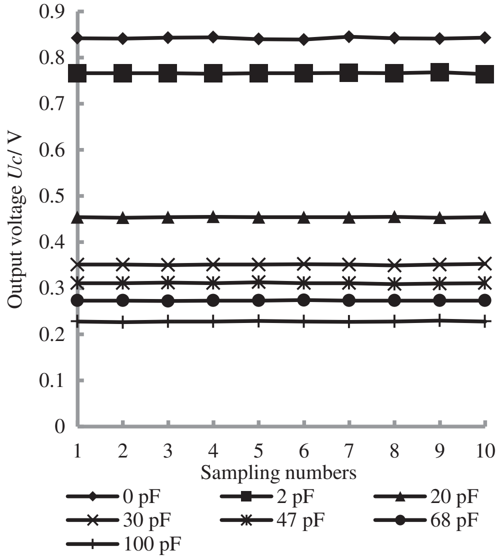

Fig. 12. Analysis on the output stability of the capacitance measurement module.

A new design thought of the critical cold temperature was provided in this research. Capacitance and temperature of tea leaf were measured by the capacitance and temperature measurement modules and the peak of capacitance was identified to extract the effective peak. Critical cold temperature was indicated by the corresponding temperature where the capacitance appeared the effective peak. A new detector was preliminarily designed to accurately and convenient measure the

Table 1
Output voltage of capacitance measurement module.

Stander capacitor pF	Output voltage U_c V	$1/U_c^2$ V^{-2}
0	0.842	1.410508855
2	0.766	1.704285938
20	0.454	4.851636942
30	0.351	8.116817234
47	0.311	10.33901635
68	0.273	13.41759584
100	0.228	19.23668821

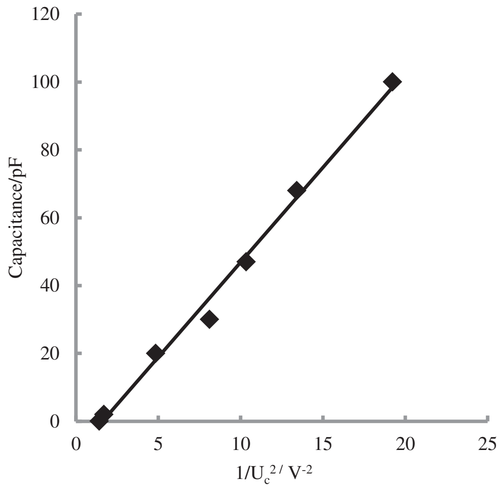

Fig. 13. Relationship between capacitance and U_c^2.

critical cold temperature, and capacitance measurement circuit which is the crucial part in the overall design is better enough responding to the change of tea leaf's capacitance in the range of 0 to 100 pF only at the room temperature.

Therefore, the further study will focus on increasing the measurement range to catch the peak of capacitance through the improvement of capacitance measurement circuit module and the test of the detector in the tea field will be conducted to validate the reliability.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.sbsr.2016.09.005.

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