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Design of capacitive displacement sensor and measuring algorithm based on modulated differential pulse width

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ABSTRACT

Differential pulse width modulation circuit is the use of charging and discharging of the sensor capacitance circuit output pulse width varies with the sensor capacitance change. Capacitive sensor is a device of the electric capacity change measured, and it is a variable capacitor, and then the voltage is obtained by measuring circuit, and the relationship between voltage and displacement are derived and realize the displacement measurement. The paper proposes design of capacitive displacement sensor and measuring circuit based on modulated differential pulse width. Through the experimental analysis of error causes, and put forward measures to improve the precision of measuring circuit.

Keywords: Capacitive Sensor; Pulse Width; Displacement Sensor; Measuring Circuit.

INTRODUCTION

Capacitive sensor is a device of the electric capacity change is measured, is a substance with variable parameters of capacitor. Compared with other sensors, capacitive sensor has good temperature stability, simple structure, strong adaptability; good dynamic response, high resolution, and reliable work, easy to realize the non-contact measurement, with average effect and other advantages, and can work in high temperature, radiation and strong vibration and other harsh conditions. Capacitance sensors are widely used in a variety of detection system, used to measure such as liquid level, pressure, displacement, acceleration and other physical quantities. Capacitive sensor also has shortcomings, such as high output impedance, load capacity is poor, the parasitic capacitance effects and so on.

Capacitive displacement sensor often exists the following problems: 1, in the design of the capacitance detection circuit nonlinear, not easy to follow the sensor characteristic curve fitting; 2, the parasitic capacitance and the influence of the distributed capacitance of capacitive displacement sensor, the measurement range of small. The capacitive displacement sensor micro-epsilon company as an example, the diameter of the detection range of capacitive displacement sensor 40mm is only 5mm; 3, the detection circuit is complex, high cost of production.

Electrical measuring non-electrical quantity measurement method, you must first be measured non-electrical converted to electricity and then enter the amount [1]. Usually quantitative non-electrical components into electrical quantity called converters; non-electrical quantity depending on the characteristics of the design of the conversion device called a sensor, and the measured mechanical quantity (such as displacement, force, velocity, etc.) into a sensor capacitance change is called capacitive sensors. From the perspective of energy conversion, the passive converter capacitance transducer, and it is the need to convert the measured mechanical after a voltage or current amplification and processing.

Because capacitive sensors are widely adopted, inevitably involves the capacitance measurement problems. For

sensing signal extraction and non-power parameter is measuring the success of the closely related. Capacitive sensors will be measured non-power signal is converted into the change in capacitance, the capacitance value can not be directly used to show the conventional display apparatus, more difficult to transport, must use the change in capacitance measuring circuit is converted to voltage, current or frequency signal to display, recording and transmission. The capacitance / voltage conversion circuit to the change in capacitance is converted to a voltage signal accurately is essential, it is directly related to the accuracy of subsequent measurements.

The project requires the design of a small displacement measuring instrument, the use of differential parallel-plate capacitor circuit with pulse width modulation signal way to achieve the micro-displacement measurements. Specific requirements are as follows: (1) establishment of experimental systems, build the entire test system; (2) development of a parallel plate capacitor; (3) developed a sensor signal processing circuit; (4) developed a micro-displacement tester. The paper proposes design of capacitive displacement sensor and measuring circuit based on modulated differential pulse width.

2. Design of Capacitive Displacement Sensor

Advantages: capacitor of capacitance sensor temperature stability of capacitance sensor value is independent of general and electrode materials, to facilitate the selection of low temperature coefficient of the material, and because of the fever is minimal, affecting the stability of success; simple structure, strong adaptability of capacitive sensor is simple in structure, easy to manufacture, easy to guarantee high precision; can do very small, in order to achieve some special measurement. Capacitive sensor generally with the metal electrodes, with inorganic material as insulating support, so it can work in high temperature, high radiation and strong magnetic field and other harsh environments, can bear great changes of temperature, high pressure, high shock, overload; measurement of ultra high pressure and low pressure difference, can be measured magnetic band for the work piece.

For these mechanical quantity, especially the measurement of slow change or small volume, generally using capacitive sensor to detect more appropriate, is this kind of sensor has the following advantages: (1) large measuring range of the relative change rate of more than 100%; (2) high sensitivity such as transformer ratio bridge measurement, relative change amount can reach 10-7 level; (3) fast dynamic response due to the moving mass is small, high natural frequency, high frequency characteristics is suitable for the measurement of dynamic, static measurements are available; (4) good stability due to capacitor plate for the metal material, plate lining for inorganic materials, such as air, of glass, ceramic, quartz and so on; so it can be in high temperature, low temperature and strong magnetic field, strong radiation under the long-term work, especially to solve the problems of high temperature and high pressure environment.

Capacitive sensors in many industrial and consumer products have a very wide range of applications, because of its small size and low power consumption, and other aspects of the characteristics of high precision, widely popular in many areas. For capacitive sensor measurements, the traditional circuit mode has its limitations can not be overcome.

Capacitive sensor has an average effect, can reduce the influence of surface roughness on the measured. Capacitive sensor in addition to the above advantages, but also because of the electrostatic attraction between the charged minimax plates, and it is so the required input energy minima, so especially suitable to solve the measurement problem of low energy input [2]. Disadvantages 1, high output impedance, capacitance load capacity differential capacitive sensor by the electrode geometry constraints, typically tens to hundreds of skin, so that the output impedance of the sensor is very high.

So the sensor load ability is poor, vulnerable to outside interference unstable phenomenon, serious and even unable to work, must take shielding measures, so as to give the design and use of the inconvenience. Capacitive high also requires sensor insulating part of the resistance value is extremely high, otherwise the insulation part will serve as the shunt resistance and influence the sensor performance, so we should also pay special attention to the influence of the surrounding environment, as is shown by equation1.

$$\overline{w}(m) := \left[\overline{w}^T(m,1), \overline{w}^T(m,2), \cdots, \overline{w}^T(m,M)\right]^T \tag{1}$$

Capacitance sensor works by using mechanical quantity change in the capacitor parameters change one way to achieve signal conversion. According to different parameters to change the capacitor, the capacitance sensor can have three types: plate covering the area of change in capacitance sensor.

Output characteristics of variable-distance capacitance sensor are nonlinear, although can be used to improve the

differential structure, but may not completely eliminate. Capacitance sensor for other types of only neglecting edge effects of electric field, the output characteristics is linear. Additional capacitance or edge effect generated by directly superimposed with the sensor capacitance, the output characteristics of nonlinear. These problems lead directly to the capacitive sensor measuring circuit complexity.

In the capacitor plate covering area of S, the distance between the two polar plates D, the measured object on the dielectric constant of medium between lower to the electrodes 1 and ε3 is determined, the capacity of the capacitor and the thickness of the material D2 and dielectric constant ε 2. If the measured dielectric constant ε2 known, can measure the thickness of teaching material thickness D2; or the thickness of the material under test known as D2, can measure the dielectric constant ε2. The working principle of this is the capacitive thickness gauge and capacitance dielectric constant measuring instrument, as is shown by figure1.

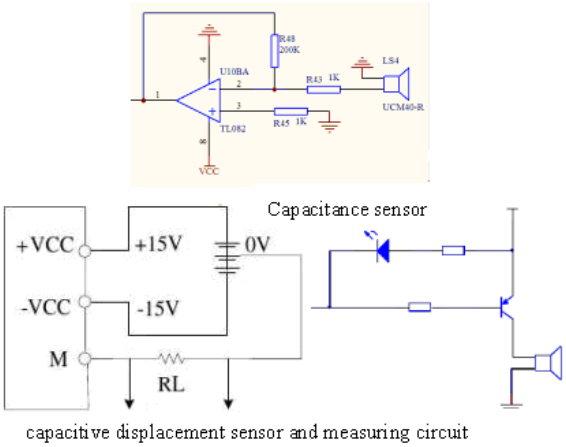

Fig. 1. Design of capacitive displacement sensor and measuring circuit

Three under the same metal plate placed parallel, in which the top plate and the bottom plate fixed in the middle of the plate as a removable plate. The movable mechanical displacement plate used in the reaction, since the movement of moving plate may cause changes in capacitance of the sensor [3]. In addition, this structure will be accompanied by a suitable measuring circuit can determine the direction of motion moving plate, which is the general structure of the sensor can not achieve. In conclusion, the introduction of a differential structure reduces the nonlinear errors and improves the sensitivity.

Obviously, capacitance sensor that unilateral activity with the increase of measuring range, and it is the corresponding error also increases. In practical application, in order to improve the sensitivity of the sensor, and improve the measurement range and reduce the nonlinear error, often make differential capacitor and transformer bridge structure, as shown in figure 1. On both sides of the plate electrode is fixed by 1 and 2, separated by movable polar plate spring bearing 3. 2 fixed polar plate and the transformer and the AC power supply is connected to both ends of U, active plate connecting terminal and a transformer center tap terminal as an output end of the sensor, voltage Δ U end of the output with the movable polar plate motion and change. If the initial position of the movable plate from the 2 fixed plate distance is d0, the fixed plate 1 and a movable plate 3, fixed 2 and a movable plate initial capacitance equal 3, if it is C0.

This circuit is of the capacitive sensor as a part of the oscillator resonant circuit. When measuring the capacitance changes, the corresponding change in the oscillation frequency is generated. Since the oscillator frequency by the capacitive sensor capacitance modulation, it is known as frequency modulation circuit. Equation 3 shows the principle of the frequency modulation circuit. Formula FM oscillator frequency determined by the following formula (2).

$$I = -\sum_{t=0}^{T} q(t)\log q(t) - (-\sum_{t=0}^{T} p(t)\log p(t)) \tag{2}$$

Mechanical quantity in line displacement, angular displacement, spacing, distance, thickness, tensile, compression, expansion, deformation, etc. are all closely linked with the amount of the length; these quantities and ratios are by measuring the length or the length of the amount, and the measurement method is also very close relationship. Also, in some conditions, these changes in the mechanical quantity rather slow, and very small range, if required to

measure the minimum distance or displacement have a high resolution, the other sensor is very difficult to achieve high resolution requirements of the precision measurement commonly used in the resolution of the sensor differential transformer reached only 1 ~ 5 μm magnitude; but there is a capacitance micrometer, a resolution of his 0.01 μm, two orders of magnitude than the former increased, the maximum range of 100 ± 5 μm.

High frequency voltage output by the oscillator is a measured signal modulated wave, whose frequency is decided. This kind of measurement circuit, high sensitivity, can be measured to 0.01 μ m displacement transformation quantity, and frequency output, connecting to and digital instrument and the computer, can send, receive to realize remote telemetry. Another strong anti-interference ability, can achieve a high level of DC signal. Drawback is the effect of oscillation frequency and the temperature of cable capacitance; complex lines, and is not easy to do a very stable; output nonlinear large, need to error compensation.

Transformer bridge the principle is that a capacitor sensor access AC bridge or two adjacent arm, the other two arms can be resistance or capacitance or inductance, can also be two the secondary coil of the transformer. When measuring the measured changes cause bridge unbalance sensor capacitance change, the output voltage of the bridge changes. This circuit for variable distance sensor, nonlinear error is large; it is only in the load impedance of the output characteristics of linear. It also does not have the automatic balance measures, constitutes a complex.

The principle and application of capacitive sensors from the cylinder 1 and cylinder 2 constitute a capacitor poles, assuming partially immersed in the liquid to be measured (the liquid should not conduct electricity, if conductive, the electrode must be insulated). Thus, the dielectric between the plates consists of two parts: the air medium and the liquid medium, thereby forming a capacitive level sensor, a liquid level of the liquid medium is changed; resulting in the capacitance C is also changed. This method is the measurement accuracy is high, and from the surrounding environment. Total capacitance C by the liquid dielectric portion and an air dielectric portion is capacitor C1 capacitor C2 of two parts.

Visible, the output voltage is proportional to the capacitance difference. The circuit is suitable for various kinds of capacitive sensor. It has the following characteristics and application requirements: (1) power supply, the sensor capacitance, load can be simultaneously at one point grounding; (2) when the diode working in high level, the nonlinear measurement error is small; (3) the frequency sensitivity and the power supply circuit, so the power supply frequency stability (; 4) will be D1, D2, R1, R2 installed to eliminate the influence of cable capacitance in C1, near C2; the circuit is simple; (5) output voltage is higher; (6) the output impedance of the circuit are only related to R1, R2 and RL, which has nothing to do with the capacitor C1, C2; (7) can be dynamic measurement.

$$\Psi(m,s) \coloneqq [\overbrace{0,\cdots,0}^{s-1}, C((m-1)M+s), \overbrace{0,\cdots,0}^{M-s}] \tag{3}$$

Differential pulse width modulation circuit is the use of charging and discharging of the sensor capacitance circuit output pulse width varies with the sensor capacitance change. The DC signal corresponding to the measured changes through the low pass filter can. Differential pulse width modulation circuit with DC power supply, the voltage stability is high, there is no stable frequency, waveform purity requirements, also does not need the phase sensitive detection and demodulation; no linear requirements on the element; the low pass filter can output larger voltage, the output square wave purity requirements is not high.

Thus, the pulse width modulation circuit, regardless of changing the parallel plate capacitor plate area or the distance between the plates, which were tested change linearly with the output level. In summary, the differential pulse width modulation circuit can be applied to any differential capacitance sensor, and has a theoretical linearity [4]. This circuit uses DC power supply, high voltage stability, there is no steady frequency, waveform purity requirements and does not require phase sensitive detector and demodulation; requirements on wireless devices; through the low-pass filter output DC voltage greater the rectangular wave output is not high purity requirements. These features are all other capacitance measurement circuit can not match.

Variation of the capacitance value and the angular displacement is proportional to; this is used to measure the angular displacement. Is the cover area using linear displacement to change the capacitor plate? If the initial state is completely cover plate, covering the area of S0=ab, when the 2 polar plates relative displacement x, the covering area plate into S1=b (A-X). The dielectric constant and the plate distance is constant, the capacitance respectively.

The circuit components are: voltage source, a comparator chip, flip-flop, gate chip resistors and capacitors, diodes, etc.. The total circuit needs a stable reference voltage source voltage. Select the YB1731A 5A dual DC regulated

power supply, the power supply has the characteristics as follows: (1) with four groups of LED display indicating two voltage and current values; (2) has a voltage, current and voltage and current state can be automatically converted; (3) the current limit protection type and current limit can be adjusted; (4) the two output voltage can be connected in series or in parallel, in series or in parallel, can be voltage or current by a main power supply (parallel) tracking; (5) has the function of overload and short circuit protection. YB1731A 5A parameters: 0-30V output voltage output current load effect; 0-5A; CV 5 × 10^-4+2mV, 5 × 10^3+10mA CC.

Measurement circuit generally use a certain amount of electronic switches, but the electronic switch charge injection effect on the measurement system is difficult to eliminate; measurement object because the rapid variability, require high speed data acquisition, the acquisition speed and lower noise contradiction difficult to resolve, there is a filter to improve the speed of data acquisition bottleneck problem. Therefore, to consider the lead capacitance, parasitic capacitance of the circuit design and environmental impact of changes in other factors, and it is so capacitive sensor conditioning circuit design is quite complex, and because too many discrete components, will also affect the capacitance measurement accuracy [5].

Capacitive sensor, the distributed capacitance of the sensor is reduced, largely to make up for the lack of capacitance sensor. Then the design of a good linearity of the capacitance detection circuit, method of overcoming parasitic capacitance, increase the detection range of capacitive displacement sensor, for the future development of capacitive sensor, has the vital significance to expand the scope of use of capacitance type sensor, the bottleneck which is currently the capacitance sensor needs to break through.

3. Using Modulated Differential Pulse Width to Measuring Circuit of Capacitive Displacement Sensor

The design requirements for measurement of small displacement, here is the variation of the displacement by capacitive sensor will not power into the power capacitor, and then the voltage is obtained by measuring circuit, through the relationship between voltage and displacement are derived and then realize the displacement measurement. The capacitive sensor as the bridge displacement and voltage is very important, in the proposed sensor design in the design.

This type of capacitive sensor are principle of nonlinear, so in practice often make differential to improve the non linear. Effective area of area change type capacitance sensor by changing electrode can be made into a variable area type capacitance sensor. Variable area type capacitance sensor, flat structure is particularly sensitive to a change; the measurement accuracy is affected by. The cylindrical structure affected by plate radial change little, become the most commonly used in the actual structure, this paper introduced a concentric cylindrical linear displacement capacitance sensor [6].

Schematic diagram of this kind of sensor, figure 2 is composed of 2 blocks of plate, the plate 2 is fixed plate, plate 1 is connected with movable polar plate of the measured object can be moved up and down. When the covering area between the polar plates is S, the dielectric constant between the plates of medium e, initial plate spacing is d0, then the initial capacitance sensor capacitor C0 together with two metal cylinder a certain height, the outer surface of the cylinder, one fixed, the other a concentric cylinder moving along the axis direction, constitute the capacitance sensor coverage area of each variable.

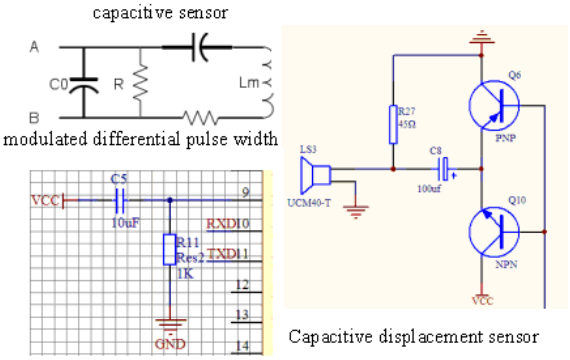

Fig. 2. Using Modulated Differential Pulse Width to Measuring Circuit of Capacitive Displacement Sensor

In fact, we have a variety of characteristics of the capacitance sensor, are purely capacitive carried out under the conditions. This sensor can be ignored in the general case the additional loss is feasible. However, if considering capacitive sensors in high temperature, high humidity and high frequency excitation conditions work, it can not

ignore its impact additional loss and electrical effects, then the capacitive sensor can be equivalent to Figure 2, C is the sensor capacitance, R p parallel resistance is low loss, which includes leakage between the plates and dielectric loss; R s is high humidity, high temperature, high-frequency excitation at work series loss resistance, which includes wire between the plates and metal bearings and other wear and tear.

Capacitive displacement sensor will be tested into the non electrical capacitance variation, must use the measuring circuit to convert it into can be applied to the quantity, such as voltage, current and frequency signals, there are a lot of this method of measurement conversion and processing [7]. The measurement method used widely at present are: frequency modulation method, alternating current bridge method, double T shaped charge and discharge.

$$x_l(t) = \sum_{i=p}^{n} c_i(t) + r_n(t) \tag{4}$$

Set the cutoff frequency ω C V IL meet V IL, the frequency is lower than the C signal can be higher than the filter circuit, C signal is attenuated as low pass filter. Low pass filter can be used as the direct-current power supply filter circuit after rectification, so as to obtain a smooth DC voltage. By differential pulse width modulation circuit theory, only through a low pass filter can be obtained by the DC output voltage of U 0. Generally speaking, filter into the active filter and passive filter two, a low pass filter is not exceptional also, here introduce the application of the two kinds of filters in the design of it.

This paper has carried on the detailed elaboration to the pulse width modulation circuit, analysis and understanding of the structure and the working principle of the circuit, a circuit for each of them there are detailed introduction. It is also noteworthy, resistance in the R 1, R 2 equal, charge and discharge time of the circuit depends on the capacitance sensor's parameters, and is independent of parameter circuit with an external, this characteristic of great value, the only focus on process design, namely to distributed capacitance reduce the wiring and installation of more or less is introduced, in order to further improve the detection accuracy of the capacitive sensor.

4. Design of Capacitive Displacement Sensor and Measuring Circuit based on Modulated Differential Pulse Width

Sensor technology plays an important role in the development of the economy, promoting social progress. Due to the wide use of capacitance sensor, inevitably involves the capacitance measurement. Change of capacitance sensor capacitance quantity generally small. Small capacitance measurement technology at this stage can not fully meet the actual needs of the application development. According to the characteristics of relatively small variation of capacitance sensor, we developed the micro capacitance sensor based on the principle of pulse width modulation (displacement) measuring circuit.

This paper discusses the production of related theory of capacitance sensor and a parallel plate capacitor. Here introduced capacitance / capacitive sensors commonly used voltage (C/V) conversion circuit. Design of small displacement measuring circuit based on pulse width modulation principle, and circuit components selection, parameters calculation. Finally, it is measurements on experimental results.

The development direction of the capacitive sensor is a capacitive sensor transformation to strengthen the integration of the circuit, in order to overcome the effects of parasitic capacitance, as far as possible circuit and the sensor is connected with tight or simply as a whole or the use of wireless access to replace the traditional cable transmission; in order to overcome the problem of capacitor materials, using radio frequency admittance to improve the requirements for the measurement of tiny displacement, in the final analysis is the measurement of small capacitance, combined with capacitive sensor and the knowledge of the design requirements, the structure of differential capacitance sensor polar distance-changing type.

Differential pulse width circuit working principle: the first differential capacitance C 1 and second differential capacitance C 2 for the measured differential capacitance [8]. The first comparator IC 1 no inverting input connected to a reference voltage U R, connected to one end of the first comparator inverting input of IC 1 and the first differential capacitance C 1, another end is grounded capacitor, a first comparator IC 1 and the output terminal of a bitable trigger FF the first output end is connected; a second comparator IC 2 the in-phase input end is connected to the reference voltage U R, connected to one end of the inverting input differential capacitance and second C 2, the other end of the capacitor is grounded, the output terminal is connected with the trigger the second input end of the second comparator.

To determine the parameters in the design of the resistance of R charging and discharging circuit of 1 C 2, the

comparator output pull-up resistors, resistor, capacitor amplifier required, comparator voltage reference set, trigger output high voltage, the following will introduce one by one. Through access to information about the initial capacitance, capacitance sensor is very small (30-200pF). Here to choose the initial capacitor C 2 =90pF, choose the resistance value R 1 = R 2 =500k. The reference voltage U R =4V, the reference voltage is 9V, namely the high potential of the U trigger output of 1 =5V.

Experimental preparation of bread plate a, a comparator LM639, trigger 7MS279 one chip 73HC04, not a LM454 operational amplifier, a resistor, 6.3K two, 950K resistance two, two 1K resistors, diodes two, 0.09 μ capacitor and two capacitor, 9574pF two, a plurality of power supply conductors,, oscilloscope, metal plate and an organic glass plate. Step 1, according to the experimental schematic wiring; 2, check whether there is shorted wire, chip pin is damaged, chip using the method of wrong phenomenon; 3, the power supply is switched on, the oscilloscope view test points (A, B, F and G) waveform. The paper proposes design of capacitive displacement sensor and measuring circuit based on modulated differential pulse width.

Because the capacitance sensor when the actual production, process requirements are very strict, and displacement measurement range is small, the inherent capacitance instead of actual sensor capacitor. Test conditions: the changing range of C1 and C2 were between 96pF-850pF, and capacitors C1 and C2 and invariant.

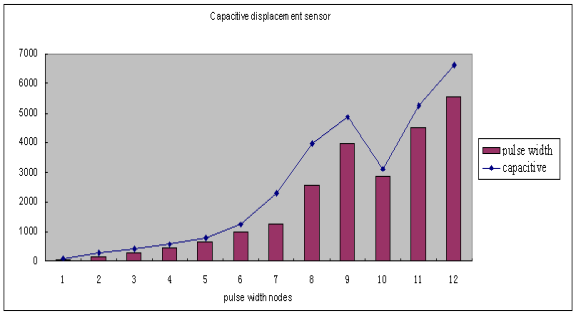

Fig. 3. Comparison results of capacitive displacement sensor and measuring circuit based on modulated differential pulse width

The error of capacitance sensor is from many aspects, such as temperature, edge effect, parasitic capacitance and capacitance. Due to the sensitivity of capacitance measurements to reach pF level, and parasitic capacitance connected with the sensor and the circuit wire cable capacitance, electronic circuit stray capacitance and inside the sensor is large, and the amount of interference is often random change, great for the stability and accuracy of measuring the impact of. So the cable selection, installation, connection method has strict requirements.

Between the capacitor plates are capacitive sensor in electrostatic field. Due to the plate edge effect, so that the edges of the electric field distribution is not uniform, causing the edge effect of the capacitor, which is equivalent to the sensor capacitor in parallel with an additional capacitor, edge effects not only decrease the sensitivity of the capacitive sensor reduces and produce nonlinear, therefore should reduce and eliminate the edge effect of the capacitor. Pole spacing decreases, the electrode diameter or length and spacing is large, can reduce the influence of edge effect, but prone to breakdown and may limit the range of measurement.

CONCLUSION

The sensor and the measurement circuit itself or the prestige are arranged in a shell, so the parasitic capacitance is reduced greatly, so that the sensor is stable, but not in the high, low temperature environment work. Capacitor used "cable" technology when the capacitive sensor value is very small, but for some reason (such as the environment of high temperature), separately measuring circuit with only the sensor, can adopt a "cable" technology, shielding the capacitive sensor and the conversion circuit, transmission cable with a shielding shell the correct selection of shielding, grounding can reduce the effects of parasitic capacitance and prevent outside interference.

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