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Design of A High Sensitivity and Non-contact Planar Capacitance Sensor

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Abstract. *Driven by the needs of special measurements, a non-contract capacitance sensor is designed, which utilizes two parallel special shape copper-foil surfaces in the inductive electrode and takes capacitance of the capacitor as the sensitive source. If there is a target medium approaching the electrode within a certain distance, the capacity of the capacitor will change and be converted into a special voltage signal by the conditioning circuit, which thereby could be utilized to detect the presence of objects such as the media. The experiments prove the presented sensor could be used to detect not only metallic and non-metallic objects, but also liquid substances, and it has the features of low cost, high stability, high sensitivity and adjustability.*
Keywords: Non-contact, High sensitivity, Planar capacitance sensor

1. **Introduction.** Sensors are the main ways and means to obtain information in nature or in the field of production. Sensor technology has already been applied in a wide range of areas such as the development of the universe, ocean exploration, environmental protection, resource investigation, medical diagnosis, and even the protection of cultural relics [1-4,13]. In modern industrial production, especially in the automatic production process, a variety of sensors have been proposed to monitor and control the various parameters to guarantee the working of equipment and the quality of products[15-17].

Capacitive sensor has the characteristics of average effect, simple structure, high resolution and high measurement accuracy, which can realize non-contact measurement and work under such severe conditions as high temperature, radiation and vibration. It has been widely used not only in the measurement of pressure, displacement, acceleration, vibration and humidity, but also in that of the mechanical parameters such as precision spindle rotary precision, acceleration and so on[14]; it is particularly suitable for measuring the liquid level, burden, the moisture of the grain, non-metal material coating, oil film thickness, density and thickness. But the leakage resistance and nonlinearity of capacitive sensor to some extent limit its application. With the continuous development of electronic technology, especially the wide application of integrated circuits, these shortcomings have been overcome to a certain extent, thus enabling a wider application of capacitive sensors[18-20].

In recent years, the traditional sensors have been gradually replaced by sensors of new types which are miniaturized, digital, intelligent, systematic, and networkable[11]. They not only promote the transformation of traditional industries, but also enact the establishment of a new industry that is a new economic growth point of the 21st century[12].

2. **Principle and type of capacitive sensor.** The basic working principle of capacitive sensors can be illustrated with a flat plate capacitor shown in Figure 1.

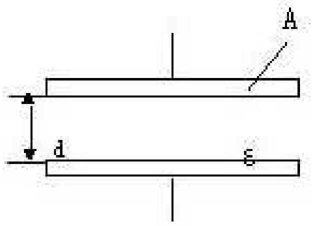

Figure 1. Plate condenser

Let the effective area of the overlapping of two electrodes be A, the distance between the two polar plates d, the dielectric constant of the medium between the plates , when plate edge effects are neglected, the capacitance of a parallel plate capacitor C is defined as follows:

$$C = \frac{\varepsilon A}{d} \tag{1}$$

Its obvious that if two of the three parameters (e.g. and A) are kept constant and the third parameter (e.g. d) changes, the electric capacity C will change. Therefore, its meaningful that a functional relation between the changing parameter and the measured parameter could be defined. So the capacitive sensors can be divided into three types: (a)the variable area type by changing the plate area; (b)the variable gap type by changing the distance between the plates; (c)the variable dielectric constant type by changing the dielectric as constant whose principle diagram is shown in Figure 2.

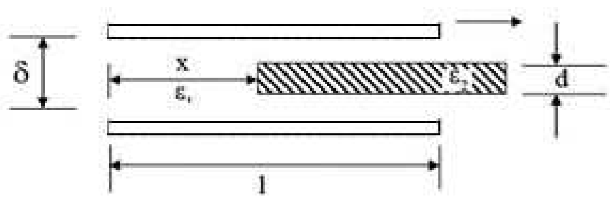

Figure 2. Variable dielectric constant capacitor

When non-air medium is charged between two plates of the capacitor, because different media have different relative dielectric constants, the capacitance of the capacitor varies according to the different media inserted . The variable dielectric constant capacitive sensors are more popular in detecting the thickness of the flake materials (e.g. paper, insulating film), the humidity of solid substances (e.g. food, textiles, wood, coal etc.), and even the liquid level and solution concentration of containers. In particular, our work, i.e. the design of non-contact capacitive sensor, is mainly based on the variable dielectric constant type[5].

3. **Circuit composition and principle design.** This paper aims to design a non-contact sensor with high stability, low cost and high sensitivity, which is capable of detecting a small amount of liquid flowing through or approaching the sensor surface or medium, and converting the detected into the output signal. The designed non-contact sensor can be used for non-contact measurement of metal, non-metal liquid and solid substances[6] and its qualification requirements are as follows: (a)the detecting distance is 0∼20mm, and adjustable; (b)the working voltage: 10∼24V; (c)the output current: less than or equal to 200mA; (d)the working temperature: -10∼75°C.

3.1. **Circuit diagram.** The overall circuit of the non-contact capacitance sensor is shown in Figure 3.

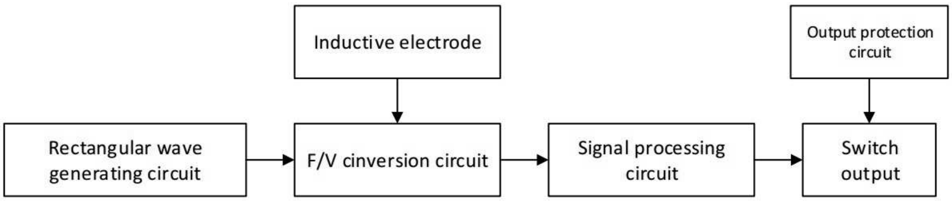

FIGURE 3. Total circuit diagram

In figure 3, the rectangular wave generating circuit provides the signal source with stable frequency and amplitude for the following circuits; and the inductive electrode of the capacitance sensor functions as a capacitance and is connected in the F/V conversion circuit. The target medium coming closer toward or passing by the plates of the capacitor triggers the change of the dielectric constant in-between the plates, correspondingly causes change in the capacity of the capacitor, and further yields the F/V conversion circuit signal change which is eventually converted into a voltage signal[7]. The voltage signal is processed by the signal processing circuit and the switching value is output. The output protection circuit prevents the circuit damage caused by over current [8].

3.2. **Principle design of signal generator circuit and F/V converter circuit.** In order to improve the sensitivity and stability of the sensor, the circuit structure as shown in Figure 4 is designed.

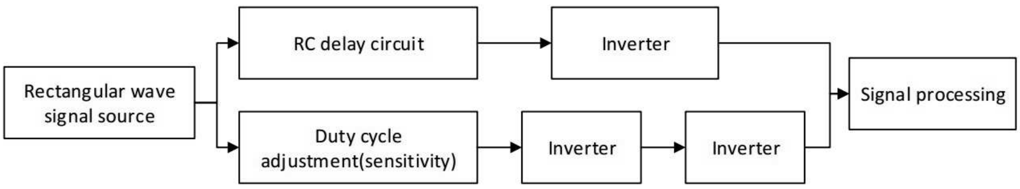

FIGURE 4. Rectangular wave generating circuit and F/V conversion circuit diagram

In the above design, the rectangular wave with stable amplitude and frequency produced by the generating circuit is used as a source signal which is further divided into two paths: one passes through the equivalent capacitance C of the induction plate, and the RC phase shift and inverting circuit; the other firstly goes through the duty cycle control circuit and a two-stage reverse correction, then its superimposed onto the former path of signal. If there is no medium interference, the superposed signal will be a constant high electric level. Otherwise, if the medium is close to or passes by the induction plate, it will produce a cycled rectangular negative pulse which can be sent to the signal processing circuit.

3.2.1. *RC delay circuit design.* Figure 5 is a simple RC delay circuit consisting of the resistance and capacitance.

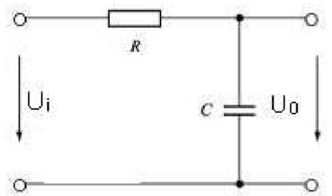

FIGURE 5. RC Delay circuit

The delay time is

$$T = -RCln\frac{U_i - U_0}{U_i} \tag{2}$$

where R is measured in ohm and C in F, U_i stands for the voltage between the series resistance and capacitance and U_0 the output voltage of the capacitor.

Suppose the capacitor C is the induction plate, since the capacitor can be initialized as some pF in the experiments and for minimizing the frequency of the rectangle wave signal source, by formula (2) the resistance R should be maximized as possible, e.g. 1M ohm. However, it should be pointed out that if R is too large, so would the noise be.

Given the input voltage U_i as 5V, the output voltage $U_0 = VT+ = 2.38V$, through the formula (2), the delay time is about 6.5uS. So the minimal period of self excitation signal source should be at least satisfying the formula (3).

$$T_{min} \geq 13uS \tag{3}$$

3.2.2. *Design of rectangular wave generating circuit.* Taking low cost into consideration, two Schmitt Inverters and a simple resistor capacitor are used to constitute a non-symmetrical multi harmonic oscillator, the output signal waveform of which is stable and easy to realize, as shown in Figure 6.

Its oscillation frequency is:

$$f = \frac{1}{T} = \frac{1}{2.2R_F C} \tag{4}$$

Through the analysis of RC delay circuit, if the T=50uS, RF=100K, by the formula (4) we have C ≈227pF and the nominal value C=220pF.

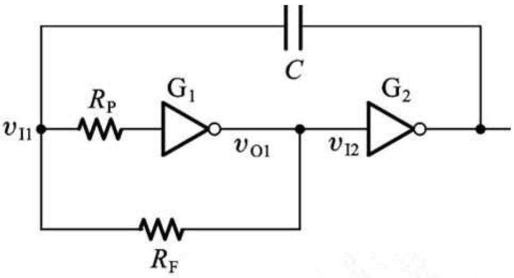

FIGURE 6. Asymmetric multivibrator /Asymmetric multi harmonic oscillator

3.2.3. *Design of F/V conversion circuit.* The circuit schematic diagram is shown in Figure 7. R1, C1, U1A, and U1B jointly generate the oscillation output square wave signal of the multi harmonic oscillator. The output signal is divided into two paths: one passes through R6, CX delay circuit and U1C phase-inverter; the other goes through U1F and U1E the two-stage complementary phase reversal. In order to realize the signal isolation, two paths of signals after flowing through the diode are reversed and superposed to output high level. R8 and C2 constitute the filter circuit, which is used to filter out a very narrow interference negative pulse. When there is no change in the dielectric capacitor, a high level signal is always generated; when the capacitor medium changes, CX increases, one path of signal is delayed, and the two paths of signal are no longer complementary, the narrow negative pulse with stable cycle is produced and transmitted to a signal processing circuit. The resistances R2, R3, R4, R5 and potentiometer RW1 constitute the duty cycle control circuit, which adjusts the sensitivity of the sensor by adjusting the duty ratio of the signal.

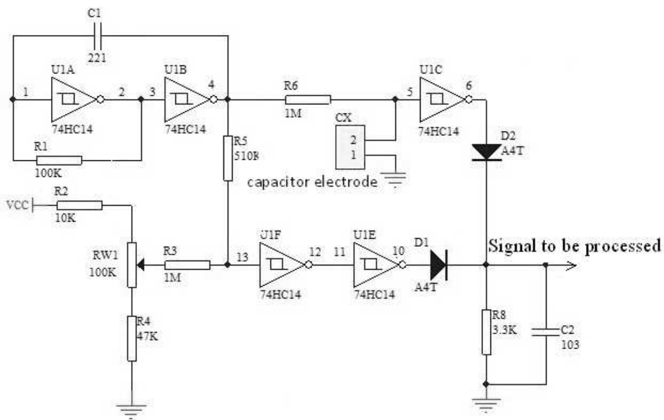

FIGURE 7. The square wave generating circuit and F/V conversion circuit

3.2.4. *Design of signal processing circuit.* When the object is close to the sensor plate (medium), the output frequency of the F/V circuit is fixed and the negative pulse width very narrow, which thus cannot be directly output to drive the load [12]. Consequently, the charging circuit composed of R9 and C3 and the discharge circuit consisting of R10 and C3, RC as well as the shaping circuit have to be used to absorb the narrow pulse, as shown in Figure 8.

Suppose the initial voltage value of the capacitor isV_0, V_1 is the eventual voltage value that can be charged or discharged into the capacitor, V_t the voltage value of time t, the time constant $\tau = RC$, we can obtain

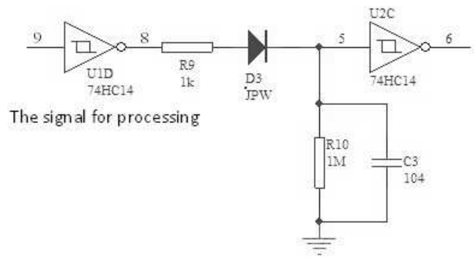

FIGURE 8. The signal for processing circuit

$$V_t = V_0 + (V_1 - V_0)\left(1 - e^{-\frac{t}{\tau}}\right) \tag{5}$$

As shown in Figure 8, after phrase-reversed by the inverter U1D, the negative pulse produced by the F/V conversion circuit becomes periodic rectangle wave with very small duty cycle and fixed frequency; the rectangular wave charges the capacitor C3 through a smaller resistor R9, whose charging time constant can be calculated by the following formula:

$$\tau_1 = R_9 C_3 = 1000 \times 0.1 \times 10^{-6} = 0.0001\,(S) \tag{6}$$

After charging and before the next periodic pulse, the capacitor C3 discharges through the resistance R10. Because the discharge time constant is:

$$\tau_2 = R_{10} C_3 = 10^6 \times 0.1 \times 10^{-6} = 0.1\,(S) \tag{7}$$

Derived from the formula (6) and (7), we have $\tau_1 << \tau_2$.

So, when inductive medium of the inductive electrode of the sensor changes, the voltage of the capacitor C3 stays at high level, and low level signal is output. Otherwise, when there is no medium change and no charging pulse, the voltage remains at low level and high level signal is produced.

This level, after the three stage inversion of U2C, U2E and U2D, controls Q2NPN triode′s OC gate in Figure 3-9 to turn off.

3.2.5. *Design of the output protection circuit.* In Figure 9, a 1.5 ohm resistor is connected to the output triode Q2′s emitter. When the output is overcurrent or short-circuited, with the increase of iE, the pressure drop on the resistance R16 is increased. If the increase is sufficient to enableQ1′s turn-on, the potential of the input end of the inverter U2F will drop, and the output end output the high level. By clamping the voltage of both ends of U2D and U2E through the diodes D5 and D6, U2D outputs low level to turn off Q2′s OC gate to fulfill the function of over-current protection. And the voltage regulator diode D9 plays the role of the output side over-voltage protection.

4. The debugging and experiment of the key circuit principle.

4.1. The square wave circuit debugging.

In order to make the sensor have a wider range of sensitivity adjustment, the period of the rectangular wave has to be reduced. Change the resistance R1 in Figure 7 from 100K to 47K and by formula (4), the oscillation frequency is as follows:

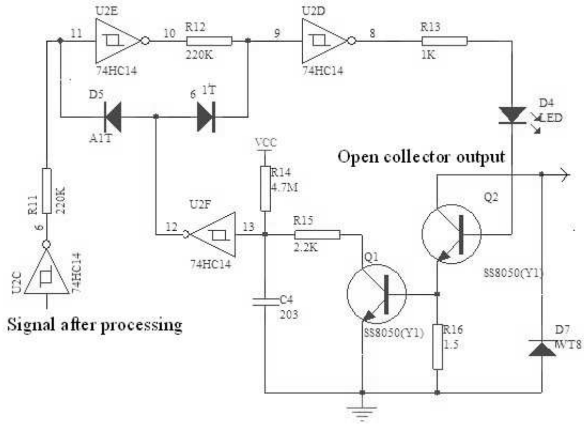

FIGURE 9. The output protection circuit

$$f = \frac{1}{T} \approx 44KHz \tag{8}$$

Figure 10 shows the measured capacitorC1′s charging and discharging waveforms of the multi harmonic oscillator. Figure 11 gives the output waveform of the multi harmonic oscillator, where the amplitude is about 5V, the frequency is $44.2KHz$, which are consistent with the calculated parameters.

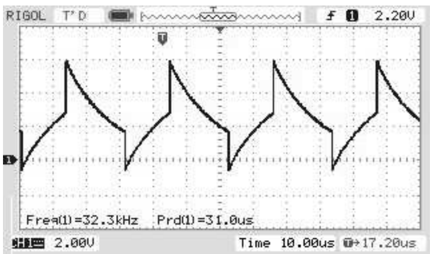

FIGURE 10. Capacitor charging and discharging waveform

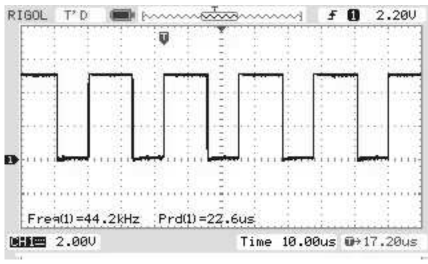

FIGURE 11. Multi harmonic oscillator output waveform

4.2. **Adjustment of the output signal in the case of medium change between the induction plates.**

4.2.1. *The output signal in the case of no medium change in the periphery of the induction plate.* Figure 12 shows the U1C and U1D output observed with a double trace oscilloscope. When there is no media change surrounding the induction plate, the two paths of signals are just complementary. Figure 13 presents the waveform superimposed on R8 of the two signals and the output is high level.

4.2.2. *The output signal in the case of medium change in the periphery of the induction plate.* When the induction plate is close to the object and the medium is changed, the capacitance C1′s capacity increases sufficiently to be able to trigger the switch of the following circuit. As can be seen from the Figure 14, when the induction plate is close to the object, the capacitance is significantly increased, which results in a significant backward delay in the CH2 waveform, and two paths of signal are no longer fully complementary.

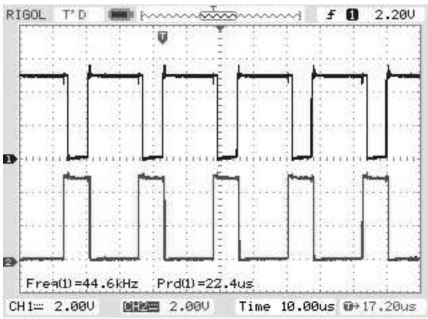

FIGURE 12. U1C and U1E output signal

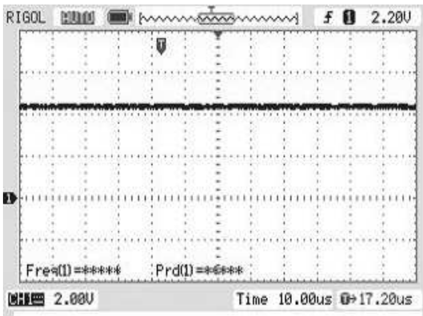

FIGURE 13. Superimposed voltage waveform

Figure 15 shows the waveform of the signal superimposed on R8, and the continuous negative pulse signal generated which is sufficient to trigger the switch level of the following circuit.

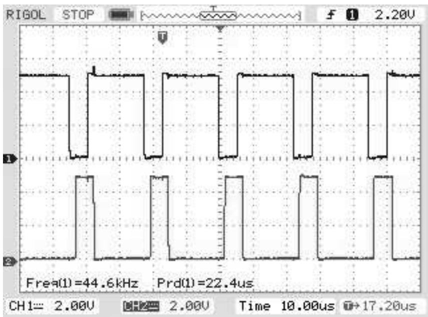

FIGURE 14. U1C and U1E output signal

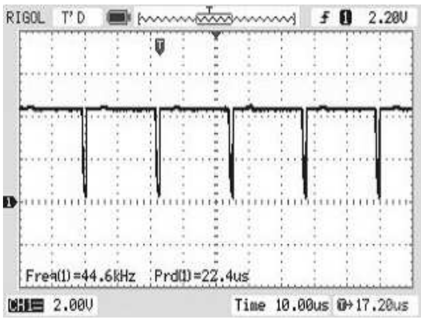

FIGURE 15. After the R8 overlay voltage waveform

4.3. **F/V conversion circuit and signal processing circuit debugging.**

4.3.1. *Treatment of very narrow pulse interference.* In some special occasions, there may be a tiny change of the output signals of U1D and U1C, which may produce the burr interference as shown in Figure 16. In that case, the resistor R9 of the signal processing circuit in Figure 8 could be adjusted from 1K to 2.2K, so as to effectively attenuate the burr interference brought by the F / V conversion circuit. Through the R9 attenuation, as could be seen in Figure 17, the sharp pulses are mostly flattened.

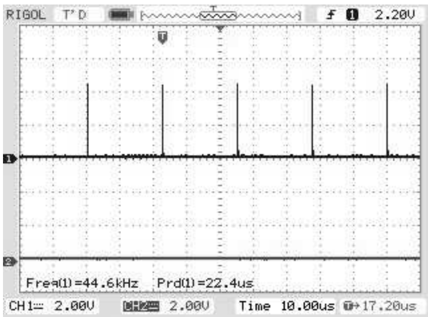

FIGURE 16. Signal interference burr

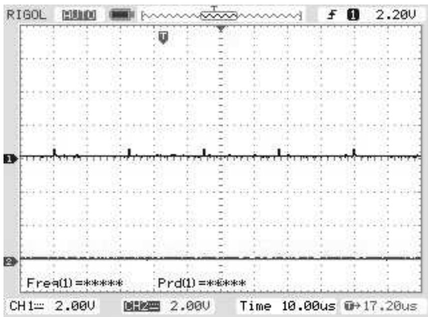

FIGURE 17. Burr signal after attenuation

4.3.2. *Output circuit.* The negative pulse in Figure 15, after going through the U1F inverter, remains in the same frequency, as shown in figure 18. The periodic sharp pulse charges capacitor C3 through D3. Due to the high impedance effect of D3 and Q1, C3′s charging and discharging time constants are of huge difference, resulting in voltage at both ends of the R10 remaining basically unchanged at a high level, which is consistent with the calculation obtained in section 2.3.4, as shown in Figure 19. As this high level continues to function at the gate of 2N7000, VGS=5V, $OD's$ gate is on, Dout′s output voltage low, and the indicator light off.

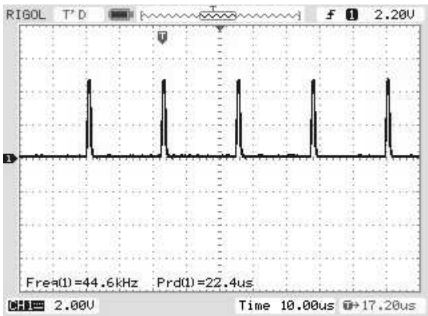

FIGURE 18. U1D invertin output spike

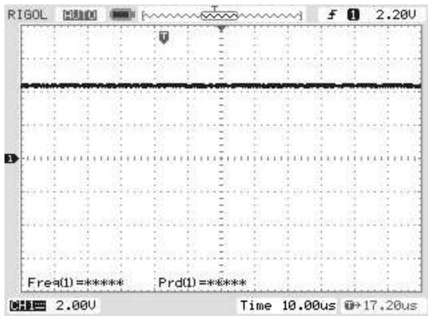

FIGURE 19. Voltage waveform on the R10

4.3.3. *Design and test of induction electrode.* For practical application, the two plates of the capacitor are turned into 180, as shown in Figure 20. The electric field lines between the plates are changed from straight ones to arc.

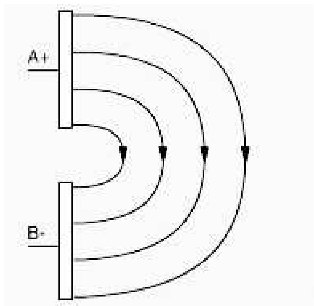

FIGURE 20. Capacitor plate

Of the two electrode plates of the expanded capacitor, one is connected with the resistance, and the other with the ground. When there is an object coming close to the plane of the two plates, due to the change of dielectric constant, the capacitance will change [9]. Therefore, the expansion of the capacitor plate will make the induction more convenient and be more practical [10]. Different shapes of the plates by way of corrosion affect the electric field distribution between the plates. Some induction plate samples are presented in Figure 21 and Table 1 presents the experimental records of maximal induction distances by using the induction plates in figure 5. The outer region of an induction plate is connected with the resistance R, and the inner with the ground.

The experiments were conducted at the same time, in the same location, and with the same medium change (water flowing through the plates). As indicated by the experimental results in Table 1, with the gaps between Plates 1, 2 and 3 enlarged somewhat, the induction distances become greater too. The larger the areas of the plates, as indicated

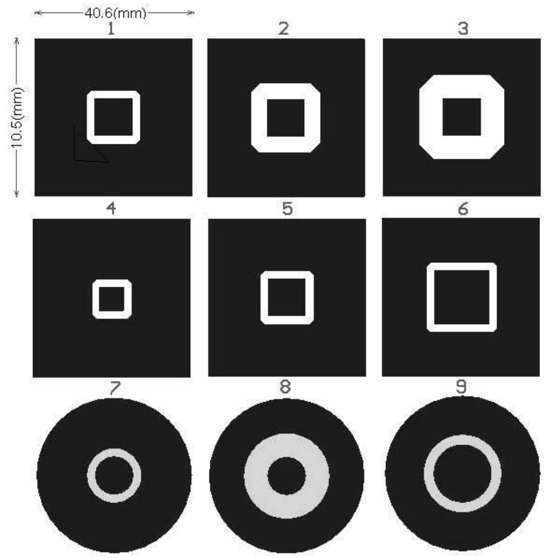

Figure 21. Induction plate samples

Table 1. Induction distance test record table

N_o	1	2	3	4	5	6	7	8	9
Maximal Induction Distancemm	3.0	11.8	30.2	1.0	5.5	20.1	1.9	19.0	15.8

by Plates 4, 5 and 6 (connected with the resistance R), the greater the measured induction distances are. The impact of the induction plate shapes as shown by the Plates 1 and 7, 2 and 8, 6 and 9 (round or square) on the induction distance is not obvious. In a word, it can be concluded that the shape and the size of the plate have greater influence on the sensitivity of the sensor.

5. Conclusions.

The capacitive sensor we design in the paper, in the case of non-contact, even if a small amount of water flows over or close to the surface of the plate, can be sensitive to the change of the media, and converted to the corresponding signal output. The model has the advantage that the shape of the induction plate can be changed at will and used in various occasions. For example, the induction plate can be made into a small round plane to detect whether there is any object approaching; it also can be made into a circular posted on the outside of a pipeline to monitor the flow of liquid inside; it can also be in strip shape to detect the liquid level. Another advantage is that the detection distance is adjustable, which means that our design can adapt to a wide range of operating voltages. However, this kind of sensor also needs to be prevented from interference, such as an object with a high dielectric constant from any direction when coming close to the sensor board can trigger the sensor action. To solve the problem, the feasible approach is to add a shielding to limit the range of induction.

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REFERENCES

[1] A. Q. Wang, The Analysis of the Situation, Characteristics and Tendency of Sensor in Testing Technology, *Journal of management*, Springer, vol.28,pp.389–389, 2013.

[2] S. H. Sun, Development trend of modern sensor, *Journal of Electronic Measurement and Instrument*, vol.23, no.1, pp.1–9, 2009.

[3] J. F. Liu, G. N. Yuan, and X. L. Gan, Research on the system for high precision-measurement rotor' surface, *Chinese Journal of Scientific Instrument*, vol.z2, pp.1650–1652, 2008.

[4] T. L. Xu, C. C. Li, The Analysis of the Situation and Tendency of Sensor and instrumentation, *Journal of Private Science and Technology*, vol.12, pp.216–216, 2011.

[5] A. A. Kazaryan, E. V. StrelTsov, A Thin-Film Capacitance Pressure Sensor, *Measurement Techniques*, vol.57, no.12, pp.1403–1410, 2015.

[6] I. Kadar, E. Blasch, C. Y. Chong. PROCEEDINGS OF SPIE Signal Processing, Sensor/Information Fusion, and Target Recognition XXIII Introduction *Proceedings of SPIE - The International Society for Optical Engineering*,2014

[7] B. Wang, S. Xu, H. Ji, et/al, Non-contact surface water conductivity measurement system, *Journal of Scientific Instrument*,vol.33, no.7, pp.1620–1625, 2012.

[8] E Zheng, Nicola Vitiello, Q. Wang, Gait phase detection based on non-contact capacitive sensing: Preliminary results, *Rehabilitation Robotics (ICORR), 2015 IEEE International Conference on*, 2015.

[9] N. A. R. Wan, Electrical capacitance tomography: a review on portable ECT system and hardware design, *Sensor Review*, vol.36, no.1, pp.64–70, 2016.

[10] S. P. Cermak, G. Brasseur, P. L. Fulmek, A planar capacitive sensor for angular measurement, *Instrumentation and Measurement Technology Conference, 2001. IMTC 2001. Proceedings of the 18th IEEE*, vol.2, pp.1393–1396, 2001.

[11] F. C Chang and H. C Huang, A Survey on Intelligent Sensor Network and Its Applications, *Journal of Network Intelligence*, Vol.1, no.1, pp.1–15, Feb 2016.

[12] J. X Zhang, B. Y. Sun, H. Z. Dai (eds.), High linear non-contact displacement capacitance sensor, *Instrument Technique and Sensor*, vol.1, pp.6–8, 2006.

[13] H. C Wu, S. C Huang and C. Y Lin, MEMS Sensors Applied in Finswimming Movement Analysis, *Journal of Computers and Applied Science Education*, Vol.2, No.1, pp.32-44, January 2015.

[14] S. Guha, K. Schmalz, W. Ch (eds.), Self-calibrating highly sensitive dynamic capacitance sensor: towards rapid sensing and counting of particles in laminar flow systems, *Analyst*, vol.140, no.7, pp.3262–3272, 2015.

[15] C. Binkowski, C. D. Paredes Crovato, Increasing sensitivity on non-contact voltage sensor using time-varying components: A numerical analysis for accuracy assessment, *AMPS*, 2015.

[16] X. Bao, J. Xu, C. Li (eds.), Temperature and frequency dependence of negative differential capacitance in a planar GaN-based p-i-n photodetector, *Journal of Alloys and Compounds*, vol.581, no.18, pp.289–292, 2015.

[17] J. Liu, Y. Jiang, and C. Ding, The high precision-measurement system of Gyro rotors surface, *Advanced Intelligent Mechatronics, 2008. AIM 2008. IEEE/ASME International Conference on. IEEE*, pp.1321–1324, 2008.

[18] C. S. S Babu, P. Manohar, Design of a low cost signal conditioning circuit for self-compensated non contact capacitive type multi threshold liquid level sensor, *Circuits, Communication, Control and Computing (I4C), 2014 International Conference on*, 2015.

[19] G. Peng, M. F. Bocko, A low noise, non-contact capacitive cardiac sensor, *Conference: International Conference of the IEEE Engineering in Medicine and Biology Society IEEE Engineering in Medicine and Biology Society Conference*, vol.2, pp.4994–4997, 2012.

[20] Z. Ren, W. Yang, A miniature two-plate electrical capacitance tomography sensor, *IEEE Sensors Journal*, vol.15, no.5 pp.3037–3049, 2015.