Capacitive Angle Sensor with Linear Current Output

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Abstract: A non-contact capacitive angle sensor was designed. Through capacitance convertor-integrated circuit CAV424 and voltage-current convertor -AM402 which developed by AMG in Germany, the signal of capacitive sensor is converted into standard industrial current output which from 4 to 20 mA. The system can realize angle non-contact measurement accurately from 0 to 90^0 with high linearity current output. It has anti-interference ability and can decrease error in measurement.

1. Introduction

In the field of modern industrial production and automatic control, angle measurement plays a crucial role. Angle measurement methods are divided into contact type and non-contact type. Non-contact measurement methods include resistance type, photoelectric type and capacitance type. Capacitive sensors have the advantages of fast dynamic response and high sensitivity, and can be widely used in measurement fields such as angle, displacement, pressure, liquid level and composition analysis [1~2]. Conventional differential capacitive angle sensors have limited measurement angles and are structurally flawed. The sensor needs a direct electrical connection between the moving piece and the outside, and the output electrode is respectively led out from the driven piece and the static piece. The moving piece lead-out electrode usually uses a bearing, a clip or a metal wire. During the rotation of the moving piece, not only the friction between the rotating shafts, but also the contact between the lead wire and the rotating shaft of the rotor is poor, mechanical failure occurs, interference and measurement errors are introduced, and the measurement accuracy is reduced [3~4].

For the design defects of the traditional capacitive angle sensor, the structure of the sensor has been improved to achieve true non-contact measurement and linear output.

2. Structural Design

The capacitive angle sensor is composed of a moving piece and a static piece, and the moving piece and the static piece have the same size. The moving piece consists of a central angle of 900 and a central angle with respect to two sector-shaped metal plates. The metal plates are connected in the middle; the static piece of the sensor consists of a central angle of 900 and a central angle with respect to two sector-shaped metal plates. The middle part is not connected. The electrode is taken out from the static piece and used as the signal output end of the angle sensor. The structural design and equivalent circuit of the sensor are shown in Fig. 1.

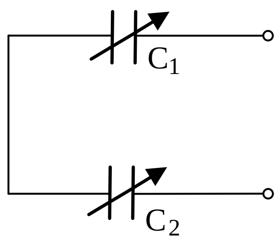

Figure 1 Sensor structure design and equivalent circuit

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It can be seen from Fig. 1 that the capacitive angle sensor can be regarded as a series connection of two variable capacitors. When the rotor rotates, the relative angle of the metal electrode of the metal plate between the rotor and the stator changes, causing the pole plate. The relative area changes to change the capacitance of the sensor. The sensor has a simple structure and effectively reduces the mechanical structure of the sensor. The design of the lead electrode from the static piece is convenient, which is beneficial to the change of the angle of the sensor, avoids the shaft friction and mechanical failure caused by the rotation during the angle measurement process, and the motor piece has no electrical connection with the outside world, and the parasitic capacitance is reduced. Produced, thus truly achieving contactless measurement, improving the accuracy of angle measurement.

3. Theoretical Analysis

Capacitive sensors utilize the relationship between the capacitance of an object and structural parameters. The plate capacitor is infinite, ignoring the edge effect of the capacitor, the capacitance is expressed as:

$$C = \frac{\varepsilon S}{d} = \frac{\varepsilon_0 \varepsilon_r S}{d} \tag{1}$$

Where ε_0 is the dielectric constant in vacuum (8.854×10-12); ε_r is the relative dielectric constant; S is the relative area of the plates and d is the plate distance. Therefore, the change in dielectric constant, relative area of the plate or the distance between the plates can be reflected as a change in the capacitance value, and the displacement of the object, the state parameter of the substance, and the like are measured according to this principle.

According to the structure shown in Fig. 1, the radius of the static diaphragm of the capacitive angle sensor is such that the distance between the movable piece and the static piece (ie, the distance between the plates) is the change amount of the relative area of the two equivalent capacitor plates. The angle of the moving piece relative to the static piece changes. In the initial state, the relative area between the moving piece and the static piece is zero; when the angle of the capacitive sensor changes, the relative area between the moving piece and the static piece changes, and the relative area of the two equivalent capacitor plates changes $\Delta S_1 = \Delta S_2 = \Delta S$.

$$\Delta C_1 = \frac{\varepsilon \Delta S_1}{d} \qquad \Delta C_2 = \frac{\varepsilon \Delta S_2}{d} \tag{2}$$

The total capacitance change is

$$\Delta C = \frac{1}{\frac{1}{\Delta C_1} + \frac{1}{\Delta C_2}} = \frac{\varepsilon \Delta S}{2d} \tag{3}$$

When $0 < \theta \leq 90^0$, the capacitance change of the capacitive sensor is

$$\Delta C = \frac{\varepsilon r^2}{4d}\theta \tag{4}$$

When $90^0 < \theta \leq 180^0$, the capacitance change of the capacitive sensor is

$$\Delta C = \frac{\varepsilon r^2}{4d}\left(180^0 - \theta\right) \tag{5}$$

When $180^0 < \theta \leq 270^0$, the capacitance change of the capacitive sensor is

$$\Delta C = \frac{\varepsilon r^2}{4d}\left(\theta - 180^0\right) \tag{6}$$

When $270^0 < \theta \leq 360^0$, the capacitance change of the capacitive sensor is

$$\Delta C = \frac{\varepsilon r^2}{4d}\left(360^0 - \theta\right) \tag{7}$$

It can be seen from Eq. (4)-(7) that the amount of change in capacitance changes periodically with an angle change. In any quadrant within the angular range of 0 to 360^0, the amount of change in capacitance is linear with the amount of change in angle. Therefore, take an angle from 0 to 90^0 for sensor measurement.

4. Capacitance Signal Measurement and Its Conversion Circuit

CAV424 is a versatile integrated circuit for processing various capacitive sensor signals. It can convert capacitive signals into voltage signals, and has the functions of signal acquisition (relative to capacitance change), processing and differential voltage output [5~7]. The chip is capable of measuring the difference between a measured capacitance and a reference capacitance, that is, a capacitance value ranging from 5% to 100% with respect to a reference capacitance value (10pf - 2nf), and converting it into a corresponding difference. The voltage output has high detection sensitivity; at the same time, the chip integrates a built-in temperature sensor, which can be used directly to monitor temperature when digital signal correction is required. Using CAV424 as a conditioning circuit for capacitive sensors, it can overcome the effects of parasitic capacitance and environmental changes, improving measurement accuracy and anti-interference ability. At the same time, the sensor has fewer external components, the processing circuit is relatively simple, and the instrument is small in size.

AM402 is an integrated circuit that handles differential signal input and current output interface. It can convert the input weak sensor differential voltage signal into two-wire output (4~20mA) or three-wire output (0/4~20mA) according to industry standards. The current signal [8] [9]. The AM402 consists of a high-precision preamplifier, a voltage-controlled current output stage, and an adjustable reference voltage. The high-precision preamplifier has a large gain adjustment range and is suitable for different signal input ranges and can be used for sensor signal processing in a variety of different ranges. The voltage-controlled current output stage allows the output current to be adjusted over a wide range by adjusting the bias voltage. The adjustable reference voltage provides 5V or 10V DC voltage to the sensor or external components.

The capacitive angle sensor measurement circuit designed in this paper is shown in Fig.2. The series connection of the variable capacitors C1 and C2 is the equivalent circuit part of the capacitance sensor.

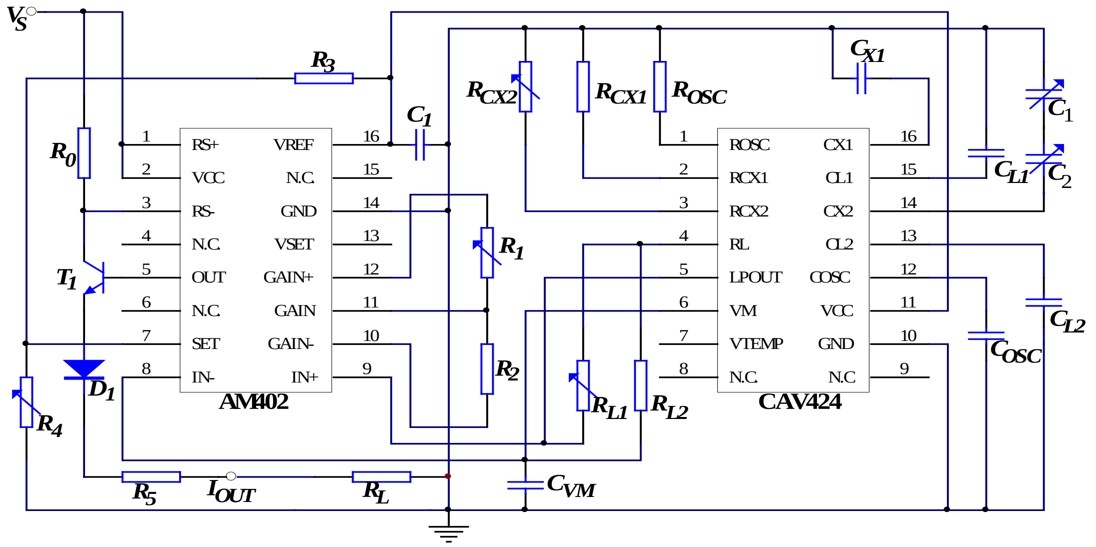

Fig. 2 Capacitive angle sensor measurement circuit

5. Experiment and Analysis

According to the value range of the output current of the three-wire system of the AM402, the external component of the capacitive sensor signal conversion integrated circuit chip CAV424 is adjusted so that the differential voltage value of the output is between 0 and 200 mV, that is, the voltage input to the voltage-current conversion interface circuit AM402. The value is in the range of 0 to 200 mV; the AM402 uses a three-wire output mode with a current output range of 4 to 20 mA. According to the theoretical analysis of the sensor, the output of the capacitive angle sensor increases linearly with increasing angle from 0 to 900. Therefore, the angle change region is taken in practical applications, and only 0 to 900 angles are measured during the measurement. The current can be output as the angle changes. The measurement results of the current output through the load as a function of angle are shown in Table 1.

Table. 1 Measurement results of current output of the load as a function of angle

Angle change θ/rad	Current output I_{OUT}/mA	Angle change θ/rad	Current output I_{OUT}/mA
0	4	9π/32	13.85
π/32	4.55	5π/16	15
π/16	5.4	11π/32	16.05
3π/32	6.3	3π/8	17.25
π/8	7.5	13π/32	18.4
5π/32	9	7π/16	19.2
3π/16	10.35	15π/32	20.55
7π/32	11.55	π/2	21.15
π/4	12.7		

According to the principle of least squares method, the experimental data is curve-fitted to obtain a linear fitting curve, as shown in Fig. 3.

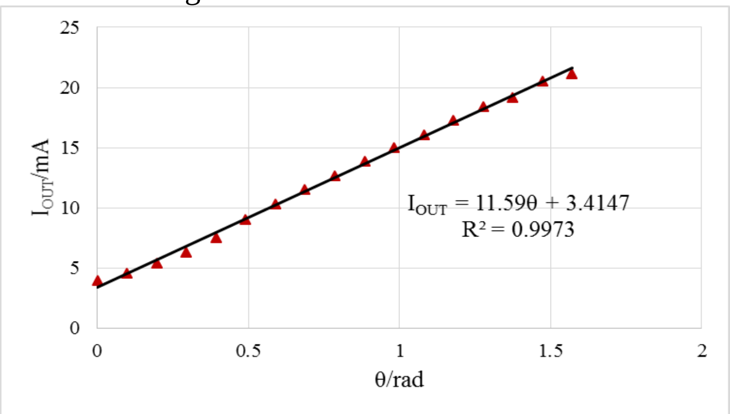

Fig.3 experimental data is curve-fitted to obtain a linear fitting curve

The curve fit is 0.9973, which is very close to 1, and the curve fit is good. As can be seen from Fig. 3, the actual measured value of the output current is linear with the amount of angular change. The experimental results show that the actual measured values are basically consistent with the theoretical values and are very close to the fitting curve; they are linearly output within the sensor angle changing range of 0 to 90^0.

It can be seen from the experimental results that the initial curve value of the output curve is slightly less than 4 mA compared with the actual measured value. This is because during the experiment, the integrated circuit AM402 is adjusted according to the actual output current value, so that the initial state bias current is 4 mA. During the adjustment process, the interference caused by the parasitic capacitance to the capacitance sensor is the initial value. The measurement results in errors. At the same time, the circuit CAV424, which converts the capacitance sensor signal into voltage, also has certain environmental interference and error. The output differential voltage is amplified by the preamplifier part inside the AM402, which will affect the output current value.

6. Conclusion

In summary, the novel capacitive angle sensor has a simple structure, high measurement accuracy, good linearity, high sensitivity, and fast dynamic response speed, and can accurately measure small angles in the range of 0 to 90^0, and is ideally obtained. The linear output DC current signal can be widely used in practical angle measurement and automatic control fields. By adopting shielding measures on the sensor itself and its external components, the interference of external interference to the system can be effectively reduced, thereby reducing the measurement error.

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