A Cylindrical Capacitance Sensor with Three Electrodes for Liquid-Level Measurement in Two Different Conditions

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In this paper, a practical sensing approach for monitoring the liquid-level in a container is presented. In this research we have developed a new structure sensor with three electrodes. When the container becomes inclined from vertical condition during measuring process, the liquid-level in the liquid container is determined correctly by detecting the change in capacitance between every two electrodes. In this process, a multidimensional regression equation based on experiment data is adopted. The result of this research proves that the designed sensor can be used to measure the liquid-level in the container unrelated to inclination.

Keywords : liquid-level sensor, capacitance sensor, regression analysis, inclination, multi-functional sensor

1. Introduction

Many kinds of sensors are installed for the liquid-level measurement, such as float type sensors, capacitance type sensors, resistant-shortcut type sensors, pressure difference type sensors, ultrasonic wave type sensors and so on.

Generally, conventional liquid-level sensors can be used to estimate the liquid-level very well in the case that the liquid-level detecting is performed in vertical condition of the container. But when the container becomes inclined from vertical condition in measuring process, the liquid-level condition inside will change. Therefore, the precise measurement of liquid-level using the general sensor becomes difficult. Popular methods adopted in practical application are omitting error induced from inclination of the container or using extra compensation assembly⁽¹⁾⁽²⁾.

When the container is inclined, true value of the liquid-level depends on three parameters without the consideration of temperature influence, liquid-level, inclined direction and inclined angle of the container.

As a common sense, different sensors are used when there are different variables to be sensed. Different from the popular technique, known as the compound sensing, multi-functional sensors have been developed in the last decade in case quantities measured more than one input signal. The schematic structure of measurement principle of a multi-functional sensor is shown in Fig.1, where x_1 and x_2 are two quantities under test, with the processing results x'_1 and x'_2 being their estimations⁽³⁾.

Structure with two electrodes can bring out big error when the container becomes inclined from vertical condition during measuring process. Structure with three or more electrodes can be adopted in corresponding to theoretical method, but the structure with the more electrodes has more complicated measurement and calculation. Considering the background of above mentioned studies, therefore we propose a new structure sensor with three electrodes⁽⁴⁾⁽⁵⁾, which detects the change of capacitance between every two electrodes, of which values are obtained at the same time. Actually the three capacitance values include both

Fig. 1. Measurement principle of a multi-functional sensor with two quantities.

information of the liquid-level in the liquid container and status of the container. Therefore, through analyzing experiment data using multidimensional regression analysis, the true value of the liquid-level can be obtained unrelated to the inclination.⁽⁶⁾

2. Structure and principle

The structure of our proposed sensor is shown in Fig. 2, where a plastic pipe is used as body of the sensor. Three rectangular copper plates in same size are pasted as three electrodes on the inside of the plastic pipe from bottom to top and another copper plate is pasted as shielding of the sensor on outside of the plastic pipe.

The measurement principle of our proposed sensor is shown in Fig. 3. In this experimental process, a regression equation based on all calibration data is obtained by using the method called multidimensional regression analysis, and then the regression equation is used to estimate unknown liquid-level by measured capacitances C_1 , C_2 and C_3 . Here C_1 , C_2 and C_3 are capacitances between Electrode#1 and Electrode#2; Electrode#1 and Electrode#3; Electrode#2 and Electrode#3, respectively.

The multidimensional regression analysis process is shown as follows.

Normally, the true value L of the liquid-level (The L is defined as vertical distance from surface of the liquid to bottom of the container in the vertical condition.) can be described by (1) in vertical condition, which means the L can be estimate only using the capacitance C_1 very well. But in inclined condition, the L isn't only decided by C_1 but also depends on D and A . Only using (1) to estimate the L will bring out big error, therefore, in this case the L expressed by (2) is sufficient.

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Fig. 2. Structure of the sensor.

Fig. 3. Sensing Principle of proposed sensor.

$$L_o = F_1(C_1) \quad (1)$$

There, L_o: estimated liquid-level to L

$$L_o = F_2(C_1, C_2, C_3) \quad (2)$$

Then (2) can be described by a three-dimensional regression equation as follows.

$$L_o = \alpha_0 + \alpha_1 C_1 + \alpha_2 C_2 + \alpha_3 C_3 + \alpha_4 (C_1)^2 + \alpha_5 C_1 C_2 + \alpha_6 (C_2)^2 + \alpha_7 C_1 C_3 + \alpha_8 C_2 C_3 + \alpha_9 (C_3)^2 + \varepsilon \quad (3)$$

where,

$\alpha_0 \sim \alpha_9$: constants

ε : higher order infinitely small

Because it is linear relationship between the L and the capacitances in our case, so higher order part in (3) is actually very small, and then this part can be omitted and obtain (4) as follows.

$$L_o = \alpha_0 + \alpha_1 C_1 + \alpha_2 C_2 + \alpha_3 C_3 \quad (4)$$

Here a deviation Δ_k exists between true value L_k and calculated value L_o (C_{1k} , C_{2k} , C_{3k}) by (4) at a random calibration point. Its variance $(\Delta_k)^2$ is given by (5).

$$(\Delta_k)^2 = [L_k - L_o(C_{1k}, C_{2k}, C_{3k})]^2 \quad (5)$$

In total m points are selected as calibration point, its mean square

deviation R should be minimum value. We can get

$$\begin{aligned} R &= \frac{1}{m} \sum_{k=1}^m [L_k - L_o(C_{1k}, C_{2k}, C_{3k})]^2 \\ &= \frac{1}{m} \sum_{k=1}^m [L_k - (\alpha_0 + \alpha_1 C_{1k} + \alpha_2 C_{2k} + \alpha_3 C_{3k})]^2 \\ &= f(\alpha_0, \alpha_1, \alpha_2, \alpha_3) \quad (6) \end{aligned}$$

From (6), R is function of $\alpha_0 \sim \alpha_3$. According to the condition of analyzing extreme value to a function of several variables, let following partial derivatives equal zero, we have

$$\begin{aligned} \frac{\partial R}{\partial \alpha_0} &= 0 & \frac{\partial R}{\partial \alpha_1} &= 0 \\ \frac{\partial R}{\partial \alpha_2} &= 0 & \frac{\partial R}{\partial \alpha_3} &= 0 \end{aligned}$$

Then four equations are given by (7).

$$\left\{ \begin{aligned} \alpha_0 m + \alpha_1 \sum_{k=1}^m C_{1k} + \alpha_2 \sum_{k=1}^m C_{2k} + \alpha_3 \sum_{k=1}^m C_{3k} &= \sum_{k=1}^m L_k \\ \alpha_0 \sum_{k=1}^m C_{1k} + \alpha_1 \sum_{k=1}^m C_{1k}^2 + \alpha_2 \sum_{k=1}^m C_{1k} C_{2k} + \alpha_3 \sum_{k=1}^m C_{1k} C_{3k} &= \sum_{k=1}^m C_{1k} L_k \\ \alpha_0 \sum_{k=1}^m C_{2k} + \alpha_1 \sum_{k=1}^m C_{1k} C_{2k} + \alpha_2 \sum_{k=1}^m C_{2k}^2 + \alpha_3 \sum_{k=1}^m C_{2k} C_{3k} &= \sum_{k=1}^m C_{2k} L_k \\ \alpha_0 \sum_{k=1}^m C_{3k} + \alpha_1 \sum_{k=1}^m C_{1k} C_{3k} + \alpha_2 \sum_{k=1}^m C_{2k} C_{3k} + \alpha_3 \sum_{k=1}^m C_{3k}^2 &= \sum_{k=1}^m C_{3k} L_k \end{aligned} \right. \quad (7)$$

With known L_k , C_{1k} , C_{2k} , C_{3k} , (7) can be analyzed and $\alpha_0 \sim \alpha_3$ will be obtained. Therefore (4) will be defined, then a unknown liquid-level will can be estimated by (4) using the capacitances C_1 , C_2 and C_3 .

3. Experiments

In order to obtain a model equation of the sensor to a liquid sample on different conditions, and investigate the identification result, the experiment using a gasoline sample as liquid is performed at a constant environment temperature of 25°C.

1) A fixed level of sample liquid is poured into the sensor, and then the sensor is sealed. Here three liquid-levels of sample are selected as a calibration liquid-level L (50, 100, 150 mm).

2) The sensor is slanted to 10, 20, 30 and 40 degree from vertical condition on four different directions X+, X-, Y+, and Y- indicated in Fig.4.

3) The capacitances C_1 , C_2 and C_3 are obtained with a LCR meter at frequency of 100 KHz on every calibration point. Calibration data in L=50 mm are shown in Figs. 5, 6, 7, 8.

Fig.5 shows changes of the capacitances C_1 , C_2 and C_3 when the sensor is slanted from vertical case to X+ direction with 10, 20, 30 and 40 degree, respectively. Here we defined C_0 is output value of the sensor when the sensor is located in vertical case. C_x is a capacitance value at radom calibration point. When the sensor is slanted with increasing of inclined angle to X+ direction, the liquid sample in the sensor move to the same direction. We can predict that the capacitances C_1 and C_3 will increase with increasing of inclined angle, but capacitance C_2 will decrease. The experimental results in Fig.5 indicate this trend.

Fig.6 shows the experimental trends of the capacitances C_1 , C_2

X+, X-, Y+, and Y-: selected calibration directions

Fig. 4. Inclined direction of sensor for calibration (top view).

Fig. 5. Response of the sensor for different inclined angles to the X+ inclined direction.

Fig. 6. Response of the sensor for different inclined angles to the X- inclined direction.

and C_3 when the sensor is slanted from vertical case to X-direction. This is opposite direction with X+ direction case, so C_1 and C_3 should decrease and C_2 should increase with increasing of inclined angle. The indicated trends in Fig.6 and analyzed results are same.

Fig.7 shows the response of the sensor when the sensor is slanted to Y+ direction. In this case, the sample liquid will move to Y+ direction, therefore capacitance C_1 will increase, and as opposite case capacitance C_3 will decrease. For capacitance C_2 should not change, because C_2 always locate in a symmetric state in the whole, the inclination on Y+ direction can't induce change of C_2 . Fig.7 shows a similar experimental result with our analysis.

Fig.8 shows response of the sensor when the sensor is slanted to Y- direction. For the opposite case, the response of the sensor will be opposite with in Y+ direction. That means C_1 should

Fig. 7. Response of the sensor for different inclined angles to the Y+ inclined direction.

Fig. 8. Response of the sensor for different inclined angles to the Y- inclined direction.

D1, D2: selected testing direction

X+, Y+: selected calibration directions

Fig. 9. Inclined direction of sensor for testing (top view).

decrease, C_2 does not change and C_3 should increase with increasing inclined angle. Fig.8 shows a analyzed trends.

4) A regression equation is obtained based on all calibration data as follows:

$$L_o = -294.01 + 20.85 \times C_1 + 14.28 C_2 \times 2 + 22.99 \times C_3 \quad \dots (8)$$

5) Tested result by (8)

In order to verify (8), other experiment data for testing, which are obtained when the sensor is slanted to D1 and D2 direction indicated in Fig.9 in different inclined angle using the L of 75, 125 mm, respectively, are used and the results are shown in Figs. 10, 11.

Fig. 10 and Fig. 11 show a good agreement between the calculated values by (8) and true values. When the true value of

Fig. 10. Estimating result for different inclined angles to the D1 inclined direction.

Fig. 11. Estimating result for different inclined angles to the D2 inclined direction.

liquid-level in the liquid container is constant, the estimated liquid-level approaches the true value. The inclined angle and inclined direction of the liquid container have little effect on the proposed sensor.

4. Results and Discussion

The response of the sensor to different liquid-level conditions is quite satisfactory. The tested results to the regression equation are almost expected straight lines unrelated to the inclination. In order to use this sensor for the determination of the L in different conditions, a regression equation should be prepared, and then true value of an unknown liquid-level can be estimated by the regression equation.

From Figs.5, 6 and Figs.7, 8, we can see some experiment errors exist such as curves of C_2 in Figs.7, 8 have little slope. We think main errors come from two aspects. One comes from the sensor to be hand made, so the symmetry of three electrodes is limited and distances between edges of every two electrodes are also not completely same. Another one should come from experimental method; for example, accuracy used liquid-level, inclined angle and direction in experimental process. Moreover the computation error in regression process and random error in experimental process also existed. The errors could be further restrained by improving the technological manufacture level of the

sensor and the accuracy of measurement system.

During our research the proposed sensor is tested in a constant temperature condition. In many cases the temperature is actually an important influence factor. Under this condition the influence have to be considered. Therefore, for the temperature compensation a new plan is necessary. This is our work now.

In this research, the most important point is how to obtain a best regression equation. Therefore, more calibration points are needed to improve the equation.

5. Conclusion

In this paper a new approach for the liquid-level measurement with a new structure was proposed. The liquid-level sensor has a very simple structure with a practical function. As its expected application that the sensor is tested for sample liquid in different conditions, with three electrodes fixed on inside of the pipe, the true value of the liquid-level in the liquid container is detected unrelated to the inclination condition of the container. We can conclude from experimental results that this sensor can be used as a monitoring apparatus to measure the true value of the liquid-level in two different conditions.

(Manuscript received Sept. 22, 2003, revised Dec. 24, 2003)

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