DESIGN AND EVALUATION OF A SINGLE-TUBE CROSS-CAPACITANCE FUEL LEVEL SENSOR

by

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In order to improve the accuracy and reduce the weight of the cross-capacitor fuel level sensor, a novel single-tube cross-capacitor fuel level sensor is designed. Specifically, the fuel level measurement model of the single-tube cross-capacitance sensor is established, and the relationship between the measured liquid level and the sensor output capacitance is derived. Then, a finite element analysis model is constructed to solve the capacitance output of the sensor. The results of experiments conducted demonstrate that the output capacitance value of the designed single-tube cross-capacitive sensor changes linearly in the range 0-14 pF, with linearity ± 0.8%, hysteresis error ± 0.1%, and maximum reference error –1.0% FS at a liquid level of 120 mm. The optimized structural parameters were as follows: plate gap angle $\theta = 2^o$, quartz tube inner radius $R_0 = 11.5$ mm, quartz tube thickness $R_1 - R_0 = 1.6$ mm, and sensitivity = 0.0723 pF/mm (representing an 11.1% increase after optimization). The cross-capacitive fuel level sensor developed in this study is both lightweight and high precision.

Key words: *single-tube sensor, cross-capacitance, liquid measurement, fuel level sensor, finite element model, capacitance output*

Introduction

With the deepening of scientific research in the aerospace field, liquid fuel is gradually replacing solid propellant, owing to the former's advantages of high specific impulse, adjustable thrust, as well as clean and non-polluting combustion products, and is widely used in satellites, spacecraft, and other aircraft [1]. The real-time and accurate measurement of the fuel level will directly influence the safety and stability of aircraft. The technology used to measure liquid level is based on a liquid level-sensitive component, whose physical characteristics change with the level of the liquid. Measurement of liquid level is realized by signal processing that converts the changed physical quantity into the liquid level, which is then displayed [2, 3]. To measure fuel level in the field of aerospace, a capacitive liquid level sensor is mostly used that has strong adaptability, exhibits good temperature stability, and can withstand a harsh measurement environment. However, presently used capacitive liquid level sensor is composed of two poles, and its structure is cumbersome [4].

In traditional capacitive liquid level sensors that have been commercialized, and advanced intelligent technologies are applied. For example, Universal IITM continuous level transmitter developed by Drexelbrook has a maximum range of 15 m and an accuracy of 0.1%.

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Honeywell's capacitive level measurement technology uses a proprietary patented Honeywell intelligent communication protocol with a high degree of automation. Stanley combined capacitor and inductor technology to develop a wireless liquid level sensor that can be adapted to low-temperature environments. Lee used a cross-capacitor structure to measure the dielectric constant of a liquid with a standard uncertainty of ± 0.02%. Pozo proposed a cylindrical structure that uses four electrodes to monitor liquid level and angle changes. Four sets of electrodes are connected in parallel to form a set of measuring electrodes to measure liquid level [5]. However, the liquid level data in this case are not adequate, and the influence of shape error during processing cannot be eliminated.

Because the traditional capacitive liquid level sensor has the problem of large area and low precision, it is not suitable for wide application in practice, so it should be improved and innovated. In this paper, a high-precision and lightweight fuel level sensor is designed based on the principle of single-tube capacitance calculation, so as to better adapt to fuel level measurement in aerospace, petrochemical and other industries and promote the continuous development and progress of the industry.

Design and evaluation of single-tube cross capacitor fuel level sensor

The calculation model of single pipe structure is constructed

Considering the actual situation of liquid fuel level measurement, the metal electrode needs to be plated on the quartz tube as a supporting structure of the designed cross-capacitance fuel level sensor [6]. That is, the insulating tube with a certain thickness is coaxially placed in a single dielectric capacitor, and the insulating tube is insulated. It is necessary to analyze the deformed calculated capacitance structure and take into account the regions of different dielectric constants to obtain a new formula for calculating output capacitance. Assuming that one of the electrodes has a unit potential, the potential distribution can be obtained by using the Laplace equation:

$$V(r,\theta)=\frac{1}{4}+\sum_{m=1}^{\infty}\frac{\left[4\varepsilon_w+(\varepsilon_w-1)^2K_m\right]\left(\dfrac{r}{R_2}\right)^m-(\varepsilon_w^2-1)K_m\left(\dfrac{R_2}{r}\right)^m}{\left[4\varepsilon_w+(\varepsilon_w-1)^2K_m\right]\left(\dfrac{R_3}{R_2}\right)^m-(\varepsilon_w^2-1)K_m\left(\dfrac{R_2}{R_3}\right)^m}\cos m\theta \tag{1}$$

where $R_i=(1/2)D_i$ $(i=1,2,3)$, R_1 is the radius of the inner wall of the insulating tube, R_2 – the radius of the outer wall of the insulating tube, and R_3 – the radius of the outer wall of the sensor after coating.

Then the charge density is given by:

$$D_r=-\varepsilon_0\frac{\partial V}{\partial r}=\sum_{m=1}^{\infty}-\frac{2\varepsilon_0\sin\left(\dfrac{m\pi}{4}\right)\cos m\theta}{\pi}\frac{r^{m-1}}{R_3^m}\frac{1+\dfrac{(\varepsilon_w^2-1)K_m}{4\varepsilon_w^2+(\varepsilon_w-1)^2K_m}\left(\dfrac{R_2}{r}\right)^{2m}}{1-\dfrac{(\varepsilon_w^2-1)K_m}{4\varepsilon_w+(\varepsilon_w-1)^2K_m}\left(\dfrac{R_2}{R_3}\right)^{2m}} \tag{2}$$

The total amount of charge Q of the surface of the casing ($R = R_3$) is:

$$Q = \int_{3\pi/4}^{5\pi/4} D_r(\theta)\mathrm{d}\theta \tag{3}$$

The capacitance value is given by:

$$C = Q = -\frac{\varepsilon_0}{\pi}\int_{3\pi/4}^{5\pi/4}\sum_{m=1}^{\infty}\frac{r^{m-1}}{R_3^m}\left\{1+\frac{\varepsilon_w^2-1}{4\varepsilon_w}\left[1-\left(\frac{R_1}{R_2}\right)^2\right]\left[\left(\frac{R_2}{r}\right)^{2m}+\left(\frac{R_2}{R_3}\right)^{2m}\right]\right\}\cdot \\ \cdot\left[\sin m\left(\frac{\pi}{4}+\theta\right)+\sin m\left(\frac{\pi}{4}-\theta\right)\right] \tag{4}$$

When $U = 1$, the cross-capacitance C of a unit length between a set of electrodes is :

$$C = \frac{\varepsilon_0 \ln 2}{\pi}\left\{1+\frac{{\varepsilon_w}^2-1}{2\varepsilon_w \ln 2}\ln\left[\frac{\left\{1+\left(\frac{R_2}{R_3}\right)^2\right\}^2\left\{1+\left(\frac{R_1}{R_3}\right)^4\right\}}{\left\{1+\left(\frac{R_2}{R_3}\right)^4\right\}\left\{1+\left(\frac{R_1}{R_3}\right)^2\right\}^2}\right]\right\} \tag{5}$$

When the capacitor is completely placed in the air, the theoretical capacitance $C_a^{'}$ of the output per unit length of the capacitor is written:

$$C_a' = C_a(1+k_a) = \frac{\varepsilon_0\varepsilon_a}{\pi}\ln 2\left\{1+\frac{\left(\frac{\varepsilon_w}{\varepsilon_a}\right)^2-1}{2\left(\frac{\varepsilon_w}{\varepsilon_a}\right)\ln 2}\ln\frac{\left\{1+\left(\frac{R_2}{R_3}\right)^2\right\}^2\left\{1+\left(\frac{R_1}{R_3}\right)^4\right\}}{\left\{1+\left(\frac{R_2}{R_3}\right)^4\right\}\left\{1+\left(\frac{R_1}{R_3}\right)^2\right\}^2}\right\} \tag{6}$$

where k_a is the correction factor in air, ε_0 – the dielectric constant of vacuum, ε_w – the relative dielectric constant of the insulating tube material.

The theoretical capacitance, C_l', of unit length capacitor output when the capacitor is completely placed in a medium with a dielectric constant ε_l is calculated:

$$C_l' = C_l(1+k_l) = \frac{\varepsilon_0\varepsilon_l}{\pi}\ln 2\cdot\left\{1+\frac{\left(\frac{\varepsilon_w}{\varepsilon_l}\right)^2-1}{2\left(\frac{\varepsilon_w}{\varepsilon_l}\right)\ln 2}\ln\frac{\left\{1+\left(\frac{R_2}{R_3}\right)^2\right\}^2\left\{1+\left(\frac{R_1}{R_3}\right)^4\right\}}{\left\{1+\left(\frac{R_2}{R_3}\right)^4\right\}\left\{1+\left(\frac{R_1}{R_3}\right)^2\right\}^2}\right\}\cdot l \tag{7}$$

Design of the single-tube cross-capacitance fuel level sensor

According to the derivation of the mathematical model of the single-tube cross-capacitance structure, the single-tube cross-capacitance fuel level sensor is designed. The

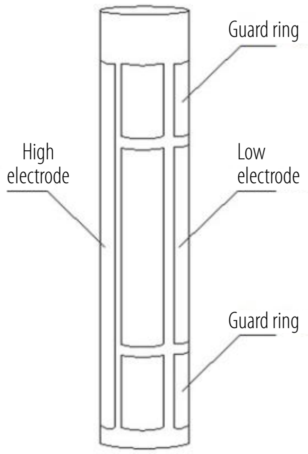

Figure 1. Structure of the cross-capacitance fuel level sensor

structure of the cross-capacitance fuel level sensor as shown in fig. 1. The new sensor uses a quartz tube as a support structure, and a metal plating layer is plated on the outer wall of the quartz tube as an electrode. The metal plating layer is divided into a protective electrode by a scribe line and two sets of high and low electrodes [7-9]. The high electrode and the low electrode constitute a calculated capacitance structure for measurement. The guard ring serves as an equipotential ring to reduce the edge effect and improve sensitivity.

When the sensor works, parts of the sensor are immersed in the liquid to be tested (dielectric constant ε_l), while others are immersed in air. When the measurement range is l, the measured fuel level is l_x, the total output capacitance, C_x, of the sensor is the sum of the sensor capacitance, C'_{a1}, of the exposed air portion and the capacitance, C'_{a1}, of the portion of the fuel being immersed:

$$C'_{a1} = \frac{\varepsilon_0 \varepsilon_a}{\pi} \ln 2 \left(1 + k_a\right)\left(l - l_x\right) \tag{8}$$

$$C'_{l1} = \frac{\varepsilon_0 \varepsilon_l}{\pi} \ln 2 \left(1 + k_l\right) l_x \tag{9}$$

When measuring the fuel level, the output capacitance of the sensor is expressed:

$$C_x = C'_{a1} + C'_{l1} = C'_a - \frac{\varepsilon_0 \varepsilon_a \ln 2}{\pi}(1 + k_a) l_x + \frac{\varepsilon_0 \varepsilon_l \ln 2}{\pi}(1 + k_l) l_x \tag{10}$$

The measured fuel level is given:

$$l_x = \frac{(C_x - C'_a)}{\left(C'_l - C'_a\right)} l = \frac{l}{C'_l - C'_a} C_x - \frac{C'_a l}{C'_l - C'_a} \tag{11}$$

The measured fuel level is only affected by the dielectric constant of the fuel being tested, the inner and outer diameters, and measurement ranges of the sensor. When the sensor is fabricated, the influencing factors will not change, and the measured fuel level varies linearly with the sensor output capacitance.

The finite element analysis model of single tube cross capacitance sensor is constructed

Inorder to obtain better parameters of the sensor, we use the finite element analysis to calculate the electrostatic field inside the sensor when the capacitive liquid level sensor is used with anhydrous ethanol as the measured liquid, and the capacitance output of the sensor is solved. Using APDL to write a finite element analysis program for cross-capacitance liquid level sensors, we obtain the relationship between sensor structure parameters and output capacitance values quickly and effectively.

Using the first type of boundary condition (Dirichlet condition), excitation voltage U is applied to two adjacent excitation plates i of the sensor (clockwise $i = 1, 2$) and the remaining two adjacent detection plates j (counterclockwise j = 1, 2), and the voltage on shield layer, s, is zero. The expression of the potential function is:

$$\varphi(x,y)=\begin{cases}U, & (x,y)\in X_i(i=1,2)\\ 0, & (x,y)\in X_j(j=1,2)+X_s\end{cases} \tag{12}$$

where $X_i(i=1,2)$, $X_j(j=1,2)$, and X_s is a set of two excitation plates, two detection plates, and nodes on the shield. The induced charge $Q_{ij}(i\neq j)$ between each pair of excitation-detection plates can be calculated:

$$Q_{ij}=\oint_{(x,y)\in\Gamma_j}\varepsilon_0\varepsilon(x,y)\vec{E}(x,y)\vec{n}\,\mathrm{d}\Gamma_j \tag{13}$$

where ε_0 is the dielectric constant of vacuum, ε – the dielectric constant of the liquid under test, Γ_j – the integral path defined counterclockwise along the edge of the detector plate, $\vec{n}$ – the unit normal vector of curve Γ_j, and $\vec{E}$ – the mapping of the electric field on the integration path.

Therefore, in the axial unit length, the capacitance $C_{ij}(i\neq j)$ between each pair of excitation-detection plates is given:

$$C_{ij}=\frac{Q_{ij}}{U} \tag{14}$$

where U is the excitation voltage applied to the excitation plate.

Then, the capacitance between the two pairs of excitation-detection plates is averaged to obtain the simulated output capacitance of the sensor per unit length:

$$C=\frac{C_{12}+C_{21}}{2} \tag{15}$$

In the 2-D electrostatic field simulation, the simulated output capacitance of the sensor per unit length is the sensitivity of the sensor (the change in the output capacitance of the sensor caused by the change of the unit liquid level). Sensitivity is used as the sensor structure parameter in simulation analysis. The higher the sensitivity value, the more sensitive the sensor is to the change in the liquid level.

Single tube cross capacitor fuel level sensor evaluation

In order to verify the practical application effect of the single-tube cross-capacitor fuel level sensor, it is necessary to evaluate it. Experimental scheme: set up the experimental environment, sample data are from real experimental data, test the accuracy and sensitivity of the designed sensor, and draw the experimental results.

Liquid level measurement experiment

We set up the measurement equipment as shown in fig. 2. The sensor is affixed using a bracket and a clamp in a 250 mL measuring cylinder. A film ruler with a minimum graduation value of 0.5 mm is attached to the outer wall of the cylinder to determine the current measured liquid level. The sensor output capacitor value is measured by a TH2617 capacitance-measuring instrument that measures capacitance with a minimum resolution of 0.0001 pF. An absolute concentration of 99.8% absolute ethanol was used as the liquid to be tested. Under the experimental conditions of test level 1 V, test frequency 100 kHz, and measurement data 10 times the average, the capacitances C_{11} and C_{22} were measured, respectively, and the average was taken as the sensor output capacitance value C. Before the test, the sensor was calibrated with a liquid level of 0 mm to eliminate the influence of stray capacitance and electromagnetic noise on capacitance measurement. During the measurement, a 10 mL dropper was used to increase the liquid level by 20 mm each time. When the liquid level stabilized, *Start* was clicked and the capacitance reading recorded.

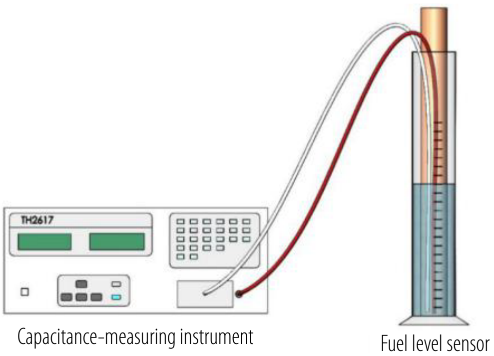

Figure 2. Measurement equipment

The input-output characteristic curve of the cross-capacitive liquid level sensor during the forward-reverse mode is shown in fig. 3. When the liquid level changes from 0 to 200 mm at intervals of 20 mm, the output capacitance value C changes linearly from 0 to 14 pF.

The output capacitance value C is linearly fitted by using the least squares, and the fitted straight line is:

$$y = 0.0651x + 0.0354 \tag{16}$$

Comparing the sensor's input-output characteristic curve with the fitting curve, the maximum deviation between the two is the maximum nonlinear error $\Delta_{L\max}$ pF. The full-scale output is y_{FS} =13.12 pF, and the linearity of the capacitive level sensor can be calculated:

$$\gamma_L = \pm\frac{\Delta_{L\max}}{y_{FS}}\cdot 100\% = \pm 0.8\% \tag{17}$$

Comparing the forward and reverse stroke output and input characteristic curve of the liquid fuel level sensor, the maximum difference between the forward and reverse stroke output is Δ_{Hmax} pF. The full-scale output is y_{FS} =13.12 pF, and the hysteresis error of the capacitive level sensor can be calculated:

$$\gamma_H = \pm\frac{1}{2}\frac{\Delta_{H\max}}{y_{FS}}\cdot 100\% = \pm 0.1\% \tag{18}$$

Figure 4 shows the measurement error curve of the sensor. The liquid level sensor has a maximum reference error of –1.0% FS at a liquid level of 120 mm. The measurement error is

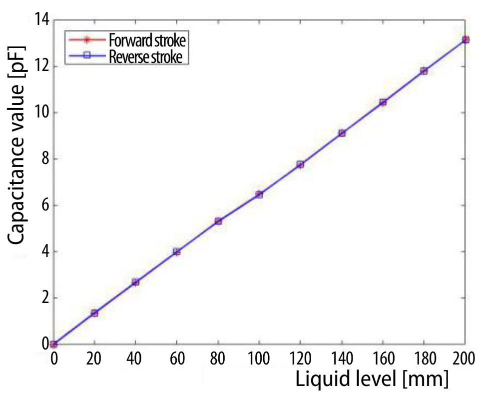

Figure 3. The input-output characteristic plot

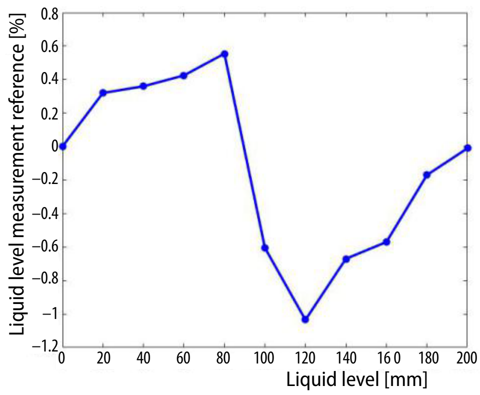

Figure 4. Measurement error plot

approximately symmetrical with respect to the midpoint of the range. The error in the first half is positive and the error in the second half is negative. Because of the system error caused by the front and rear half-range structure and process asymmetry of the sensor, the liquid level measurement error is small near the two ends of the range and near the midpoint and is close to zero.

Sensitivity verification of the optimized sensor

Using the optimal structural parameters – plate gap angle $\theta = 2^{\circ}$, quartz tube inner radius $R_0 = 11.5$ mm, and quartz tube thickness $R_1 - R_0 = 1.6$ mm – we designed and manufactured the optimized cross-capacitive liquid level sensor. The output-input characteristic curve of the designed sensor is shown in fig. 5.

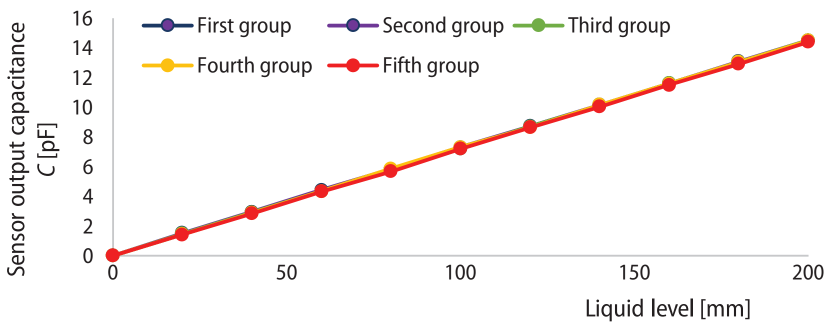

Figure 5. Output-input characteristic curve of the designed optimized cross-capacitive liquid level sensor

The maximum repeatability error can be calculated as $\Delta_{R\max} = 0.18$ pF and full range $y_{FS} = 14.52$ pF. Thus, the output repeatability of the cross-capacitive level sensor after structural optimization is:

$$\gamma_R = \pm \frac{\Delta_{R\max}}{y_{FS}} \cdot 100\% = \pm 1.2\% \tag{19}$$

The experimental sensitivity is 0.0723 pF/mm after the sensor is optimized. Thus, after structural optimization, the sensor sensitivity increased by 11.1%.

Conclusions

- Based on the cross-capacitance principle, we designed a new single-tube cross-capacitive fuel level sensor.
- A fuel level measurement model was established for the developed sensor, and the relationship between the measured liquid level and sensor output capacitance derived. The feasibility of applying the capacitance principle to the measurement of fuel level was also theoretically proved.
- According to finite element analysis of the electrostatic field, the finite element of the cross-capacitance liquid level sensor was calculated.
- The level was measured using a TH2617 capacitance meter. The experimental results showed that the output capacitance value changes linearly in the range 0-14 pF. Linearity is ± 0.8%, hysteresis error is ± 0.1%, and the maximum reference error is –1.0% FS at a liquid level of 120 mm.

- The designed sensor not only provides a new idea for applying the cross-capacitance principle to the fuel level sensor but also provides a basis for the development of high-precision liquid level sensors.
- In the future, a comprehensive system to study the market present situation and development prospect of liquid level sensor industry, pay attention to the timeliness of information, so as to better grasp the market change and industry development trend, and to conduct the thorough research to the capacitive fuel liquid level sensor, its application in aviation and oil industry such as maximum increase its compatibility, improve their practical applications.

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