Design of a Rainfall Sensor for Mobile Offshore Platform

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Abstract: A rainfall sensor which adopts the ratio of water volume as the measurement parameter was designed in this study. The ratio of water volume is unaffected by the platform movement on the sea. The sensor uses a corresponding relationship model of the ratio of water volume and electric capacitance established by experiments and regression analysis. With this corresponding relationship model, the rainfall data is obtained from the measured electric capacitance. According to the subsequent verification test of a prototype, the maximum measurement error of the prototype was 0.24mm, which is able to meet the accuracy requirements of marine rainfall measurement in specifications for oceanographic survey.

1. Introduction
Rainfall is an important component of climate monitoring in the global scale. However, due to the lack of offshore observation stations, it is difficult for the global rainfall monitoring system to obtain accurate rainfall data [1]. It is almost impossible to measure rainfall accurately with traditional land-based rainfall measuring instruments due to the pitching, rolling and heave motions of measurement platforms.

There are four types of rainfall measuring sensors commonly used at present: tipper rainfall sensor, load rainfall sensor, ultrasonic rainfall sensor and piezoelectric rainfall sensor. Tipper rainfall sensor can calculate rainfall accurately by recording the pulse generated by tipping buckets, but it needs a high stability of platforms. The tipping bucket caused by mobile offshore platform will generate fake rain signals. Load rainfall sensor can measure the weight of water and convert to rainfall. Yet the heave motions of mobile offshore platforms will increase measurement errors on the sea[2-5]. Ultrasonic rainfall sensor can calculate the rainfall with water level height, which can be measured by ultrasonic, but the measurement data can be affected by the pitch and roll motions of mobile offshore platforms and the measurement error will increase[6]. The core of piezoelectric rainfall sensor is pressure sensor, which can be used to measure the impact force of raindrops. The rainfall can be
calculated according to the impact force of raindrops and duration. However, the accuracy of measurement results will be affected by the motion of mobile offshore platform and the false rainfall will be shown when sea wave splashes onto the sensor [7-8].

To solve the problem of accurate rainfall measurement on mobile offshore platforms, a new type of sensor was designed to use the ratio of water volume as measured parameters, which will not change even if the container rocks and sways. The working principle and design scheme of the sensor are described in detail in the follows, and then the prototype performance is tested and verified.

2. Working principle

There is a definite correspondence between rainfall and the ratio of water volume in the container. The ratio will not change even if the container rocks and sways. The container acts as a capacitor cavity, and water and air are the medium between the electrodes of the capacitor. There is a linear relationship between the ratio and the output electric capacitance of the capacitor [9-11]. The output electric capacitance is converted into an easily measured voltage signal by a capacitive signal converter. The voltage signal is converted by an A/D chip and processed by the rainfall numerical model, and then rainfall can be obtained. The working principle diagram of rainfall sensor is shown in Figure 1.

3. Hardware design

The rainfall sensor hardware includes three parts: a rain collector, a capacitive signal converter and an information processing module.

3.1. Rain collector

The rain collector is composed of a rainfall hopper and a cylindrical capacitor. Rainfall is collected into the cylindrical capacitor by rainfall hopper. A metal cylinder is used as external electrodes of cylindrical capacitors with a bottom area of 64 cm² and height of 5 cm. A stainless steel rod of Φ 10 mm is used as the capacitor inner electrode, which is coated with polytetrafluoroethylene (PTFE). The two electrode leads are connected to the input of capacitive signal converter.

There are three mediums with different dielectric constants between the two electrodes: air, water and PTFE. The capacitance of cylinder capacitor is composed of three parts: the capacitance C1 formed by water as a medium, the capacitance C2 formed by air as a medium and the capacitance C3 formed by PTFE as a medium. The equivalent capacitance of the cylindrical capacitor Cx is shown in Equation 1.

\[ C_x = \frac{C_1 \cdot C_2}{C_1 + C_2} + C_2 \]  

The capacitance C equation of cylindrical capacitor is as follows:

\[ C = \frac{2\pi\varepsilon H}{\ln(r_1/r_2)} \]  

Substitute (2) into (1) and we can get
In Equation 3, \( r_0 \) is the radius of the inner electrode, \( r_1 \) is the distance from the coating outside of the center point, \( r_2 \) is the radius of cylindrical capacitor, which are shown in Figure 2. \( C_0 \), B and \( V_c \) are constant terms related to the physical size of the capacitor, and the capacitance \( C_X \) is proportional to the ratio of water volume \( w \)[12-13].

3.2. Capacitive signal converter

The capacitive signal converter is composed of dual timer oscillation circuit, phase discriminator circuit, integrating and amplifying circuit as shown in Figure 3. The capacitance is converted into a DC voltage signal by capacitive signal converter. The output voltage is proportional to the capacitance[14].

3.3. Information processing module

The AT90CAN128 microcontroller was selected as the core of the information processing module. It is internally installed an 8-channel 10-bit ADC with optional differential input stage with programmable gain, which can be used to convert the voltage into digital signal. The rainfall numerical model is
compiled into an executable program, which is written in the C language, and embedded in the information processing module. The program can finally calculate the rainfall according to the voltage from capacitive signal converter.

4. Design of rainfall numerical model

During the actual measurement, the measured capacitance includes not only the capacitance of cylindrical capacitor but also stray capacitance and parasitic capacitance between the leads, etc. This will affect the linear correspondence between the electric capacitance and the ratio of water volume. A method combining experiment and modeling is adopted to determine accurate corresponding relations between the electric capacitance and the ratio of water volume. As shown in Figure 4, the specific modeling steps are as follows:

![Flow diagram of rainfall numerical model establishment](image)

Fig4. Flow diagram of rainfall numerical model establishment

1) Test data acquisition

Power on the prototype and record the initial output voltage $V_0$. Take water volume of $20mL$ with measuring cup and slowly inject it into the prototype each time. Record the output voltages $V_i$ ($i=1,2,...$) after the water injection is finished for 5 minutes. Repeat it 16 times and make the total volume of $320mL$ as one sample set. 6 sets of sample data were obtained as shown in Table 1.

| Water injection ml Group No. | Output voltage V |
|-----------------------------|------------------|
| 0                           | 0.722 0.739 0.711 0.706 0.693 0.699 |
| 20                          | 0.804 0.839 0.815 0.792 0.82 0.791 |
| 40                          | 0.904 0.942 0.917 0.899 0.931 0.902 |
| 60                          | 1 1.034 1.014 0.996 1.027 1.009 |
| 80                          | 1.101 1.134 1.111 1.087 1.123 1.075 |
| 100                         | 1.199 1.233 1.204 1.183 1.219 1.189 |
| 120                         | 1.294 1.329 1.3 1.288 1.311 1.292 |
| 140                         | 1.391 1.429 1.394 1.379 1.405 1.396 |
| 160                         | 1.482 1.519 1.484 1.476 1.499 1.488 |
| 180                         | 1.568 1.606 1.571 1.568 1.597 1.567 |
| 200                         | 1.647 1.686 1.659 1.655 1.67 1.644 |
| 220                         | 1.726 1.76 1.735 1.733 1.745 1.726 |
| 240                         | 1.8 1.83 1.811 1.817 1.819 1.803 |
| 260                         | 1.863 1.893 1.873 1.883 1.881 1.872 |
| 280                         | 1.918 1.949 1.92 1.929 1.93 1.929 |
| 300                         | 1.965 1.999 1.971 1.983 1.989 1.983 |
| 320                         | 2.02 2.035 2.021 2.029 2.031 2.03 |
32mL water injected into the prototype is equivalent to the rainfall of 5mm based on the physical size of the capacitor. Take 32mL water each time with measuring cup and inject it slowly into the prototype, record the output voltage after the injection is finished for 5 minutes. Do this 10 times to simulate the rainfall of 50mm. The output voltage data are recorded as correction group and shown in Table 2.

Table 2 Test data of correction group

| No. | Simulated rainfall/mm | Output voltage / V |
|-----|-----------------------|--------------------|
| 1   | 0                     | 0.713              |
| 2   | 5                     | 0.878              |
| 3   | 10                    | 1.024              |
| 4   | 15                    | 1.178              |
| 5   | 20                    | 1.329              |
| 6   | 25                    | 1.488              |
| 7   | 30                    | 1.628              |
| 8   | 35                    | 1.754              |
| 9   | 40                    | 1.866              |
| 10  | 45                    | 1.958              |
| 11  | 50                    | 2.026              |

(2) Model set-up

The sample group data (Table 1) was plotted in the same coordinate system. It can be seen from the data curve in the Figure 5 that the measurement repeatability of the prototype is good.

![Fig.5 Data curve of test group](image)

We used regression analysis to process the data in Table 1, and the mapping Relation between output voltage U and ratio of water volume w was established with nonlinear least square method as shown in Equation 4:

\[ U = -0.518w^3 + 0.3181w^2 + 1.497w + 0.7151 \]  

(4)

When combining the relationship between rainfall p and ratio of water volume w, as shown in Equation 5, the relationship model of rainfall p and output voltage U is obtained as shown in Equation 6:

\[ w = \frac{p \cdot S_{\text{capacitor}}}{V_{\text{capacitor}}} = \frac{p}{H_{\text{capacitor}}} \]  

(5)

\[ U = -4.144 \times 10^{-6} p^3 + 1.2724 \times 10^{-4} p^2 + 2.994 \times 10^{-2} p + 0.7151 \]  

(6)

The correction group data recorded in Table 2 is taken into Equation 6 for calculation, and the
calculation result is compared with the simulated rainfall, as shown in Table 3.

Table 3 contrast table of rainfall between calculated and simulated values

| No. | Simulated rainfall/mm | Calculated rainfall/mm | Error/mm |
|-----|------------------------|-------------------------|----------|
| 1   | 0                      | -0.7                    | -0.7     |
| 2   | 5                      | 5.34                    | 0.34     |
| 3   | 10                     | 10.03                   | 0.03     |
| 4   | 15                     | 14.97                   | -0.03    |
| 5   | 20                     | 19.91                   | -0.09    |
| 6   | 25                     | 25.34                   | 0.34     |
| 7   | 30                     | 30.46                   | 0.46     |
| 8   | 35                     | 35.55                   | 0.55     |
| 9   | 40                     | 40.75                   | 0.75     |
| 10  | 45                     | 45.99                   | 0.99     |
| 11  | 50                     | 51.26                   | 1.26     |

The least squares fitting is performed on the error data calculated in Table 3, and a rainfall value compensation model \( \Delta \) based on the output voltage \( U \) is established:

\[
\Delta = -7.146U^4 + 41.54U^3 - 86.52U^2 + 76.94U - 24.63
\] (7)

Combining equation 6 and 7, the rainfall numerical model in the prototype is as follows:

\[
\begin{cases}
p' = p - \Delta \\
\Delta = -7.146U^4 + 41.54U^3 - 86.52U^2 + 76.94U - 24.63 \\
U = -4.144 \times 10^4 p' + 1.2724 \times 10^4 p^2 + 2.994 \times 10^{-2} p + 0.7151
\end{cases}
\] (8)

5. Accuracy verification test

The maximum measurement error of rainfall sensor in Specifications for Oceanographic Survey—Part 3: Marine Meteorological Observations (GB/T 12763.3-2007) is less than \( \pm 0.4 \) mm (\( \leq 10 \) mm) or \( \pm 4\% \) (\( > 10 \) mm). The prototype accuracy test has been done to verify prototype performance. The test data are recorded in Table 4, which show that the maximum measurement error of this prototype is 0.24 mm. The result demonstrates that the measurement accuracy of this prototype is satisfied.

Table 4 Data sheet of verification test

| No. | Simulated rainfall/mm | Measured data/mm | Error/mm |
|-----|------------------------|------------------|----------|
| 1   | 5                      | 5.24             | 0.24     |
| 2   | 10                     | 9.85             | -0.15    |
| 3   | 15                     | 14.88            | -0.12    |
| 4   | 20                     | 19.89            | -0.11    |
| 5   | 25                     | 25.22            | 0.22     |
| 6   | 30                     | 30.1             | 0.1      |
| 7   | 35                     | 34.89            | -0.11    |
| 8   | 40                     | 39.81            | -0.19    |
| 9   | 45                     | 44.88            | -0.12    |
| 10  | 50                     | 50.09            | 0.09     |

6. Conclusion

In this paper, a new type of rainfall sensor suitable for offshore mobile platforms was designed according to the characteristic that the ratio of water volume in the container will not change due to
swaying and shaking. The sensor adopts capacitive measurement with compact structure and no moving parts and it can meet the requirements of rainfall measurement accurately on mobile offshore platform.

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