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5 Development of capacitive water level sensor

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Abstract

Disasters are on the rise in the world and Japan. In particular, rural cities in mountainous areas have also faced landslides or flooding of small rivers crisis. Although flood control systems of large rivers managed by the national governments have been in place for decades, disaster prevention measures in small water bodies aren't on the way due to segmentalized water jurisdictions. In addition, the cost of water level sensors has hindered the introduction of the system, so low-cost robust capacitive water level sensors are in demand.

We have developed high-precision capacitance detection technology for MEMS (Micro Electro Mechanical Systems) accelerometers. Now, we are trying to exploit the technology to the capacitive water level sensor. This paper shows the mechanism of a capacitive detection circuit and a prototype water level sensor.

1. Introduction

Due to the coronavirus, changes have accelerated in various areas, from social conditions to individual consciousness.[1–3] The pandemic reminds us of crises in humanity. At the same time, present concerns such as widening income gaps or infectious diseases have affected our sense of value. Moreover, with once in 100 years weather events, awareness of sustainable societies has expanded.[4, 5] The values other than economic rationality have been growing with perceptions of these crises and activating consumption or investment. So initiatives directed at social issues have increased significantly. Amid these shifts, regional cities facing declining birth rates, aging, and depopulation have been developing with research institutions and enterprises. They actively pursue sustainable regional societies on the local resources of the town.[2]

One of these issues is how to deal with climate change risks. Flood disasters are increasing yearly in Japan,[6] and regional cities in mountainous areas have faced the risk of flooding and landslides in small-scale water areas. However, these water areas, in addition to being managed by a wide range of entities, including individuals, local governments, cities, towns, and villages, are characterized by being small in scale, numerous, and widespread, so the introduction of flood control systems has so far not advanced. We have developed sensors of IoT (“Internet of Things”) devices necessary for flood control systems[7] and are working on these problems through industry–government collaboration.

There is a problem that water level meters conventionally used in large-scale rivers are high-cost. Because of this, a highly robust and low-cost water level meter that can be realized by capacitive sensing is promising.[8,9] With a capacitive water level meter, the water level corresponds to the changes in electrostatic capacity between the electrodes that have space for the water to enter. In order to measure several meters of water depths, the circuit's capacity detection range has to be wide. Generally, the detection range and accuracy have been in a trade-off relationship. Increasing electrode dimensions to improve accuracy makes a more significant difference in an electrostatic capacity relative to the water level. However, it causes increasing nominal capacity. We have developed a water level meter that applies our accelerometers' electrostatic capacity detection technology. The detection circuit obtains high accuracy by amplifying capacity differences to cancel the nominal capacity. The measurement range also can be adjusted easily through digital control. This paper will introduce this detection circuit and a prototype water level sensor.

2. Detection principles and circuit configuration

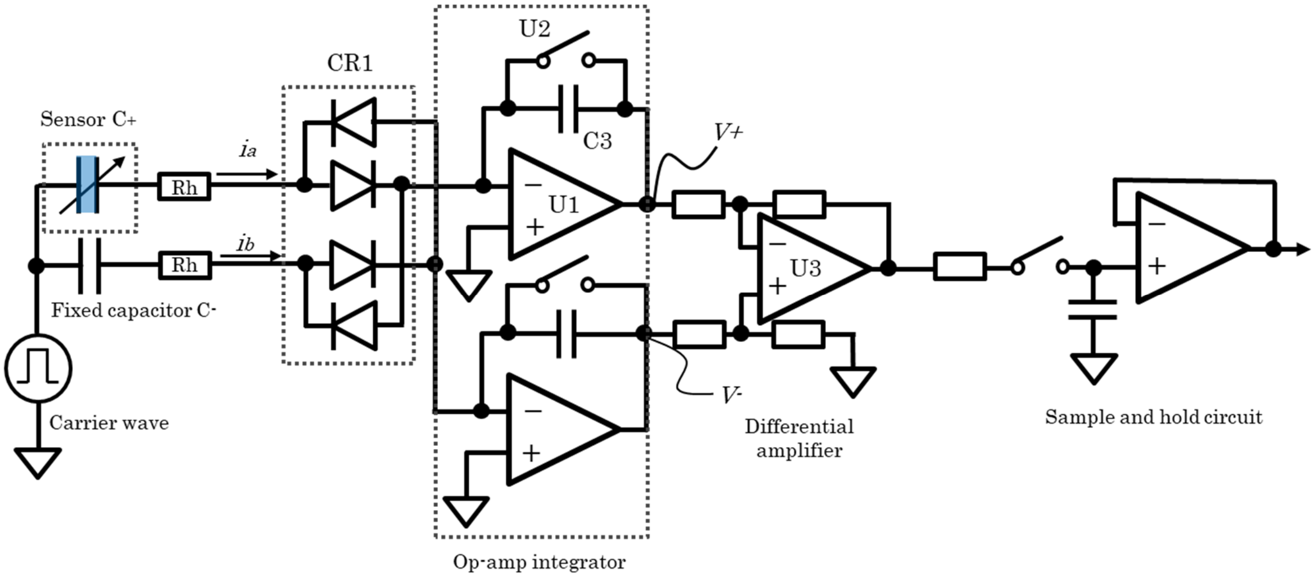


Figure 1. Electrostatic capacity detection circuit for use in water level meter

Figure 1 shows an electrostatic capacity detection circuit used in a capacitive water level meter. C_+ indicates a sensor that increases capacity as water enters the space between the electrodes. A fixed capacitor C_- is used to subtract the offset value of C_+. During water level measurement, a square wave voltage is applied to C_+ and C_- as a carrier wave. In a state of no initial charge load, as the current flowing through the capacitor i_a is dependent on the CR time constant, it can be expressed as follows.

$$i_a = \frac{V_{pp} - 2V_F}{R_h} e^{-\frac{t}{R_h C_+}} \qquad \text{Eq. (1)}$$

In Eq.(1), R_h represents the series parasitic resistance component, V_{pp} represents the amplitude of the carrier wave, and V_F represents the voltage drop caused by the rectifier circuit CR1., The time constant from a carrier wave differential value becomes greater with capacitance, so the electrical current flow increases. i_a and i_b pass through the rectifier circuit CR1, and these currents are converted into a voltage by the integrating circuit of the op-amp U1. If the integrating capacity is represented as C_3, the integrating circuit output V_+ per period of the carrier wave can be expressed as follows.

$$V_{+} = -\frac{1}{C_3}\int_0^{\infty} i dt$$
$$= -\frac{V_{pp} - 2V_F}{R_h C_3}\int_0^{\infty} e^{-\frac{t}{R_h C_+}} dt$$
$$= \frac{(2V_F - V_{pp})C_+}{C_3} \qquad \text{Eq. (2)}$$

Moreover, the rectifier circuit CR1 rectifies i_b to be inverted relative to i_a, so opposing signals appear. Thus, the output V_- per period of the carrier wave can be expressed similarly to Eq(2).

$$V_{-} = -\frac{(2V_F - V_{pp})C_-}{C_3} \qquad \text{Eq. (3)}$$

The timing chart for circuit operation is shown in Figure 2. As explained above, the carrier wave is applied to the sensor capacitor and the fixed capacitor when the circuit is in operation. Larger capacity increases integrated signals because the cr constant becomes larger. The opposite diodes rectify opposite signs, and the signals are differentially amplified, sampled, and held.

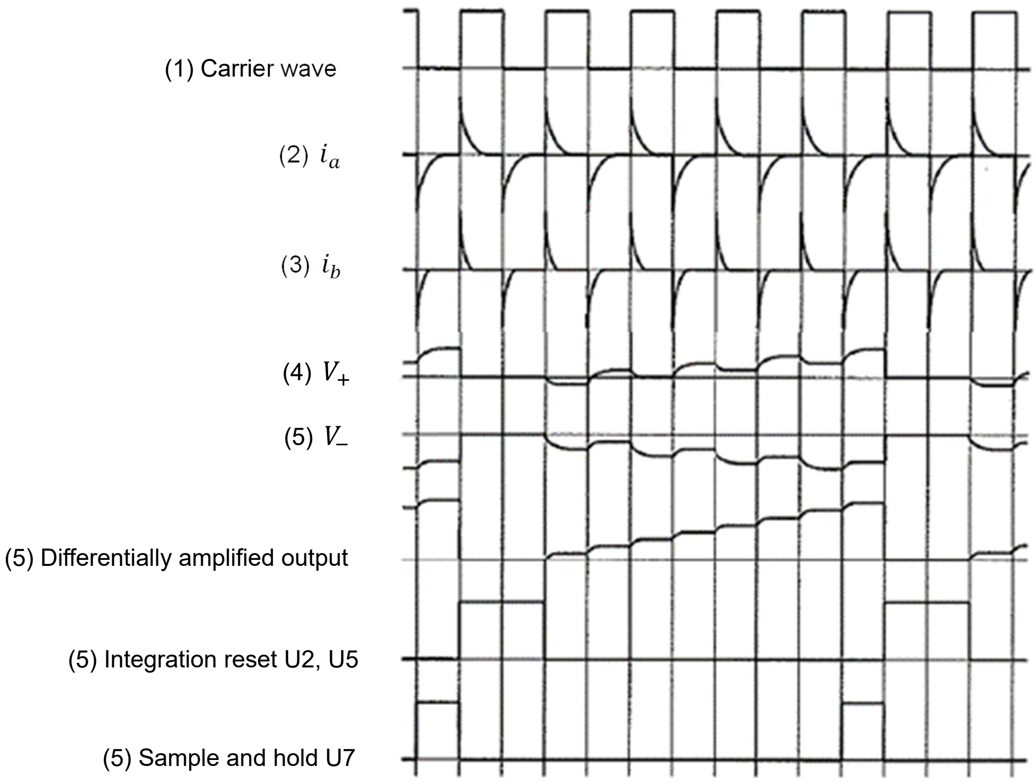


Figure 2. Timing chart for detection

Switches U2 and U5 perform resetting of the integrating circuit. As shown in Figure 2, the integrated value increases during the interval between reset cycles. Here, if the change in capacity caused by the water level is represented as $C_+ - C_- = \Delta C\ [pF/mm]$, the differential circuit output ΔV after x times of integrations will be as follows.

$$\Delta V = x \times (V_- - V_+) = \frac{x(V_{pp} - 2V_F)\Delta C}{C_3} \qquad \text{Eq. (4)}$$

The differential circuit output ΔV is proportional to the capacity change ΔC so the detection circuit can measure the water level. The output voltage value of the detection circuit is proportional to the number of integrations, so the detection circuit allows the sensitivity to be easily adjusted when output saturation or the like occurs by adjusting the count-up cycle using an MCU (microcontroller unit). Furthermore, if the integration cycle is lengthened, the noise produced by analog switches in the sensor signal can be made relatively smaller.

In standard capacitive water level meters, it has been necessary to increase electrode dimensions to make changes in electrostatic capacity greater relative to the water level. However, this increases the nominal capacity of the electrodes, and detection circuit noise worsens simultaneously. So the accuracy cannot be improved. On the other hand, with this detection circuit, the nominal capacity can be eliminated as the capacities difference from Eq.(4). So it has the advantage of detecting any electrostatic capacity accurately.

3. Evaluation of dynamic range

Water has a high dielectric constant, so a wide capacity detection range is necessary to measure several meters of water depths. However, if the amplification factor is lowered to widen the detection range, the signal becomes buried in the noise floor of the circuit, and resolution worsens. Because of this, the noise level of the circuit is a bottleneck. For example, the circuit noise that meets the resolution required for predicting reservoir failure is described as follows.

In case a parallel flat-plate capacitor with a cavity for water to enter into is used for measuring the water level of a 1m depth reservoir, the specific dielectric constant between the electrodes is 1. Suppose this cavity is entirely flooded with water. In that case, the specific dielectric constant of water is 74 to 88, so it is necessary to detect capacity changes on the order of 100 times the nominal value. Prediction of reservoir failure requires a resolution of 1 mm for a water level meter 1 m in length, so it must be possible to detect changes as small as 1/1000 while keeping the capacity within a range that has a maximum of 100 times the nominal value. Thus, the required dynamic range for the circuit is 100 dB as a voltage ratio.

Next, to find the noise level of the circuit, the noise n_{cv}, derived before the integrating circuit stage shown in Figure 1, is represented as follows. k is the Boltzmann constant (1.38×10^{-23} $m^2 kg \cdot s^{-2} K^{-1}$), and T is a room temperature of 300 K. Here, voltage noise R_h from input current noise of U1 and transistor, capacitor, and analog switch noise are disregarded. If op-amp input voltage noise is represented as N_{opa}, the voltage spectrum density of noise will be as follows based on the above.

$$n_{CV} = \sqrt{4\mathrm{kT}R_h + 4\mathrm{kT}R_1 + {N_{opa}}^2} \approx 10\sim30 \left[\frac{nV_{rms}}{\sqrt{Hz}}\right] \qquad \text{Eq. (5)}$$

The differential amplification circuit stage used in the detection circuit is shown in Figure 3. As design reference values, R3 = R4 = R5 = R6 = 1 kΩ. So thermal noise due to R3 (= R4, R5, R6) will be as follows.

$$\sqrt{4\mathrm{kT}R_3} = \sqrt{4 \times 1.38 \times 10^{-23} \times 300 \times 1 \times 10^3} = 4.07 \left[\frac{nV_{rms}}{\sqrt{Hz}}\right] \qquad \text{Eq. (6)}$$

Also, the noise N_j produced by R3 from the input current noise (reference value: 0.8 $[pI_{rms}/\sqrt{Hz}]$) of the op-amp will be as follows.

$$N_i = 0.8 \times 10^{-12} \times 1 \times 10^3 = 0.8 \left[\frac{nV_{rms}}{\sqrt{Hz}}\right] \qquad \text{Eq. (7)}$$

Based on Eq.(5), (6), and (7), if the voltage noise (reference value: 10 $[nV_{rms}/\sqrt{Hz}]$) of the op-amp U3 is taken into consideration, the total noise n_{diff} in the differential amplification circuit will be as shown in the following Equation.

$$n_{dif} = \sqrt{(2n_{CV})^2 + (2 \times 4.07)^2 + (2 \times 10)^2 + (2 \times 0.8)^2 + 2 \times 4.07^2} < 90 \left[\frac{nV_{rms}}{\sqrt{Hz}}\right] \qquad \text{Eq. (8)}$$

Next, Figure 4 shows a sample-and-hold circuit. Here, the slight noise of capacitors and analog switches is can be ignored. R7 and R8 are derived from a time constant considering charge-discharge time for sampling and holding by U11.Assuming that R7 = 100 Ω, R8 = 47 Ω, and the op-amp U3 voltage noise N_{opa} is a reference value of 10 $[nV_{rms}/\sqrt{Hz}]$, the final circuit-derived noise n via the sample-and-hold circuit according to Eq.(8) will be as follows.

$$n = \sqrt{{n_{dif}}^2 + 4\mathrm{kT}R_3 + {N_{opa}}^2 + 4\mathrm{kT}R_8} = \sqrt{{n_{dif}}^2 + 1.29^2 + 10^2 + 0.88^2} < 100 \left[\frac{nV_{rms}}{\sqrt{Hz}}\right] \qquad \text{Eq. (9)}$$

If bandwidth is 100 Hz, the noise level of the circuit according to Eq.(9) is −112 dB or less, which clearly meets the dynamic range required for the water level meter described above.

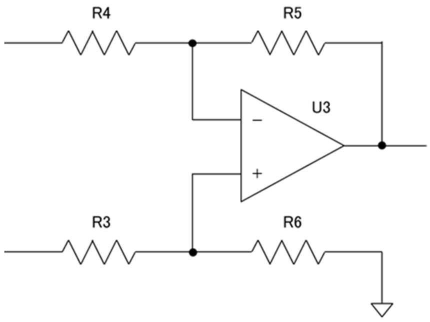


Figure 3. Differential amplification circuit

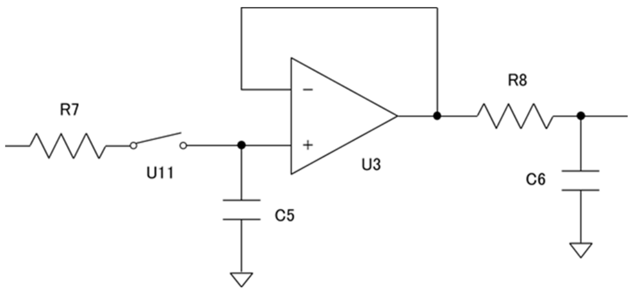
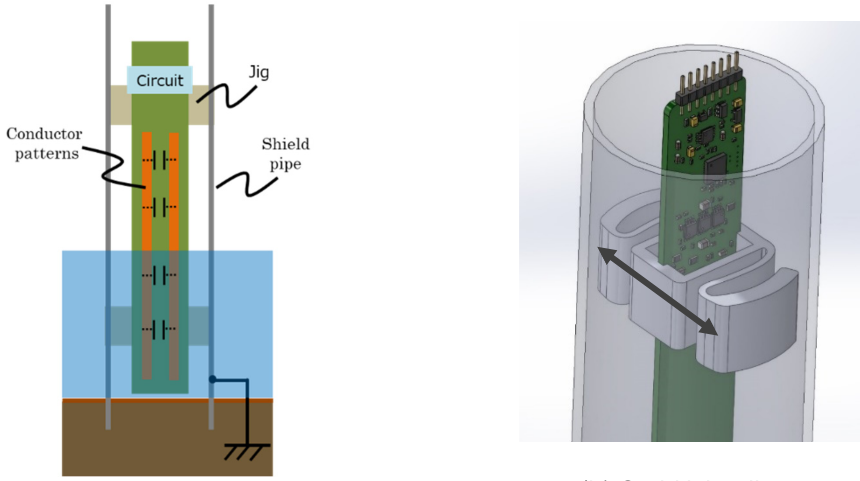


Figure 4. Sample-and-hold circuit

4. Water level meter prototype

We created a prototype for measuring water level with the electrostatic capacity detection circuit introduced above. This prototype detects water level by measuring parasitic capacity between linear conductor patterns prepared on a PCB (printed circuit board), as shown in Figure 5. Water entering between the conductor patterns causes electrostatic capacity between the electrodes to change, which is detected as an analog voltage corresponding to the water level. A structure with the circuit and the detection patterns on the same PCB can save space, an advantage of electrostatic capacity sensors. The sensor is housed in a stainless-steel shield pipe because the output of electrostatic capacity sensors is affected by nearby objects. Moreover, the pipe makes it easy to field installation. In addition, variability in the distance between the shield and the detection patterns affects sensor output, so a stabilizing jig was prepared using a 3D printer to achieve a structure in which the substrate was fixed in the center of the pipe (Figure 5(b)). The electrostatic capacity detection circuit used in this prototype has a capacity difference as circuit output, as in Figure 1, so the sensor capacitor is compared with a fixed capacitor on the circuit.

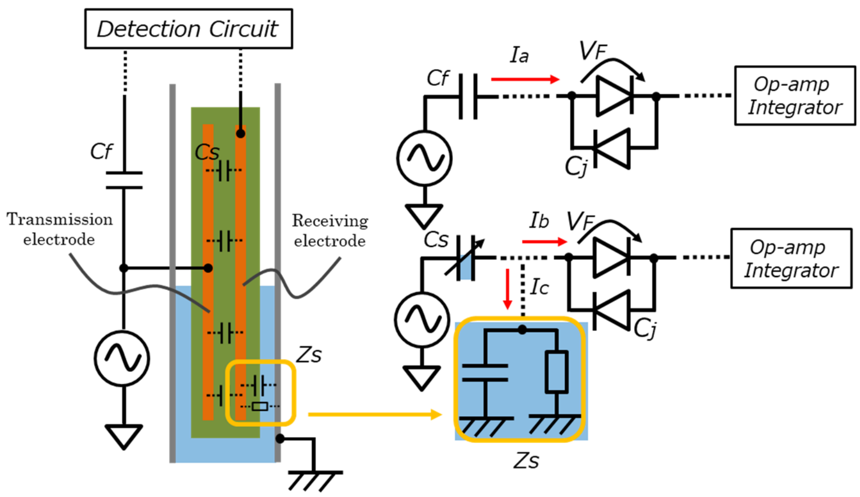


(a) Cross-sectional view

(b) Stabilizing jig

Figure 5. Capacitive water level meter

The measurement of capacity change with water level has a unique problem that does not arise with the measurements of MEMS sensors. As shown in Figure 6, the carrier wave is first input into the transmission electrode. A charge is delivered from this transmission electrode to the receiving electrode via parasitic capacity. However, a parasitic component Z_X with the external shield also increases together with the water level. The current through the capacitor is integrated with the circuit as described above. But a parasitic component arises between the receiving electrode and the shield pipe, allowing the current I_c to flow to the ground, as shown in Figure 6(b). The phenomenon can affect the original capacity change and the integrated value.



(a) Side view (b) Equivalent circuit

Figure 6. The effects of a parasitic component that increases together with water level

Thus, we created a structure that produces a parasitic component by a dummy electrode on the receiving electrode of the fixed-capacity side. As shown in Figure 7(a), the dummy electrode has line symmetry with the receiving electrode of the water level detection section realizing the same parasitic components with the pipe between the sensor and the fixed capacity side. These parasitics can be canceled out by differentiating at the sensor section.

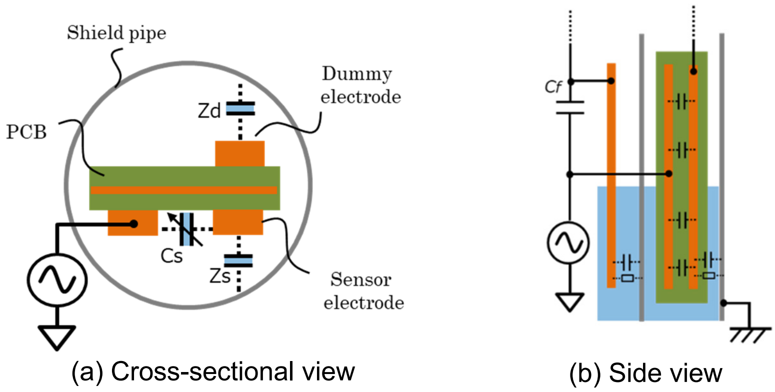


Figure 7. Addition of dummy electrode

Figure 8 shows the evaluation results of the prototype water level meter. A comparison of linearity with and without the dummy electrode is shown. The non-linearity appears without the dummy electrode. We believe it comes from the current flowing to GND via the parasitic component increasing as the water level increases. On the other hand, the sensor with a dummy electrode achieved a non-linear error of 1 mm or less of water level thanks to the cancelation of parasitics.

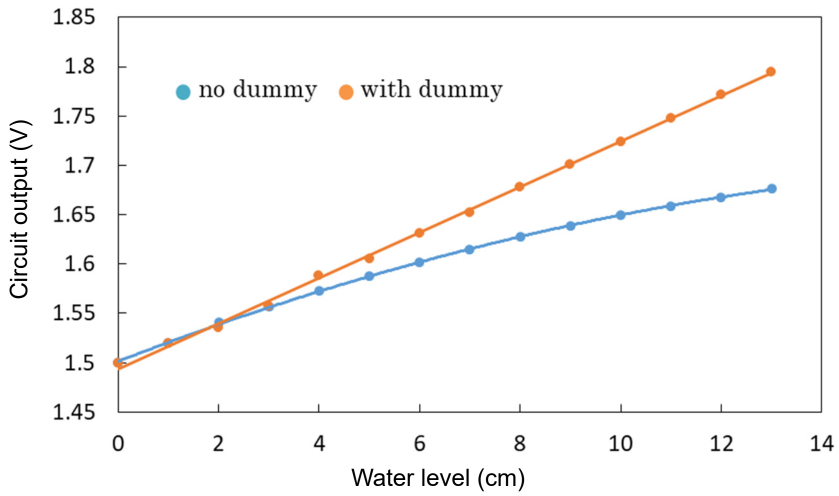


Figure 8. Water level meter output

5. Summary

This paper reported on developing a capacitive water level meter that applies the electrostatic capacity sensing technology of JAE's MEMS accelerometers. In response to the risks of flooding and landslide disasters in small-scale water areas held by regional cities in mountainous regions, we have tried applying the sensor to flood control systems with small, numerous, and widespread features.

By applying nominal capacity cancellation in a MEMS accelerometer's electrostatic capacity detection circuit and low noise feature, we have ensured a high dynamic range measurement on a high dielectric constant and high nominal capacity such as a water level meter. However, there is a problem unique to the water level meter of parasitic components between the shield pipe that was not present during the MEMS electrostatic capacity measurements. We improved the linearity of circuit output by compensating the parasitics with a dummy electrode. In addition, we devised a structure to fix the sensor in the pipe's center that suppresses electrostatic capacity variability between the shield and the electrodes. We're going to forward with the study of long-term stability, temperature characteristics, water resistance, and verifications based on field installation.

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