Designing preamplifier for sensing atmospheric electrostatic field strength via supercapacitive sensor

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Abstract. In order to effectively obtain the signal from sensor, the analogue signal needs to be amplified and then converted into a digital signal for matching to the sensor characteristics. With a supercapacitive electric field sensor based on graphene aerogel, the response current signal from the electric field sensor is weak and unstable. Herein, a high gain and low noise preamplifier is developed, and an amplifier circuit with double T-type feedback network is proposed to reduce the Johnson noise for the amplifier. This design can reduce the thermal noise of resistance by using the smaller resistance under the same gain, and it can effectively reduce the interference of peak noise by adding the feedback capacitance, so as to improve the detection accuracy. The simulation results show that under the same gain condition, the Johnson noise can be reduced by 46% and the detection accuracy can be improved by 12% compared with the traditional T-type feedback network.

1. Introduction
Electric field measurement is widely used in electric power, aerospace, oceanic environments monitoring and other industries [1]. Currently, different electric field sensors with various materials and structures are developed, most of which are capacitive [7-9]. Generally, capacitive sensors are in non-invasive type with the advantages of simple structure and wide application scenarios. In the process of evolution, the capacitive sensors are gradually coupled with more interesting functions, which also stimulated the improvement of various front-end signal acquisition circuits.

High accuracy, anti-noise performance is needed in signal conditioning circuits for capacitive sensors and can be used with a variety of capacitive sensors. Hartley oscillation circuit based on operational amplifier is used to convert the capacitance change into the frequency change, which improved signal to noise ratio (SNR) of output, but the amplifier with large bandwidth is needed [10]. A simple signal conditioning circuit based a transformer ratio arm (TRA) bridge to convert capacitance change into frequency for capacitive sensors is proposed, which reduces parasitic earth
capacitance effect [11]. The circuit can provide a suitable output with microcontrollers for calibration and display. The purpose of these oscillator-based interface circuits is to convert the capacitance changes into frequency changes. However, for signal processing in single chip microcomputer, the frequency signal will eventually be converted into a voltage signal, which will make the circuit complex. To translate the capacitance change into the voltage change, charge amplifier circuits is an excellent choice [12]. A low-cost interface circuit for lossy capacitive sensors which is highly linear for a wide range of capacitance measurement (162 pF~3.680 nF) is presented. An interface circuit for lossy capacitive sensors with low cost is presented. This circuit realized a wide range of capacitance measurement (162 pF-3.680 nF) in high linearity [13]. In order to amplify and convert the sensor's response current into a voltage signal, the trans-impedance amplifier is often used. A faint optical signal detection circuit which uses a T-type feedback network is designed to reduce the static error caused by temperature drift and obtain a large amplification factor [14]. A trans-impedance amplifier (TIA) has low noise and high gain is designed, which makes it suitable to interface with analog-to-digital converter (ADC) [15]. An electronic circuit stabilizes an ultrahigh input impedance amplifier by altering the amplifier's input potential, which minimized the noise [16]. Now, the weak signal of capacitance sensors is just for small capacitance (hundreds pF to hundreds μF). What’s more, the feedback network design of amplifiers for larger capacitance is still limited.

There are various methods of signal conditioning for capacitive electric field sensors. But very few circuits were proposed for capacitive sensors with large capacitance. Weak current is hard to be measured directly so it is usually converted to other quantities and amplified to perform the measurement indirectly. The most common methods are the current-to-voltage conversion and the current-to-frequency conversion [17]. The trans-impedance amplifier can convert current to voltage. But it requires a larger feedback resistor which will lead to circuit has poor temperature stability, moreover, the measurement precision is also affected by the input resistance, bias current and other factors of the operation amplifier [18]. IFC is a current-to-frequency convertor circuit whose core part is a capacitor integrator. However, the IFC has poor real-time performance and the complex structure makes it difficult to debug [19]. In voltage conversion circuits, the feedback network plays an essential role in signal amplification and interference control. The advantage of the TIA based on the T-type feedback network is to avoid the large feedback resistor in the I-V transformation process and to reduce the Johnson noise [20]. However, the T-type feedback network is still required to be advanced for further improvement.

In our previous work [21], a supercapacitor based PEDOT:PSS/graphene oxide aerogel (P-rGOA) which has a sandwich-liked structure is proposed, it can sense electric field strength in the range of 1100~19000 Vꞏm⁻¹, and the capacitance value of supercapacitive sensor is several hundred millifarads which indicate that the relevant circuit methods need to be improved. The performance of the TIA based T-type feedback network is still limited for the sensor. So, a double T-type feedback network is tried to further improve the performance. When the sensor is in the electric field, it can generate 0.1~0.5 μA direct current (DC), which requires high gain and as low noise as possible in the circuit, while suppressing the peak signal. Based on this, we hope to improve the existing T-type feedback network to achieve the above requirements.

Herein, a kind of double T-type feedback (DTF) network is proposed to improve the SNR with high gain. Compared with the traditional T-type network, the resistance noise can be reduced by 46% with the unchanged gain, and the peak noise is effectively suppressed. Furthermore, the three-stage amplifier has apparent advantages for suppressing harmonic distortion, DC gain, and power-supply rejection ratio.

2. Description of the P-rGOA based electric field sensor

2.1. The Sensor Principle
The fundamental diagram of sensor is shown as figure 1. Its internal structure can be equivalent to the inset to equivalent to a capacitor $C_{P-rGOA}$ which in parallel with resistor $R_{CT}$, and they are in series with

2
a resistor $R_S$, as shown in the dotted box. The sensor needs to be added 3.3V DC voltage between the two plates at working state. In an external environment, the ion concentrations in electrolyte around the electrode is affected by adding the space electric field. Then, the internal recombination current will increase and the external response current will be enhanced correspondingly. Therefore, the larger the electric field intensity brings the larger the external response current. Then, the external response current will degenerate once the external electric field is removed. Hence, a sensor effect on space electric field in electrochemical mechanism is established [21]. Here, the electrochemical workstation for measure is expensive and not portable, and the operation process is complex. Hence, a small and light portable measure equipment used to read the current signal of the sensor is urgently needed.

**Figure 1. The fundamental diagram of sensor.**

**2.2. Electrical characteristics of the sensor**

Experiment showed that in the equivalent circuit, the $R_S$, $R_{CT}$ and $C_{P-rGOA}$ are 3.8 $\Omega$, 238.2 $\Omega$, and 190 mF cm$^{-2}$, respectively [21]. It indicated the internal resistance is small and the capacitance is large, which has advantages in reducing distributed capacitance generated by the connection line.

**3. Description of measurement circuit**

The front-end receiving circuit of the electric field sensor based on the cross-impedance amplifier is designed. According to the intrinsic characteristic that the current response of the sensor with several milliampere capacitance, the following measurement circuit is proposed.

**Figure 2. Circuit design block diagram.**

To realize the electric field measurement in wide sensor range, a circuit that can transform the current of 0.1–0.5 $\mu$A into the voltage of 0–5 V linearly is needed. In this context, the gain of the circuit is required to reach 120 dB. The design block diagram of the amplifier is shown in figure 2. Here, the $C_{P-rGOA}$ represents the capacitance of the sensor itself, $C_{PAR}$ represents the parasitic capacitance of the amplifier, and $R_f$ is the feedback circuit of the feedback network. According to the design requirements, the three-stage amplification scheme is used and the design block diagram is
shown in figure 2. As the first stage, the IV transform circuit collects current signals and transforms them into voltage signals. As the second stage, the gain adjustment circuit adjusts the gain in a certain range based on the amplified signal of the first stage. The third stage is a DC bias regulating circuit based on subtraction function, which is used to offset the DC bias caused by the circuit.

3.1. Selection of the operational amplifier

Generally, the contradiction exists between bandwidth and gain in operational amplifier, which means high gain at the expense of bandwidth. Fortunately, unlike other sensors, the response signal in the sensors in form of DC means the minimal bandwidth is required. According to the data sheet from Texas Instruments, some of the different types of operation amplifier and compare their performance is listed in Table 1 [22]. With the relatively high performance, the TLC2201 is used in this equipment.

| Operational Amplifier | Common-mode rejection ratio (dB) | Noise of Voltage at 1kHz (nV/√Hz) | Slew rate (V/μs⁻¹) | Gain-bandwidth product (MHz) |
|------------------------|----------------------------------|-----------------------------------|-------------------|--------------------------|
| OPA549                 | 95                               | 70                                | 9                 | 0.9                      |
| LM358                  | 65                               | 40                                | 0.3               | 0.7                      |
| TLC4502                | 100                              | 12                                | 2.5               | 4.7                      |
| TLC2201                | 110                              | 12                                | 2.5               | 1.8                      |
| OPA4251                | 124                              | 45                                | 0.01              | 0.035                    |

3.2. The Design of Double T-type Feedback Network

Using large resistances in amplifiers will result in loud Johnson noise. The Johnson noise can be calculated by equation (1), where \( K_B \) represents Boltzmann constant, \( T \) is the absolute temperature of the resistance in Kelvin, \( R \) represents the resistance in ohm. The feedback can be realized by substituting T-type feedback network for \( R_f \), which the temperature drift error was reduced and both the larger amplification factor and the higher input impedance can be obtained. It not only solves the problem of large resistance of the traditional amplifying circuit, but also to simply realize on circuit. And the DTF has only two more resistances than the T-type feedback network [27]. The simple T-type feedback network model is shown in figure 3 (a), and the voltage input-output relationship based on this model is as equation (2).

\[
V_{\text{n}}^2 = 4K_B TR
\]

\[
V_{\text{out}} = -V_{\text{in}}(\frac{R_2 + R_3 + \frac{R_1 R_3}{R_4}}{R_1}) + V_{\text{REF}}(1 + \frac{R_2 + R_3 + \frac{R_1 R_3}{R_4}}{R_1})
\]

\[
V_{\text{out}} = -I_{\text{in}} \left[ R_1 + R_3 + \frac{R_1 R_3}{R_2} + R_5 \left( 1 + \frac{R_1}{R_2} + \frac{R_1 R_3}{R_2 R_4} \right) \right]
\]

In order to further reduce the noise, a double T-type feedback (DTF) network is proposed. The structure of the circuit is shown as figure 3 (b). The current-voltage relation formula of this feedback network can be obtained as equation (3). According to the comparison between equation (1) and the above model, the component parameters and circuit performance of non-feedback network, T-type feedback network and double T-type feedback network are listed in Table 2, which indicates that although DTF increases the number of resistors, it greatly reduces the maximum resistance value in the case of the same temperature and similar gain. Assume that \( J_S \), \( J_T \), \( J_D \) represent the Johnson noise of
single resistor network, T-type network and DTF respectively. According the data from Table 2, \((J_T-J_D)/J_T=0.67\) and \((J_S-J_D)/J_S=0.94\), which indicates that DTF reduces Johnson noise by 67% compared to T-type feedback networks, and 94% compared to single-resistance feedback networks.

![Figure 3. a) The TIA based T-type feedback. b) The TIA based double T-type feedback.](image)

Table 2. Performance comparison of various operational amplifiers.

| Temperature (K) | Gain (dB) | Number of resistors | Maximum resistance (kΩ) | Johnson noise (nV/√Hz) |
|-----------------|-----------|---------------------|--------------------------|------------------------|
| Single Resistor | 298       | 120                 | 1                        | 1000                   | 405                    |
| T-type          | 298       | 121                 | 3                        | 100                    | 70.2                   |
| DTF             | 298       | 123                 | 5                        | 10                     | 22.9                   |

4. Experiment

Based on the simulation result, a signal amplifying device equipped with DTF was designed. A plasma ball as spherical field source to generate a strong electric field, and combined with the sensor to test the performance of the circuit.

Experience showed that the electric field strength of the spherical field source is inversely proportional to the distance. Hence, the relationship between the reciprocal of the distance and the voltage of our device output can be analyzed. The part of data is shown in Table 3, where D represents the distance from the plasma sphere to sensor, P represents the quantized value of the circuit after digital signal processing and E represents the electric field strength. The correlation of the \(1/D^2\) and E was verified by a linear fitting software of Linear Interactive and General Optimizer (LINGO). Then, the correlation coefficient \(R=0.967\) was got, revealing the variables are highly correlated. Thereby, the expression as equation (4) and (5) can be obtained.

\[
V = \frac{47.357}{D^2} - 0.821 \tag{4}
\]

\[
E = 570.05U - 345.08 \tag{5}
\]

The T-type feedback network was used as the control group, and the correlation coefficient \(R=0.922\) was also obtained. The experiment indicated the linearity and accuracy of the device with DTF was improved by reducing Johnson noise.
Table 3. Comparison of the noise performance of different feedback networks

| D(cm) | D^2 (cm^2) | P  | U(V)   | E(V·m⁻¹) |
|-------|------------|----|--------|----------|
| 8     | 64         | 247| 4.843  | 2800.00  |
| 14    | 196        | 167| 3.275  | 914.29   |
| 20    | 400        | 74 | 1.451  | 448.00   |
| 26    | 676        | 32 | 0.627  | 265.10   |

5. Simulation

The noise of three kinds of circuits is simulated by Multisim in figure 4. It is clear that single resistance feedback has worst performance of anti-noise in the three networks, and DTF has lower noise than T-type feedback network in the range of 0–1 GHz. The simulation results show that the noise of DTF is lower than the other two.

It shows that Johnson noise is reduced in the circuit by optimizing the structure of the feedback network and using smaller resistors. Therefore, it can be seen that in the amplifier circuit, the DTF network can get a larger amplification factor and reduce the thermal noise of the resistance better at the same time. However, we also found that the structure is at the cost of bandwidth, which is in line with the previous analysis. The DTF network will experience a sharp rise in noise at about 80 Hz. Therefore, DTF is suitable for sensors with low frequencies and extremely weak signals.

6. Conclusion

We successfully design a new feedback network for front-end amplifying circuit by double T-type network to detect electric field sensors based on supercapacitors, which has the following advantages. Firstly, the Johnson noise of DTF is 22.9 nV/√Hz, which can be reduced by 67% theoretically with the smaller resistances. It has been experimentally verified that our network has a better linearity which the correlation coefficient R could be increased to 0.967. Secondly, the current to voltage conversion capacity is improved, which means the weaker current can be detected. Thirdly, the Johnson noise is reduced by 46% compared to other circuits. This work indicates that capacitance sensors with large resistance and low frequency can achieve better performance by using DTF.
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