Study on Zero Drift of Charge Amplifier Based on MOSFET 3N165 and OPA LF356N

Zongjin Ren¹, Cong Sun¹, Jun Zhang¹a, Lulu Ma¹, Kai Zhao¹
¹Mechanical engineering school, DaLian University of Technology, China
a Corresponding author: Zhanji@dlut.edu.cn

Abstract. The compensation of zero drift of charge amplifier is of great significance to its application in testing field. In this paper, the zero drift theory of charge amplifier used in an integrated piezoelectric torque dynamometer is studied, which lays a theoretical foundation for the design of high cost-effective zero drift compensation circuit. The charge amplifier is designed based on MOSFET 3N165 and LF356N operational amplifier. The analysis of the charge conversion circuit of this charge amplifier and the establishment of a reasonable equivalent circuit model are the key to design the compensation circuit. In this paper, the equivalent circuit model of charge conversion is established for this charge amplifier, and the theoretical formula of zero drift at 25°C~40°C is derived. By comparing theoretical value of zero drift with measured value, the compensation ratio coefficient \( \varepsilon \) of junction temperature is introduced to modify the formula. Finally, the correctness of the revised formula is verified by experiments. The result shows that the modified formula is applicable to the actual zero drift prediction in the experimental process, which lays a theoretical foundation for the design of zero drift compensation circuit for the integrated piezoelectric torque dynamometer with this charge amplifier.

1. Introduction

With the rapid development of modern science and technology, piezoelectric sensors for measuring non-electrical physical quantities have been more and more widely used in various technical fields. The output of piezoelectric sensor needs to be converted by a charge amplifier (charge-voltage conversion) before it is used for subsequent amplification and data processing. Therefore, charge amplifier is an indispensable secondary instrument for measuring with piezoelectric sensor and its main function is to convert charge signal into voltage signal. So, the design of charge amplifier with good performance is of great significance to the measurement with piezoelectric sensor. However, when measuring static or low-frequency charge signals with charge amplifier, the instrument itself will have a stability problem, namely zero drift, which causes instrument's output to be unstable. This problem limits the application of charge amplifier and piezoelectric sensor in static or low-frequency long-term measurement¹, and it seriously affects the processing results of data processing results. The presence of zero drift will cause the drift signal and the effective signal voltage to be indistinguishable. In severe cases, the drift voltage will even drown the effective signal voltage, making the charge amplifier unable to work properly. Therefore, the zero drift of the charge amplifier must be considered while designing good performance charge amplifier. A smaller zero drift is an important index of high performance charge amplifier. At present, the problem of eliminating zero drift of charge amplifier is studied both at home and abroad.
Zhende Hou and Ruiting Gao of Tianjin University have proposed a method to eliminate the zero drift of charge amplifier through the feedback compensation network in circuit\(^2\). However, they do not consider the specific ambient temperature and have their limitations in use. Chunfei Zhang and Jiarong Luo, have proposed a method to remove zero drift with software\(^3\) which is written in object-oriented C++ language. The reusability of code, extensibility of function and portability of system are better\(^4\), but it is not applicable for long-term measurement. Zhenxing Li, Zhiwu Xuan, and Hongzhou Xu, have proposed a method of sliding the segmental average to remove zero drift when dealing with vibration signals\(^5\). The sliding average method can effectively remove the step-type zero drift, which can improve the accuracy of data processing results and the reliability of spectrum analysis. The problem is that the selection of the width of the window function and the setting of the threshold value require the experimental data processing personnel to make human judgments based on the actual data, but there is no general method and theoretical basis. Miran Milkovic of General Electric Company of the United States proposed a zero drift compensation method for long-term operation of an operational amplifier or integrator. Compared with the chopper-stabilized compensation method\(^7\), this method requires no external components and recovers faster under overload conditions\(^8\), but the system has lower cost performance and higher cost. The series of charge amplifiers 5015A produced by Kistler from Switzerland, has a large measuring range, wide operating frequency and zero-point automatic correction function\(^9\). It has a good effect of removing zero drift and meets the needs of long-term measurement, but the cost is usually 8–10 times the price of similar products in China. And the introduction of the zero drift compensation part in the manual is not specific enough to be used for reference.

A high cost-effective zero drift compensation circuit can be designed for the charge amplifier of the integrated piezoelectric torque dynamometer. The expression of zero drift on time and temperature is obtained by collecting the zero drift signal, which lays a theoretical foundation for achieving the goal of eliminating zero drift. The charge amplifier is based on the 3N165 MOSFET and the LF356N integrated operational amplifier. In this paper, the charge conversion circuit is analyzed for this type of charge amplifier to establish a reasonable equivalent circuit model. Then the corresponding expressions are listed by the Kirchhoff’s law\(^10\), and the zero drift formula is deduced, and the formula is further modified. This is the key to design the zero drift compensation circuit of the charge amplifier.

2. Modeling the core of a charge-transfer circuit
An equivalent circuit model is established for the charge amplifier studied in this paper. In the process of model building, the schematic diagram of the charge-transfer circuit is given first, and its principle is analyzed. Then, the equivalent circuit analysis of the two core components of the dual P-channel enhancement MOSFET model 3N165 and the integrated operational amplifier model LF356N are carried out respectively. Finally, the whole circuit model of the core of the charge-transfer circuit is established. For LF356N, the rate of increase in internal input bias current varies with temperature. Generally speaking, the bias current raises with increasing temperature, but at low temperatures, other sources of leakage in the operational amplifier may change this trend. Such stray leakage may have different temperature characteristics. Little is known about leakage below room temperature. However, more attention is paid to leakage at room temperature and above it in the research at present. Combining with the operating conditions of charge amplifier and data of LF356N, the temperature range studied in this paper is between 25°C and 40°C.

2.1 The schematic diagram of charge-transfer circuit
The charge-transfer circuit is the core circuit of the charge amplifier. The schematic diagram of the charge-transfer circuit is shown in Fig.1, which is based on the principle of integrator. The core components are the dual P-channel enhancement MOSFET 3N165 and integrated operational amplifier LF356N. Where \(Q\) is the input charge signal, \(R_d\) is the insulation resistance of piezoelectric sensor and \(C\) is the feedback capacitor. With LF356N as the core of the integration circuit, \(R_d\) and \(C\) constitute the integral conversion circuit, which converts the charge signal \(Q\) into voltage signal. The
first channel D1, G1 and S1 of the MOSFET 3N165 mainly serves to improve the input resistance of the operational amplifier and can make it up to $10^{14} \Omega$. The second channel D2, G2 and S2 of the MOSFET 3N165 and sliding rheostat $R4$ and resistance $R5$ constitute a control circuit to regulate the negative input offset voltage of LF356N, so as to ensure that the output $V_o$ of the whole circuit is zero when the charge input is zero.

Figure 1. The schematic diagram of the charge-transfer circuit.

2.2 Model of charge-transfer equivalent circuit

In order to simplify the analysis and keep its generality, assuming that the input charge signal $Q$ is zero, then the output $V_o$ of the charge conversion circuit is equated to zero drift. In order to meet the actual working conditions of components, the offset voltage $V_{os}$ and input bias current $I_b$ of integrated operational amplifier LF356N should be taken into account here (Due to the accuracy problem of the components controlling the input offset voltage of LF356N with the second channel of 3N165 as the core, the offset voltage $V_{os}$ still exists after adjustment. In order to simplify the analysis, the unbalanced voltage $V_{os}$ before adjustment is still used for analysis. Therefore, the negative input of LF356N can be used as direct grounding). The equivalent circuit of charge-transfer is shown in Fig.2, in which the direction of the diagram is the direction of current and voltage direction. Among them, where $R$ is the first channel equivalent resistance of MOSFET 3N165, whose value is about $10^{14} \Omega$, $R_d$ is the insulation resistance of piezoelectric sensor, $C$ is the feedback capacitor, $V_{os}$ and $I_b$ are the input offset voltage and input bias current of integrated operational amplifier LF356N, $R_i$ is the input impedance of LF356N and $K$ is the open-loop gain of LF356N.

Figure 2. The equivalent charge-transfer circuit.

2.3 Derivation of drift formula under single sensitivity

Based on equivalent charge-transfer circuit, the Kirchhoff Voltage Law (KVL) is applied. And it is applied at point a in Fig.2. The Kirchhoff voltage law at a point is expressed as:

\[ I_c = I_1 - I_2 \]  \hspace{1cm} (1)

\[ I_1 = -\frac{V_u}{R_d} \]  \hspace{1cm} (2)

\[ I_2 = I_b + \frac{V_i}{R_i} \]  \hspace{1cm} (3)
\[ V_o = -KV_i \] (4)
\[ V_a = V_{os} + V_i + I_v R \] (5)
\[ V_o = -\int_0^t \frac{I_v dt}{C} + V_a \] (6)

The six formula of simultaneous (1), (2), (3), (4), (5), and (6) are:
\[ V_o = -\left(\frac{KR}{(R_i+R+KR_i)C}\int_0^t \left(\frac{1}{R_i+R+KR_i}V_o - I_v - \frac{V_{os} + R_i}{R_d}\right)dt + \left(V_{os} + \frac{R_i}{R_d}\right)\right) \] (7)

At a certain temperature, the last term of formula (7) is constant and can be eliminated as a systematic error. After removing the constants in formula (7), \( t \) is derived from both sides of the formula (7):
\[ V_o = -\frac{KR}{(R_i+R+KR_i)C} \left(\frac{1}{R_i+R+KR_i}V_o - I_v - \frac{V_{os} + R_i}{R_d}\right) \] (8)

When \( t=0 \), \( V_o=0 \) is the initial condition of equation (8), and the solution is:
\[ V_o = -\frac{KR}{(R_i+R+KR_i)C} \left(\frac{e^{\frac{KR}{R_i+R+KR_i}t} - 1}{\frac{1}{R_i+R+KR_i}}\right) \] (9)

For a charge amplifier at a certain temperature under a single sensitivity, \( V_o \) in Formula (9) is an exponential function of \( t \). Because the power supply voltage of the charge conversion stage circuit is +15V, the zero drift extremum will not exceed +15V. For the MOSFET 3N165 and integrated operational amplifier LF356N, the other variables are known except \( V_{os} \) and \( I_b \) which need to be selected according to temperature. Among them, where \( K = 10^5 \Omega \), \( R_i = 10^{12} \Omega \), \( R = 10^{14} \Omega \), \( R_d = 10^{13} \Omega \) and \( C \) is determined by a single sensitivity, and it is 10000pF. \( V_{os} \) and \( I_b \) need to be selected by combining LF356N datasheet with charge-transfer circuit.

3. Experiment of zero drift

The zero-drift measurement experiment is carried out for the target charge amplifier in this paper to explore the relationship between the calculated theoretical value and the actual value. \( V_{os} \) and \( I_b \) in the formula (9) need to be selected on the basis of the temperature, consequently, it be controlled in the experiment. In this experiment, the temperature is controlled by the thermostat, and the temperature of the incubator is monitored by the thermocouple temperature detector, so that the temperature error value is within plus or minus 0.5°C. To simulate the actual connection of charge amplifiers, the input terminals need to be connected to a piezoelectric sensor. Finally, the zero drift signal is transmitted to the host computer on the PC terminal through the data acquisition card, and then the data is exported. In this experiment, when collecting the zero drift value of charge amplifier, the continuous acquisition time of one experiment is 20min.

![Figure 3. Experimental diagram of zero drift acquisition.](image)

The physical map of the zero drift collection of this experiment is shown in Fig.3. The input terminal of the charge amplifier is connected with a piezoelectric sensor to simulate the high input impedance in actual usage and the output terminal is connected with the data acquisition card, connected with the PC host computer for data acquisition. And the grounding end of the charge...
amplifier is reliably grounded to ensure its normal operation. Charge amplifier is placed in the thermostat and heated in the experiment. The temperature change in the thermocouple is observed by thermocouple thermometer, so as to change the ambient temperature.

Because the temperature can directly affect the $V_{os}$ and $I_b$ values, zero drift experiments were carried out at 25°C, 30°C, 35°C and 40°C respectively for the reasons mentioned above. Fig. 4, Fig. 5, Fig. 6 and Fig. 7 are data comparison diagrams of experimental data and theoretical formula (9) calculation at different temperatures respectively.

![Figure 4. Comparison of measured zero drift and theoretical zero drift at 25°C.](image1)

![Figure 5. Comparison of measured zero drift and theoretical zero drift at 30°C.](image2)

![Figure 6. Comparison of measured zero drift and theoretical zero drift at 35°C.](image3)
Figure 7. Comparison of measured zero drift and theoretical zero drift at 40°C.

The difference between the measured zero drift value and the theoretical zero drift value at four temperatures is compared and analyzed. It is found that there are different multiplier relations among them. This reason is that there are different junction temperatures of transistors in LF356N at different temperatures, which leads to the change of bias current of operational amplifier. In order to improve the accuracy of the theoretical formula, it is necessary to further modify the theoretical formula (9) at different temperatures.

4. Correction of theoretical formula

According to the problem that the theoretical value of zero drift has different ratio relationship with the measured value at different temperatures, the relevant data are analyzed. A coefficient $\varepsilon$ is introduced on the basis of formula (9) and expressed in formula (10), which refers to the junction temperature compensation ratio required by integrated operational amplifier LF356N at different operating temperatures. The data analysis at four temperatures is shown in Table 1, and the compensating ratio coefficients of junction temperature at each temperature are obtained.

$$V_o = -\varepsilon \frac{K_R(V_o + I_b R + I_d R)}{R + R_d + R}[e^{\frac{K_R}{R_d(R + R_d + R)}} - 1]$$

(10)

Table 1. Junction temperature compensation rate coefficient at different temperatures.

| Temperature (°C) | Coefficient of junction temperature compensation ratio $\varepsilon$ |
|------------------|---------------------------------------------------|
| 25               | 0.389                                             |
| 30               | 0.313                                             |
| 35               | 0.245                                             |
| 40               | 0.182                                             |

Figure 8. Junction temperature compensation rate coefficient and temperature relationship diagram.

After obtaining the compensation ratio coefficient of junction temperature at different temperatures, the data are fitted as shown in Fig.8, and the functional relationship of $\varepsilon$ and temperature $T$ is obtained. Comparing the coefficients $\varepsilon'$ calculated from the formula with that $\varepsilon$ obtained from the previous data analysis, the following table 2 is obtained. It can be seen from Table 2 that the maximum difference.
The analysis coefficient $\varepsilon$ of the compensation coefficient and the calculated value of the compensation coefficient $\varepsilon'$ is only 0.012. And the

Table 2. Comparison of calculated value and analytical value of junction temperature compensation rate coefficient.

| Temperature (°C) | Analytical value of compensation coefficient $\varepsilon$ | Calculated value of compensation coefficient $\varepsilon'$ | Deviation |
|------------------|----------------------------------------------------------|---------------------------------------------------------|-----------|
| 25               | 0.389                                                    | 0.401                                                  | 0.012     |
| 30               | 0.313                                                    | 0.312                                                  | -0.001    |
| 35               | 0.245                                                    | 0.243                                                  | -0.002    |
| 40               | 0.182                                                    | 0.189                                                  | 0.007     |

temperature is 25°C. At 25°C, the maximum drift of zero drift is less than 0.4mV, which is within the allowable range of actual measurement. Therefore, the relationship is consistent with the actual situation and can be used for correction in equation (9). The final form of the correction formula is formula (11).

$$V_i(T,t) = -1.39\times10^{-6}e^{0.05T} \frac{K R}{R_i + R + I_i R_i} \left[ e^{\frac{R_i}{R_i (R + I_i R_i) (e^{0.05T})}} - 1 \right] \tag{11}$$

Where $T$ is the ambient temperature, the unit is °C, $t$ is time, the unit is s, and the remaining values are selected as described above.

According to the correction formula (11), the theoretical formulas at 25°C, 30°C, 35°C and 40°C are modified to obtain a comparison chart of the theoretical zero drift value and the actual zero drift value, which are shown in Fig.9, Fig.10, Fig.11, and Fig.12. By analyzing the difference between the corrected zero drift value and the actual value, it can be seen that the maximum error value at 25°C, 30°C, 35°C and 40°C is 0.5mV, 0.2mV, 0.5mV and 0.5mV respectively, and these errors are allowed in the actual measurement under this sensitivity. Therefore, formula (11) can be used as a zero-drift expression formula for charge amplifiers based on MOSFET 3N165 and LF356N operational amplifiers in the range of 25°C to 40°C.
Figure 11. Comparison of zero drift of measured zero drift and correction formula at 35°C.

Figure 12. Comparison of zero drift of measured zero drift and correction formula at 40°C.

5. Verification experiment of correction theoretical formula
Experiments under the same conditions are carried out to verify the correctness of the revised theoretical formula after correcting the theoretical formula. The ambient temperature is set at 28°C, and the modified formula is verified experimentally. The other conditions are the same except that the ambient temperature need to be changed by the incubator. The temperature is controlled in the range of 28±0.5°C by the incubator and thermocouple temperature detector. One experiment is still 20 minutes. The comparison between measured experimental data and theoretical formula (9) are shown in Fig.13.

Figure 13. Comparison of measured zero drift and theoretical zero drift at 28°C.
Figure 14. Comparison of zero drift of measured zero drift and correction formula at 28°C.

It can be seen from Fig.13 that the measured zero drift value has a large difference from the theoretical zero drift, so it needs to be corrected by using the correction formula. According to the coefficient $\varepsilon$ of compensation ratio of junction temperature introduced in the previous paper, the theoretical zero drift value at 28 °C was corrected, and the comparison chart between the measured zero drift and the theoretical correction formula at 28°C is shown in Fig.14. After correction, the maximum difference between the measured zero drift and the corrected theoretical formula is only 0.5mV, which meets the actual measurement requirements. It is further shown that the introduced coefficient $\varepsilon$ of junction temperature compensation ratio conforms to the zero drift compensation law of this type of charge amplifier.

6. Conclusion
In this paper, the zero-drift of the charge amplifier of the charge-transfer circuit is analyzed based on a charge-transfer circuit of 3N165 MOSFET and LF356N integrated operational amplifier. The equivalent circuit model of charge conversion stage is established and the theoretical formula of zero drift of this type of charge amplifier is derived. After the comparison between the theoretical and measured values of zero drift, the coefficient $\varepsilon$ of compensation ratio of junction temperature is introduced and the theoretical formula is corrected. Finally, the verification experiment was carried out by the zero drift value at 28°C. The results show that the correction theoretical formula is applicable for the actual zero drift prediction. The results of this study provide a reliable theoretical basis for the application of this charge amplifier to remove zero drift on a rotary torque dynamometer. Based on this theory, the compensation circuit can be used to compensate for the zero drift of this charge amplifier.

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