Design and analysis of singal conditioning circuit for vibration sensor

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Abstract: A piezoelectric sensor charge/voltage conversion circuit is designed based on the principle that piezoelectric sensor can convert the vibration or shock acceleration into the charge proportionally. Effect of temperature characteristic of feedback capacitor on the switching circuit output is analyzed based on the acquisition and measurement system in this paper. The characteristics of different filters are analyzed, and the corresponding filter circuit is configured according to the actual sensor bandwidth. Experiments show that the circuit can effectively filter out noises among the vibration signal and obtain vibration signal accurately.

Key words: vibration; piezoelectric sensor; singal conditioning circuit; feedback capacitor

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0 Introduction

In the modern industrial and automated production process, the shock and vibration signals of equipment are usually obtained by using a piezoelectric accelerometer, and the charge signals produced by the piezoelectric sensor need to be amplified and processed by a charge amplifier. However, the traditional design of charge amplifier circuit is very complicated, and the price of the machine is very high, so the cost performance is not ideal, which seriously affects the widespread use of piezoelectric accelerometer. It is very necessary to develop a cost-effective and practical charge amplifier. By using the integrated operational amplifier chip to replace a large number of discrete components to optimize the design of the charge amplifier could improve the integration of the circuit, which makes the whole circuit has advantages such as a small size, low power consumption, parasitic factors and anti-jamming performance; at the same time, aiming at the problem that the noise signal is easy to be mixed in the vibration signal measurement, the corresponding filter circuit is designed by analyzing the characteristics of different high order filter chips. The experimental results show that the design of the conditioning circuit is feasible and simple in the production and debugging, and it has very great practical value.

1 Design of conditioning circuit

1.1 Piezoelectric sensor equivalent circuit

Piezoelectric sensor is designed based on the piezoelectric effect. The sensitive component is made by piezoelectric material. Once being subjected to external force, the surface of piezoelectric material would generate some weak charges. When the piezoelectric sensor is forced in the direction of the sensitive axis, polar opposite charges are got on the two electrodes, which are equivalent to a charge source (electrostatic generator)[1]. The equivalent circuit is shown in Fig. 1.

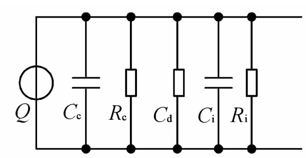

Fig. 1 Piezoelectric sensor equivalent circuit

In Fig. 1, C_c equals the sensor capacitor; C_d is the cable capacitor; C_i is the amplifier input capacitor; R_c is the sensor insulation resistance; R_i is the amplifier input resistor. According to Fig. 1, the resistor and the capacitor constitute the RC circuit, and the

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charge generated by the force of piezoelectric sensor will be released through the RC circuit.

Set

$$\begin{cases} \frac{1}{R} = \frac{1}{R_c} + \frac{1}{R_i}, \\ C = C_c + C_i + C_d, \end{cases} \tag{1}$$

and also there are

$$C = \frac{Q}{U},\ I = \frac{dQ}{dt},\ U = IR. \tag{2}$$

Thus the voltage of piezoelectric sensor is obtained by Eqs. (1) and (2) as

$$U = RC\frac{dU}{dt}. \tag{3}$$

Using initial conditions $t=0$ and $U=U_0$, U can be obtained by

$$U = U_0 e^{\frac{t}{RC}}. \tag{4}$$

Setting $\tau=RC$, the voltage of piezoelectric sensor is related to the time constant τ; the larger the time constant τ is, the slower the charge leaks out, and the smaller the measurement error of the sensor gets. The cable capacitance C_d and the sensor capacitor C_c are usually fixed values, the amplifier input capacitance C_i depending on the op-amp output sensitivity can not be increased arbitrarily, and the sensor and the signal input should be in high insulation resistant to prevent the charge measurement error caused by rapid leak[2].

1.2 Charge-voltage conversion circuit

1.2.1 Design of charge-voltage conversion circuit

The charge-voltage conversion circuit is shown in Fig. 2.

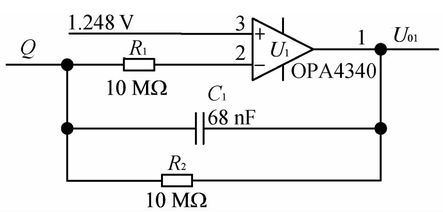

Fig. 2 Charge-voltage converting circuit

The piezoelectric vibration sensor is ranged in $\pm 10\ 000\ g$ with sensitivity of 3.5 pC/g, and the sensor produces charges as follow

$$Q = \pm 10\ 000\ g \times 3.5\ \text{pC}/g = \pm 35\ 000\ \text{pC}. \tag{5}$$

If the output voltage range of the op amp is set from −0.51 V to +0.51 V, the feedback capacitor C_1=68 nF can be obtained by applying the formula $C=-Q/U$. Since OPA4340 is rail-to-rail input/output amplifier and takes the +5 V power supply, so negative voltage signal (from −0.51 V to 0 V) will be cut-off and not through the op-amp output, which causes the measurement result incompleted. In order to ensure the integrity of signal measurement, the offset voltage of 1.248 V is added to the forward end of the U_1 integrated operational amplifier, and the output voltage range of the operational amplifier is from 0.738 V to 1.758 V.

In order to avoid the capacitor C_1 being charged for a long time to saturate the integrated operation, it is necessary to connect a resistor R_2 in parallel at the capacitor C_1. Meanwhile, another important role is to introduce the direct current negative feedback, which can effectively inhibit input offset voltage due to integrated op-amp, input offset current and drift caused by temperature drift integral[3].

The lower cut-off frequency of the system test is $f=1/2\pi R_2 C_1$. The cut-off frequency of the input signal is calculated as 0.1 Hz, and the resistance is R_2 = 10 mΩ. The resistor R_1 of the operational amplifier inverting input plays a major role in protecting the circuit and limiting the current[4].

1.2.2 Analysis of feedback capacitance

The main function of feedback capacitor C_1 is to convert the charge signal generated by sensor into the voltage signal, so the feedback capacitor needs to select a capacitor with low drift, low drift temperature and high leakage resistance. In the highest and the lowest temperature resistance test chamber, 0.1 μF value capacitors of nominal monolithic capacitor, round ceramic, ceramic chip, polystyrene are picked up as the feedback capacitors. The experimental results of op-amp output voltages with the different temperatures are shown in Fig. 3.

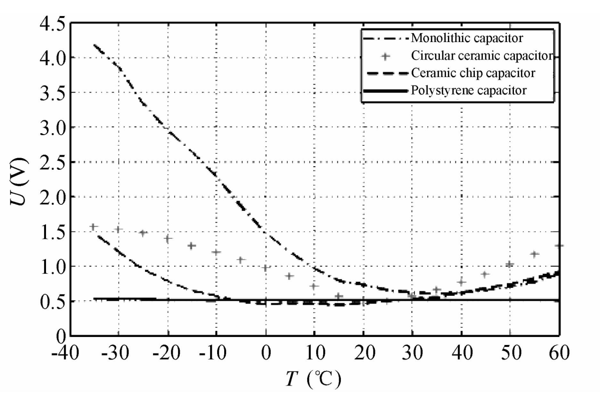

Fig. 3 Different feedback capacitors output voltage

As shown in Fig. 3, the temperature characteristics of the capacitor would strongly influence the output of the piezoelectric sensor conditioning circuit. Selecting 104 monolithic capacitors as feedback capacitors, they will produce a measurement error of up to 800%, while the equivalent capacity of polystyrene capacitor is only 1%.

It is not difficult to find that the temperature characteristics of polystyrene capacitor are ideal. In engineering practice, it is also proved that the use of polystyrene capacitors as feedback capacitors will greatly reduce the measurement error caused by the change of environment.

1.3 Design of isolation and voltage amplification circuit

The isolation and voltage amplifying circuit is shown in Fig. 4.

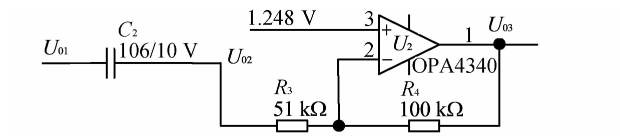

Fig. 4 Isolation and voltage amplification circuit

The 1.248 V DC bias component of the charge-voltage conversion circuit can be filtered out by capacitor C_2, and the U_{02} is changed into an alternating voltage signal from −0.51 V to 0.51 V. The forward bias voltage of 1.248 V is added to the U_2 positive input, and the bias voltage is superimposed to the U_{02}, so the U_{02} input is converted to an AC voltage signal of 0.738 V to 1.758 V.

The voltage output range of the charge amplifier is not consistent with the input range of the subsequent AC/DC converter, so the voltage amplification circuit is used to adjust the voltage. The voltage amplifying circuit can change the magnification factor by adjusting the ratio of the resistance R_4 to the resistance R_3. According to the principle of "virtual short" and "virtual broken"[5], the relationship between the output voltage U_{03} and the input voltage U_{02} is

$$U_{03} = 1.248\ \text{V} + R_4/R_3(1.248\ \text{V} - U_{02}) = 1.248\ \text{V} + R_4/R_3(1.248\ \text{V} - (1.248\ \text{V} - Q/C_1)). \quad (6)$$

According to Eq. (6), U_{03} ranges from 0.248 V to 2.248 V, so the output voltage meets the input range of the subsequent circuit AC/DC converter AD7667.

1.4 Design of filter circuit

1.4.1 Selection of filter

The output voltage of the charge-voltage converter circuit is accompanied with sensor body noise, device noise and other high-frequency noise, which will blend into the voltage amplifier circuit[6] together with the real signal, and the interference signal will be further amplified, which makes the vibration signal measurement inaccurate. A high-order low-pass filter can be used to further process the signal to suppress the aliasing of the noise signal and the effective signal.

An integrated filter chip can usually be used to filter the signal to eliminate the noise and the effect of interfering signals. Common filter types include butterworth filter, elliptical function filter, Bessel type filter and so on[7].

Through the access to the chip manual, we can obtain MAX291 filter, MAX7400 elliptic filter and LTC1569 Bessel filter, and the three filter chip DC bias output error are shown in Table 1.

Table 1 Filter DC offset voltage

Filter type	DC offset output bias (mV)
MAX291	±150
MAX7400	±5
LTC1569	±2

As can be seen in Table 1, MAX291 Butterworth filter DC bias output deviation is the largest, which is suitable for applications in low accuracy. MAX7400 elliptic function filter and LTC1569 Bessel filter with smaller DC bias deviation are more suitable for this measurement circuit.

The phase-frequency characteristic curves of the MAX7400 elliptic function filter and the LTC1569 Bessel filter are shown in Fig. 5.

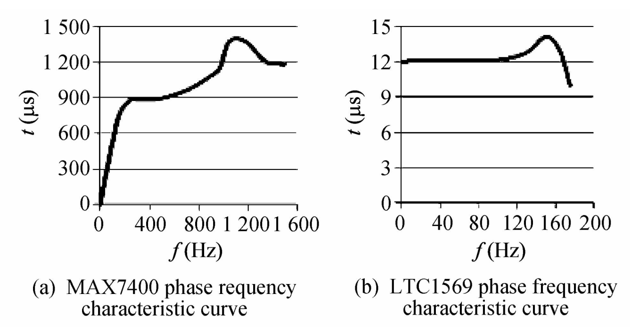

Fig. 5 Phase frequency characteristic curves

As shown in Fig. 5, the phase-frequency characteristic of the LTC1569 Bessel filter is better, and the signal output delay in the band is basically the same with the linear phase characteristic in the passband, which is 12 μs; the MAX7400 elliptic function filter has different delay in signal output in the band, and the delay time is basically up to the millisecond level at the cutoff frequency.

A filter circuit consisting of LTC1569 Bessel filter and MAX7400 elliptic filter is connected to the square wave of 1 Hz generated by the signal generator, and the output is shown in Fig. 6.

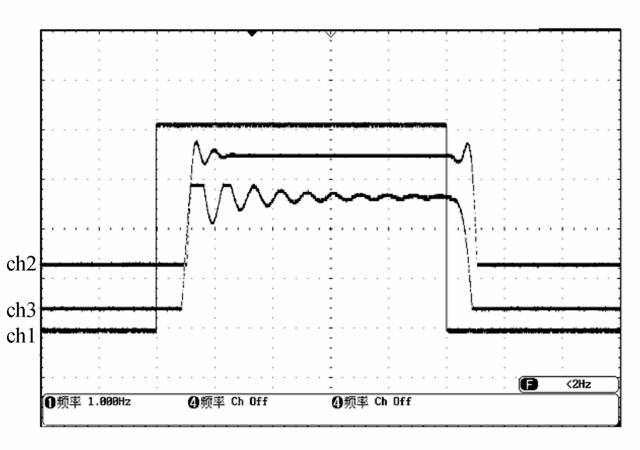

Fig. 6 MAX7400 and LTC1569 square wave signal response graph

The ch1 channel generates 1 Hz square wave signal, the waveform of the ch2 channel is 1 Hz square wave after the LTC1569 filter circuit, and the ch3 channel waveform is the output waveform after the MAX7400 filter circuit. Accroding to the MAX7400 phase-frequency characteristic curve, it can be seen that due to different frequency signal output delay time is different, so different frequency signals mixed together will resulte in serious signal distortion. LTC1569 filter has the same delay time in the frequency signal output in the passband, so the output waveform is closer to the input square wave signal.

In comparison, the DC bias output deviation of the low pass filter composed of LTC1569 is smaller, and the passband has a linear phase characteristics, which can protect the signal without distortion and ensure the accuracy of the signal measurement results.

1.4.2 Design of filter circuit

The filter circuit composed of LTC1569 filter chip is shown in Fig. 7.

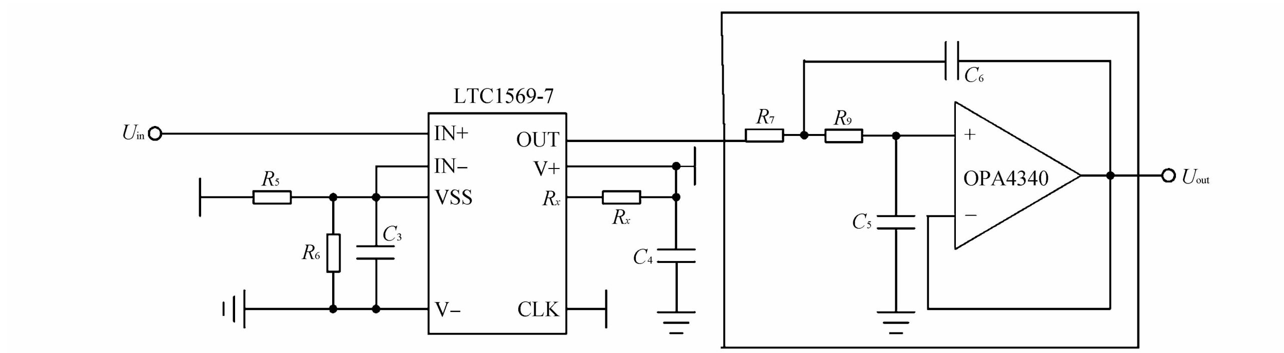

Fig. 7 Filter circuit

LTC1569 is an adjustable 10 order lowpass filter with linear phase and high DC accuracy. In Fig. 7, when the LTC1569 filter CLK pin is connected to the V+pin, the frequency division is set to 16 frequency division[8]. Therefore, the relationship of LTC1569 circuit cutoff frequency f and external resistor R_x is

$$f = 128\ \text{k}\Omega \times (10\ \text{k}\Omega / R_x)/16. \quad (7)$$

According to the vibration signal cutoff frequency of 9.76 kHZ, $R_x = 8.2$ kΩ can be calculated, and the R_x requires a resistance of 1% accuracy to ensure the accuracy of the cutoff frequency[9].

Although the LTC1569 filter can provide high quality filter characteristics, the chip filter principle is based on the switching capacitor effect, which results in high frequency switching noise at the output. The switching noise is filtered by adding a second-order low-pass filter after the LTC1569 filter. The waveform of the ch1 channel is sine wave after the LTC1569 filter circuit in Fig. 8.

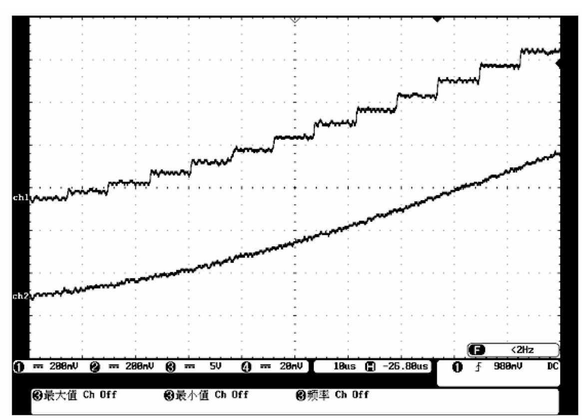

Fig. 8 Comparison of waveforms before and after filtering out switching noise

Due to the impact of switching noise, the waveform is mixed with the steps similar to the noise. The waveform of the ch2 channel is sine wave after adding a second order low-pass filter, and the signal of the sine wave can be clearly seen that the switch noise is effectively filtered and the waveform becomes smoother.

2 Results and analysis

2.1 Amplitude response of vibration signal conditioning circuit

The measurement system that contains the vibration signal conditioning circuit will connect the piezoelectric sensor to the amplitude verification first to check the correctness of the tuned circuit. During the verification process, the sensor is fixed on the vibrating table, and the output signal of the sensor is collected by the sinusoidal sweep mode. The data collection is shown in Fig. 9. The maximum control reference spectrum of sinusoidal sweep frequency is $\pm 30g$, and the corresponding frequency range is (200±50) Hz. It can be seen from the Fig. 9 that the piezoelectric sensor vibration frequency is about 160 Hz, and the actual control spectrum is $\pm 30g$. The measurement system through the calibration of the linear fitting calibration shows the experimental process of sine sweep more truly.

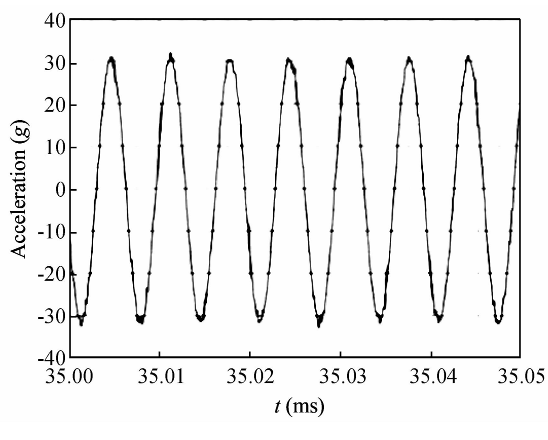

Fig. 9 Piezoelectric sensor sine sweep frequency curve

2.2 Frequency response of vibration signal conditioning circuit

Using the signal generator to sweep the conditioning circuit test, the channel frequency response curve is obtained as shown in Fig. 10. The cutoff frequency of the channel obtained by Fig. 10 is 9.76 kHz which meets the design requirements.

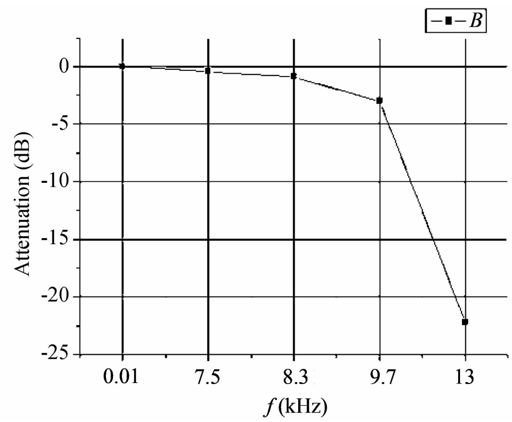

Fig. 10 Frequency response test plot

2.3 System function verification

A standard charge generator is used as the charge source to simulate the output of the vibration sensor, and it is connected to the circuit to measure. The theoretical voltage value is calculated by using the Eq. (5), and the results are shown in Table 2.

Table 2 Conditioning circuit functional verification

Input charge (pC)	Theoretical voltage (V)	Measured voltage (V)	Voltage measurement error (%)
30 000	2.113	2.120	0.331
−30 000	0.383	0.386	0.783
20 000	1.825	1.840	0.822
−20 000	0.671	0.676	0.745
10 000	1.536	1.548	0.781
−10 000	0.960	0.969	0.938

It can be seen from Table 2 that the measured voltage is basically consistent with the theoretical value. The measurement error of the conditioning circuit is less than 1%, which can meet the requirements of vibration signal measurement accuracy and accurately measure the vibration signal.

3 Conclusion

In this paper, piezoelectric sensor is the research object, the sensor equivalent circuit and the regulating circuit are introduced in detail, and the capacitance and filter of the key components of the regulating circuit are analyzed and studied. The vibration signal conditioning circuit introduced in this paper has been tested in many missile telemetry experiments, and the obtained data is highly accurate. The collected vibration signal data provides reliable data support for the design of the missile structure and the installation of the electronic devices in the internal environment.

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振动传感器信号调理电路设计及分析

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摘　要： 基于压电式传感器能把振动或冲击的加速度转换成与之成正比的电荷这一原理，提出了该类型传感器的等效电路。设计了基于采集测量系统的压电式传感器电荷/电压转换电路，分析了电路中关键元器件——反馈电容的温度特性对于转换电路输出的影响，对不同类型滤波器进行了特性分析，并根据实际传感器带宽配置了相应滤波电路。通过试验表明，该信号调理电路能有效滤除振动信号中的噪声信号，并能获取精确的振动信号。

关键词： 振动；压电传感器；信号调理电路；反馈电容

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