Signal detection technology of digital closed-loop quartz flex accelerometer

Zhang Xi[1], Zhang Shengyan[2]

(1. School of Instrumentation Science and Opto-electronics Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China;
2. Research and Development Center of China Academy of Launch Vehicle Technology, Beijing 100076, China)

Abstract: The digital closed-loop quartz flex accelerometer (DCLA) can effectively solve the precision loss which exists in the output current to the digital conversion of the traditional analog quartz flex accelerometer, and the accuracy of the DCLA mainly depends on the differential capacitance detection circuit. The working principle of DCLA was introduced, and the signal detection scheme was studied. According to the signal characteristics, with the method of single carrier modulation and demodulation technology, triangle wave modulation technique was applied to implement the capacitance detection, and the digital correlative demodulation scheme was proposed to extract the amplitude signal. To build the DCLA experimental prototype, under the 0 g/±1 g stability test, the bias stability of 0 g/±1 g was 17.595 0 μg, 19.363 7 μg and 20.715 3 μg, respectively. Currently, the result shows that the precision of the DCLA is basically equal to the traditional analog accelerometer, which verifies the correctness of the signal detection method.

Key words: correlative detection; accelerometer; digital closed-loop; differential capacitance; modulation and demodulation

CLC number: V441 **Document code:** A **Article ID:** 1007-2276(2014)10-3356-07

数字闭环石英挠性加速度计信号检测技术

张 晞[1],张声艳[2]

(1. 北京航空航天大学 仪器科学与光电工程学院,北京 100191;
2. 中国运载火箭技术研究院研究发展中心,北京 100076)

摘 要: 数字闭环石英挠性加速度计可以有效地解决传统模拟式加速度计在模数转换中引起的精度损失问题,而数字式加速度计的精度主要取决于差动电容检测环节。阐述了数字式加速度计的工作原理,重点设计了差动电容检测方法,利用单载波调制与数字自相关解调技术构建完整的数字式加速度计信号检测方案。搭建数字式加速度计原理样机,对其进行 0 g/±1 g 稳定性测试,得到数字式加速度计 0 g/±1 g 零偏稳定性分别为 17.595 0 μg、19.363 7 μg、20.715 3 μg。测试结果表明,当前的数字式加速度计精度达到了模拟式加速度计精度量级,有效验证了该方案的可行性及正确性。

关键词: 自相关检测; 加速度计; 数字闭环; 差动电容; 调制解调

收稿日期: 2014-02-13; **修订日期:** 2014-03-19

作者简介: 张晞(1972-),高级工程师,博士,主要从事光纤传感与光电检测技术方面的研究。Email:zhangxi@buaa.edu.cn

0 Introduction

As a kind of typical capacitive accelerometer, the limit precision of quartz flexible accelerometer is determined by the sensitivity of differential capacitance detection circuit. However, considering the limitation of the capacitive accelerometer, which includes the processing technology and the volume, the header static capacitance is about pF level(10^{-12}F), moreover, the capacitance variation of the sensitive mass displacement produced by acceleration is more exiguous, generally is at the fF (10^{-15}F) or aF (10^{-18}F) level[1]. As a result, the header output signal is so weak that it is easily affected by the various kinds of parasitic capacitance. How to detect the header tiny capacitance is one of the key problems of the capacitive accelerometer.

Currently, several methods are used in the capacitance detection, including capacitance to frequency conversion[2], Capacitance Bridge[3], switch capacitance method[4], modulation and demodulation[5], etc. Among which the modulation and demodulation method is also divided into single carrier dual-channel amplifier and double carrier single-channel amplifier[6]. Compared with other methods, the single carrier and dual-channel modulation scheme has more notable advantages on low noise, high linearity, weak affection and simple design, so it is widely used in differential capacitance detection circuit of accelerometer. Such as LB309, single carrier modulation technology was used in current mirror differential capacitance detection circuit, which through two PNP current mirrors and a current inverter to realize the header capacitance detection.

High precision inertial navigation system puts forward higher performance on the quartz flexible accelerometer. Due to the traditional analog quartz flexible accelerometer needs an external analog to digital conversion circuit to provide digital information for the navigation computer; the precision loss is inevitably produced in the conversion[7]. Based on the digital closed-loop detecting technology, the digital quartz flexible accelerometer (DCLA) can effectively solve the above problem and output digital information directly. As a new kind detection scheme, how to realize the precise capacitance and signal detection of the DCLA are of great significance in improving the system precision.

1 System scheme design

1.1 System overall scheme

As shown in Fig.1, the DCLA is mainly composed of mechanical header components and digital closed loop detection circuit[8]. The latter is controlled by the FPGA, which includes differential capacitance detection circuit, A/D conversion circuit, digital signal processing circuit, D/A conversion circuit and feedback driver circuit. It is obvious that the differential capacitance detection circuit is in the front end of signal, which plays a vital role on the

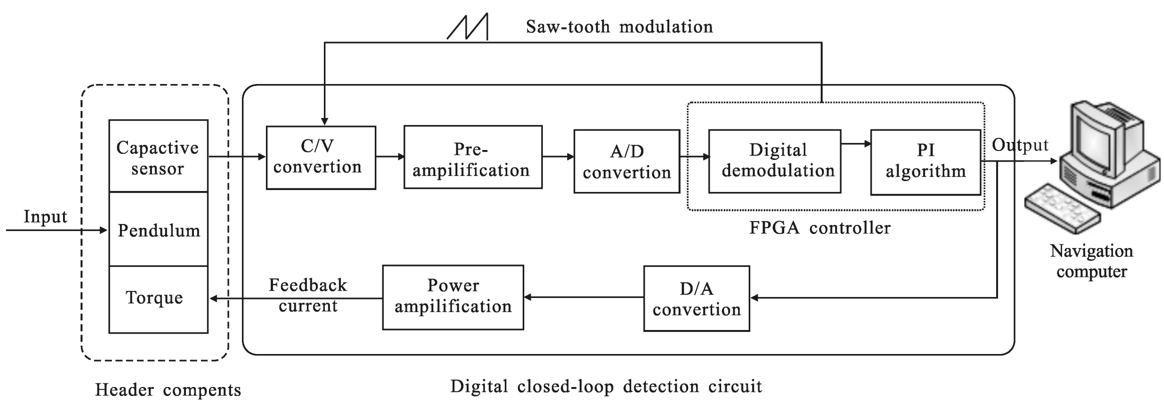


Fig.1 Principle of digital closed-loop quartz flex accelerometer

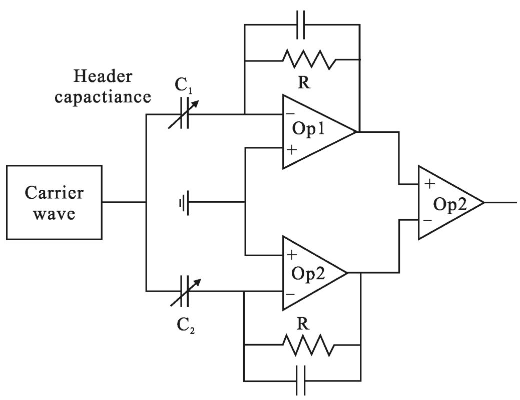
whole detection system.

When the quartz flexible pendulum is sensitive to the external acceleration, it will produce a capacitance change, and then the change of capacitance will be converted into the amplitude proportional to the current or voltage signal through the differential capacitance detection circuit.

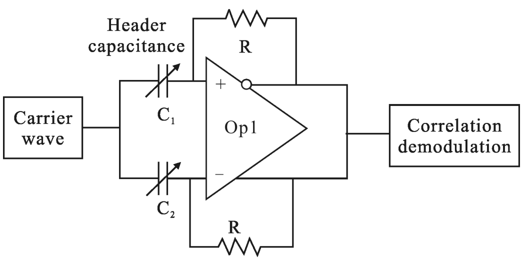
1.2 Scheme of capacitance detection

Quartz flex accelerometer is so easily affected by the parasitic capacitance that the output signal to noise ratio is rather low. Therefore, in order to improve the detection sensitivity, in this paper, the single carrier modulation and demodulation technique is used in the differential capacitance detection scheme.

Figure 2 is the principle of the differential capacitance detection circuit. Among which Fig.2 (a) is the common used scheme, instead, Fig.2 (b) is the scheme configured in the digital accelerometer. Through the differential function, the circuit can convert the weak capacitance signal into the amplitude of high frequency carrier signal.



(a) Principle of common used scheme



(b) Principle of DCLA

Fig.2 Principle of differential capacitance detection scheme

By all appearances, a differential operational amplifier is used in Fig.2 (b) to realize the same function in Fig.2 (a), which adopts three operational amplifiers. On one hand, the configuration of Fig.2(b) can effectively reduce the error which brought by the two dual signal parameters mismatch; on the other hand, it is conducive to realize the miniaturization of the system.

2 Analysis of carrier wave

As is shown in Fig.2(b), modulation waveform is produced by the FPGA, through the D/A converter, output the analog waveform on the movable plate of the header differential capacitance. Here carrier signal is determined by the waveform, frequency, amplitude and stability.

2.1 Carrier waveform

For the capacitive accelerometer, the commonly used carrier signals are sine wave, square wave and triangle wave. As shown in Tabl.1, there is a detailed comparison about the frequency, bandwidth and realization of each carrier signal, respectively. It can be seen that selecting the triangle as a modulation waveform has an advantage that the differential signal is a square wave, which facilitates the digital demodulation subsequently.

Tab.1 Comparison of modulation signal wave

Parameter	Sin wave	Square wave	Triangle wave
Frequency	Singleness	Complex	Complex
Bandwidth	Low	>10 times of signal	High
Realization	Complex	Easy	Easy

2.2 Carrier frequency

Usually, for the fixed capacitance detection, the higher the frequency, the smaller the capacitive reactance, and for the quartz flex accelerometer system, the small capacitive reactance is beneficial to improve the system measurement sensitivity. Due to the high impedance of the header, high frequency signal should be used as an incentive in order to reduce the output impedance. Additionally, in terms of the noise, high frequency carrier signal is the best choice to reduce the noise influence[9]. However, with the increase of carrier frequency, it will put forward higher request on the operation amplifier, such as the SR(slew rate) and the GBW(gain bandwidth product). Therefore, the selection of carrier frequency should consider the following points.

(1) Carrier frequency is associated with the output noise power spectrum. Theoretical analysis shows that higher carrier frequency can reduce the thermal noise of the capacitance detection circuit effectively. When the carrier frequency is set within the range of 1 kHz to 1 MHz, the square root spectral density of voltage and current is the least.

(2) AD sampling frequency is also influenced by the carrier frequency. Under the Shannon sampling theorem, we often choose sampling frequency as 10 times of the signal frequency for the engineering practice. After the differential function of the carrier signal, the pulse along is useless, in other words, it is not the whole cycle sampling points are valid. Therefore, in order to ensure adequate signal to noise ratio, sampling points should be increased in appropriately. In return, the larger carrier frequency is bad for the increasing of A/D sampling frequency, so the carrier frequency should also not be large. Through the comprehensive consideration, the carrier frequency is set as 100 kHz.

2.3 Carrier amplitude

The charge electrostatic force exists in the space between a certain distances, opposites charges attract and like charges repel. While the movable plate of the quartz flex accelerometer is loaded with a high frequency carrier signal, the movable and fixed plate will store the same amount of opposite charges, respectively. Because of the potential difference between the two plates, there is an electrostatic force exists. When the carrier amplitude is greater than a certain value, the electrostatic force will exceed the scope of the stiffness of elastic beams, and then the movable plate will be close to the fixed plate. Consequently, in order to avoid the phenomenon of the electrostatic absorption, the voltage which applied on the movable plate must be controlled in a certain range.

On the other hand, increasing the carrier amplitude can improve the output voltage in the case of other conditions unchanged, thus improving the sensitivity and the SNR of the whole system. Therefore, it should try to improve the carrier amplitude in the limited scope. Notice that the differential signal amplitude needs to meet the range of A/D converter, so the carrier amplitude is set as 3.38 V.

2.4 Carrier stability

The carrier signal stability includes frequency stability and amplitude stability, and the former will directly affect the output amplitude due to the frequency characteristics of each circuit module. For a practical circuit, the carrier frequency fluctuation is small, and as long as the gain remains the same within the scope of carrier frequency change, the effects of carrier frequency can be ignored. In fact, in the differential capacitance detection circuit, the mismatch of two dual parameters, such as the initial capacitance values, will increase the noise influence. And the more serious mismatch of the carrier signal, the greater influence of the noise and the lower resolution of the system. Therefore, for the purpose of improving the accelerometer noise performance, the first method is increasing the carrier amplitude to improve the SNR of the capacitance detection carrier. The second method is that minimizing the initial differential capacity which caused by the machining error, the latter can be compensated by the method of paralleling a certain value capacitance with the corresponding pin in the external. The third method is that trying to improve the matching degree of charge amplifier, by choosing a high accuracy of the feedback resistor or capacitor.

As is shown in Fig.3, the amplitude fluctuation of the triangle is basically in the range of 0.01 V.

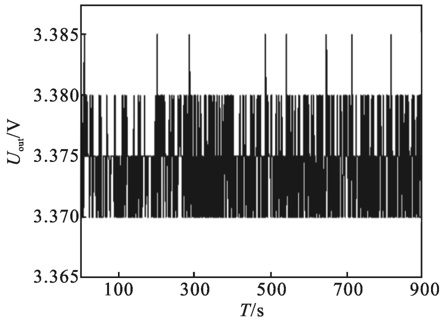


Fig.3 Amplitude fluctuation of triangular

3 Correlative detection

As shown in Fig.2 (b), modulated by the triangle wave, the differential capacitance circuit output is a square wave, whose phase and frequency are in consistent with the input triangle wave strictly. In order to obtain an accurate output voltage, a better linearity of the triangle wave is necessary. The output waveform of the differential circuit is as shown in Fig.4.

If the positive slope of the triangle wave is dU_u/dt, and the absolute value of the decline slope is dU_d/dt, then the relationship between the output voltage amplitude and the header capacitance is given as formula (1):

$$\begin{cases} U_A=-RC_1\left(\dfrac{dU_u}{dt}-\dfrac{dU_d}{dt}\right)=-KC_1 \\ U_B=-RC_2\left(\dfrac{dU_u}{dt}-\dfrac{dU_d}{dt}\right)=-KC_2 \end{cases} \tag{1}$$

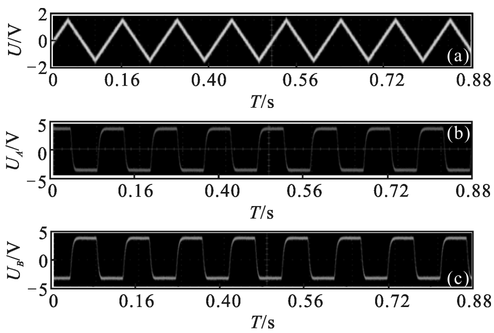


Fig.4 Output waveform of the differential capacitance circuit

As shown in formula (1), the capacitance value caused by the acceleration can be effectively detected through the differential capacitance detection circuit. When there is an input positive acceleration, the quartz flexible pendulum will deviate from the equilibrium position. Might as well $C_1>C_2$, the difference voltage amplitude of the square wave is as $U_A(t)$. On the contrary, when there is a reverse acceleration input, might as well $C_1<C_2$, the difference output voltage amplitude is as $U_B(t)$. Consequently, as long as the amplitude of the square voltage is detected, the value and the direction of the input acceleration can be distilled.

Based on the above analysis, through the triangle wave modulation function, the header capacitance variation can be modulated into the high frequency square wave, whose amplitude is a function of the capacitance variation. Here a method of the weak signal detection should be adopted to extract the output weak signal which is aliased in the complex noise.

As a kind of effective means to extract the weak signal from strong noise, correlation detection is based on the characteristic that the signal is not related with the noise. Through the auto correlation and cross correlation method to detect the weak signal. Might as well there are two continuous smooth and ergodic random processes, are $x(t)$ and $y(t)$, so the definition of the cross correlation function of random function is can be given as formula (2)[10]:

$$R_{xy}(\tau)=\lim_{T\to\infty}\frac{1}{T}\int_0^T X(t)Y(t+\tau)dt \tag{2}$$

It can be seen that when using a pure reference signal for cross correlation, the noise influence can be effectively reduced. So the output weak signal can be detected even if the input SNR is very low.

For the output signal of differential capacitance circuit, the digital demodulation can be realized by extracting the difference value of the positive and negative cycle of the differential square[11]. The sampling process is as shown in Fig.5.

In the process, the output signal is converted into digital quantity through the A/D circuit. Assumed that in each half cycle of the square wave, the number of sample data is n, the demodulation output can be obtained after subtraction, just set the output square

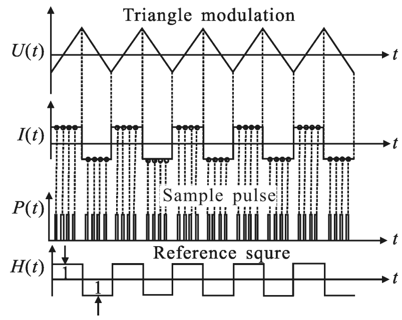


Fig.5 Sampling process of digital correlation

wave as $I(t)$, and the reference square wave is $H(t)$ whose amplitude is 1, thus in each time the demodulation output is ΔS_{out}:

$$\Delta S_{out}=\sum_{i=n+1}^{2n} S_{out+}(i)-\sum_{i=1}^{n} S_{out-}(i)=\sum_{i=n+1}^{2n} S_{out+}(i)+\sum_{i=1}^{n} -S_{out-}(i)=\sum_{i=1}^{2n} I(i)H(i) \quad (3)$$

Compared the formula(2) with (3), it can be seen that the minus of the positive and negative square wave signal is equal to the product of this differential square wave and another square wave with the same frequency and phase. The digital demodulation process actually achieves the correlation detection of output and reference square wave.

4 System design and implementation

According to the above signal detection scheme, the prototype of the DCLA is built in our research, which is as shown in Fig.6. According to GJB1037–2004 method[12], the scale factor of DCLA is acquired by the four positions gravitational field static rollover test, and the scale factor is 3 557 LSB/g, obviously, it can be seen that the system can effectively distinguish the value and the direction within the scope of the ±1 g acceleration.

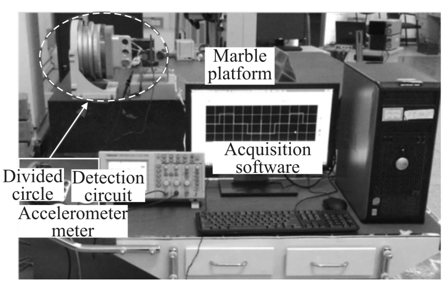


Fig.6 Ptorotype of DCLA

Bias stability is as a general index to measure the accelerometer accuracy performance. Figure 7 shows the 0 g/±1 g stability test results. The results show that the bias stability of the 0 g position is 17.595 0 μg, the bias stability of the 1 g position is 19.363 7 μg, and the bias stability of the −1 g position is 20.715 3 μg.

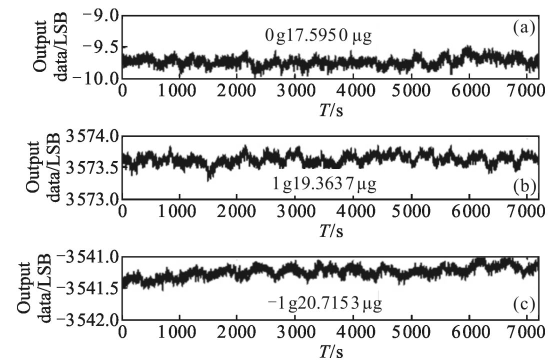


Fig.7 Experimental results of 0 g/±1 g stability

5 Conclusion

In this paper, the signal processing scheme of the DCLA is investigated and validated. With the single carrier modulation and demodulation technology, the header meter differential capacitance was achieved by the triangle wave modulation, moreover, the common mode interference was restrained to some extent. The output weak signal of the header meter was successfully detected by adopting the digital correlative demodulation method. To build the system prototype, under the condition of 0 g/±1 g stability test, the experimental results are 17.595 0 μg, 19.363 7 μg, 20.715 3 μg, respectively. The results show that the signal detection method can effectively achieve the acceleration detection, and currently, the precision of the DCLA is basically equal to the analog accelerometer, which verifies the correctness of the signal detection method.

References:

[1] Lotters J C, Olthuis W, Veltink P H, et al. A sensitive differential capacitance to voltage converter for sensor applications [J]. ***IEEE Transactions on Instrumentation and***

Measurement, 1999, 48(1): 89–96.

[2] Hierold C. A pure CMOS micro machined integrated accelerometer [C]//IEEE, 1996: 174–179.

[3] Josselin V, Touboul P, Kielbasa R. Capacitive detection scheme for space accelerometers applications[J]. ***Sensors and Actuators***, 1999, 78: 9298.

[4] Zhou Haitao. Research in the detection circuit of the digital closed-loop accelerometer [D]. Beijing: Beihang University, 2010. (in Chinese)

[5] Kaznyuki Kondo, Kenzo Wantanabe. A switched-capacitor interface for capacitive sensors with wide dynamic range[J]. ***IEEE Trans on Instrumentation and Measurement***, 1993, 42(5): 926931.

[6] Li Lin, Zhang Chunxi, Zhang Xi, et al. Investigation on noise of digital close-loop Q-Flex accelerometer [C]// IEEE Conference on Industrial Electronics and Applications, 2011: 614–619. (in Chinese)

[7] Zhang Chunxi, Wei Yuan, Zhang Xi, et al. Model analysis and emendation design of digital close-loop accelerometer system [J]. ***Chinese Journal of Scientific Instrument***, 2012, 33(12): 2833–2839. (in Chinese)

[8] Wei Yuan. Design and realization of digital close–loop quartz flex accelerometer system [D]. Beijing: Beijing University of Aeronautics and Astronautics, 2012. (in Chinese)

[9] Josselin V, Touboul P, Kielbasa R. Capacitive detection scheme for space accelerometers applications[J]. ***Sensors and Actuators***, 1999, 78: 9298.

[10] Gao Jinzhan. Detection of Weak Signals [M]. Beijing: Tsinghua University Press, 2011. (in Chinese)

[11] Zhang Chaoyang, Zhang Chunxi, Wang Xiaxiao, et al. Signal processing system for digital closed-loop fiber optic current sensor[J]. ***Proceeding of the CSEE***, 2009, 29(30): 42–46. (in Chinese)

[12] GJB 1037A–2004 Test methods for single-axis pendulous servo linear accelerometers[S]. Beijing: COSTIND, 2004. (in Chinese)