Design of Data Acquisition System for Silicon Micro Machined Resonant Accelerometer

XU Yuna, QU Yaohui and LUO Zhihang
School of Mechanical Engineering & Automation, Zhejiang Sci-Tech University, Hangzhou, Zhejiang Province 310018, China

Abstract: The output of the silicon micro machined resonant accelerometer is a frequency signal, in which the measured acceleration has been converted. Thus, it can realize a better performance. The output of the silicon micro machined resonant accelerometer in this paper is the differential frequency signal. The resolution of it is ±1mg, the scale factor is 100Hz/g, the measuring range is ±50g, and the resonant center frequency is 20 kHz. Aiming at the above technical indexes, and based on multiple-period synchronous method, the data acquisition system is designed in this paper. The data acquisition system contains the signal shaping module, the counter module, and the microcontroller and the communication module. The test experiment shows that the designed data acquisition system can satisfy the measurement requirement of the silicon micro machined resonant accelerometer.

1. Introduction
Silicon micro machined accelerometers can be divided into the capacitive accelerometer, the piezoresistive accelerometer, the piezoelectric accelerometer, the resonant accelerometer, etc. [1-4]. Based on different detection principles, the inertial force can be converted to different electrical signal, such as voltage signal, frequency signal and so on. Resonant accelerometer can convert the detected acceleration to the frequency signal [5]. It has the advantage of stability and reliability. What’s more, the output frequency of the accelerometer will not distort during the signal transmission, and there’s no need for A/D converter [6]. Therefore, design of data acquisition system for silicon micro machined resonant accelerometer can be simplified.

In this paper, a data acquisition system is designed to measure the frequency output by the silicon micro machined resonant accelerometer. The organization of this paper is as follows. First, the working principles for the silicon micro machined resonant accelerometer and multiple-period synchronous method are introduced in section 2. Second, each module for the designed data acquisition system is analyzed. And then, experiment tests have been carried out and discussed. Finally, the conclusion is drawn.

2. Working Principles

2.1 Working principle for silicon micro machined resonant accelerometer
Ideally, according to the measuring principle, when there’s no acceleration, the force of the two resonant beams in the resonant accelerometer will be the same, and then the nature frequencies for the two resonant beams will also be the same [7]. It can be expressed by:
\[ f_1 = f_2 = f_0 \] \hspace{1cm} (1)

Where, \( f_0 \) is the resonant center frequency. \( f_1 \) and \( f_2 \) are the frequency output by the two resonant beams. When there’s the acceleration, the frequency output by the two resonant beams will be changed as:

\[ f_1 = f_0 + \Delta f \quad f_2 = f_0 - \Delta f \] \hspace{1cm} (2)

Then, the acceleration can be obtained from equation (2) by:

\[ 2\Delta f = f_1 - f_2 = Ka \] \hspace{1cm} (3)

In equation (3), the frequency difference of the two resonant beams has a linear relationship with the input acceleration. Thus, it should detect the frequencies of the two resonant beams, and then the acceleration can be obtained [8].

### 2.2 Working principle for multiple-period synchronous method

Multiple-period synchronous method is one of the most important methods for frequency measurement [9]. The gate time can be auto-adjusted to be an integer times of the measured signal’s period, thus it is synchronize with the measured signal [10], and ±1 error from the traditional frequency method can be avoided which improves the measured accuracy obviously. The waveform graph for frequency measurement principle of multiple-period synchronous method is illustrated in figure 1.

![Principle of Multiple-Period Synchronous Method](image)

#### Figure 1 principle of multiple-period synchronous method

First, open the reference gate, and the counters will be triggered by the rising edge of the measured signal. Counter A will count the measured signal and counter B will count the time base signal. Then, close the reference gate, the counters will stop counting when the rising edge of the measured signal comes. Suppose the time for opening the actual gate is \( \tau \), and the time for opening the reference gate is \( \tau' \), then there will be a difference between \( \tau \) and \( \tau' \). According to the working principle of the multiple-period synchronous method, this difference will no more than one period of the measured signal.

Suppose \( N_x \) is the count number for the measured signal, and \( N_0 \) is the count number for the time base signal, \( f_0 \) is the frequency for the time base signal. During the gate time \( \tau \), the frequency for the measured signal can be obtained by:

\[ f_x = N_x f_0 / N_0 \] \hspace{1cm} (4)

The counter is triggered by the measured signal. Therefore, there are integral times of the measured signal during the actual gate time, and ±1 error from the traditional frequency method will be avoided. Calculate the differentiation for equation (4) by:

\[ df_x = -N_x f_0 \cdot dN_0 / N_0^2 \] \hspace{1cm} (5)

Where, \( dN_0 = \pm 1 \), and \( \tau = N_x / f_x \), then the measuring resolution of this method is:

\[ df_x / f_x = \pm 1 / (\tau f_0) \] \hspace{1cm} (6)

Suppose, the crystal oscillator for the time base signal is 40MHz, the gate time \( \tau = 10ms \), the frequencies of the two measured signals are 22.5 kHz and 17.5 kHz, then, the measurement errors for them are:
\[
\begin{align*}
\left\{ \frac{df_1}{f_0} &= \pm 22.5kHz / (10ms \cdot 40MHz) = \pm 0.05625Hz < 0.1Hz \\
\frac{df_2}{f_0} &= \pm 17.5kHz / (10ms \cdot 40MHz) = \pm 0.04375Hz < 0.1Hz
\end{align*}
\] 

(7)

Measurement error analysis shows that the proposed frequency measurement error will be less than 0.1Hz, which will satisfy the measurement requirement.

Equation (6) illustrates that the measuring resolution is not relate to the measured signal, but relate to the actual gate time and the time base signal. Thus, equal precision measurement can be realized, and the resolution will be improved when prolong the actual gate time or increase the frequency of the time base signal.

2.3 Scheme for the data acquisition system

According to the working principle of multiple-period synchronous method, the scheme of data acquisition system for silicon micro machined resonant accelerometer is shown in figure 2.

Figure.2 Scheme of data acquisition system for silicon micro machined resonant accelerometer

Two frequency signals output from the silicon micro machined resonant accelerometer will be transmitted to the counters through the shaping circuits. Then, the counter will be triggered and the counter number will be transmitted to micro controller, which will carry out the data processing and obtain the measured acceleration from the observed frequency. The host computer will receive the measured acceleration for the test experiment.

3. Hardware design of the data acquisition system

The hardware of the data acquisition system shown in figure 2 contains the shaping circuit, counting circuit, micro controller. Counting circuit will be realized in CPLD (Complex Programmable Logic Device).

3.1 Shaping circuit

Shaping circuit will transform the output signal output by silicon micro machined resonant accelerometer to be the pulse signal. And it is realized by LM311.

3.2 Counting circuit

Counting circuit will be realized by CPLD. It contains 2 function parts. (1) Function of frequency division. It will divide the frequency of the crystal oscillator and generate a period signal with 10ms, which will be used as the interrupt signal for the micro controller. (2) Function of Counting. It will count the frequency of \( f_1 \) and \( f_2 \) output by the silicon micro machined resonant accelerometer.

In this paper, EPM550T100 is used to realize the above functions. And it is simulated in QUARTUSII software by VHDL language. Suppose the period of the two frequency signal is \( T_{ain}=52us \) \( \left( f_{ain}=19.230769kHz \right) \) and \( T_{bin}=50us \) \( \left( f_{bin}=20kHz \right) \), then the simulation waveform is shown in figure 3.

Figure.3 the simulation waveform of CPLD
In Figure 3, signals of ain and bin are the two frequency signals that need to be counted. Signal of clkin is the time base signal with the oscillation frequency of 40MHz. Signal of int is the interrupt signal. When interrupt signal comes, the counting number will be send to micro controller. Signal of SEL is the input of CPLD, and FOUT is the output of CPLD, which will connect to micro controller. When there’s the interrupt signal, micro controller will send 0-7 to CPLD, and then it will read the counting number from CPLD. As show in figure 3, when interrupt comes, the counting number for signal ain and bin are 192 and 199 respectively, which means that there are 399360 and 398000 clock cycles of the crystal oscillation. Then, the frequencies of ain and bin are \( f_{ain} = 19.230769 \) kHz, \( f_{bin} = 20 \) kHz. It can satisfy the measurement requirement.

3.3 Micro controller

Micro controller will read the counting number from CPLD, and then it will calculate the input acceleration from the measured frequency. Then the acceleration will be read out. ATmega16 is used in this design. The designed data acquisition system is shown in figure 4.

![Figure 4 Designed data acquisition system](image)

4. Experiment

4.1 Test by the input from signal source

Square waves will be generated by signal source to simulate the differential outputs from silicon micro machined resonant accelerometer. After the shaping circuit, the signal will be counted and then micro controller will output the counting number to the host computer. Table 1 shows the test results.

| Input acceleration(g) | \( f_1 \) (Hz) | \( f_2 \) (Hz) | Measured \( f_1 \) (Hz) | Measured \( f_2 \) (Hz) | Frequency difference(\( f_2 \)-\( f_1 \)) (Hz) | Measured acceleration(g) |
|-----------------------|----------------|----------------|------------------------|------------------------|---------------------------------|-------------------------|
| 50                    | 22500          | 17500          | 22500.04              | 17499.97              | 5000.07                         | 50.0007                 |
| 40                    | 22000          | 18000          | 22000.02              | 17999.99              | 4000.06                         | 40.0006                 |
| 30                    | 21500          | 18500          | 21500.05              | 18499.96              | 3000.09                         | 30.0009                 |
| 20                    | 21000          | 19000          | 21000.04              | 18999.96              | 2000.08                         | 20.0008                 |
| 10                    | 20500          | 19500          | 20500.01              | 19499.96              | 1000.05                         | 10.0005                 |
| 0.2                   | 20010          | 19999          | 20010.02              | 19989.98              | 20.04                            | 0.2004                  |
| 0.002                 | 20001          | 19999.9        | 20001.02              | 19998.97              | 2.05                             | 0.0205                  |
| 0                     | 20000          | 20000          | 20000.02              | 19999.97              | 0.05                             | 0.0005                  |
| -10                   | 19500          | 20500          | 19499.96              | 20500.01              | -1000.05                        | -10.0005                |
| -20                   | 19000          | 21000          | 18999.96              | 21000.04              | -2000.08                        | -20.0008                |
| -30                   | 18500          | 21500          | 18499.96              | 21500.05              | -3000.09                        | -30.0009                |
| -40                   | 18000          | 22000          | 17999.96              | 22000.02              | -4000.06                        | -40.0006                |
| -50                   | 17500          | 22500          | 17499.97              | 22500.04              | -5000.07                        | -50.0007                |

Table 1 shows that there are measurement errors for the test results of data acquisition system by
signal source. These errors mainly come from the actual gate time, which will calculate the time base signal, and there will be ±1 error for the counter of time base signal. According to the measurement errors analyzed in equation (7), the above measurement errors are consistent with the errors analyze.

4.2 Test by silicon micro machined resonant accelerometer

The output signals of silicon micro machined resonant accelerometer will be shaped by the shaping circuit, and then they will be counted by CPLD. In our test experiment, multimeter made by Agilent will be used to compare with the test results from the designed data acquisition system. The measurement period of the designed data acquisition system is 10ms, and the measurement period of the multimeter is about 12ms. By the average processing, the test results of the designed data acquisition system and the multimeter are illustrated in figure 5.

![Figure 5 Result comparison for multimeter and the designed data acquisition system](image)

In Figure 5, one frequency output by accelerometer is measured for the comparison. It is obvious that the measurement curve from the designed data acquisition system is coincided with the measurement curve from the multimeter, thus, it can be used for the future application.

5. Conclusion

A data acquisition system is designed in this paper for the silicon micro machined resonant accelerometer. First, the working principles of the resonant accelerometer and the multi-period synchronous method are introduced with the measurement errors analyzed. Next, the hardware design is illustrated and the function of each module has been explained. And then, the experiments have been implemented. And the experiment results have been compared, which obviously indicates that the designed data acquisition system can meet the requirement. The designed data acquisition system can be used for the future application.

Acknowledgments

The author would like to thank all reviewers for their helpful suggestions on this article which will help us in the further research.

Funding

This research was supported by the Young Researchers Foundation of Zhejiang Provincial Top Key Academic Discipline of Mechanical Engineering of Zhejiang Sci-Tech University (Grant Number: ZSTUME02B14), the Initial Scientific Research Foundation of Zhejiang Sci-Tech University (Grant Number:17022148-Y).

Reference

[1] Mo Y, Du L, Qu B, et al. Damping ratio analysis of a silicon capacitive micromechanical accelerometer[J]. Wireless Sensor Network, 2017, 9(05): 178.
[2] Messina M, Njuguna J, Palas C. Mechanical Structural Design of a MEMS-Based Piezoresistive
Accelerometer for Head Injuries Monitoring: A Computational Analysis by Increments of the Sensor Mass Moment of Inertia[J]. Sensors, 2018, 18(1): 289.

[3] Raaja B P, Daniel R J, Sumangala K. A Simple Analytical Model for MEMS Cantilever Beam Piezoelectric Accelerometer and High Sensitivity Design for SHM (structural health monitoring) Applications[J]. Trans. Electr. Electron. Mater.(TEEM), 2017, 18(2): 78-88.

[4] Zou X, Seshia A A. A high-resolution resonant MEMS accelerometer[C]//Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS), 2015 Transducers-2015 18th International Conference on. IEEE, 2015: 1247-1250.

[5] Wang Y, Ding H, Le X, et al. A MEMS piezoelectric in-plane resonant accelerometer based on aluminum nitride with two-stage microleverage mechanism[J]. Sensors and Actuators A: Physical, 2017, 254: 126-133.

[6] Wang Y, Zhang J, Yao Z, et al. A MEMS Resonant Accelerometer With High Performance of Temperature Based on Electrostatic Spring Softening and Continuous Ring-Down Technique[J]. IEEE Sensors Journal, 2018, 18(17): 7023-7031.

[7] Zhang J, Wang Y, Zega V, et al. Nonlinear dynamics under varying temperature conditions of the resonating beams of a differential resonant accelerometer[J]. Journal of Micromechanics and Microengineering, 2018, 28(7): 075004.

[8] Zhang J, Su Y, Shi Q, et al. Microelectromechanical resonant accelerometer designed with a high sensitivity[J]. Sensors, 2015, 15(12): 30293-30310.

[9] Wang X, Li Z W, Wonham W M. Dynamic multiple-period reconfiguration of real-time scheduling based on timed DES supervisory control[J]. IEEE Transactions on Industrial Informatics, 2016, 12(1): 101-111.

[10] Vejdan S, Sanaye-Pasand M, Malik O P. Accurate dynamic phasor estimation based on the signal model under off-nominal frequency and oscillations[J]. IEEE Transactions on Smart Grid, 2017, 8(2): 708-719.