

# High Precision Digital Inclinometer Based on Over Sampling Theory

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**Abstract.** A kind of high precision digital inclinometer is designed based on over sampling theory. The analog signal micro accelerometer FXLN8361 as the measure component, and the single chip computer with high performance and low power consumption MSP430F5529 from TI is used as controller. The incline of side is detected by the double axis measurement, so that the constant of incidence sensitivity could be achieved. The over sampling theory is designed. After the experimental results were analyzed by linear fitting, it is concluded that the measuring instrument has used the sampling algorithm; the minimum measured angle could be increased from  $0.8^\circ$  to  $0.05^\circ$ . We get the standard deviation of the slope of the measurement curve:  $5.2993 \times 10^{-5}$ , the standard deviation of intercept was 0.00277; linear error was less than 0.00525%. The results show that the inclinometer was with high precision, and the structure was rational and feasible.

**Keywords:** over sampling, inclinometer, single chip computer.

## 1. Introduction

The inclinometer is device which measures horizontal inclination, and it is widely used in the astronomical instrument, housing construction, geological survey, aerospace, medicine, shipping, precision automation equipment, robot, railway and bridge, and other engineering technology areas. The existing inclinometers can be divided into mechanical, optical and electronic pattern.

The traditional bubble level-meter is still used when most industries measure angles. Its detection method determines whether it is horizontal by the position bubble and the operation experience. [1,2]. The bubbles in the liquid are highly unstable, and vulnerable to disturb, the judgment of the levelness can only be roughly estimated, and can't indicate the specific slope, it is unable to carry out quantized treatment, so the application range is very limited. Optical inclinometer are mainly the optical quadrant [3], the readings in the optical dial is used to calculate the angle, but optical quadrant with low precision, complex mechanism, weak shockproof performance, and not easy to maintain, which cannot meet the requirement of digital high precision measurement. The electronic inclinometer can convert the inclination of the horizontal plane to specific digital signal or analog signal to dedicated processor with the inclinometer [4, 5]. The common electronic inclinometers mostly adopt suspended micro free pendulum structure, pendulum is affected by gravity and point to the center of the earth in measurement, when there are inclination in inclinometer and horizontal plane, there will be a included angle in

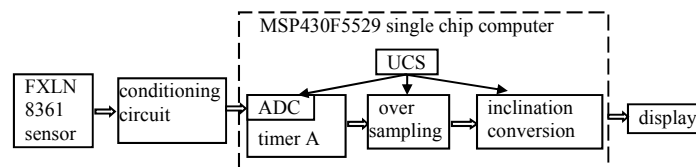


pendulum and horizontal plane, cause the voltage and polar plate capacitance of the induction coil connected to the pendulum to be changed, the corresponding angle of inclination is obtained by the operation circuit. This kind of inclinometer has weak shock resistance, large volume and high price. Therefore, it is of great significance to design electronic level-meter with high precision, good portability and strong stability.

Now there are already micro high-precision accelerometer manufactured by semiconductor material surface corrosion process, which has high precision, good stability, small volume advantages and so on, and it provides a good foundation for the digitization, intellectualization and miniaturization of the level-meter.. This paper uses micro accelerometer based on MEMS (Micro company Mechanical System) technology [6, 7], design a high-precision digital inclinometer, integrate the over sampling algorithm, under the premise without using high-precision AD conversion chip, improve the resolution of the AD conversion, change the shortcomings which traditional measuring instrument can't quantify angle, poor anti-interference and unable to digitize angle.

## 2. Composition of Inclinometer

The core device of the inclinometer is the sensor which can detect the change of gravity with inclination change. This measuring instrument adopts FXLN8361, the latest differential capacitive three-axis acceleration transducer of Freescale, and analog output is adopted. Because the signal output by the sensor is inevitably noisy, and the variation range of electrical level is not within the ideal range of single chip microcomputer. So the integrated operational amplifier is added between the sensor and the single chip computer to carry out signal processing. The high-performance single chip computer MSP430F5529 of TI company as the control core, the interior RAM of the single chip computer is up to 10KB, which can meet the needs of data cache. The program storage space FLASH reaches 128KB, which enables the interior space of the single chip computer to meet the storage of the operation program. The interior have multi-channel clock selection register BCM (Basic Clock Module), it can allocate different clock frequencies for different modules in accordance with the needs of program operation, and reduce the power consumption and improve the operation efficiency. At the same time, the ADC with 12 bits inside the single chip computer, which can realize high precision inclination detection after adopting the over sampling technology to further improve the resolution. The system block diagram of the measuring instrument is shown in Figure.1.



**Figure.1** structure diagram of the measuring instrument

## 3. Analysis of Inclination Measurement Method

### 3.1. Calculation of uniaxial inclination

The uniaxial measurement is used; the output of the measured axis acceleration and the conversion of inclination have the following relation:

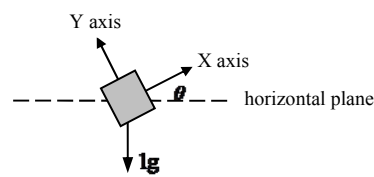
$$\theta = \arcsin \frac{A_x}{1g} \quad (1)$$

Among them,  $A_x$  is the acceleration value of measuring axis, the unit of inclination  $\theta$  is radian. According to the existing measurement methods and experiences, this kind of measurement relationship has a good sensitivity when the inclination is small. When the included angle between the measuring

axis and the horizontal plane increases, the sensitivity decreases. The error of this linear relationship will increase [8], when the inclination is close to 90 degrees, the change of inclination will hardly affect the change of the measurement result, so that the measurement cannot be carried out. Thus the generated limit is that the high-resolution ADC chip is required to achieve a wide range of effective inclination measurement, and the existing ADC chip is difficult to meet the requirements. Therefore, the key problem to measure angle is to solve the problem that the sensitivity decreases with the increase of inclination.

### 3.2. Calculation of double axis inclination

This paper adopts a method to measure the measuring axis which is perpendicular to the original measuring axis to solve this problem. Its measurement principle is shown in Figure.2.



**Figure.2** principle diagram of double axis measurement

The use of a double axis measurement will make the measuring instrument have constant sensitivity. Because of the double axis vertical relationship, the measured acceleration of the X-axis is proportional to the sine of the included angle, and the measured acceleration of the Y axis is proportional to the cosine of the corresponding included angle. Because the sensitivity of inclination of measurement axis is the highest when it is close to 0°, the acceleration rate of axis is first identified in the double axis vertical measurement. When the inclination increases, the sensitivity of an axis decreases must along with the increase of sensitivity of another axis. The result is that the sensitivity value is basically constant.

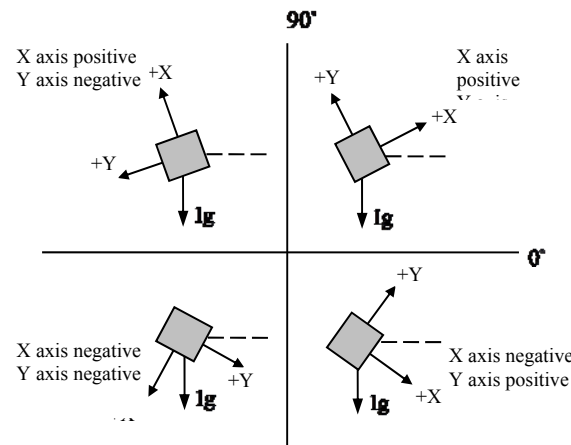
Therefore, the measurement method can be changed: calculate the anti-sine function of the X-axis and the anti-cosine function of the Y axis, and calculate the ratio of the two,

$$\frac{A_x}{A_y} = \frac{\sin \theta}{\cos \theta} = \tan \theta \quad (2)$$

$$\theta = \arctan \frac{A_x}{A_y} \quad (3)$$

The  $\theta$  unit is radians

The use of double axis measurement enables the level-meter to distinguish the various quadrant and measure angles within the entire 360-degree range, as shown in Figure 3.



**Figure.3** measuring diagram of four quadrants

Each quadrant has a combination associated with the acceleration symbols the X axis and the Y axis. The located quadrant of the accelerometer can be judged by the size of the data collected by the accelerometer.

#### 4. Over Sampling Algorithm

Because the double axis inclination measurement is used, the sensitivity of the sensor is constant in the measurement range, so the resolution of the inclination measurement is determined by the resolution of the ADC chip. The measuring instrument adopts 12 bits of slice ADC, and the over sampling algorithm can improve the resolution greatly without increasing the hardware.

The over sampling technology is used to ADC sampling rate higher than Nyquist sampling frequency to carry out sample [9]. According to the Nyquist sampling theorem, the sampling frequency must be more than twice sampled frequency to be able to reliably recover the sampling signal. The Nyquist frequency  $f_n$  of the sampled signal is defined as:

$$f_n = 2f_m \quad (4)$$

is the highest frequency of the sampled signal, when the sampling frequency  $f_s$  is higher than the sampling frequency  $f_n$ , it is called over sampling, and over sampling rate is used to indicate:

$$\text{OSR} = \frac{f_s}{f_n} = \frac{f_s}{2f_m} \quad (5)$$

In general, there will the interference components which are less than  $f_s/2$  alias in the measurement band, and the energy density spectrum (ESD) of in-band noise is shown:

$$E(f) = e_{\text{rms}} (2 / f_s)^{1/2} \quad (6)$$

is the in-band ESD,  $e_{\text{rms}}$  is the noise average power. It is known that the noise brought by ADC sampling is white noise with zero mean value, and the average power of noise is measured by variance.

$$e_{\text{rms}}^2 = \int_{-\Delta/2}^{\Delta/2} \left( \frac{e_q}{\Delta} \right) de = \frac{\Delta^2}{12} \quad (7)$$

In the formula:  $\Delta = \frac{V_{\text{ref}}}{2^N}$ ,  $N$  is the number of ADC,  $V_{\text{ref}}$  is the reference voltage of ADC. When over sampling is used, the overlap part of the noise part and the signal is reduced, and the low-pass filter can be used to filter more noise, after the low-pass filter of the mean, the in-band noise power is:

$$n^2 = \int_0^{f_m} e_{\text{rms}}^2(f) df = e_{\text{rms}}^2 \left( \frac{2f_m}{f_s} \right) = \frac{e_{\text{rms}}^2}{\text{OSR}} \quad (8)$$

Formula (6) mentioned OSR can reduce in-band noise power, under the premise without reducing the signal power, the in-band noise power is reduced, thus improving the signal-to-noise ratio SNR; it is equal to improve the resolution of the ADC. It can be found From (6) (7) (8) that the formula for  $n$  noise power, over sampling rate and resolution is:

$$n^2 = \frac{1}{12\text{OSR}} \left( \frac{V_{\text{ref}}}{2^N} \right)^2 \quad (9)$$

Solve the expression of  $N$ .

$$N = \log_2^{V_{\text{ref}}} - \log_2^n - \frac{1}{2} \log_2^{12\text{OSR}} \quad (10)$$

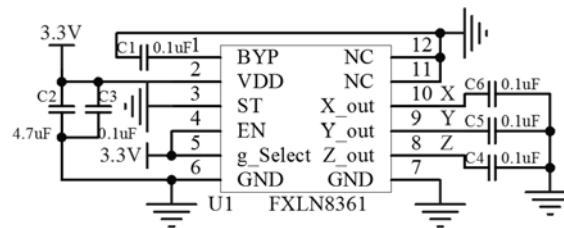
The difference calculation method is used, it can be seen from the formula (10) that the sampling frequency is doubled every time, and the in-band noise is reduced by 3 decibels, and the resolution will be increased by one/two bits. When the sampling frequency is increased by four times, the resolution of the measurement will be increased by one bit.

$$f_{\text{os}} = 4^N f_s \quad (11)$$

According to the measurement principle of the inclination, resolution of interior ADC of single chip computer only is 12, which can put the 1g gravitational acceleration to bisect 4096, when the any axis measures 1/4096g change, and can get corresponding curve changes with 0.014 radians, and it is converted to the angle of 0.8 degrees. If the over sampling algorithm is used to increase the 4 bit resolution to 16 bits. Then the minimum angle that can be measured is 0.05 degrees, and the resolution of the level-meter increases 16 times.

## 5. Hardware Circuit Design of Sensor

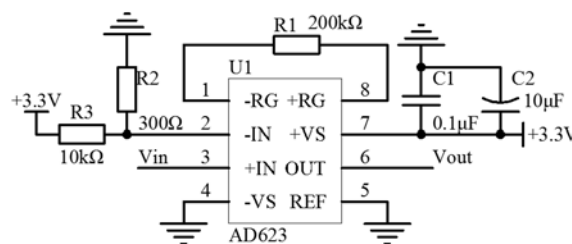
FXLN8361 is a new differential capacitive three-axis high-performance micro-accelerometer based MEMS technology launched by Freescale[10], The chip is powered by 1.71V~3.76V DC voltage,  $\pm 2g$  or the  $\pm 8g$  range can be selected. The interior integrates conversion circuit from capacitance to voltage, operational amplifier, output follower and other units. QFN encapsulation is used in the whole chip. The schematic diagram of sensor circuit is shown in Figure.4.



**Figure.4** circuit diagram of sensor

## 6. Conditioning Circuit

The analog voltage output by the sensor should be adjusted before it can enter the ADC of the single chip to deal with. The main function of the conditioning circuit is to amplify the weak signal output by the sensor to meet the ADC requirement. The output voltage of FXLN8361 is 0.75V at static 0g, and the output voltage is 0.979V at 1g, and the output voltage at -1g is 0.535V. The gravitational acceleration of the side inclination of the level-meter changes in the  $\pm 1g$  range, therefore, the output change range of the sensor is 0.535V~0.979V. The AD623 instrument amplifier is used to constitute the conditioning circuit in the design, as shown in Figure. 5.



**Figure.5** conditioning circuit diagram

After the signals  $V_{in}$  output by sensor enter into AD623, in order to make the reference voltage of the single chip computer ADC match 1.5V, through the internal differential operation, the circuit reduces two-stitch 0.75V of 0g and then amplifies. The effect of resistance R1 is to adjust the amplification factor. The signal is shifted after the amplification, add the five-stitch reference voltage, and the final output calculation formula is as follows:

$$V_{out} = (V_{+IN} - V_{-IN})G + V_{REF} \quad (12)$$

The amplification factor  $G = \frac{R1}{100k\Omega} + 1$ . The output voltage 0.22V increase 3 times when  $\pm 1g$  change, it make the full range output close to 1.5V and improve the accuracy of the measurement.

## 7. Register Setting of Single Chip Computer

### 7.1. Timer module setting

The function of the timer is to precisely control the sampling interval and interrupt internal start ADC [11]. The timing of the timer is realized by counting overflow of counter, and the measurement system adopts count-up, and produces overflow interruption method. After overflow, the counter TA1CCR0 is automatically cleared, and SMCLK is used as the counting pulse source, and the corresponding 16-bit register is set as: TA1CTL = 0x0216.

The sampling interval is the interrupted frequency after the analysis of the over sampling algorithm, which is set to 25.6 KHz, and the system clock is 25MHz. The calculation formula of the upper limit of the counter is:

$$TA1CCR0 = \frac{f_{SMCLK}}{f_{Interrupt}} - 1 \quad (13)$$

The value of the TA1CCR0 register is 97.

### 7.2. ADC module setting

Because the ADC is controlled by a timer interrupt, the ADC is only performed once within the interrupt. The ADC module is set as follows: the internal 1.5V reference power is adopted, and the main clock 16 frequencies as the ADC clock and channel 0 as the ADC channel, single channel uses single sampling.

## 8. Experiment and Data Analysis

### 8.1. Level-meter calibration

The level-meter must carry out determination of zero before the experiment is carried out. Because the coordination of the measuring circuit and the sensor is not ideal, the output time of the zero point is drifting, so there must be offset errors  $A_{off}$ . The adjustment method is used to deal with the offset error. In the two-axis precision rotating platform, let one axis in and near the location of the  $+1g$  and  $-1g$ , and slightly adjust the angle of the rotating platform, when the voltage output largest sensor, record the location of the vertical downward, as a reference point, record  $A_{+1g}$  and  $A_{-1g}$ . The output value can be recorded as the sum or difference of the existing offset voltage and actual gain, as shown in formula (14) (15).

$$A_{+1g} = A_{off} + (1g \times Gain) \quad (14)$$

$$A_{-1g} = A_{off} - (1g \times Gain) \quad (15)$$

The gain and disorder are calculated as follows:

$$Gain = 0.5 \times \left( \frac{A_{+1g} - A_{-1g}}{1g} \right) \quad (16)$$

$$A_{off} = 0.5 \times (A_{+1g} + A_{-1g}) \quad (17)$$

The results can be used to reduce the disorder from measurement result, then divide gain, and the acceleration  $A_{real}$  is obtained.

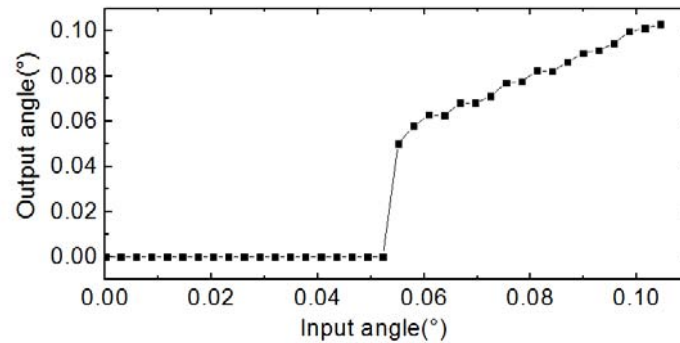
$$A_{real} = \frac{A_{out} - A_{off}}{Gain} \quad (18)$$

The acceleration value is used and integrate double axis inclination algorithm, then can obtain inclination value.

### 8.2. Resolution experiment

The double axis precision rotating platform adopts step motor to drive, the minimum step angle is  $0.36^\circ$ , the reduction gear ratio of the mechanical drive is 124:1, then the minimum step angle of actual rotating platform is  $0.0029^\circ$ . The rotating platform is rotated from  $0^\circ$ , increase progressively with minimum step angle, and the data collected in the software is processed by moving-average filter algorithm. In the

data collected from the measuring instrument, extract the point from the first angle output and nearby points to draw, as shown in Figure 6.

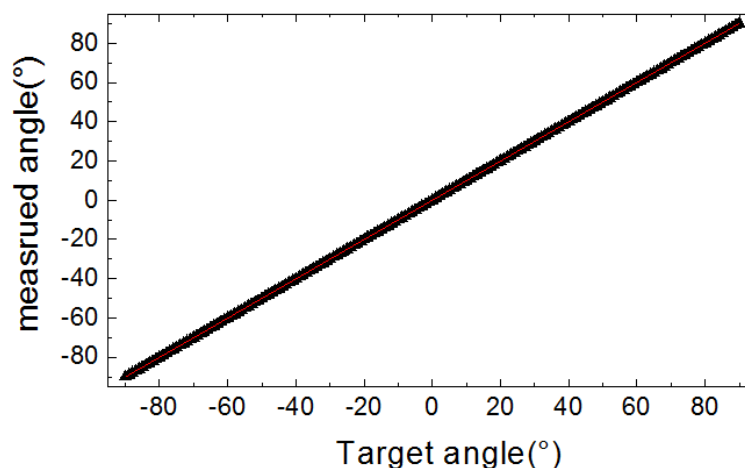


**Figure.6** resolution experiment diagram

It can be found from data analysis that when the input angle of rotating platform reaches  $0.0551^\circ$ , the inclinometer starts to have the first output, the value is  $0.0532^\circ$ , the error is  $0.0019^\circ$  degree. It is basically agreement with the minimum measurement angle calculated by the over sampling algorithm.

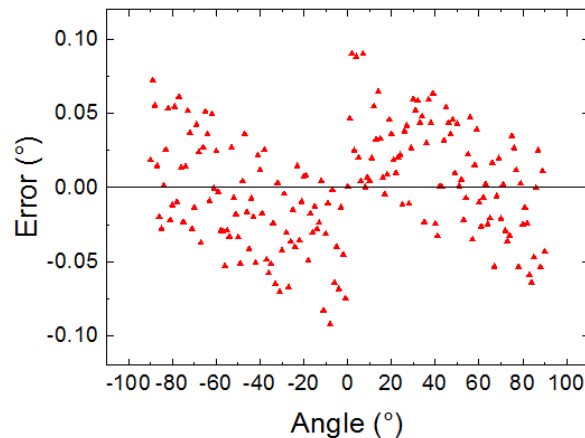
### 8.3. Measurement contrast experiment

The inclination measurement experiment is carried out on the double axis precision rotating platform. The plane of X and Y is perpendicular to the measurement plane, the X axis is parallel to the measured plane, and the Y-axis is perpendicular to the measured plane. The X axis and horizontal plane included angle increase every  $0.1^\circ$  from  $-90^\circ \sim +90^\circ$ , reach  $+90^\circ$  and back to  $-90^\circ$  again, thus calculating the linear error, return difference and fiducial error of measuring instrument and so on. The results are shown in Figure.7. The error distribution diagram as shown in Figure 8, the error maximum is  $0.092^\circ$ , and angle gradually decrease with increase.



**Figure.7** measurement contrast experiment





**Figure.8** error distribution diagram

After the analysis of data linear fitting [12], the relation between the input angle  $x$  and output angle  $y$  of the precision rotating platform can be obtained:  $y = 1.00082x - 5.6821 \times 10^{-4}$ , the standard deviation of the slope is:  $5.2993 \times 10^{-5}$ , the intercept standard deviation is 0.00277. The linear error is less than 0.00525%, the return difference is 0.006231%. The experimental results show that the inclinometer with sampling algorithm has very high measuring accuracy, linearity and return difference characteristics verify the structure rationality of this new type of inclinometer, and can realize a wide range and high-precision measurement of inclination.

## 9. Conclusion

One high-precision inclinometer is designed, which use micro accelerometer FXLN8361 as the measuring element and high-performance single chip computer as processing core. It is innovative to integrate the over sampling algorithm into the data processing algorithm, which greatly improves the resolution of the inclinometer without increasing the hardware signal processing circuit. In the experiment, the zero point of the measuring instrument is calibrated, the validity of the over sampling algorithm is verified, and the measuring instrument have very good measuring performance through the comparison experiment, which achieved the design goal. The measuring instrument provides a new design approach for the design of digital inclinometer.

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