

# Anti-acceleration Disturbance Method for Pendulum Tiltmeter

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**Abstract.** With the practical application of silicon micro-machined gyro driven by rotation aircraft, it is found that the rotation aircraft's rudder surface vibration significantly influences the performance of the gyro. In this paper, as the background of the silicon micro-machined gyro, the vibration mechanism is analyzed according to the mathematics model and dynamics. Under the influence of vibration, both of the silicon pendulum's stress form and output signal are obtained. The paper proposes a reasonable installation method to suppress the vibration. The experimental result shows that the method is effective to reduce the gyro's output signal noise. And the result is good.

## Introduction

Pendulum type tiltmeter has high accuracy in static test, but it is susceptible to the disturbance of linear acceleration and angular acceleration [1]. Experience of test shows that linear acceleration and angular acceleration disturbs pendulum tiltmeter in different way: the disturbance of linear acceleration is devastative, and the output of pendulum tiltmeter will be seriously distorted. When carrier vector angle changes without linear acceleration exist (called dynamic process), the test accuracy of the tilt sensor is decline. Because the disturbance of linear acceleration is much bigger comparative, the past research is concentrated on linear acceleration.

Based on the structure and principle of the pendulum tiltmeter, the reason that linear acceleration and angular acceleration disturbs pendulum type tiltmeter in different way is analyzed, and present corresponding scheme to restrain the disturbance of acceleration. The scheme can identify linear acceleration sensitively, and control the disturbance in a short time. In addition, the scheme can restrain angular acceleration disturbance effectively.

## Acceleration Disturbance on Pendulum Tiltmeter

According to the type of medium, pendulum tiltmeter can be divided into solid pendulum tiltmeter, liquid pendulum tiltmeter and gas pendulum tiltmeter. All of the pendulums tiltmeter use character of pendulum in the gravitational field as well as Newton's second law [2-5]. For tiltmeter, gravity is a acceleration with constant magnitude and direction, so any other acceleration forced on the pendulum will disturb detection of pendulum tiltmeter. And because three types pendulum tiltmeter have same detection basis, the character of acceleration disturbance will be similar. Then acceleration disturbance on solid pendulum tiltmeter will be researched, as an example.

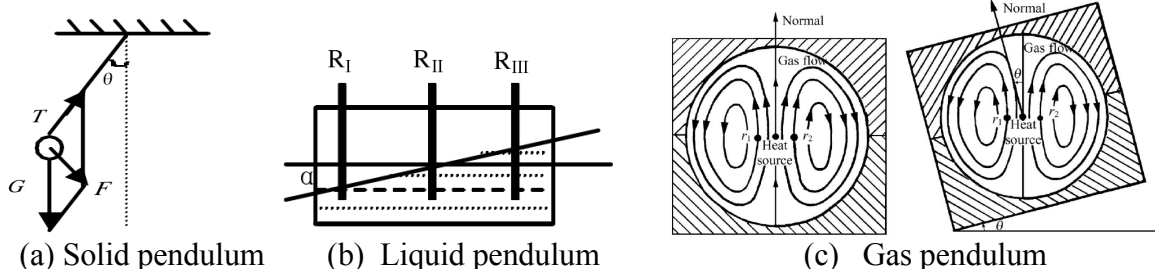


Figure 1. Principle of pendulum tiltmeter

As shown in Fig.1(a), force balance servo system is widely used in solid pendulum tiltmeter which composed by pendulum, cycloid, bracket, pendulum subject to gravity  $G$ , tension  $T$  and their combined force  $F$  is:

$$F = G \sin \theta = mg \sin \theta \quad (1)$$

$\theta$  is the angle between the cycloid and the vertical direction. In small-angle range, relationship between  $F$  and  $\theta$  is linear. Other solid pendulum tiltmeter including strain gauge type, potentiometer type, inductive type, vibrating-wire type and force-balance tilt sensor are also based on the principle.

The (1) will no longer valid with any acceleration exists. But the influences of linear acceleration and angular acceleration are different. Linear acceleration disturbance is destructive. The reason is the direction of linear acceleration could be in any direction, so force balance shown in Fig.1(a) will be destructed seriously and (1) cannot be valid. Then pendulum tiltmeter signal will be seriously distorted.

In dynamic process, angular acceleration direction will be same as or adverse to the direction of  $F$ . The direct range of pendulum tiltmeter is small. Then usually the magnitude of angular acceleration which proceeds from angular change in a small-angle range is small. For the two reasons above, angular acceleration disturb pendulum tiltmeter is minor relatively.

As showed in Fig.1(b) and Fig.1(c), liquid pendulum tiltmeter and gas pendulum tiltmeter also use gravity in angular detection. So they have similar characters of acceleration disturbance to solid pendulum tiltmeter. For the devastative effects of linear acceleration, pendulum tiltmeter signal should not be used when any linear acceleration exist. And angular acceleration reduces detection accuracy of the pendulum tiltmeter.

### Anti-acceleration Disturbance Method

Structure of Prototype. The test prototype consists of pendulum tiltmeter, angular rate gyro, microcontroller, AD chip and other peripheral components. The detailed information of main components are shown in Tab.1.

TABLE I. INFORMATION OF COMPONENTS

components	detailed information	
	<i>Version</i>	<i>company</i>
Pendulum tiltmeter	SCA103T-D05	VTI
Angular rate gyro	LCG50	BEI
MCU	MSC1214Y3	TI
AD chip	AD7656	ADI

The sensitive direction of the tiltmeter and angular rate gyro should coincide with each other. Analog signals of tiltmeter and gyro are sampled by AD chip and processed by MCU. After some digital data processing, the MCU output the final angle signal in analog voltage.

For sensitive direction of the tiltmeter and gyro is coinciding with each other, in a short time, angular variation sensed by tiltmeter should equate to the integration of angle velocity sensed by gyro in dynamic process. This feature will be applied into linear acceleration disturbance suppression.

Before dynamic detection, some kinds of static test and adjustment should be done, including: the zero voltage of tiltmeter test and gyro zero voltage test, linearity compensation, DA output range adjustment, and so on. Static adjustment objectives are: non-linearity <1% FS, resolution is 0.01°.

**Detection and Suppress the Disturbance of Linear Acceleration.** For destructive impact on tiltmeter, linear acceleration must be detected. Angular rate gyro is sensitive to angular velocity, and angular acceleration can also be sensed indirectly. According to classical physics, the change in vector angle should be equal to the integral of the vector angular velocity in corresponding period.

When the disturbance of the linear acceleration does not exist, in a short time, the angle change amount detected by tiltmeter and gyro should be the same. The angle change amount is:

$$V_{\theta T} - V_{\theta 0} = K_{\theta} \int_0^T \frac{V_{\omega} - V_{\omega 0}}{K_{\omega}} dt \quad (2)$$

where  $K_\theta$  is scale factor of the tiltmeter, and  $K_\omega$  is the scale factor of gyro.  $V_{\theta 0}$  is zero voltage of the tiltmeter, and  $V_{\omega 0}$  is zero voltage of the gyro.  $V_{\theta T}$  and  $V_\omega$  are the voltage of tiltmeter and gyro.

The (2) cannot be used in digital data processing. When  $T$  equate to the sample cycle of AD chip, the (2) can be turned to be (3) as follow.

$$Q_{\theta T} - Q_{\theta 0} = K_1 \frac{(T_n + T_{n-1} - 2T_0)}{2} \Delta t \quad (3)$$

Where  $\Delta t$  is sample cycle of the AD chip;  $T_{n-1}$  and  $T_n$  is the sample data of gyro,  $T_0$  is the sample data of gyro zero.  $Q_{n-1}$  and  $Q_n$  is the sample data of tiltmeter.  $K_1$  is scale factor between tiltmeter data and gyro data.

When tiltmeter is disturbed by linear acceleration, the left side of (3) will change faster than the right side. The difference  $Ca$  is:

$$Ca = Q_{\theta T} - Q_{\theta 0} - K_1 \frac{(T_n + T_{n-1} - 2T_0)}{2} \Delta t \quad (4)$$

A constant value  $M$  should be use. When the absolute value of  $Ca$  is bigger than  $M$ , linear acceleration is existing. And in that case, angle change amount should be detected by integral of angular rate other than tiltmeter signal.

Because Integral error will increase with time, this method of calculation can only be used in a short time.

**Elimination the Disturbance of Angular Acceleration.** High accuracy turntable is used to implement the dynamic process. Because the accuracy of turntable is much higher than tiltmeter, the data output by turntable is considered to be the real angle of prototype. Then deviation of tiltmeter could be test.

The test method is: install the prototype in the middle frame of three-axis turntable. After sample, smoothing, linearization and other process, angle signal and angular rate signal of prototype is output in analog voltage. The voltages are caught by a independent digital device which receives turntable synchronously.

The middle frame of three-axis turntable worked in angle vibration mode, the angle range is from  $-20^\circ$  to  $20^\circ$ , and vibration cycle is 5s. One cycle output voltage of tiltmeter and gyro is shown in Fig.2, and the synchronous angle of turntable is shown in Fig 3.

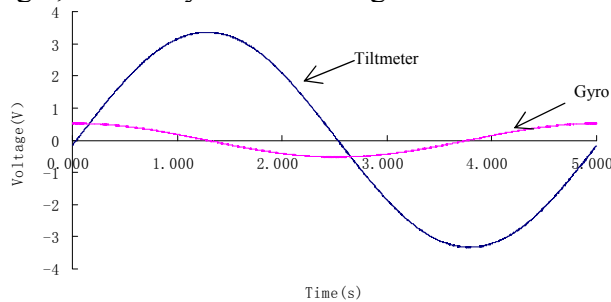


Figure 2. Analog output of tilt and gyro

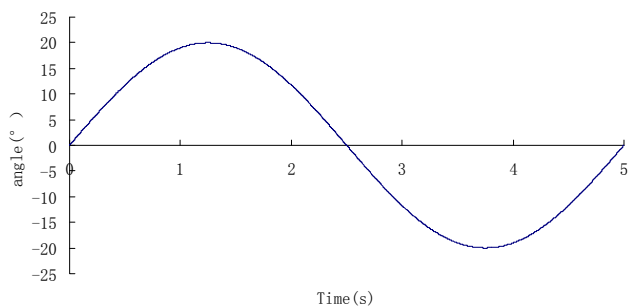


Figure 3. Angular output of Turntable

After converting angle value of turntable into voltage value, deviation value could be calculated by comparing the voltages of tiltmeter and turntable. The deviation curve is shown in Fig. 4.

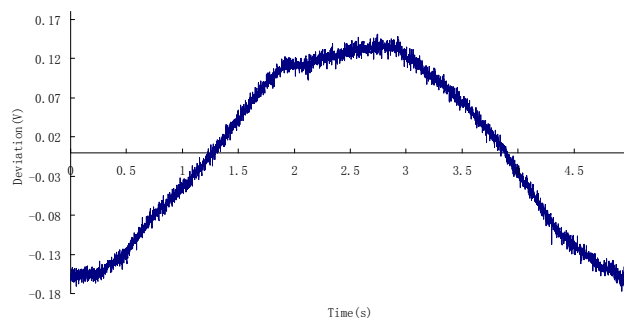


Figure 4. Deviation voltage



$$\theta_{n-1} = \theta_n \quad (7)$$

$$T_{n-1} = T_n \quad (8)$$

### Scheme verification

**Test of the Disturbance Suppression of Linear Acceleration.** Using a shaking table to create linear acceleration in the vertical direction, to observe the final output voltage of the tilt sensor output voltage and MCU DA. Observe the test system of linear acceleration interference suppression effect. Set the parameters to test the linear vibration amplitude of 0.5mm when the vibration frequency is 10Hz, 20Hz, 30Hz; line vibration amplitude of 0.75mm when the vibration frequency is 10Hz, 20Hz, 30Hz; line vibration amplitude of 1.5mm vibration frequency 10Hz, 20Hz, the 30Hz acceleration interfere with the output. Elect line vibration 0.75mm-30Hz, the tilt sensor and microcontroller DA output as shown below.

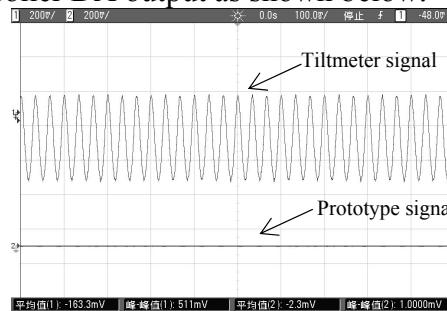


Figure 8. Linear vibration test

From Fig8, the prototype can detect the existence of linear acceleration, and avoid the influence of linear acceleration. Such method cannot guarantee that the linear acceleration in case detection accuracy, because of the integration error increases with the increase in integration time, a long period of continuous integration will inevitably lead to the error increases to unacceptable levels. So the scheme can only be a short period of time to resist the interference of the linear acceleration, to maintain measurement accuracy. Its significance lies in the identification of linear acceleration, and to avoid severe output error angle signal.

**Test of suppression of angular acceleration disturbance.** According to the linear relationship shown in Fig.6, the disturbance of angular acceleration can be calculation. The prototype is used to test the suppression of disturbance caused by angular acceleration. Using turntable to make the prototype to vibrate. The parameters of angle vibration is shown in Tab.2.

TABLE II. PARAMETER OF TURNTABLE

	Turntable set	
	Angle vibration range	Cycle(s)
Case 1	-15~15	5
Case 2	-20~20	5
Case 3	-10~10	4

According to the scale factor of tiltmeter, the tiltmeter voltage should be convert into angle before calculation of RMS(root mean square).The test results are shown in Tab. 3.

$$RMS = \sqrt{\sum_{i=1}^N (\theta_{zi} - \theta_i)^2 / N} \quad (9)$$

where  $N$  is sample number in one period.,  $\theta_i$  is the  $(i)$ th data of prototype,  $\theta_{zi}$  is the  $(i)$ th data of turntable.

TABLE III. ANTI-ANGULAR ACCELERATION DISTURBANCE TEST

	Case 1	Case 2	Case 3
Before deviation suppression	0.649°	0.675°	0.712°
After deviation suppression	0.051°	0.0469°	0.053°

Table 3 shows that the RMS decreased by an degree of magnitude after disturbance suppression. So the angular acceleration compensation algorithm is significantly reduce the disturbance caused by angular acceleration.

## Conclusion

Experiments of the prototype show that the scheme can effectively identify the linear acceleration disturbance, avoid serious error caused by linear acceleration. More importantly, the method to eliminate the disturbance of angular acceleration was verified by angular vibration test. The results of three case show that the scheme can effectively reduce the disturbance of angular acceleration. The scheme cannot resist the disturbance of linear acceleration for a long time, but the elimination of the disturbance caused by angular acceleration is effective when linear acceleration exists.

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