Error-Compensation Method for Inclination Measurement Under the Influence of the Dynamic Interference

Yanshun Zhang, Yajing Guo, Kui Li, Chaoying Pei, and Ming Li

***Abstract*— To deal with the problem of the inclination measurement errors caused by the dynamic motions, such as rotational and accelerated rectilinear components, this paper puts forward an effective inclination measurement scheme and the corresponding error-compensation method based on one accelerometer and two gyroscopes. In addition, the principle prototype of the dynamic inclination measurement apparatus is set up to conduct experiments of turntable rotation test, trolley test, and the turntable sway test at different inclined angles, thus verifying the feasibility of the error-compensation method under the effects of the rotational motion, accelerated rectilinear motion or both motions at the same time. Experimental results show that the aforementioned method can effectively compensate the inclination measurement errors resulting from the rotational and accelerated rectilinear motions.**

***Index Terms*— Accelerated rectilinear motion, dynamic error compensation, dynamic inclination measurement, rotational motion.**

I. INTRODUCTION

INCLINATION measurement is widely used in fields of level posture measuring, deformation monitoring, vibration test, and attitude control [1]–[4]. The inclination measurement based on accelerometers has advantages such as convenience, celerity, and high accuracy [5]–[8]. The static inclination measurement based on accelerometers can achieve high precision, while sensor interference from the rotational and accelerated rectilinear motions deteriorates its dynamic properties [9], [10]. In order to compensate the inclination measurement errors resulting from the dynamic disturbances, scholars all over the world have researched abundantly and made theirs voice heard in different journals. Reference [10] analyzed the effects of the rotational and accelerated rectilinear motions on the output of the accelerometer and the resulting errors in navigation and positioning. Reference [11], [12] fused the angular velocity information from gyroscopes and the specific force information from the accelerometer by using the complementary filter. This method, to some degree, can improve the dynamic properties and measurement precision. In order to tackle the dynamic interference, in reference [13] the Inertial Measure Unit (IMU) was used to calculate the navigation attitude by using the strapdown inertial navigation algorithm. Reference [14] combined single dual-axis accelerometer with multiple single/dual axis accelerometers to measure inclination, counteracting the dynamic errors induced by rotational motions in some certain range. In view of the dynamic interference resulting from accelerated rectilinear motions, reference [15] presented a method of compound inclination measurement based on four accelerometers, with three of them to measure inclination, and the other one to identify the disturbance of linear accelerations. This method can effectively compensate the effect of accelerated rectilinear motions on inclination measurement.

Carrier movement is usually found followed by the rotational and accelerated rectilinear motions. In this case, the mechanism of inclination measurement errors is complex and not easy to compensate. Taking the dynamic errors caused by rotational and accelerated rectilinear motions into consideration comprehensively, this paper presents a scheme of inclination measurement and an error-compensation method based on one accelerometer and two gyroscopes, and then the experimental platform is built for the experimental validation.

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The authors are with the School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing 100191, China (e-mail: zhangyanshun@buaa.edu.cn; gyj_buaa@163.com; xflikui@126.com; buaaxskx_pcy@163.com; liming_m@163.com).

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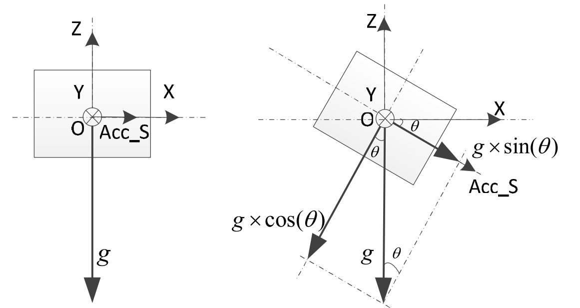
II. THE METHOD OF DYNAMIC INCLINATION MEASUREMENT

A. The Inclination Measurement Method Based on Accelerometer in Static State

In the scheme of uniaxial inclination measurement based on one accelerometer, the accelerometer is usually installed on the carrier. Then the angle between the accelerometer's sensitivity axis and the horizontal plane is estimated by means of processing the components of gravitational acceleration measured by the accelerometer. The measuring principle is shown in Fig.1. When the carrier to be measured is static and free from external force, this scheme can ensure a high precision [16].

In Fig. 1, $OXYZ$ is the local horizontal reference coordinate system, in which the OZ axis, pointing upwards, is collinear with the direction of the gravitational acceleration. The OX axis and the OY axis are in the horizontal plane



(a) (b)

Fig. 1. The principal diagram of uniaxial inclination measurement based on accelerometer. (a) Horizontal setting. (b) Slant setting.

and form a right-hand coordinate system with the OZ axis. When the accelerometer is placed horizontally, its sensitivity axis Acc_S is in the line with the OX axis, as is shown in the Fig. 1(a). At this moment the components of gravitational acceleration measured by accelerometer is 0. That is, the specific force outputted by the accelerometer meets:

$$f = 0 \tag{1}$$

When the accelerometer is rotating solely around the OY axis, the incline angle θ is created between the sensitivity axis of the accelerometer Acc_S and the horizontal plane, namely the angle between Acc_S axis and OX axis. The components of gravitational acceleration measured by the accelerometer is $g \times \sin(\theta)$. That is, the output of the accelerometer is:

$$f = g \times \sin(\theta) \tag{2}$$

The specific force outputted by accelerometer varies with the angle θ, therefore, the incline angle θ can be calculated using (2):

$$\theta = arc\sin(f/g) \tag{3}$$

For small angular variation, the incline angle θ is calculated using (3) with high-precision. But under the dynamic interference of rotational and accelerated rectilinear motions, the output signal of the accelerometer will be polluted by harmful accelerations independent of the inclination, and the calculation errors of the inclination should be compensated to make the estimated angle with high-precision.

B. The Error-Compensation Scheme of Inclination Measurement Under Dynamic Conditions

1) The Analysis of the Dynamic Inclination Measurement Errors: When the incline angle is calculated with single accelerometer, the factors leading to the calculation errors mainly include: if there is an angular velocity parallel to the two vertical axes which are orthogonal to accelerometer's sensitivity axis, the angular velocity will lead to centripetal acceleration parallel to accelerometer's sensitivity axis, which will contribute to interference error; the linear acceleration collinear to the sensitivity axis will also result in interference error. To compensate the dynamic errors mentioned above, the paper presents a scheme of dynamic inclination measurement and the corresponding error-compensation method using one accelerometer and two auxiliary gyroscopes. The measuring principle is shown in Fig. 2.

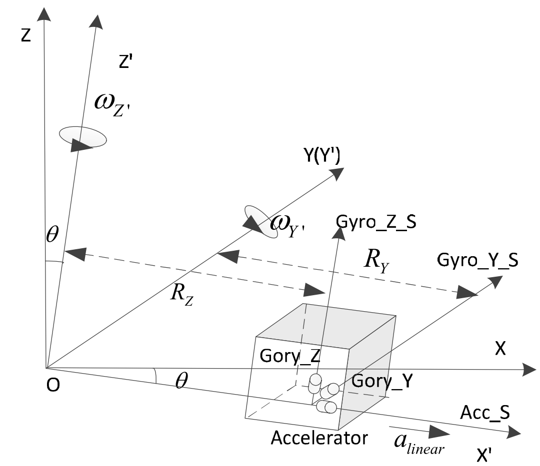


Fig. 2. The measuring principle.

In Fig. 2, the $OX'Y'Z'$ is the measuring-coordinate system, in which the OX' axis is coincide with the sensitivity axis of the accelerometer Acc_S, the OY' axis is parallel to the horizontal plane and coincide with the OY axis in coordinate system $OXYZ$. The OZ' axis forms a right-hand rectangular coordinate system with the OX' axis and the OY' axis. The angle θ caused by $OX'Y'Z'$ coordinate system rotating around the $OY'(OY)$ axis is the incline angle to be measured. The sensitivity axes of the gyroscopes are parallel to the OY' axis and the OZ' axis respectively, therefore, the two gyroscopes $Gyro\_Y$ and $Gyro_Z$ are used to measure angular velocities $\omega_{Y'}$ and $\omega_{Z'}$, on the OY' axis and the OZ' axis. R_Y and R_Z are the respective radius of gyration when the accelerometer is rotating around the OY' axis and OZ' axis. a_{linear} is the linear acceleration on the OX' axis.

Under the effects of the linear acceleration a_{linear}, the angular velocities $\omega_{Y'}$ on the OY' axis and $\omega_{Z'}$ on the OZ' axis, the specific force outputted by the accelerometer comes down to:

$$f = g \times \sin(\theta) + f_{\omega Y'} + f_{\omega Z'} + f_a \tag{4}$$

Where $f_{\omega Y'}$, $f_{\omega Z'}$ are the interference accelerations caused by the rotation on the OY' axis and the OZ' axis respectively, and f_a is the interference acceleration induced by the linear acceleration on the OX' axis. The dynamic interference accelerations are harmful for the measurement of inclination and must be compensated to ensure high-accuracy.

2) The Compensation Scheme of the Dynamic Inclination Measurement: Two uniaxial gyroscopes are used in this paper, measuring the angular velocity, to estimate and compensate the errors of inclination just measured by the accelerometer. The scheme of dynamic error-compensation is shown in the Fig.3.

As is shown in the Fig.3, realization steps of the error-compensation of inclination measurement are as followed: 1) The interference acceleration $f_{\omega Y'}$ and $f_{\omega Z'}$ are obtained according to the output of gyroscopes under the rotating state.

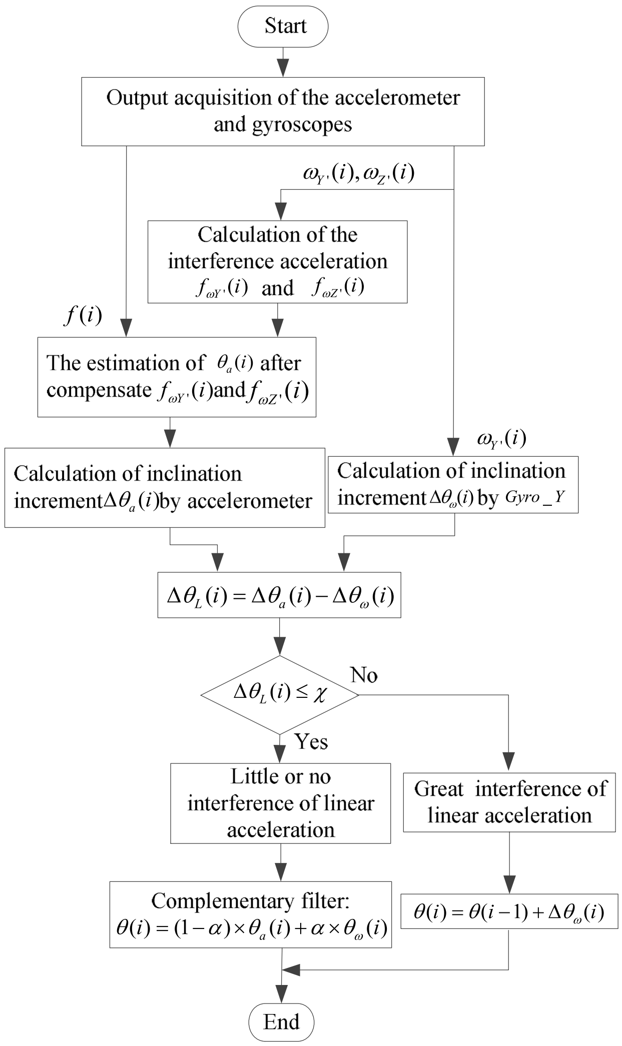


Fig. 3. The dynamic error-compensation scheme of inclination measurement.

2) The incline angle θ_a and its increments $\Delta\theta_a$ are estimated according to the output of the accelerometer after compensated the interference acceleration $f_{\omega Y'}$ and $f_{\omega Z'}$ caused by the rotational motions. 3) The increment of the dynamic inclination $\Delta\theta_\omega$ is obtained by the information of angular velocity $\omega_{Y'}$ outputted by the gyroscope on the Y-axis. 4) Judging whether the sensor is disturbed by the accelerated rectilinear motion through the value of angle difference $\Delta\theta_L$, which is calculated by comparing $\Delta\theta_a$ and $\Delta\theta_\omega$. 5) If $\Delta\theta_L$ is less than the threshold χ, it indicates that the linear acceleration has little or no influence on the sensor, then go to the next stage of calculation. If $\Delta\theta_L$ is greater than χ, it means that the linear acceleration has a greater interference, so the inclination estimated according to the gyroscope output is regarded as the determination results. 6) When the linear acceleration has little or no influence on the sensor, the incline angles calculated by the accelerometer and gyroscope is fused, by using the complementary filter, to calculate the true value of the inclination θ.

3) The Principle of Error-Compensation Method for Dynamic Inclination Measurement: The rotational motion of the carrier results in the centripetal acceleration on the sensitivity axis of the accelerometer Acc_S, while the accelerated rectilinear motion leads to the linear acceleration on Acc_S. The two kinds of accelerations make the output of the accelerometer polluted by the harmful accelerations. Also they contribute to the increase of the measurement errors of the inclination. Aiming at that, calculation and compensation is needed, that is, $f_{\omega Y'}$, $f_{\omega Z'}$, and f_a are needed to isolate from (4).

(1) The harmful accelerations derived from rotational motion

As is shown in the Fig.2, rotational motions around OY' and OZ' axis can result in harmful acceleration for the output of the accelerometer. Among them, centripetal acceleration caused by the angular velocity $\omega_{Y'}(i)$ on the OY' axis, is $\omega_{Y'}(i)^2 \times R_{Y'}$. The corresponding harmful acceleration can be expressed as:

$$f_{\omega Y'} = \omega_{Y'}(i)^2 \times R_{Y'} \tag{5}$$

In the same way, harmful acceleration corresponding to the angular velocity $\omega_{Z'}(i)$ on the OZ' axis, is

$$f_{\omega Z'} = \omega_{Z'}(i)^2 \times R_{Z'} \tag{6}$$

The harmful accelerations, $f_{\omega Y'}$ and $f_{\omega Z'}$, can be obtained by (5) and (6), according to the angular velocity $\omega_{Y'}(i)$ and $\omega_{Z'}(i)$ measured by the gyroscopes. The harmful accelerations caused by the rotational motions can be compensated according to (4).

(2) Calculation of the harmful accelerations caused by the accelerated rectilinear motion

The linear acceleration a_{linear} which is projected onto the Acc_S axis may lead to the interference error f_a, and then may cause the measuring error of the inclination. To inhibit this interference error, this paper firstly verdicts whether there is linear acceleration using the output angular velocity ω_Y from the gyroscope $Gyro\_Y$. Thereafter, several different processing modes are given according to different verdict results.

The increment of angle can be calculated by the output of the gyroscope $Gyro\_Y$:

$$\Delta\theta_\omega(i) = \omega_Y \times T \tag{7}$$

Where, T is the sampling period.

The incline angle $\theta_\omega(i)$ can be obtained by integrating the angular velocity measured by the gyroscope on the OY' axis. Due to the fact that the integration cycle is short, using the accurate angle of the last instance, the $\theta_\omega(i)$ can be expressed as:

$$\theta_\omega(i) = \theta(i-1) + \omega_Y \times T \tag{8}$$

After compensating the centripetal acceleration from the specific force outputted by the accelerometer, the inclination can be calculated as:

$$\theta_a(i) = arc\sin((f(i) - f_{\omega Y'}(i) - f_{\omega Z'}(i))/g) \tag{9}$$

Here, $\Delta\theta_a(i)$ is the increment of angle estimated with the output signal of the accelerometer:

$$\Delta\theta_a(i) = arc\sin((f(i) - f_{\omega Y'}(i) - f_{\omega Z'}(i))/g) - \theta(i-1) \tag{10}$$

The corresponding interference error f_a caused by the accelerated rectilinear motion is directly proportion to the value of angle difference $\Delta\theta_L$ between accelerometer and gyroscope, which can be expressed as:

$$\Delta\theta_L(i) = \Delta\theta_a(i) - \Delta\theta_\omega(i) \tag{11}$$

If $\Delta\theta_L$ is greater than the threshold χ, that is $\Delta\theta_L(i) > \chi$, there are more interference signal effected by accelerated rectilinear motion in the output of the accelerometer. Under this condition, the incline angle $\theta_\omega(i)$ computed by the output of the gyroscope is regarded as the result of the measurement. If $\Delta\theta_L(i) \le \chi$, it means that the interference signal from the accelerated rectilinear motion has little or no influence on the sensor. In this case, the incline angles calculated by accelerometer ($\theta_a(i)$) and gyroscope ($\theta_\omega(i)$) are fused with complementary filter algorithm to estimate the inclination $\theta(i)$.

(3) Complementary filter

After compensating the harmful accelerations caused by the rotational and accelerated rectilinear motions, affected by these motions, the incline angle obtained based on the accelerometer contains dynamic random errors, which are mainly in high frequency. When the incline angle is changing fast, the inclination measured by gyroscope which can sensor the angular velocity, can effectively compensate the disadvantage of the measurement based on the accelerometer. Therefore, taking the advantage of the difference in the frequency domain for the measurement errors of the gyroscopes and the accelerometer, this paper uses the method of complementary filter to fuse the output of the gyroscopes and the accelerometer, to inhibit the random errors and to improve the precision and the stability of the inclination measurement on the frequency band.

The factor α $(0 \le \alpha \le 1)$ is the weight factor of the inclination measurement based on the gyroscope, meanwhile $(1-\alpha)$ is the weight factor of the inclination calculation based on the accelerometer. Then the inclination $\theta(i)$ can be expressed as:

$$\theta(i) = (1-\alpha) \times \theta_a(i) + \alpha \times \theta_\omega(i) \tag{12}$$

Weight factor α is determined by the difference between the increments obtained respectively by the accelerometer and the gyroscope, namely $\Delta\theta_a(i)$ and $\Delta\theta_\omega(i)$, which can be presented as:

$$\alpha \propto |\Delta\theta_a(i) - \Delta\theta_\omega(i)| \tag{13}$$

Combined with the s (7) and (10), the (13) can be expressed as:

$$\alpha \propto |(\theta_a(i) - \theta(i-1)) - \omega_Y \times T| \tag{14}$$

As is seen from (14), if the inclination increment computed by accelerometer is much greater than the inclination increment obtained by the gyroscope, it can be proved that there are great dynamic errors in the inclination information obtained by the accelerometer. At this state, α, the weight factor of $\theta_\omega(i)$ which is the estimated by the gyroscope, should be enlarged, while the weight factor $(1-\alpha)$ of the accelerometer's calculating result $\theta_a(i)$ should be decreased.

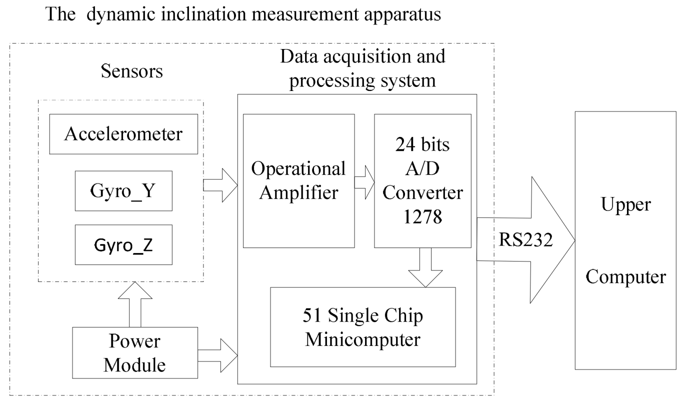


Fig. 4. The design of the principal prototype of the dynamic inclination measurement apparatus.

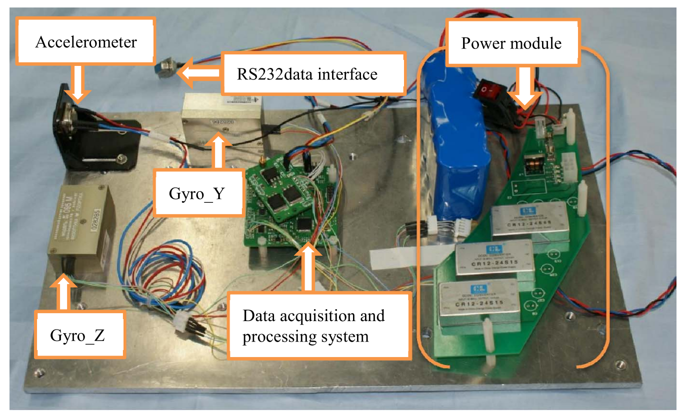


Fig. 5. The dynamic inclination measurement apparatus.

TABLE I
PARAMETERS OF USED ACCELEROMETER AND FOG

	Accelerometer (JSD-ⅡC)	Gyro_Y (VG095M)	Gyro_Z (VG095M)
random drift	100mg	20deg/h	20deg/h
scale factor	1mA/g	11.9mV/(deg/s)	11.9mV/(deg/s)
measuring range	±5**g**	±300*deg / s*	±300*deg / s*

III. THE EXPERIMENTAL EQUIPMENT

A. The Principal Prototype of the Dynamic Inclination Measurement Apparatus

To validate the error-compensation method of dynamic inclination measurement presented in this paper, the principal prototype of the dynamic inclination measurement apparatus is built based on one accelerometer and two gyroscopes. The composition block diagram and the factual picture of this device are shown in Fig. 4 and Fig. 5.

As is shown in Fig.5, the accelerometer uses JSD-IIC quartz accelerometer. The Gyro_Y and Gyro_Z both use FOG VG095M. More parameters of used accelerometer and FOG are shown in TABLE I. CPU of the data acquisition system uses 51 Single Chip Minicomputer (SCM). The analog-digital converter uses 24 bits $\Delta\Sigma$ A/D converter 1278. Signal is transferred to the upper computer by data interface RS232.

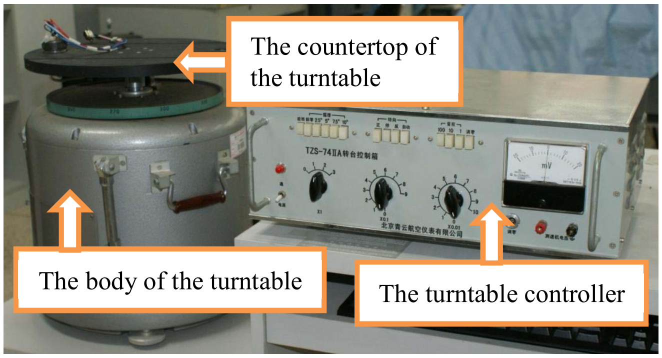


Fig. 6. The rate controllable turntable.

B. The Principal Prototype of the Dynamic Inclination Measurement Apparatus

To validate the error-compensate method of dynamic inclination measurement presented in this paper, the turntable rotation test and dynamic sway test on the TZS-74IIA, a comprehensively experimental turntable with gyroscopes, are conducted. TZS-74IIA is a single-shaft rate controllable turntable, which can rotate or sway with the inclination between the countertop and the body of the turntable. The experimental device is shown in the Fig.6.

In this device, the turntable controller is used to making the turntable rotate, tilt and sway. The range of the rotate speed of the turntable is $\pm 400\,\mathrm{deg}/s$, the incline angles of the turntable can be set as 2.5 deg, 5 deg, 7.5 deg and 10 deg.

IV. The Experiments

By turntable rotation test, trolley test, and the turntable sway test, the performance of the error-compensation of the dynamic inclination is validated respectively under the effects of the rotational motion, accelerated rectilinear motion or both motions.

A. The Turntable Rotation Test

To verify the performance of the error-compensate method under the rotational motion, the experimental platform shown in section III.A is mechanically mounted on the countertop of the TZS-74IIA turntable, and the rotating test is done respectively in the states of 0 deg and 5 deg inclination of the countertop. Then the output signal of the gyroscopes and the accelerometer are collected under the conditions of the various angular velocities. The incline angle can be calculated by the collected signal, as is shown in Fig.7.

1) Horizontally Rotating Test: In this test, the turntable is mounted horizontally firstly, and then controlled to rotate at different speeds of $\pm 20\mathrm{deg}/s$, $\pm 40\mathrm{deg}/s$, $\pm 60\mathrm{deg}/s$, $\pm 80\mathrm{deg}/s$, $\pm 100\mathrm{deg}/s$, $\pm 150\mathrm{deg}/s$ and $\pm 200\mathrm{deg}/s$ respectively. When the turntable ensures a stable speed, with every speed, the output signal of the gyroscopes and the accelerometer are collected to calculate the incline angles. The results before and after compensating are shown respectively as follows:

As is shown in Fig. 8, before compensating, the incline angle calculated only based on the accelerometer brings in

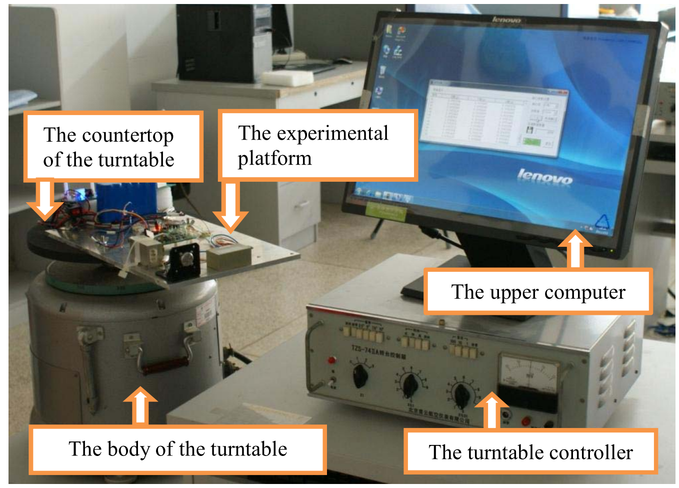


Fig. 7. The device of turntable rotation test.

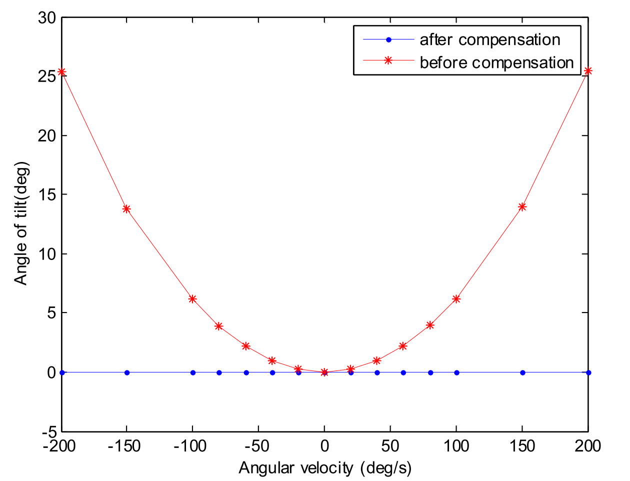


Fig. 8. Estimated horizontal incline angles under the different rotating velocities.

big error. Also the error increases with the growing angular velocity. When the angular velocity is $\pm 200\mathrm{deg}/s$, the calculation error of the incline angle can reach up to 25.4443 deg. After compensating, the maximum residual error is 0.0168 deg, the average error of the 14 groups is 0.0038 deg, the standard deviation is 0.0098 deg. Therefore, the error-compensate method presented in this paper can effectively inhibit the inclination error caused by the rotational motion.

2) The Rotating Test on 5 Deg Incline Angle of the Turntable Countertop: The incline angle of the turntable is set as 5 deg, and the rotating velocity of the turntable is controlled to be $\pm 100\mathrm{deg}/s$. Then the experimental data are collected to calculate the incline angle. The calculation results and the error curves, before and after compensating, are shown as follows:

As is shown in the Fig.9, before compensating, the averages of the estimated incline angle with the clockwise and anticlockwise speeds are 11.3817 deg and 11.3805 deg respectively, the averages of the corresponding errors are 6.3817 deg and 6.3805 deg. After compensating, the averages of the estimated incline angle with the clockwise and anticlockwise

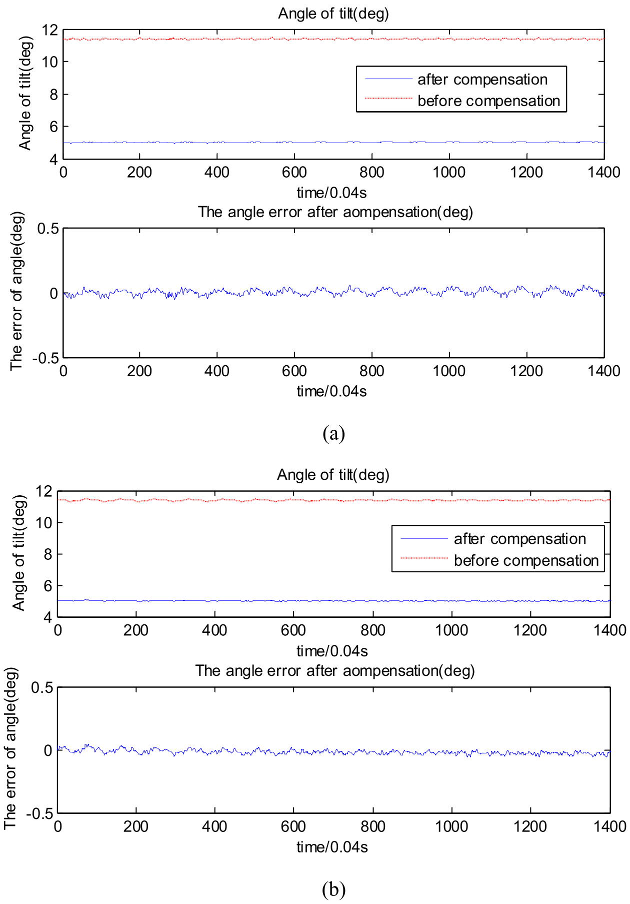


Fig. 9. The experimental results of 5 deg incline angle under $\pm 100\mathrm{deg}/s$ velocity. (a) Incline angle and error under $+100\mathrm{deg}/s$. (b) Incline angle and error under $-100\mathrm{deg}/s$.

Fig. 10. The trolley experiment.

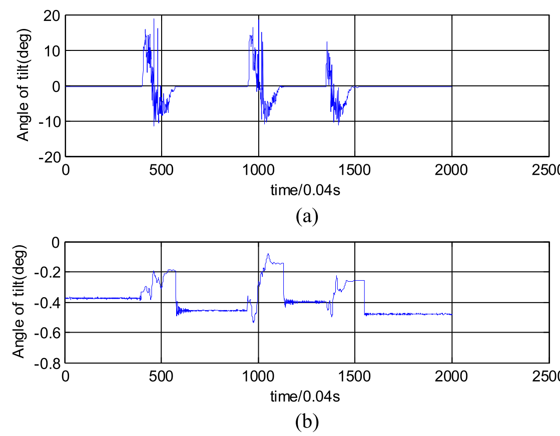


Fig. 11. The results of the trolley experiment. (a) The incline angle before compensating. (b) The incline angle after compensating.

speeds are 5.0036 deg and 5.0066 deg respectively, averages of corresponding errors are 0.0036 deg and 0.0066 deg, and the corresponding standard deviations are 0.0217 deg and 0.0168 deg. The results show that the error-compensate method put forward in this paper can effectively compensate the measurement error induced by the rotational motion at different incline angles.

B. The Trolley Test

To test the compensation effect of the dynamic error-compensation method under the effect of accelerated rectilinear motion, the trolley experiment is operated in the corridor of our researching building, shown in Fig.10. In this experiment, the inclination measurement device is fixed on the trolley. Firstly, the trolley remains statically for a while. Secondly, the trolley does accelerated and decelerated motions. When it returns to the static condition, let it hold on for a while. Finally, such periodic motions are repeated for three times. During this experiment, the trolley experiences static condition, accelerated process and decelerated process. So there exist the interferences of linear acceleration, which would contribute to significant measurement errors using the accelerometer to estimate the inclination alone. So, this experiment can be used to estimate the compensation effect of the dynamic error-compensation method under the effect of accelerated rectilinear motion. The results of this experiment are shown in Fig. 11.

The Fig.11(a) illustrates that, in this experiment the measurement equipment located in horizontal position approximately under static states. In addition, the maximum measurement error of level inclination induced by accelerated and decelerated motions of the trolley is up to 18.38 deg. However, after the compensation using the method provided in this paper, the measured value of level inclination is around -0.4 deg and the inclination measurement error resulting from linear accelerated motion is effectively compensated. In Fig.11(b), average values of level inclination in four static periods are -0.3744 deg, -0.4554 deg, -0.3521 deg, -0.4790 deg respectively, with a bit differences. The differences among them may be derived from two reasons: (1) Different places of the corridor are not in the same horizontal plane. Also the inclinations in the corridor's different places are not zero. (2) The trolley's wheel is not a standard circle, which would lead to the fluctuation of inclinations between horizontal plane and the setting surfaces of dynamic inclination measurement device when trolley is static in

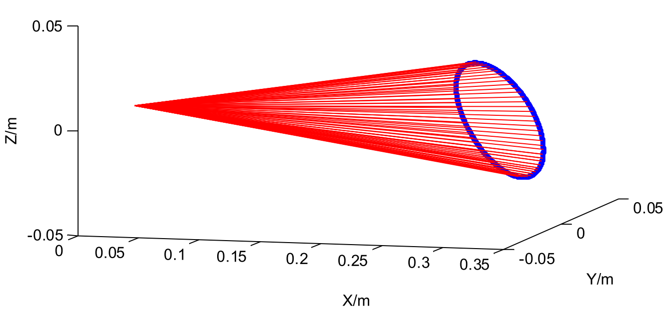


Fig. 12. The sway trajectory of measurement equipment's endpoint.

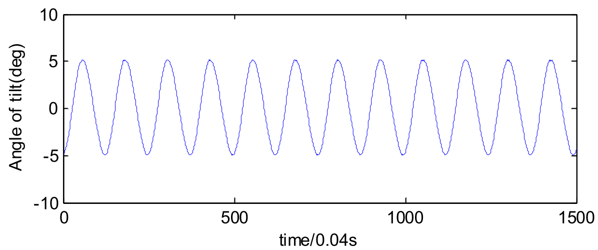


Fig. 13. The sway inclination of turntable.

difference places. Results of this experiment show that the dynamic inclination measurement errors induced by translational accelerated motions are significantly decreased by the use of dynamic error-compensation method proposed in this paper.

C. The Turntable Sway Test

To evaluate the reliability of the dynamic error-compensate method under the effects of both rotational and accelerated rectilinear motions, the measurement equipment is fixed on the turntable of comprehensive experimental turntable TZS-74IIA. Meanwhile, the turntable is set to do the rotational sway motion with a specific angle. The turntable is set with an incline angle 5 deg to sway. Thereafter the incline angle of the turntable in real time, where the measurement equipment is fixed, is measured. The trajectory of measurement equipment's endpoint is an elliptic curve shown in Fig.12. The turntable's inclination to be measured is the angle between the horizontal plane and the line connecting rotation center with the endpoint. Such sway motion includes the interference resulting from the double axis rotational motions of Y axis and Z axis and the interference deriving from accelerated rectilinear motion projecting on X axis. The inclination of turntable changes with rotational motion according to sine rule appearing in Fig. 13.

In the situation of sway motion, the output data is collected of the accelerometer and gyroscopes, and then the inclination and the compensate errors based on these data is estimated. After compensating, the graph of the estimated values of the turntable's inclination is a sine curve with 5 deg amplitude conforming to Fig. 13, and its inclination measurement errors are demonstrated in Fig. 14.

The Fig. 14 demonstrates that the maximum error of the inclination measurement of the turntable is 0.3616 deg and the average error during that period of calculation is -0.1027 deg. The periodic errors in this figure are derived from the

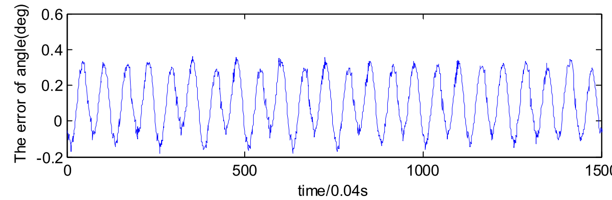


Fig. 14. The calculated inclination under the sway state.

acceleration measurement errors and the nonlinearity of scale factor errors of open-loop FOG resulting from the angular acceleration. So, the further study should focus on how the angular acceleration affects inclination measurement errors and how to compensate such errors. Thus, applying this method on compensation can significantly decrease the dynamic errors of the inclination measurement caused by both of the rotational and accelerated rectilinear motions.

V. Conclusion

By analysis of the dynamic inclination measurement errors under the effects of the rotational and accelerated rectilinear motions, this paper presented a dynamic inclination measurement method to calculate the dynamic incline angle based on two gyroscopes and one accelerometer. In addition, the principle prototype with two FOGs and one quartz accelerometer is built to validate the error-compensate method by experiments. Turntable rotation test, trolley test, and turntable sway test show that error-compensation method proposed in this paper can effectively compensate inclination errors derived from some interference factors such as rotational and accelerated rectilinear motions, thus rendering high-precision measurement of dynamic inclinations possible.

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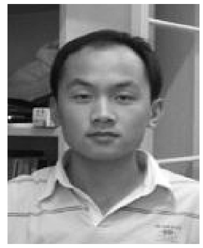
Yanshun Zhang was born in Harbin, China, in 1973. He received the B.S. and M.S. degrees from the Department of Physic and Automation, Northeast Forestry University, China, in 1995 and 1998, respectively, and the Ph.D. degree in automation from Harbin Engineering University, China, in 2003.

He has been an Assistant Professor with the School of Instrumentation Science and Optoelectronics Engineering, Beihang University, Beijing, China, since 2004. His research interests are related to inertial navigation and multisensor information fusion. He has authored over 30 articles, and more than ten inventions. He has acquired and participated in four National Natural Science funds.

Yajing Guo was born in Hebei, China, in 1991. She received the B.S. degree in measurement and control technology and instrumentation from Yanshan University, China, in 2013. She is currently pursuing the M.S. degree with the School of Instrumentation Science and Opto-Electronics Engineering, Beihang University, Beijing, China. Her research interests include navigation, guidance, and control.



Kui Li was born in Xi'an, China, in 1985. He received the B.S. and Ph.D. degrees from the School of Instrumentation Science and Opto-Electronics Engineering, Beijing University of Aeronautics and Astronautics, China, in 2007 and 2012, respectively.

He was a Senior Engineer with the AVIC Xi'an Flight Automatic Control Research Institute, Xi'an, from 2012 to 2014. Since 2014, he has been a Post-Doctoral Fellow with the Beijing University of Aeronautics and Astronautics. His research interests include Inertial Navigation, Global Navigation Satellite System and Multisensor Information Integration. He has authored over 20 articles, and more than five inventions.

Chaoying Pei was born in Luoyang, China, in 1992. She is currently pursuing the B.S. degree at the School of Instrumentation Science and Opto-Electronics Engineering, Beihang University, Beijing, China.

Ming Li was born in Heilongjiang, China, in 1978. She received the M.S. and Ph.D. degrees from Bauman Moscow State Technical University, Moscow, Russia, in 2004 and 2009, respectively. Her tutor is Prof. S. A. Chernikov. She is now taking charge of the National Natural Science Foundation of China. Her current research interest is inertial instrumentation and system, and its vibration analysis and control.