Second-order coefficient calibration method of accelerometer in platform inertial navigation system tested on double turntable centrifuge

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Abstract. This paper proposes a method of accurately calibrating the second-order coefficient of accelerometer in platform inertial navigation system(PINS) being calibrated by double turntable centrifuge. Firstly, the errors of specific force caused by the angular rate error about spindle system of the centrifuge are derived, and the relationship between the PINS's output displacements and the centrifuge errors, the accelerometer errors is developed. By way of this, a test plan of calibrating the second-order coefficient of accelerometer by the identification with twice least squares method is drawn up. Secondly, the test plan can separate the angular rate error and the second-order coefficient of accelerometer from the output displacement errors of the PINS's, and eliminate the effect of the angular rate error on the calibration accuracy of the second-order coefficient, so the calibrating accuracy of the second-order coefficient is greatly raised. Finally, simulation results verified that the calibration accuracy of the second-order coefficient of the accelerometer can be raised to an order of $10^{-7} g / g^2$.

Keywords: second-order coefficient, double turntable centrifuge, platform inertial navigation system(PINS), accelerometers, least squares method, error separating technology.

1. Introduction

When PINS is tested on a precision centrifuge, its error model coefficients can be calibrated by the intrinsic relationship between its output displacements and its error model coefficients. However, the accelerometers in PINS are also sensitive to the specific force error caused by the centrifuge errors[1], and the specific force errors affect the calibration accuracy of error model coefficients through its contribution to the computed displacement errors[2]. The bias and the first-order coefficient of the accelerometers can be calibrated accurately in gravity field using the multi-position tumbling-test[3-6] , and this calibration technology is already quite mature[7]. This paper mainly introduces the method of calibrating the second-order coefficient using double turntable centrifuge.

The influence of centrifuge main axis angular rate error on the accelerometer second-order coefficient is eliminated by separating the centrifuge errors from the PINS's displacement errors.

2. Organization of the Text

2.1 The centrifuge axis angular error

The main axis of centrifuge cannot guarantee accurately and completely uniform angular rate ω_0 , more or less there are some angular rate errors[8,9]. The angular rate of centrifuge main axis ω can be expressed as follows:

$$\omega = \omega_0(1+Ct) + \omega_p \sin(\omega_0 t + \phi) \tag{1}$$

where, ω_0 is the nominal angular rate(rad/s);

C is the angular rate drift rate(1/s);

ω_p is the amplitude of angular periodic fluctuation(rad/s);

ϕ is the phase angle of angular rate periodic fluctuation(rad).

If θ(t=0)=0，the rotation angle of the main axis at time t is:

$$\theta = \int_0^t \omega \mathrm{d}t = \omega_0 t + \frac{1}{2}C\omega_0 t^2 - \frac{\omega_p}{\omega_0}\cos(\omega_0 t + \phi) + \frac{\omega_p}{\omega_0}\cos\phi \tag{2}$$

The rotation angle of centrifuge main axis versus time can be monitored in real-time during the experiment. The Eq.(2) can be used to identify parameters such as ω_0, C, ω_p and ϕ.

According to Eq.(2), the angular rate and the angular acceleration are:

$$\dot{\theta} = \omega = \omega_0(1+Ct) + \omega_p \sin(\omega_0 t + \phi) \tag{3}$$

$$\ddot{\theta} = C\omega_0 + \omega_p\omega_0 \cos(\omega_0 t + \phi) \tag{4}$$

The input specific force errors of the platform base can be expressed as follows:

$$\Delta a_x = -2R_0[C\omega_0^2 t + \omega_0\omega_p \sin(\omega_0 t + \phi)]\cos\omega_0 t + R_0[C\omega_0 + \omega_0\omega_p \cos(\omega_0 t + \phi)]\sin\omega_0 t \tag{5}$$

$$\Delta a_y = -2R_0[C\omega_0^2 t + \omega_0\omega_p \sin(\omega_0 t + \phi)]\sin\omega_0 t + R_0[C\omega_0 + \omega_0\omega_p \cos(\omega_0 t + \phi)]\cos\omega_0 t \tag{6}$$

It can be seen that the specific force errors contain the drift rate, the amplitude and the phase angle of periodic fluctuation of the angular rate.

2.2 Analysis of the impact of centrifuge error on the calibration accuracy of PINS

The relationship between the PINS's output displacement and the error of accelerometer, and the centrifuge main axis angular rate error is established below.

2.2.1 Error model of quartz accelerometer

The error model of quartz accelerometer:

$$a_{ind} = K_F + K_I a_I + K_{II} a_I^{\ 2} + K_{III} a_I^{\ 3} + K_{IP} a_I a_P + \varepsilon \tag{7}$$

where, a_{ind} is the indicated output of accelerometer, unit: g;

K_F is the bias, unit: g;

K_I is the scale factor, unit: g/g;

K_{II} is the second-order coefficient about input axis, unit: g/g^2;

K_{III} is the third-order coefficient about input axis, unit: g/g^3;

K_{IP} is the cross-coupling coefficient, unit: g/g^2;

ε is random error, unit: g

The installation error of the accelerometer has a small impact on displacement accuracy. The system configuration diagram of internal instruments in PINS is shown in Figure 1.

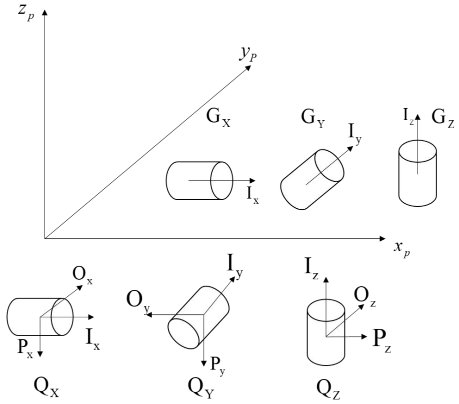

Figure 1 The configuration diagram of internal instruments for PINS

As shown in figure 1, the specific force vector of accelerometer Qx is:

$$\boldsymbol{a}_{1A} = \begin{bmatrix} a_{1AI} & a_{1AP} & a_{1AO} \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} a_x & -a_z & a_y \end{bmatrix}^{\mathrm{T}} \tag{8}$$

Owing to K_{II} , K_{III} , K_{IP} is relatively numerical small, their related input terms such as a_{1An}^2 , a_{1An}^3 , $a_{1AIn}a_{1APn}$ can be substituted nominal terms into Eq. (9), while the related input term a_{1AI} of larger K_{I1} , a_{1AI} must be precise to a first-order small quantity. So

$$a_{ind1} = K_{F1} + K_{I1}a_{1AI} + K_{II1}a_{1AIn}{}^2 + K_{III1}a_{1AIn}{}^3 + K_{IP1}a_{1AIn}a_{1APn} + \varepsilon \tag{9}$$

where, $a_{1AIn} = a_{xn} = -R_0\omega_0{}^2 \cos\omega_0 t / g$, $a_{1APn} = -a_{zn} = -1$, which can be seen as figure 2.(The platform is excited by angular rate so that the platform coordinate system tracks the geographic coordinate system. The input axis Ix of accelerometer Qx always points east, and the pendulum axis Px of accelerometer Qx points to the ground)

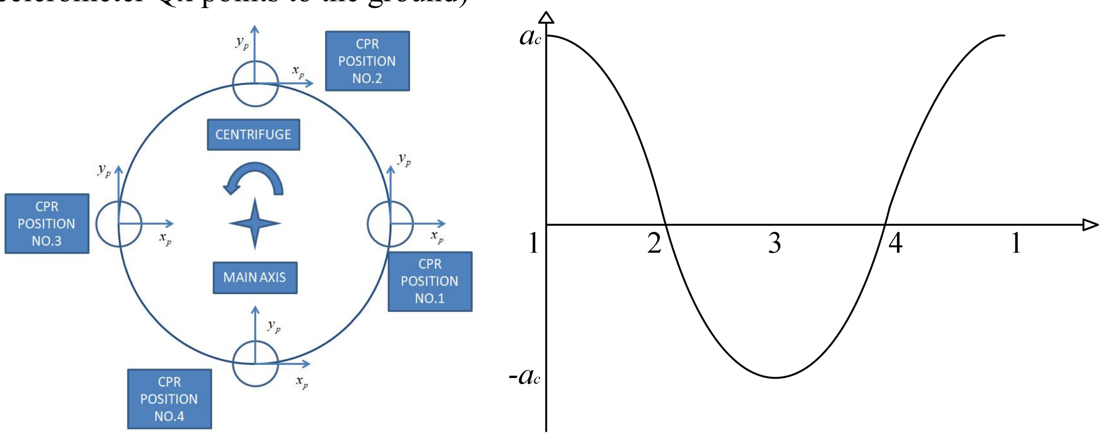

Figure 2 Simplified Centrifuge Acceleration Profile

Legend: a_c -centrifuge centripetal acceleration(always directs inward)

x_p , y_p , z_p -three coordinate axes fixed on the platform base

2.2.2 Least squares method identification

To simplify the process of calculation, the platform is excited by command angular velocity so that the platform coordinate system coincides with the geographic coordinate system.

When calculating the displacements, it should be the quadratic integral of the motion acceleration of the PINS, which is the quadratic integral obtained by subtracting the harmful acceleration from the indication output of accelerometer. Therefore, the displacement of accelerometer Qx is:

$$S_x = \iint (a_{ind1} \cdot g)\mathrm{d}t^2 - \iint (a_{hx} \cdot g)\mathrm{d}t^2 \tag{10}$$

In the Eq.(10), $a_{hx} \cdot g$ is the harmful acceleration, which is the sum of the projection of gravity acceleration and Coriolis acceleration in the platform base coordinate system.

Due to the platform base tracking the geographic coordinate system, so the input axis line of Qx is always theoretically in the east direction, the displacement computed by Qx is equal to the eastward displacement of PINS, so

$$S_{xn} = R_0 \cos\omega_0 t \tag{11}$$

The displacement error can be calculated by the difference between the displacement output of PINS and the one accurately provided by the double turntable centrifuge, through the displacement errors the second-order coefficient can be identified. The displacement error of PINS is $S_x - S_{xn}$:

$$S_x = \iint (a_{ind1} \cdot g)\mathrm{d}t^2 - \iint (a_{hx} \cdot g)\mathrm{d}t^2 \tag{12}$$

$$\iint a_{ind1}\mathrm{d}t^2 = \iint K_F \mathrm{d}t^2 + \iint K_I a_x \mathrm{d}t^2 + \iint K_{II} a_{xn}{}^2 \mathrm{d}t^2 + \iint K_{III} a_{xn}{}^3 \mathrm{d}t^2 + \iint K_{IP} a_{xn} \cdot (-a_{zn})\mathrm{d}t^2 \tag{13}$$

Expanding the Eq.(13), we have

$$\iint (a_{ind1} \cdot g)\mathrm{d}t^2 = \frac{1}{2}K_F g t^2 \mathrm{d}t^2 + \iint K_I a_x g \mathrm{d}t^2 + \iint (K_{II}(\frac{-R_0\omega_0{}^2\cos\omega_0 t}{g})^2 \cdot g)\mathrm{d}t^2 +$$

$$\iint (K_{III}(\frac{-R_0\omega_0{}^2\cos\omega_0 t}{g})^3 \cdot g)\mathrm{d}t^2 + \iint (K_{IP}(\frac{-R_0\omega_0{}^2\cos\omega_0 t}{g}) \cdot (-1) \cdot g)\mathrm{d}t^2$$

Where,

$$\iint (K_{II}(\frac{-R_0\omega_0{}^2\cos\omega_0 t}{g})^2 \cdot g)\mathrm{d}t^2 = \frac{1}{2}K_{II}\frac{R_0{}^2\omega_0{}^4}{g}t^2 - \frac{1}{8}K_{II}\frac{R_0{}^2\omega_0{}^4}{g}\cos 2\omega_0 t + \frac{1}{8}K_{II}\frac{R_0{}^2\omega_0{}^4}{g}$$

$$\iint (K_{III}(\frac{-R_0\omega_0{}^2\cos\omega_0 t}{g})^3 \cdot g)\mathrm{d}t^2 = \frac{1}{36}K_{III}\frac{R_0{}^3\omega_0{}^6}{g^2}\cdot\cos 3\omega_0 t + \frac{3}{4}K_{III}\frac{R_0{}^3\omega_0{}^6}{g^2}\cdot\cos\omega_0 t - \frac{7}{9}K_{III}\frac{R_0{}^3\omega_0{}^6}{g^2}$$

$$\iint (K_{IP}(\frac{-R_0\omega_0{}^2\cos\omega_0 t}{g}) \cdot (-1) \cdot g)\mathrm{d}t^2 = -K_{IP}R_0\cos\omega_0 t + K_{IP}R_0$$

After the integration of the high-order term, only the displacement error caused by the second-order term accumulating over time is proportional to the square of time.

Before using the double turntable centrifuge to calibrate PINS, both the bias and the scale factor can be calibrated in the $\pm 1g$ gravity field, so they can be considered as known quantities.

In the input specific force a_x of the platform base, the harmonic components of a_x will not cause cumulative displacement errors, while the main axis angular rate, the installation misalignment angle, and the periodic fluctuation amplitude ω_p of the centrifuge main axis system will cause cumulative errors proportional to t^2.

After quadratic integral with respect to time, the displacement error is:

$$\begin{aligned} S_x - S_{xn} &= \frac{1}{2}K_F \cdot g t^2 + \iint K_I(-\Delta r)\omega_0{}^2\cos\omega_0 t / g \cdot g\mathrm{d}t^2 + \\ &\iint K_I(-2R_0\left(C\omega_0{}^2 t + \omega_p\omega_0\sin(\omega_0 t + \phi)\right)\cos\omega_0 t / g) \cdot g\mathrm{d}t^2 + \\ &\iint K_I(-R_0\left(C\omega_0{}^2 t + \omega_p\omega_0\cos(\omega_0 t + \phi)\right)\sin\omega_0 t / g) \cdot g\mathrm{d}t^2 + \iint K_{II}(\frac{-R_0\omega_0{}^2\cos\omega_0 t}{g})^2 \cdot g\mathrm{d}t^2 + \\ &\iint K_{III}(\frac{-R_0\omega_0{}^2\cos\omega_0 t}{g})^3 \cdot g\mathrm{d}t^2 + \iint K_{IP}(\frac{-R_0\omega_0{}^2\cos\omega_0 t}{g}) \cdot (-1) \cdot g\mathrm{d}t^2 \end{aligned} \tag{14}$$

where, Δr is the deviation from nominal radius.

Let: $\omega_0 t = \frac{\pi}{2} + 2k\pi \quad k = (0,1,\mathrm{L}\ )$, the displacement error expression can be expressed as:

$$S_x - S_{xn} = \frac{1}{2}K_F \cdot gt^2 + \frac{1}{2}K_{II}\frac{R_0^{\ 2}\omega_0^{\ 4}}{g}t^2 - \frac{3}{4}K_I R_0\omega_0\omega_p \sin\phi t^2 + 2K_I R_0 Ct + K_I(\Delta r) + K_I\frac{4R_0C}{\omega_0} + \frac{3}{8}R_0\sin\phi + \varepsilon_n \tag{15}$$

Write it in matrix form:

$$\boldsymbol{S}_x - \boldsymbol{S}_{xn} = \boldsymbol{\varphi K} + \boldsymbol{\varepsilon}_A \tag{16}$$

Expanding the Eq.(16), we have

$$\begin{bmatrix} S_{x1} - S_{xn1} \\ S_{x2} - S_{xn2} \\ \vdots \\ S_{x5} - S_{x5} \end{bmatrix} = \begin{bmatrix} 1 & t_1 & t_1^{\ 2} \\ 1 & t_2 & t_2^{\ 2} \\ & \vdots & \\ 1 & t_5 & t_5^{\ 2} \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_5 \end{bmatrix} \tag{17}$$

The least square estimation of b_2 is expressed as:

$$\boldsymbol{B} = \left[(\boldsymbol{\varphi}^{\mathrm{T}}\boldsymbol{\varphi})^{-1}\boldsymbol{\varphi}^{\mathrm{T}}(\boldsymbol{S}_x - \boldsymbol{S}_{xn})\right] \qquad \hat{b}_2 = \boldsymbol{B}(3,1) \tag{18}$$

The theoretical value of b_2 is the coefficient of t^2 term, which is

$$b_2 = \frac{1}{2}K_{II}\frac{R_0^{\ 2}\omega_0^{\ 4}}{g} - \frac{3}{4}K_I R_0\omega_0\omega_p \sin\phi + \frac{1}{2}K_F \cdot g \tag{19}$$

In the first time least squares identification, the results identified by determining the coefficients concerned t^2 term in the displacement errors include the centrifuge main axis angular rate error, which has a significant impact on the calibration accuracy of the second-order nonlinearity coefficient K_{II}. In the case of only one setting angular rate ω_0, K_{II}, ω_p and ϕ cannot separated, and at least three setting angular rates are required to separate these three parameters.

Perform the second time identification by separating the second-order coefficient K_{II} from the main axis angular rate error of the centrifuge, so that the main axis angular rate error doesn't affect the calibration accuracy of K_{II}.

Through three different angular rates exciting, three values of b_2 is obtained as follows:

$$b_2(\omega_1) = \frac{1}{2}K_{II}\frac{R_0^{\ 2}\omega_1^{\ 4}}{g} - \frac{3}{4}K_I R_0\omega_1\omega_p \sin\phi + \frac{1}{2}K_F \cdot g \tag{20}$$

$$b_2(\omega_2) = \frac{1}{2}K_{II}\frac{R_0^{\ 2}\omega_2^{\ 4}}{g} - \frac{3}{4}K_I R_0\omega_2\omega_p \sin\phi + \frac{1}{2}K_F \cdot g \tag{21}$$

$$b_2(\omega_3) = \frac{1}{2}K_{II}\frac{R_0^{\ 2}\omega_3^{\ 4}}{g} - \frac{3}{4}K_I R_0\omega_3\omega_p \sin\phi + \frac{1}{2}K_F \cdot g \tag{22}$$

The bias and the scale factor of the accelerometer in PINS have been calibrated in the gravity field and can be considered as known quantities in the centrifuge calibration environment.

K_{II}, $\omega_p \sin\phi$ will be identified using the least squares method. The observation matrix $\boldsymbol{B}$ is:

$$\boldsymbol{B} = \left[b_2(\omega_1) - \frac{1}{2}K_F \cdot g \quad b_2(\omega_2) - \frac{1}{2}K_F \cdot g \quad b_2(\omega_3) - \frac{1}{2}K_F \cdot g\right]^{\mathrm{T}} \tag{23}$$

The coefficient matrix $\boldsymbol{K}_2$ is:

$$\boldsymbol{K}_2 = \left[K_{II} \quad \omega_p \sin\phi\right]^{\mathrm{T}} \tag{24}$$

Written in matrix form:

$$\boldsymbol{B} = \boldsymbol{\varphi}_2\boldsymbol{K}_2 + \boldsymbol{\varepsilon}_B \tag{25}$$

Expanding the Eq.(25), we have

$$\begin{bmatrix} b_2(\omega_1)-\frac{1}{2}K_F\cdot g \\ b_2(\omega_2)-\frac{1}{2}K_F\cdot g \\ b_2(\omega_3)-\frac{1}{2}K_F\cdot g \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\frac{R_0^{\ 2}\omega_1^{\ 4}}{g} & -\frac{3}{4}K_I R_0\omega_1 \\ \frac{1}{2}\frac{R_0^{\ 2}\omega_2^{\ 4}}{g} & -\frac{3}{4}K_I R_0\omega_2 \\ \frac{1}{2}\frac{R_0^{\ 2}\omega_3^{\ 4}}{g} & -\frac{3}{4}K_I R_0\omega_3 \end{bmatrix} \begin{bmatrix} K_{II} \\ \omega_p\sin\phi \end{bmatrix} + \begin{bmatrix} \varepsilon_{b1} \\ \varepsilon_{b2} \\ \varepsilon_{b3} \end{bmatrix} \tag{26}$$

The least square estimate is:

$$[\begin{matrix} \hat{K}_{II} \\ \hat{\omega}_p\sin\hat{\phi} \end{matrix}] = \left[(\boldsymbol{\varphi}_2^{\ \mathrm{T}}\boldsymbol{\varphi}_2)^{-1}\boldsymbol{\varphi}_2^{\ \mathrm{T}}\boldsymbol{B}\right] \tag{27}$$

2.3 Analysis of factors affecting calibration accuracy

Error analysis is performed to illustrate the influence of the accuracy of the displacement output on calibrating K_{II} .

Set accelerometer simulation parameters as shown in Tab.1, and centrifuge simulation parameters as shown in Tab. 2.

Table1 the simulation parameters of accelerometer

Numble	Parameters	Set values
1	K_F	0.004g
2	K_I	1.001g/g
3	K_{II}	2×10^{-5}g/g^2
4	K_{III}	4×10^{-6}g/g^3
5	K_{IP}	6×10^{-6}g/g^2

Table2 the simulation parameters of centrifuge

Numble	Parameters	Set values
1	R_0	2.5m
2	$\frac{\omega_P}{\omega_0}$	5×10^{-7}
3	ϕ	30°

Taking the displacement outputs of 100 moments as observables,

s.t. $\omega_0 t = \frac{\pi}{2} + 2k\pi \quad k = (1,2,\text{L} \ ,100)$

Set the standard deviation $\sigma_{\Delta S_x} = 0.01\text{m}$ for the ground computer displacement output of the PINS at these sampling moments, with the displacement expression at each moment t_n as:

$$S_{xz}(t_n) = S_x(t_n) + \Delta S_x(t_n) \tag{28}$$

The nominal displacement S_{xn} is subtracted simultaneously on both sides of the formula:

$$(S_{xz} - S_{xn})(t_n) = (S_x - S_{xn})(t_n) + \Delta S_x(t_n) \tag{29}$$

Written in matrix form:

$$\boldsymbol{S}_{xz} - \boldsymbol{S}_{xn} = \boldsymbol{S}_x - \boldsymbol{S}_{xn} + \boldsymbol{\varepsilon}_A \tag{30}$$

where, $\boldsymbol{\varepsilon}_A = \left[\Delta S_x(t_1) \quad \Delta S_x(t_2) \quad \text{L} \quad \Delta S_x(t_{100})\right]^{\mathrm{T}}$.

According to Eq.(16), let $(\boldsymbol{\varphi}^{\mathrm{T}}\boldsymbol{\varphi})^{-1}\boldsymbol{\varphi}^{\mathrm{T}} = \boldsymbol{P}$, the measurement uncertainties for the individual error model coefficients can be obtained, where the measurement uncertainties for b_2 are:

$$\sigma(b_2)=\sqrt{\frac{\boldsymbol{\varepsilon}_A{}^T\boldsymbol{\varepsilon}_A}{n-3}}\cdot\sqrt{\boldsymbol{p}_{31}{}^2+\boldsymbol{p}_{32}{}^2+\cdots+\boldsymbol{p}_{3n}{}^2},n=100 \tag{31}$$

After calculation, if $\omega=\omega_1=\frac{\pi}{2}\text{rad/s}$, then $\sigma(b_2(\omega_1))=6.6220\times10^{-5}g^2$; if $\omega=\omega_2=\pi\text{rad/s}$, then $\sigma(b_2(\omega_2))=6.5837\times10^{-5}g^2$; if $\omega=\omega_3=2\pi\text{rad/s}$, then $\sigma(b_2(\omega_3))=6.6725\times10^{-5}g^2$.

Let's define:

$x_1=b_2(\omega_1)-\frac{1}{2}K_F\cdot g$, $x_2=b_2(\omega_2)-\frac{1}{2}K_F\cdot g$, $x_3=b_2(\omega_3)-\frac{1}{2}K_F\cdot g$

Owing to the constant value of $-\frac{1}{2}K_F\cdot g$, so 3 following formulae hold true:

$\sigma_{x_1}=\sigma(b_2(\omega_1))$, $\sigma_{x_2}=\sigma(b_2(\omega_2))$, $\sigma_{x_3}=\sigma(b_2(\omega_3))$.

Eq.(26) is written as:

$$\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}=\begin{bmatrix}\frac{1}{2}\frac{R_0{}^2\omega_1{}^4}{g} & -\frac{3}{4}K_IR_0\omega_1\\ \frac{1}{2}\frac{R_0{}^2\omega_2{}^4}{g} & -\frac{3}{4}K_IR_0\omega_2\\ \frac{1}{2}\frac{R_0{}^2\omega_3{}^4}{g} & -\frac{3}{4}K_IR_0\omega_3\end{bmatrix}\begin{bmatrix}K_{II}\\ \omega_p\sin\phi\end{bmatrix}+\begin{bmatrix}\varepsilon_{b1}\\ \varepsilon_{b2}\\ \varepsilon_{b3}\end{bmatrix} \tag{32}$$

According to the result of identification $\hat{K}_{II}=\left[(\boldsymbol{\varphi}_2{}^T\boldsymbol{\varphi}_2)^{-1}\boldsymbol{\varphi}_2{}^T\boldsymbol{B}\right]_1$, let $\boldsymbol{Q}=(\boldsymbol{\varphi}_2{}^T\boldsymbol{\varphi}_2)^{-1}\boldsymbol{\varphi}_2{}^T$, then we have

$$\hat{K}_{II}=\boldsymbol{Q}(1,1)x_1+\boldsymbol{Q}(1,2)x_2+\boldsymbol{Q}(1,3)x_3 \tag{33}$$

According to the principle of independence of errors, the measurement uncertainties of K_{II} is:

$$\sigma(K_{II})=\sqrt{(\frac{\partial\hat{K}_{II}}{\partial x_1}\sigma_{x_1})^2+(\frac{\partial\hat{K}_{II}}{\partial x_2}\sigma_{x_2})^2+(\frac{\partial\hat{K}_{II}}{\partial x_3}\sigma_{x_3})^2} \tag{34}$$

After calculation, $\sigma(K_{II})=3.0362\times10^{-7}g/g^2$.

3. Summary

This paper proposes the second-order coefficient calibration method of accelerometer in PINS tested on double turntable centrifuge, which makes use of the double turntable centrifuge to excite high g harmonic acceleration environment so that the second-order error term achieve a high level of confidence in the process of calibrating. The displacement errors output of the PINS are set as observables, and the second-order coefficient is identified by least squares method. The centrifuge errors are eliminated by separating the second-order coefficient of accelerometer and the angular rate error of the centrifuge form the output displacement errors of the PINS's. Finally, simulation results proved that the measurement uncertainties of K_{II} are less than $5\times10^{-7}g/g^2$, while the displacement errors of PINS being less than 0.01m.

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