# Error Analysis and Reduction for Shearer Positioning using the Strapdown Inertial Navigation System

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**Abstract**

Shearer dynamic positioning is a key factor for coal mine equipment automation, and it is feasible to shearer positioning using the strapdown inertial navigation system(SINS). Yet, it is very difficult to guarantee positioning accuracy by error influence. This paper provided a method for shearer positioning error analysis. Firstly, we built the shearer state equation and put forward a method called quaternion method rule. This method can deduce misalignment angle of the shearer Inertial Navigation System. Secondly, we considered the initial alignment error of INS is the main system error, the nonlinear Extended Kalman Filter (EKF) is proposed to estimate and adjust the misalignment angles, as well as the shearer velocity. Shearer dynamic positioning accuracy is guaranteed by precise and fast alignment of the INS. Based on the shearer state equation; this paper derived the observation equation. Finally, we simulated the initial alignments process which contains the observation equation and initial condition, and did experiment using ADIS16350. Results show misalignment angles model and EKF is feasible for initial alignments of INS in shearer positioning.

***Keywords:*** *Shearer, Initial Alignment, Inertial Navigation System(INS), Extended Kalman Filter(EKF)*

## 1. Introduction

With the development of coal mine exploitation and importance improvement of coal mine safety, it is a tendency to achieve man-less exploitation [1]. Mechanization and automation of the underground mining equipment (the shearer, the hydraulic support and the scraper conveyor) is a necessary [2]. The shearer dynamic position determines the hydraulic support automation [3], [4]. This paper mainly discuss the strategy of shearer dynamic positioning.

As shown in Fig.1, the shearer walks on the flexible scraper conveyor and cuts the coal; the hydraulic support supports the roof and the coal wall. The hydraulic support begins pushing when the shearer moves from the left to the right, at the distance of D from the end of the shearer. The shearer position is described by D.

Using INS for shearer dynamic positioning is workable for its autonomy and reliability [5]. The principle is: the shearer precise velocity and location is derived from the shearer inertial parameters by the shearer attitude algorithm and the integral operation. The shearer inertial parameters are achieved by the acceleration sensor and the angular velocity sensor. As shown in Fig.2, the INS module is set inside the shearer, which contains three accelerometers and three gyroscopes. The three accelerometers output the linear accelerations of the three axis, which are ax、ay and az, respectively. The three gyroscopes output the angular velocities, which are p, q and r.

INS accuracy is a key for shearer position accuracy, and it has many factors such as the shearer complex working condition. To sum up, we have revealed four system error sources.

1) Sensor drifts of the INS acceleration sensor and the angular velocity sensor makes output error [6];

2) Shearer complex working condition such as the random vibration causes acceleration and angular velocity output error;

3) In the attitude calculation, truncation error brought about by numerical integration causes output error;

4) Initial alignment error between the coordinate axes of the INS and the reference axes [7-10].

We reveal that the initial alignment error is the main error of the system. Initial alignment includes coarse initial alignment and precise adjustment. Coarse initial alignment gives the rough strap down matrix while precise adjustment establishes the accuracy strap down matrix. Furthermore, we find out the inertia sensitive element output before precisely adjust misalignment angle to zero, because the misalignment angle determines the precise strap down matrix. This paper uses nonlinear filter in the initial alignment on the basis of shearer misalignment angle, to achieve shearer precise position.

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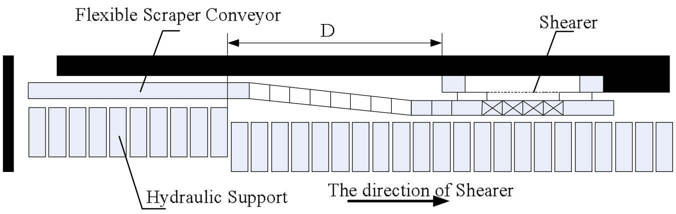


Fig.1 The three machines on the fully mechanized coal face

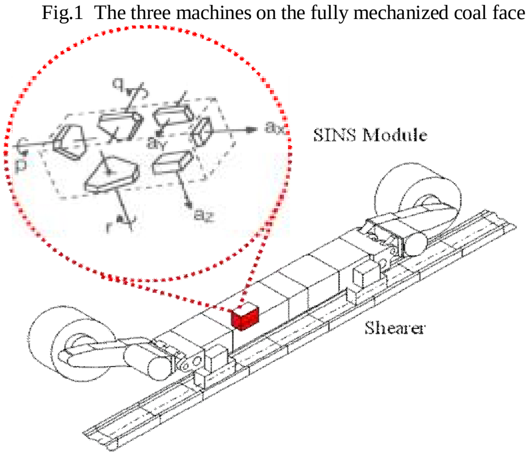


Fig. 2 The shearer SINS positioning system schematic diagram

## 2. Principle of INS initial alignments on shearer positioning

On the basis of the shearer position system error equation, the shearer state equation is established to estimate the misalignment angle value. We calculate the direction cosine between the mathematic axes and the real geographic axes when the misalignment angle value is zero. Then we revise the INS attitude matrix for alignment. If the misalignment angle value is not zero, we carry on error compensation of the accelerometer and the accelerometer output. By updating the INS attitude matrix, we revaluate the misalignment angle value. The principle is shown in Fig.3.

The INS simulates the geographic coordinate by substituting the mathematic platform for the hardware platform. The quaternion method is applied to calculate the output of the inertia device. Because the output of the inertia device is under the carrier coordinate (called *b* coordinate), we firstly transform it in the geographic coordinate.

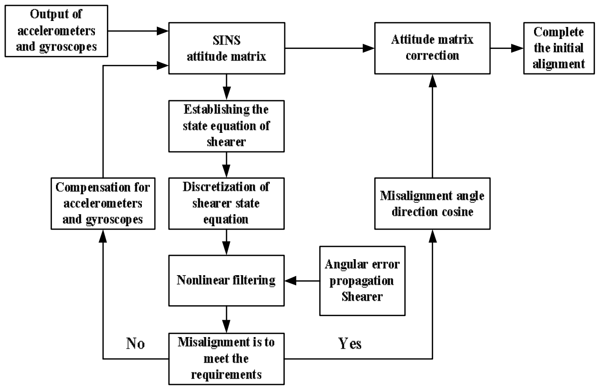


Fig.3 The error analysis and compensation scheme of the shearer SINS

Generally, the quaternion differential equation is shown as [11]:

$$\dot{q} = \frac{1}{2} q w_b^b \tag{1}$$

Where $q$ is the quaternion, which is rotation of the carried coordinate to the geographic coordinate. $\omega_b^b$ is the shearer angular velocity in the carried coordinate.

The accurate value of shearer attitude matrix in the geographic coordinate is shown as:

$$Q_E = q Q_b q^{-1} \tag{2}$$

Where $Q_E$ is the accurate value of shearer attitude matrix in the geographic coordinate. $Q_b$ is the accurate value of shearer attitude matrix in the carried coordinate.

Considering calculation error of the quaternion, then:

$$Q_E{}' = q_C Q_b q_C{}^{-1} \tag{3}$$

Where: $Q'_E$ is the amended accurate value of shearer attitude matrix in the geographic coordinate. $q_C$ is the calculation error.

Combining formula (2) with formula (3), $Q_E$ could be calculated through the following formula:

$$Q_E = q q_C{}^{-1} Q_E{}' q_C q^{-1} \tag{4}$$

We define $dq$ as the rolling quaternion between $Q_E$ and $Q'_E$:

$$dq = q q_C{}^{-1} \tag{5}$$

Then

$$d\dot{q} = \dot{q} q_C^{-1} + q \dot{q}_C^{-1} \tag{6}$$

The differential equation of rolling quaternion is [12]:

$$\dot{q} = \frac{1}{2} q (w_{ib}^b - w_{iE}^b) \tag{7}$$

Where $\omega_{ib}^b$ is angular velocity of the carrier coordinate relative to the inertia reference coordinate; $\omega_{iE}^b$ is angular velocity of the geographic coordinate relative to the inertia reference coordinate.

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Similarly, the calculation error differential equation of rolling quaternion:

$$\dot{q}_C = \frac{1}{2} q_C (w^b_{ibm} - w^b_{iEC}) \quad (8)$$

Where: $\omega^b_{ibm}$ is error angular velocity of the carrier coordinate relative to the inertia reference coordinate; $\omega^b_{iEC}$ is error angular velocity of the geographic coordinate relative to the inertia reference coordinate.

Combining the formula (7) and formula (8):

$$\begin{aligned} d\dot{q} &= \frac{1}{2} q (w^b_{ib} - w^b_{iE}) q_C^{-1} + \frac{1}{2} q(-w^b_{ibm} + w^b_{iEC}) q_C^{-1} \\ &= \frac{1}{2} dw^E_{ib} dq - \frac{1}{2} w^E_{iE} dq + \frac{1}{2} dq w^E_{iEC} \end{aligned}$$

(9)

As misalignment angle matrix on the mathematic platform is:

$$\dot{\Phi} = [\dot{\alpha} \quad \dot{\beta} \quad \dot{\gamma}]^T$$

(10)

Where $\dot{\alpha}$, $\dot{\beta}$ and $\dot{\gamma}$ are Euler angles of the shearer in the three axis.

As:

$$\begin{cases} dq = \cos\frac{\Phi}{2} + \sin\frac{\Phi}{2} \cdot \frac{\boldsymbol{\Phi}}{\Phi_0} = 1 + \frac{\Phi}{2} \\ d\dot{q} = \frac{\dot{\boldsymbol{\Phi}}}{2} \end{cases} \quad (11)$$

Replacing formula (9) by formula (11), ignoring the second-order term:

$$\dot{\boldsymbol{\Phi}} = dw^E_{ib} + dw^E_{iE} - w^E_{iE} \times \boldsymbol{\Phi}$$

(12)

Given the shearer northern velocity $V_N$, the shearer eastern velocity $V_E$, the shearer eastern velocity $dV_E$, the latitude $\varphi$, the latitude error $d\varphi$, the earth radius $R$ then $\omega^E_{iE}$ and $d\omega^E_{iE}$ in formula (12) could be calculated:

$$\begin{cases} \boldsymbol{\omega}^E_{iE} = \begin{bmatrix} -\frac{V_N}{R} \\ \frac{V_E}{R} + w_e \cos\varphi \\ \frac{V_E}{R} tg\varphi + w_e \sin\varphi \end{bmatrix} \\ \boldsymbol{\delta\omega}^E_{iE} = \begin{bmatrix} -\frac{dV_N}{R} \\ \frac{dV_E}{R} - w_e \sin\varphi d\varphi \\ \frac{dV_E}{R} tg\varphi + \frac{V_E}{R} \sec^2\varphi d\varphi + w_e \cos\varphi d\varphi \end{bmatrix} \end{cases} \quad (13)$$

Adding random error from NEU coordinates:

$$\Delta\varepsilon = [\varepsilon_E \quad \varepsilon_N \quad \varepsilon_z]^T$$

(14)

Misalignment angles of the shearer in the three axes are :

$$\begin{cases} \dot{\alpha} = -\frac{V_N}{R} + (\frac{V_E}{R} tg\varphi + w_e \sin\varphi)\beta - (\frac{V_E}{R} + w_e \cos\varphi)\gamma + \varepsilon_E \\ \dot{\beta} = \frac{dV_E}{R} - w_e \sin\varphi - (\frac{V_E}{R} tg\varphi + w_e \sin\varphi)\alpha - \frac{V_N}{R}\gamma + \varepsilon_N \\ \dot{\gamma} = \frac{dV_E}{R} tg\varphi + (\frac{V_E}{R} \sec^2\varphi + w_e \cos\varphi) d\varphi + (\frac{V_E}{R} + w_e \cos\varphi)\alpha \\ \quad + \frac{V_N}{R}\beta + \varepsilon_z \end{cases}$$

(15)

Misalignment angles in formula (15) have random noise which could not be expressed by equation, next we use nonlinear filter to estimate the misalignment angles, in order to improve system accuracy.

## 3. Nonlinear filter of the shearer inertial navigation system

Gyroscope error is a parameter regarded as the constant migration plus white noise with a short alignment period [13], state estimation model of initial alignments of inertial navigation system on shearer could be modeled by Extended Kalman Filter [14], the shearer state equation is:

$$\begin{aligned} \dot{\boldsymbol{X}}(t) &= \boldsymbol{AX}(t) + \boldsymbol{g}(t) + \boldsymbol{BW}(t) \\ &= \begin{pmatrix} A_1 & A_2 \\ 0_{5\times5} & 0_{3\times3} \end{pmatrix} \boldsymbol{X}(t) + \boldsymbol{g}(t) + \begin{pmatrix} A_2 \\ 0_{3\times3} \end{pmatrix} \boldsymbol{W}(t) \end{aligned} \quad (16)$$

Where:

$\boldsymbol{X}(t)$ is the system state vector,

$\boldsymbol{A}$ is state transition matrix,

$\boldsymbol{g}(t)$ is zero drift of the accelerometer and the gyroscope,

$\boldsymbol{W}(t)$ is system procession noise sequence,

$\boldsymbol{B}$ is noise input matrix.

And:

$$\boldsymbol{A} = (dV_E, dV_N, \dot{\alpha}, \dot{\beta}, \dot{\gamma}, \varepsilon_E, \varepsilon_N, \varepsilon_z)^T \quad (17)$$

$$\boldsymbol{W} = (w_{gx}, w_{gy}, w_{gz})$$

(18)

As spin velocity of the earth in the NEU coordinates is:

$$\boldsymbol{\omega} = [w_E, w_N, w_U]^T$$

(19)

Within the static base, $A_1$, $A_2$ and $g(t)$ in formula (16) are:


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$$A_1 = \begin{pmatrix} 0 & 2w_U & 0 & -g & 0 \\ -2w_U & 0 & g & 0 & 0 \\ 0 & -\frac{1}{R} & 0 & w_U & 0 \\ \frac{1}{R} & 0 & w_U & 0 & 0 \\ \frac{\tan j}{R} & 0 & 0 & 0 & 0 \end{pmatrix} \quad A_2 = \begin{pmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{pmatrix}$$

$$g(t) = \begin{pmatrix} 0 \\ 0 \\ -w_N \sin\hat{g} \\ w_N(1-\cos\hat{g}) \\ -w_N(\hat{b}\times\sin\hat{g} - \hat{a}\times\cos\hat{g}) \\ 0_{5\times1} \end{pmatrix}$$

(20)

Using the Taylor series expansion method, and ignoring orders above the second term, state equation of EKF is:

$$Z_k = H_k X_k + V_k = (I_{2\times2} \;\; 0_{2\times6}) X_k + V_k$$

(21)

Where $V_k$ is observation noise sequence.

Recurrence formulas of EKF are [15], [16]:

1. System state prediction: $\hat{X}_{k,k-1} = A_{k,k-1} X_{k-1}$
2. System state estimation:
$$\hat{X}_k = \hat{X}_{k,k-1} + K_k[Z_k - H_k \hat{X}_{k,k-1}]$$
3. EKF filtering gain matrix: $K_k = P_k H_k^T R_k^{-1}$
4. Covariance matrix of one-step prediction error:
$$P_{k,k-1} = \Phi_{k,k-1} P_{k-1} \Phi_{k,k-1}^T + \Gamma_{k,k-1} Q_{k-1} \Gamma_{k,k-1}^T$$
5. Covariance matrix of estimated error:
$$P_k = [I - K_k H_k] P_{k,k-1}$$

Given initial value $\hat{X}_0$ and $P_0$, state estimation of the shearer at time $k$ is deduced by observation value $Z_k$.

## 4. Simulation analysis

Based on error transmission model of shearer inertial navigation system, we apply EKF for on-line filtering in rapid initial alignment. Giving initial values of shearer inertial navigation system are:

Spin velocity of the earth is $\omega$=7.2916×10$^{-5}$ rad/s, acceleration of gravity is $g$=9.84m/s$^2$, initial deviation of the accelerometer is $ac$=9.84×10$^{-4}$ m/s$^2$, and the random drift is $ar$=4.92×10$^{-4}$m/s$^2$, initial deviation of the gyroscope is $pc$=0.02deg, and the random drift is $pr$=0.01deg, the latitude is $\varphi$=45deg, Speed measurement noise is $vr$=0.05m/s.

Initial condition of EKF is: state estimated initial value is zero, state initial value is $\hat{X}_0$ =(0.1,0.1,1deg,1deg,1deg, 0,0,0), system initial noise covariance matrix is $Q(0)=(ar^2, ar^2, pr^2, pr^2, pr^2$,0,0,0),system initial covariance matrix is $P(0)=(0.1^2, 0.1^2, (1deg)^2, (1deg)^2, (1deg)^2$, 0,0,0),results of initial alignments of shearer inertial navigation system are shown in Fig.4, Fig.5, Fig.6.

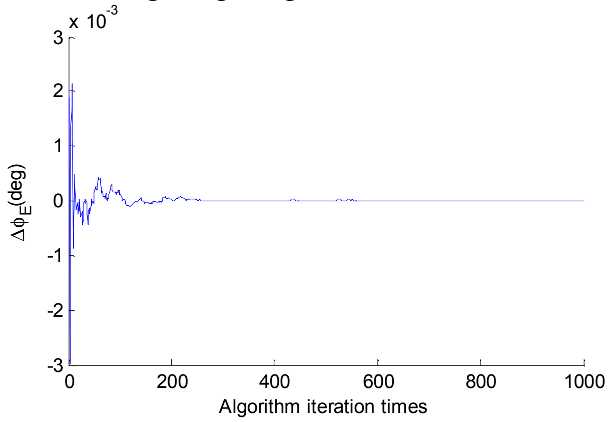

Fig. 4 Aligning simulation of shearer eastern misalignment angle

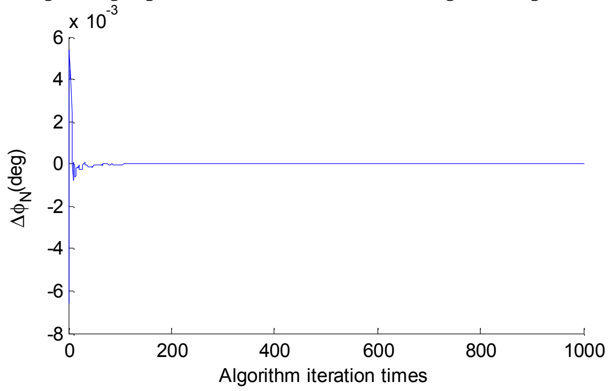

Fig.5 Aligning simulation of shearer northern misalignment angle

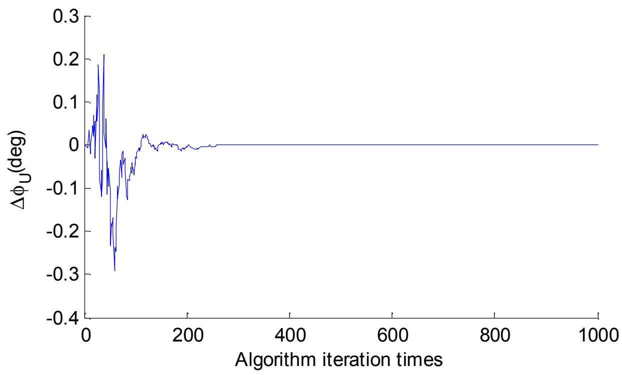

Fig.6 Aligning simulation of shearer up direction misalignment angle

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## 5. Experimental researches

As shown in Fig.7 and Fig.8, CleverNavi type SINS is used in the experiment, which includes six degree freedom IMU ADIS16350. ADIS16350 is made up of a triaxial accelerometer and a triaxial gyroscopes. This type of the SINS has been used for unmanned aerial vehicle and automatic car driving successfully. Triaxial acceleration sensor outputs $a_E^b$, $a_N^b$ and $a_U^b$ in three axes. Meanwhile, Triaxial gyroscope is used to obtain $\omega_E^b$ and $\omega_N^b$ and $\omega_U^b$.

Other configurations are as follows: processor is TMS320C6713, which is a DSP chip with high performance. TMS320C6713 data read from ADIS16350 by SPI Interface. Data transmission uses serial communication and the baud rate is 115200 bit/s, the sampling period is 0.01s.

Fixed northern reference precision is 10", testing latitude is 34.316°, latitude accuracy is not less than 1', $g$=9.795207 m/s$^2$, gravitational acceleration accuracy is not less than 2×10-5 g.

In Fig.9, Fig.10, and Fig.11, we respectively show the aligning procession of the shearer attitude angles.and the initial attitude angles are:

The pitching angle: $\alpha$=-0.0474°

The roll angle: $\beta$=-0.008°

The yawing angle: $\gamma$=-0.0398°

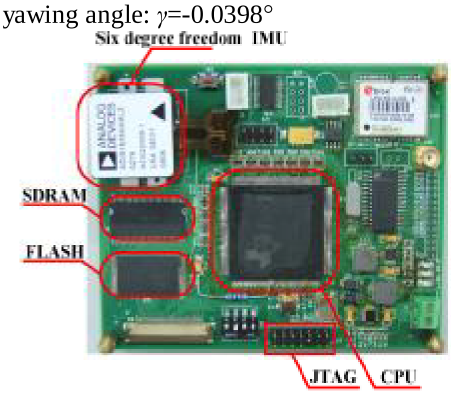


Fig.7 SINS used in the experiment

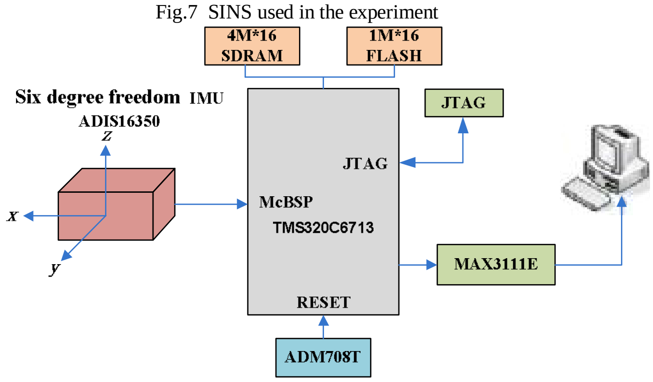


Fig.8 SINS hardware diagram

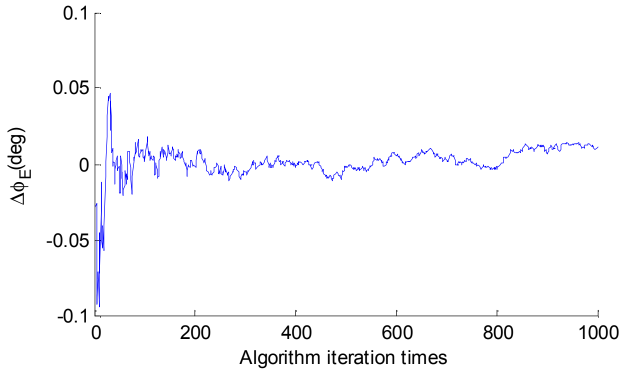


Fig. 9 Aligning procession of shearer eastern misalignment angle

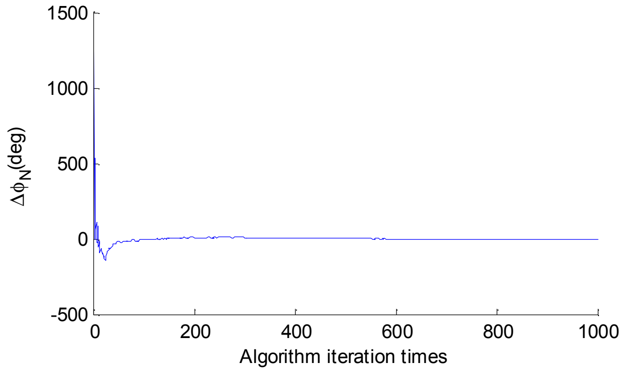


Fig. 10 Aligning procession of shearer northern misalignment angle

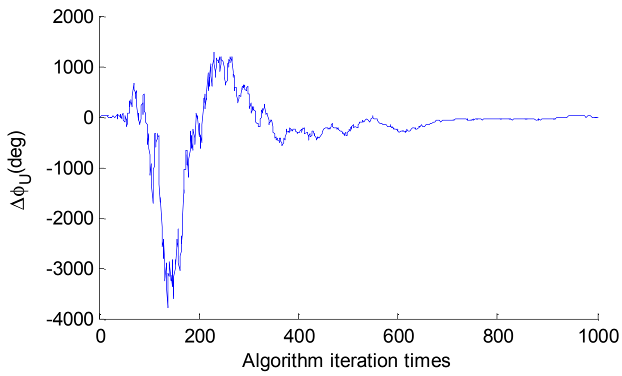


Fig.11 The pitch angle tracking used SINS module

## 6. Conclusion

(1) It is feasible to apply inertial navigation in the coal mine for shearer positioning in the three-dimensional space. We built error transmission model based on error source research. As the inertial navigation initial aligning error constructs the major factor, we also applied EKF for on-line filtering in rapid initial alignment.

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(2) EKF filtering satisfies accuracy and rapidity of the shearer position system. we can achieve misalignment angle alignment in 200 seconds.

This paper mainly researched error source and compensation scheme of the inertial navigation system in the shearer position. Research achievement will be made use of improving coal mining machine automation level.

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