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Gyrocompass Alignment Method of Sins Based on Kalman Filtering Pretreatment and Dynamic Gain Adjustment on a Rocking Base

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Abstract: Land combat vehicles are inevitably subject to the vibration disturbance by wind gust or engine idling, etc. in the stationary initial alignment process of the Strapdown Inertial Navigation System (SINS). Obviously, it's necessary to consider the impact of vibration disturbance during the alignment process to achieve better performance. In order to guarantee the alignment accuracy on the rocking base and shorten the convergence time of alignment, a gyrocompass alignment method of SINS based on Kalman filter pretreatment and dynamic gain adjustment was proposed. The output of gyros and accelerometers was firstly pre-filtered by Kalman filter to remove the impact of high-frequency small-amplitude rocking interference. The low-frequency large-amplitude rocking interference on vehicle was tracked through dynamic gain adjustment of gyrocompass alignment. The vehicle test of a ring laser SINS showed that the new gyrocompass alignment method can suppress high-frequency disturbances when the vehicle underwent low-frequency large-amplitude rocking interference. And the alignment process can track the attitude change of vehicle caused by low-frequency large-amplitude rocking interference. Comparing with traditional gyrocompass alignment algorithm and Kalman filter alignment method, the performance of the new gyrocompass alignment method is much improved by filtering random noise caused by vibration disturbance of vehicle effectively.

Key words: Strapdown inertial navigation system, vibration disturbance, gyrocompass alignment, dynamic gain adjustment, Kalman filter

INTRODUCTION

Initial alignment is a very important process for Strapdown Inertial Navigation System (SINS). The alignment result contains the initial value of attitude, velocity and position updated by the later navigation mode (Song *et al.*, 2010). As a result, the alignment performance can directly affect the navigation accuracy of the SINS. For those navigation systems that need to achieve the positioning accuracy less than 1 nmile h^{-1}, alignment with high accuracy is extremely necessary to guarantee the longtime positioning performance (Britting, 2010).

As is known that land combat vehicles equipped with SINS almost use the initial alignment method requiring stationary base for better result, it is inevitable for vehicles to undergo various rocking interference caused by wind gust, engine idling, cargo loading and unloading and so on (Jiang, 1998). Considering that the earth rotation rate is a little number and even tiny rocking of vehicle can lead to serious interference on stationary base, the alignment process must find effective method to eliminate the impact of interference (Qin *et al.*, 2010).

Initial alignment on stationary base can be summed into two kinds of techniques, with one kind the Kalman filter alignment algorithm and the other gyrocompass alignment method (Qin *et al.*, 2008). The Kalman filter alignment algorithm deals with error model of SINS and it's very sensitive to the rocking interference. The gyrocompass alignment method has low-pass filtering characteristics and it can suppress other disturbance by adjusting specific controlling parameters (Chen and Cheng, 2007; Li *et al.*, 2005). This alignment method has good robustness to the rocking interference but compared with the former algorithm, it always costs much more time to finish the alignment process.

In order to maintain the alignment accuracy and shorten the convergence time of alignment on the rocking base, the study results in a new gyrocompass alignment method of SINS, which uses a Kalman filter to remove the noise in output of inertial instruments and dynamically tuned gain parameters of gyrocompass alignment loops to

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track the rocking movement of vehicle. A test of the new alignment method is conducted on a land vehicle equipped with a ring laser SINS and better performance is acquired compared with the Kalman filter alignment algorithm and conventional gyrocompass alignment method (Chen and Cheng, 2007; Li *et al.*, 2005).

GYROCOMPASS ALIGNMENT

The gyrocompass alignment of SINS contains two processes: analytical coarse alignment and fine alignment. The rude initial attitude can be achieved through the analytical coarse alignment process. And the attitude errors could be modified by proportional plus derivative (PID) feedback control during fine alignment period.

Analytical coarse alignment: When SINS is on a stationary base, the output of gyros and accelerometers has a relationship with computed earth rotation rate and gravity vector as follows (ignoring various disturbances):

$$-f^b = C_n^b g^n$$
$$\omega_{ib}^b = C_n^b \omega_{ie}^n \tag{1}$$

where, C_b^n is the transformation matrix from body frame (b) to navigation coordinate (n), also called attitude matrix; ω_{ie}^n is the earth rotation rate projected to n frame; g^n is the gravity vector projected to n frame; It is known that:

$$g^n = [0\ 0\text{-}g]^T,\ \omega_{ie}^n = [0\ \omega_{ie}\cos L\ \omega_{ie}\sin L]^T \tag{2}$$

where, L is the local latitude. The attitude matrix C_b^n can be computed through the next equation:

$$C_b^n = \begin{bmatrix} (g^n)^T \\ (g^n \times \omega_{ie}^n)^T \\ (g^n \times \omega_{ie}^n \times g^n)^T \end{bmatrix}^{-1} \begin{bmatrix} (-f^b)^T \\ (-f^b \times \omega_{ib}^b)^T \\ (f^b \times \omega_{ib}^b \times f^b)^T \end{bmatrix} \tag{3}$$

where f^b is the measured specific force and ω_{ib}^b is the gyro output.

Actually the output of gyros and accelerometers contains random noise because of various vibration disturbances. It is necessary that averaging instruments' output and orthogonalization of attitude matrix should be conducted for coarse alignment to improve accuracy. This kind of analytical coarse alignment method can reach limited alignment accuracy on a stationary base (Hou *et al.*, 2005; Zhou *et al.*, 2004).

Gyrocompass fine alignment: During the fine alignment period, misalignment angles of initial attitude matrix are firstly computed based on the output of both eastern accelerometer and northern accelerometer. Then misalignment angles are weighted to form the PID feedback command signal, which is continuously used for attitude matrix calibration, until misalignment angles diminish to zero. And like that, the horizontal leveling and heading alignment are finished. The gyrocompass fine alignment process is described in Fig. 1, where, (ϕ, θ, γ) represents (head, pitch, roll), C_b^n is attitude matrix, fi (i = e, n) is specific force projected in axis Q_b^n, is attitude quaternion, ω_b^n represents earth rotation rate and K_{ij}(i = e, n, c; j = 1, 2) is gain adjustment parameter. In Fig. 1, the second order leveling loop is used to both eastern and northern loop. The heading alignment is conducted by a fourth order alignment loop, which results from the modification of second order northern horizontal leveling loop.
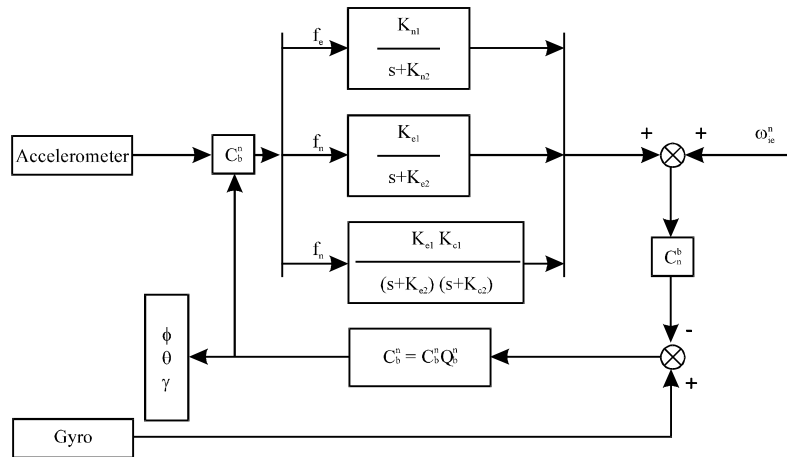

Fig. 1: Block diagram of traditional strapdown gyrocompass alignment

The gain adjustment parameters in the figure are K_{ij} (i = e, n, c; j = 1, 2). The natural oscillation frequency of loop can be increased by appropriately selecting K_{i1} (i = e, n, c) and the damping ratio of loop can be amplified by choosing K_{i2} (i = e, n, c). Although, high natural oscillation frequency can shorten the whole alignment time and strengthen the capability to track attitude change of vehicle, it is inevitable to increase the overshoot of system. And increasing the damping ratio can reduce overshoot, while tuning time is also increased, which means that the whole alignment time also rises up. In a word, the selection of K_{i1} (I = e, n, c) and K_{i2} (i = e, n, c) is a conflicted process with each other. Generally, the gyrocompass alignment method always chooses large damping ratio and small natural oscillation frequency to improve accuracy, which directly results in a very long time to finish alignment when vehicle undergoes rocking interference (Grewal *et al.*, 2007; Groves, 2008).

DYNAMIC GAIN ADJUSTMENT AND KALMAN FILTER PRETREATMENT

Dynamic gain adjustment: In order to track the attitude change of vehicle in time and suppress noise, a new method to dynamically adjust gain parameters of gyrocompass alignment loops is proposed based on the time change of alignment process. By adjusting gain parameters dynamically, the alignment error caused by vibration disturbances can be significantly reduced, Fig. 2, shows where K_r and f(t) represent dynamic gain adjusting parameter.

The dynamic gain adjusting parameter K_r in Fig. 2 is:

$$K_r = f(t) = \begin{cases} 1 + \dfrac{k-1}{t_1} \cdot t & 0 < t \le t_1 \\ k & 1 \le k \le 1.5 \end{cases} \qquad (4)$$

where, t_1 is the dynamic gain adjusting time, $t_1 \in$ (0, align_time].

From above, it's easy to find that the gyrocompass alignment using dynamic gain adjustment will change into traditional gyrocompass alignment process when k is set as k = 1. Different alignment results can be achieved by choosing different value of t_1 and k, as illustrated in Fig. 3. The Fig. 3 shows that the transition time of alignment process can be reduced through increasing the value of k but the negative effect accompanied is the lightly fluctuating stable process.

Kalman filter pretreatment: It is known that traditional FIR filter and IIR filter cannot acquire efficient results when the signal is corrupted by low frequency interference (Titterton and Weston, 2005), because the two filters both suppose that the signal wanted and the signal to be removed have different frequency band. The filters cannot distinguish whether the signal is useful or not and obviously leads to bad filtering result.

Kalman filter is good at suppressing the impact of low frequency because of its known variable damping characteristic and usually converges as fast as about 100 sec. The initial alignment is conducted on a stationary base (i.e., a rocking base), the random drift of gyros and accelerometers can be supposed as a first order autoregressive (AR(1)) process. Then Kalman filter can be used to pre-filter the output of inertial instruments under
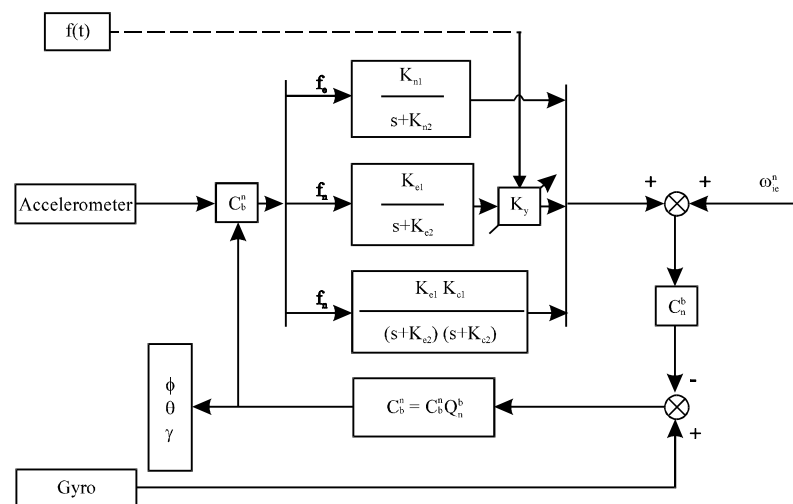

Fig. 2: Block diagram of strapdown gyrocompass alignment based on dynamic gain adjustment
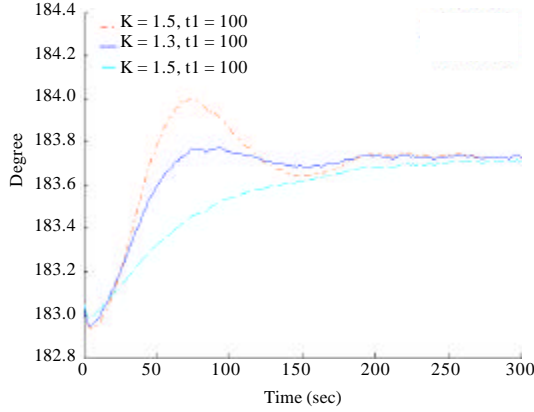
Fig. 3: Yaw curve of strapdown gyrocompass alignment under different gain adjustment parameters

the assumption that system noise is colored and measurement noise is white and then the gyrocompass alignment process starts.

It is supposed that random drift of gyros and accelerometers are set as follows:

$$\omega_i\,(k) = \varphi_i \omega_i\,(k\text{-}1)\text{-}a_1\,(k) \qquad (5)$$

$$f_i\,(k) = \phi_i f_i\,(k\text{-}1)\text{-}b_1\,(k) \qquad (6)$$

where, i represents body axis, i (i = x, y, z), ω_i (k-1) and ω_i (k) are outputs of gyro i at time t_{k-1} and t_k, f_i (k-1) and f_i(k) are outputs of accelerometer I at time t_{k-1} and t_k, φ_i and ϕ_i are regression coefficients of gyro i and accelerometer i, respectively, a_i (k) and b_i(k) are white noises of gyro and accelerometer with zero mean and variances to be $\delta^2_{\omega i}$ and δ^2_{fi}. The regression coefficients φ_i and ϕ_i can be acquired by least square estimation method and timing series analysis of inertial instruments' output.

By selecting the system state as:

$$X\,(k) = [\omega_x\,(k),\,\omega_y\,(k),\,\omega_z\,(k),\,f_x\,(k),\,f_y\,(k),\,f_z\,(k)]^T \quad (7)$$

And the process noise is:

$$W\,(k) = [a_x\,(k),\,a_y\,(k),\,a_z\,(k),\,b_x\,(k),\,b_y\,(k),\,b_z\,(k)]^T$$

The state equation and observation equation can be summarized as follows:

$$X\,(k) = FX\,(k\text{-}1)+GW\,(k) \qquad (8)$$

$$Z\,(k) = HX\,(k)+V\,(k) \qquad (9)$$

where, the transition matrix $F = \text{diag}\,[\varphi_x,\,\varphi_y,\,\varphi_z,\,\varphi_x,\,\varphi_y,\,\varphi_x]$, the interference matrix $G = -I_6$, the measurement matrix $H = I_6$, I_6 is a six-order unit matrix.

The process noise W (k) and measurement noise V (k) are assumed to be unrelated sequences which hold the statistical properties as follows:

- The means: E (W (k)) = 0, E (V (k)) = 0
- Autocorrelation function: γ_{ww} (k, j) = $Q\delta_{kj}$, γ_{vv} (k,j) = $R\delta_{kj}$
- Cross-correlation function: γ_{wv} (k, j) = 0

where, R is variance of observation noise, Q is variance of process noise and $Q = \text{diag}\,[\delta^2_{\omega x},\,\delta^2_{\omega y},\,\delta^2_{\omega z},\,\delta^2_{fx},\,\delta^2_{fy},\,\delta^2_{fz}]$.

The Kalman filter algorithm can be separated into two parts: time updating and measurement updating. The time updating equations are as follows:

$$\hat{X}_k^- = F\hat{X}_{k-1} \qquad (10)$$

$$P_k^- = FP_{k-1}F^T+Q \qquad (11)$$

The measurement updating equations are as follows:

$$K_k = P_k^- H^T\,(HP_k^- H^T+R)^{-1} \qquad (12)$$

$$\hat{X}_k = \hat{X}_k^- + K_k\left(Z_k - H\hat{X}_k^-\right) \qquad (13)$$

$$P_k = (I\text{-}K_k H)P_k^- \qquad (14)$$

In order to validate the effectiveness of Kalman filter pretreatment, real test is conducted. And the gain resistor of accelerometers' temperature controlling loops of a laser SINS is set as three times large as usual to maintain accelerometers' temperature controlling loops on a critical steady state.

As the temperature sensitive characteristics of the accelerometers is 50 ppm, the change of temperature will lead to low frequency interference with cycle about 20~30 sec on the output of accelerometers. This kind of interference is similar to the impact of vehicle's rocking disturbance but the real system does not exist such disturbance and the attitude of vehicle should be a stable value, then the new alignment method is needed. Comparisons between gyrocompass alignment with both Kalman filter pretreatment and dynamic gain adjustment (KFP/DGA-Gyrocompass) and alignment method with only the latter one (DGA-Gyrocompass) are plotted in Fig. 4-6.

Figure 4 describes the roll angle errors of both DGA-Gyrocompass and KFP/DGA-Gyrocompass alignment methods, in which there is no jitter and fluctuation in the line of KFP-DGA-Gyrocompass alignment method after 35 sec. In Fig. 5, after the maximal
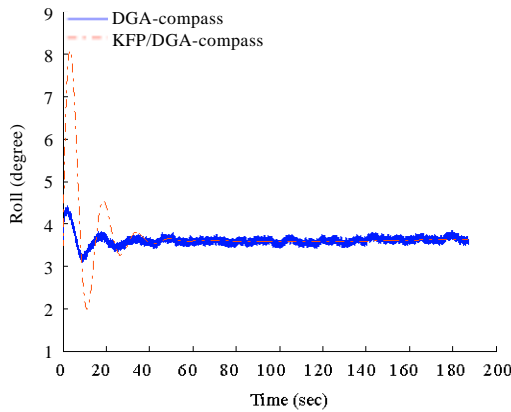
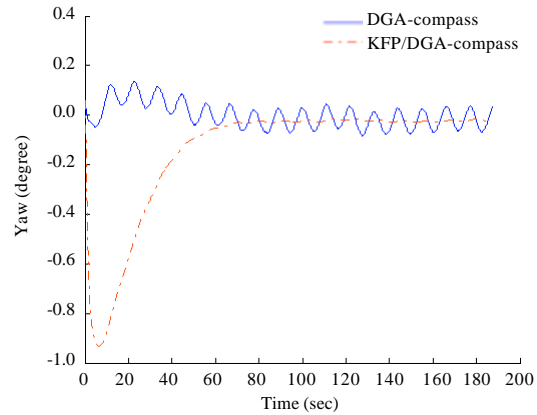Fig. 4: Roll of DGA-gyrocompass and KFP/DGA-gyrocompass alignment methods

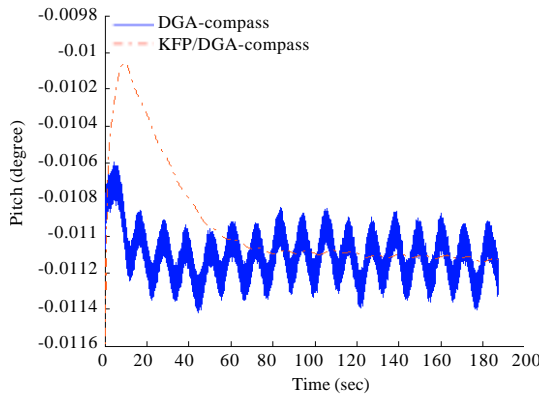Fig. 6: Yaw of DGA-gyrocompass and KFP/DGA-gyrocompass alignment methods

Fig. 5: Pitch of DGA-Gyrocompass and KFP/DGA-gyrocompass alignment methods

Fig. 7: Roll of three alignment methods

pitch value at 10 sec the line of KFP/DGA-Gyrocompass alignment method is monotonic decreasing and after 50 sec there is smaller jitter in the line of KFP/DGA-Gyrocompass than the other one. In Fig. 6, the minimum yaw value is -0.94 at 7 sec and which become almost zero after 70 sec. From the above three figures, an obvious conclusion is that the KFP/DGA-Gyrocompass alignment method can effectively eliminate the impact of high frequency interference and track the attitude change caused by low-frequency large-amplitude interference more precisely and stable.

LAND VEHICLE TEST OF THE KFP/DGA-GYROCOMPASS ALIGNMENT METHOD

In order to validate the effectiveness of the new gyrocompass alignment method, a real test is conducted on a land vehicle equipped with a ring laser SINS.
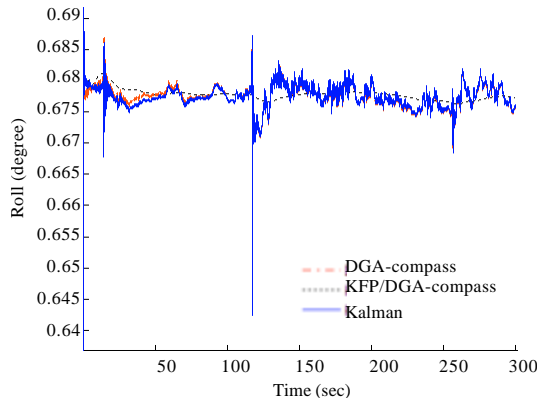
The trajectory of the vehicle is set as the shape "L" and the test condition is as follows:

- **Weather:** Sunny, level 5~6 wind
- **Vehicle:** Engine start

The alignment results of three different methods (i.e., Kalman filter algorithm, DGA-Compass method and KFP/DGA-Compass method) are described in Fig. 7-9.

Figure 7 depicts the roll angle errors of the three alignment method, in which only KFP/DGA-Compass method has smaller fluctuation than others. In Fig. 8, the pitch angle error of KFP/DGA-Compass method is larger than others at the beginning but after 50 sec, the line of the new method becomes more accurate and stable. Fig. 9 shows the similar discipline as in Fig. 8 and after a relatively long period of 150 sec, the yaw angle error of the new method becomes convergent and stable.
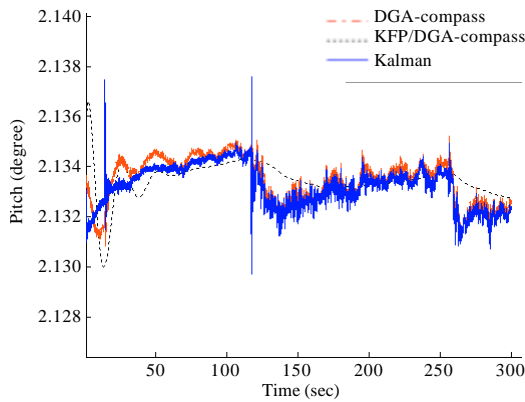
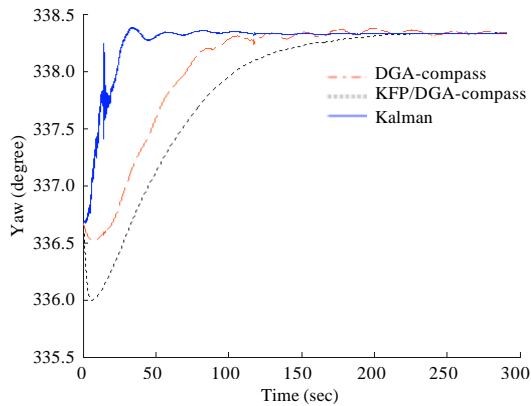Fig. 8: Pitch of three alignment methods

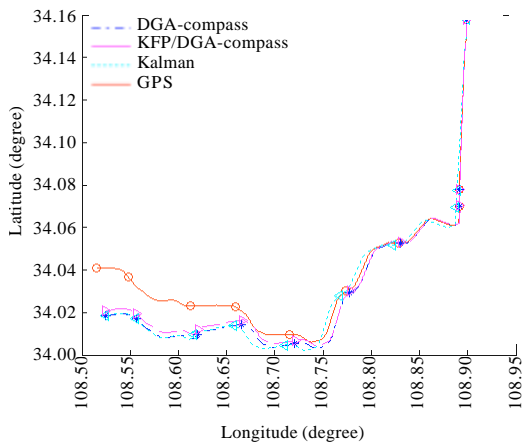Fig. 9: Yaw of three alignment methods

Fig. 10: Positioning results of three alignment methods compared with GPS

Figure 10 and Table 1 show the different navigation results after the three alignment methods compared with the GPS positioning results.

Table 1: Positioning error results of three alignment methods and GPS

Navigation time (sec)	Horizontal drift (nmile)		
	KFP/DGA-Compass	DGA-Compass	Kalman
9.62E±00	6.57E-02	6.92E-02	6.92E-02
4.32E±02	6.22E-02	6.56E-02	6.61E-02
9.32E±02	4.62E-02	5.08E-02	4.87E-02
1.32E±03	6.59E-02	8.97E-02	1.13E-01
1.78E±03	1.70E-01	2.05E-01	2.49E-01
2.81E±03	6.92E-01	7.36E-01	7.94E-01
3.21E±03	9.61E-01	1.00E±00	1.06E±00
3.44E±03	1.09E±00	1.12E±00	1.18E±00
3.57E±03	1.15E±00	1.18E±00	1.23E±00
3.71E±03	1.21E±00	1.24E±00	1.29E±00

Figure 7-10 show and Table 1 that the roll direction of vehicle exists angular vibration of 0.05° when the vehicle undergoes the high frequency rocking interference. And compared with the DGA-Gyrocompass method and Kalman filter alignment algorithm, the KFP/DGA-Gyrocompass method can effectively remove the impact of high frequency noise. It also concludes that the SINS with KFP/DGA-Gyrocompass alignment method has higher accuracy than the SINS with the other two alignment methods for a long time navigation mode (>1 h).

CONCLUSIONS

The traditional gyrocompass alignment method and Kalman filter alignment algorithm almost cannot study so well when vehicle undergoes both low-frequency large-amplitude interference and high-frequency small-amplitude interference. The gyrocompass alignment method based on Kalman filter pretreatment and dynamic gain adjustment can acquire good performance in such a situation. The new alignment method can effectively remove the impact of high frequency rocking interference and dynamically track the attitude change caused by low-frequency large-amplitude interference. And the navigation accuracy can be significantly improved. The new alignment method proposed in this study can achieve better alignment performance and higher navigation accuracy compared with the traditional gyrocompass alignment method and Kalman filter alignment algorithm.

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