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A Novel Damping Method for Strapdown Inertial Navigation System

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ABSTRACT There are periodic oscillation errors in the strapdown inertial navigation system (SINS) when it works in pure inertial navigation mode. It seriously restricts the navigation accuracy of the system. In order to improve the accuracy of the system, the traditional idea of the external horizontal damping in the stabilized inertial navigation system is introduced into SINS. We find that they are equivalent through comparing the damping network of the stabilized inertial navigation system with the compass alignment network. According to the equivalence, the external horizontal damping network of SINS is designed. And the difference between the velocity of the system itself and the velocity of the electromagnetic log are utilized to damp the periodic oscillation. At the same time, a horizontal damping algorithm based on the external velocity is proposed on the basis of the external horizontal damping idea. The effectiveness of the algorithm is verified by the static base of the three-axis turntable, the swing base experiment, and the vehicle simulation experiment. The experiment shows that the external damping network designed in this paper can suppress the system Schuler periodic oscillation error and improve the accuracy of the system.

INDEX TERMS Schuler oscillation, external horizontal damping, strapdown inertial navigation system (SINS), compass alignment network, inertial navigation system (INS).

I. INTRODUCTION

The SINS is required to provide high-precision navigation information under long-term working conditions. Through improving the accuracy of components, accurately calibrating component error parameters, and improving the initial alignment method, the accuracy of the INS can be improved. However, how to make full use of the existing technical conditions during using SINS and the efficient error suppression means to maximize the accuracy of the system is an issue that requires an in-depth study of the inertial navigation scheme.

The undamping SINS is a critically stable system. The error of the system is cyclically oscillating and the amplitude is not attenuated. Under the action of the constant error source, except for the longitude error increases with time, another six error quantities, two velocity error quantities, three attitude error angles and latitude error can maintain a periodic oscillation of limited amplitude, including the Shuler period, Foucault period and Earth period. The three oscillation periods are: Schuler oscillation period: $T_s = 2\pi/\omega_\mathrm{s} = 2\pi/\sqrt{R/\mathrm{g}} = 84.4\,\mathrm{min}$; Earth oscillation period: $T_e = 2\pi/\sqrt{\omega_\mathrm{ie}} = 24h$; Foucault oscillation period: $T_c = 2\pi/\omega_\mathrm{ie}\sin\varphi_\mathrm{c}$ [1]. This oscillation error has a serious impact on the accuracy of the long-running ship navigation system. Therefore, it is necessary to introduce a damping network in the INS to suppress the oscillation error.

In Reference [2], a new method based on control theory is put forward. The method uses Kalman filtering and feedback calibration to damp the Schuler oscillation of INS. In References [3], [4], a new damping method of the dual INS is proposed based on the fact that two or more sets of backup INS are generally equipped in the ship. A design method of damping network based on logarithmic amplitude-frequency characteristic curve is proposed in Reference [5]. It is directed

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against the different performance characteristics of different frequency bands of the amplitude-frequency characteristic curve. In References [6], [7], an internal horizontal damping method based on variable damping proportional control is proposed. A proportional control segment is added in the east and north correction loops of undamping INS respectively. And accelerations are utilized to damp the Schuler periodic errors of INS. In Reference [8], a high-order horizontal damping network based on the idea of complementary filtering is proposed. Two Schuler circuits with excellent high frequency and low frequency characteristics are combined by a pair of complementary filters to form a double Schuler loop combinatorial system. In Reference [9], by introducing the idea of damping algorithm, a fuzzy Kalman filter of damp attitude algorithm is proposed. When the system acceleration is small enough, the system can use the three accelerometer outputs and the Kalman filter to compensate attitude errors. The system acceleration must be small enough, then the damping algorithm can be applied in the fuzzy logic adaptive controller to judge the damping Kalman filter usability and adjust the filter measure error matrix. In Reference [10], an internal damping algorithm is proposed to solve the problem of the Schuler oscillation amplitude of INS errors diverging with time in long-endurance applications. A second-order damping network is designed where a fuzzy controller is used to determine the current motion states and data fusion strategies are developed to accomplish conversion of INS between the damping state and non-damping state. The INS velocity at the moment when the damping conditions are satisfied was used as a reference to ensure the working in-dependence of INS, getting rid of the dependence on external measurements. In Reference [11], an adaptive damping network based on fuzzy inference system is proposed, the system is based on the principle of SINS and utilizes electromagnetic log (EM log) and damping equalizer to bound oscillatory errors existing in attitude and heading. In Reference [12], a digital filter-based strapdown algorithm is proposed to achieve the damping state. In Reference [13], aiming at the limitations of the conventional damping method, a new design idea is proposed, where the adaptive control method is used to design the horizontal damping network of the system. In Reference [14], aiming at overcoming the disadvantages of traditional damping methods, a damping SINS based on Kalman filtering is proposed. Using the measurement data of accelerometers and calculated navigation parameters during the navigation process, the expression of the observation equation is derived. The calculation process of the observation in both the internal damping state and the external damping state is presented. In Reference [15], an optical 2-order horizontal damping networks in various damping coefficients is given. In Reference [16], the Kalman filter based on the grid SINS error model which applies to the ship is established. The errors of grid-level attitude angles can be accurately estimated when the external velocity contains constant error, and then correcting the errors of the grid-level attitude angles through feedback correction can effectively dampen the Schuler periodic oscillation.

The outline of this paper is as follows: Section 1 is the introduction; the equivalence of damping network and compass alignment network is adopted to design and implement the external horizontal damping network in Section 2; Section 3 verifies the correctness of the damping algorithm by carrying out the static base experiment, swing base experiment of triaxial turntable and vehicle simulation experiment; and Section 4 concludes.

II. DESIGN AND IMPLEMENTATION OF DAMPING NETWORK

A. EQUIVALENCE OF DAMPING NETWORK AND COMPASS ALIGNMENT NETWORK

The initial alignment of the stabilized INS is generally divided into two steps, the first is horizontal leveling, then is azimuth alignment. The azimuth alignment is carried out on the basis of the horizontal leveling, and the azimuth compass alignment method is generally adopted. The compass effect is used by the azimuth compass alignment, namely, if there is a deviation angle of the azimuth axis of the platform, the platform will emerge an inclination angle around the eastward axis under the correct command of the platform tracking the angular rate control of the local geographical coordinate system. The inclination angle can be sensed by the northern accelerometer. The output of the northern accelerometer is adopted and the appropriate control law is designed, the azimuth axis of the platform can be controlled to turn towards the direction of reducing the azimuth deviation, and the platform can be automatically located north. The initial alignment principle of SINS is consistent with that of the stabilized compass, only the physical platform is replaced by the mathematical platform, and the physical platform in the stabilized compass is replaced by the attitude matrix of the mathematical platform during the navigation calculation. The error structure of the horizontal alignment of the northern channel is shown in FIGURE 1.

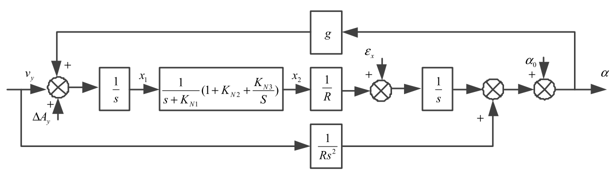

FIGURE 1. Error structure of the horizontal alignment of the northern channel [17].

The damping of the stabilized inertial navigation system is realized by the form of being in series with the damping network $H(s)$. Its northern horizontal damping loop is shown in FIGURE 2 .Compared with the structure diagram of the compass alignment network, it can be found that the two damping networks are equivalent, and the relationship between the parameters and coefficients in the two networks

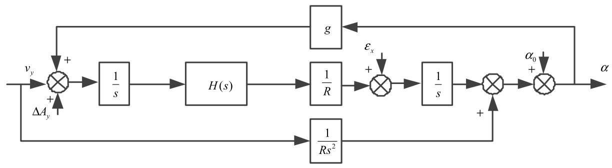

FIGURE 2. Northern horizontal damping loop [18].

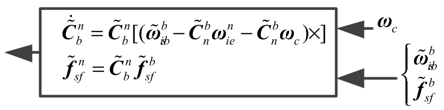

FIGURE 3. Mathematical platform of SINS.

can be derived. Due to the equivalence, the transfer function between x_1 and x_2 in FIGURE 1 is equal to function of the corresponding damping network in FIGURE 2, then

$$H(s) = \frac{(1+K_{N2})\left(s+\frac{K_{N3}}{1+K_{N2}}\right)}{s\left(s+K_{N1}\right)} \tag{1}$$

According to Equation (1), the corresponding relationship between the parameters and coefficients of the northern channel damping network and the alignment network can be obtained, and the eastern channel and the azimuth channel can also be deduced by the same method.

In the damping network of the stabilized inertial navigation system, one part of the signal flow represents the motion law of the solid platform, the other part of the signal flow represents the damping control law, and the damping control law is equivalent in the two forms of damping networks. This provides an idea for the design of damping network of SINS. The difference between the two kinds of systems is that SINS uses the mathematical platform to replace the physical platform of the stabilized inertial navigation system. Therefore, we only need to change the signal flow which represents the motion law of the solid platform into the motion law of the mathematical platform, and transplant the part of the damping control law into it.

B. DESIGN OF THE DAMPING NETWORK

The mathematical platform of SINS is used to simulate the solid platform of the stabilized inertial navigation system, as shown in FIGURE 4. $\tilde{C}_b^n$ is the calculation attitude matrix, which acts as a mathematical platform. $\tilde{\omega}_{ib}^b$ and $\tilde{f}_{sf}^b$ are the measurements of the gyroscopes and accelerometers, respectively. $\omega_c = [\omega_{cE}\ \omega_{cN}\ \omega_{cU}]^T$ is the angular rate applied to the mathematical platform and gyro torqueing information relative to the stabilized inertial navigation system. $\omega_{ie}^n = [0\ \omega_{ie}\ cos\ L\ \omega_{ie}\ sin\ L]^T = [0\ \omega_N\ \omega_U^T]$ is the component of the Earth rotation angular rate in navigation system, $\tilde{f}_{sf}^n = [\tilde{f}_{sfE}^n\ \tilde{f}_{sfN}^n\ \tilde{f}_{sfU}^n]^T$ is the output of $\tilde{f}_{sf}^b$ through the transformation of $\tilde{C}_b^n$.

Changing the signal flow part representing the physical platform into the mathematical platform, while the signal flow part representing the control law remains unchanged, the damping network of SINS is formed, and the horizontal damping network is shown in FIGURE 4.

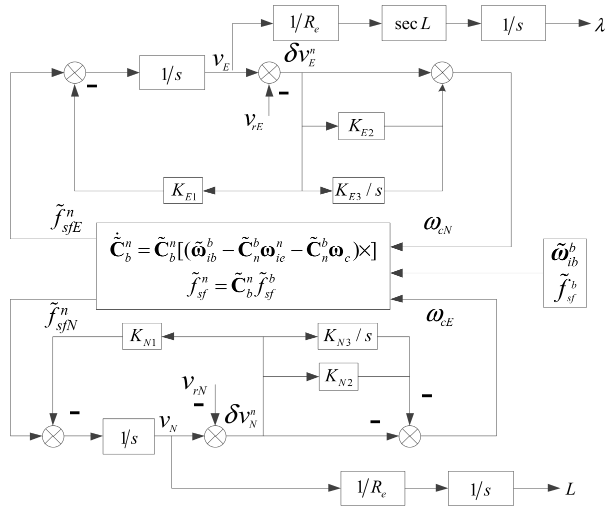

FIGURE 4. Block diagram of the horizontal damping network of SINS.

If the signal flow representing the control law is replaced by being in series with the damping network $H(S)$, another damping network of SINS can be obtained. Unlike the stabilized inertial navigation system, the measurement errors of gyros and accelerometers are implicit in the calculation of the mathematical platform. The platform error angle is expressed in the stabilized compass, which shows the transfer law of the platform error directly. SINS is expressed directly by mathematical platform, which is convenient for software algorithm programming and intuitionistic understanding. In fact, the error transfer between the two systems is essentially same (except the influence symbol of gyroscope drift).

In FIGURE 4, $\boldsymbol{v}_r = [v_{rE}\ v_{rN}]^T$ is the external reference horizontal velocity, $\boldsymbol{v}_r = [v_E\ v_N]^T$ is the horizontal calculation velocity of the system, $\delta\boldsymbol{v} = [\delta v_E\ \delta v_N]^T$ is the difference between the horizontal calculation velocity of the system and the external reference velocity.

A three-order damping network is adopted for the horizontal damping, where $K_{ij}(i = E, N, U; j = 1, 2, 3, 4)$ of the horizontal damping can be adjusted according to the vehicle mobility. The horizontal damping parameters are selected according to Equation (2) [19].

$$\begin{cases} K_{E1} = K_{N1} = 3\sigma \\ K_{E2} = K_{N2} = \frac{\sigma^2(2+1/\xi^2)}{\omega_s^2} - 1 \\ K_{E3} = K_{N3} = \frac{\sigma^3}{\omega_s^2\xi^2} \end{cases} \tag{2}$$

where, σ, ξ and $\omega_s = \sqrt{g/R_e}$ are attenuation coefficient, damping ratio and Schuler frequency, respectively. Note that we need to adjust the attenuation coefficient according to the actual moving environments, and the attenuation coefficient of the horizontal channel is generally smaller.

C. DAMPING ALGORITHM

According to the form of the horizontal damping network of SINS, the damping algorithm of SINS can be deduced. In FIGURE 4, the external horizontal damping control law can be obtained according to the transfer function:

$$\begin{cases} \delta v_E^n = v_E^n - v_{rE}^n \\ v_E^n = \left(\tilde{f}_{sfE}^n - K_{E1}\delta v_E^n\right)/s \\ \delta p_E = K_{E3}\delta v_E^n/s \\ \omega_{cN} = \delta v_E^n\left(1+K_{E2}\right)/R_e + \delta p_E \\ \delta v_N^n = v_N^n - v_{rN}^n \\ v_N^n = \left(\tilde{f}_{sfN}^n - K_{N1}\delta v_N^n\right)/s \\ \delta p_N = K_{N3}\delta v_N^n/S \\ \delta p_N = K_{N3}\delta v_N^n/S \\ \omega_{cE} = -\delta v_N^n\left(1+K_{N2}\right)/R_e - \delta p_N \end{cases} \tag{3}$$

The control law of the external horizontal damping is discretized and the update time of strapdown mathematical platform is assumed to be T_s. Because the time parameters of the damping loop are generally much larger than T_s, the first-order difference can be directly used instead of approximately differential operation. The discrete control law and the discretization equation of SINS can be used to obtain the external damping algorithm of SINS.

$$\begin{cases} \delta v_{Ek}^n = v_{Ek-1}^n - v_{rEk}^n \\ v_{Ek}^n = v_{Ek-1}^n + (\tilde{f}_{sfEk}^n - K_{E1}\delta v_{Ek-1}^n)T_s \\ \delta p_{Ek} = \delta p_{Ek-1} + K_{E3}\delta v_{Ek}^n T_s \\ \omega_{cNk} = \delta v_{Ek}^n(1+K_{E2})/R_e + \delta p_{Ek} \\ \delta v_{Nk}^n = v_{Nk-1}^n - v_{rNk}^n \\ v_{Nk}^n = v_{Nk-1}^n + (\tilde{f}_{sfNk}^n - K_{N1}\delta v_{Nk-1}^n)T_s \\ \delta p_{Nk} = \delta p_{Nk-1} + K_{N3}\delta v_{Nk}^n T_s \\ \omega_{cEk} = -\delta v_{Nk}^n(1+K_{N2})/R_e - \delta p_{Nk} \\ \tilde{\boldsymbol{C}}_{bk}^n = \tilde{\boldsymbol{C}}_{bk-1}^n[\boldsymbol{I} + (\tilde{\boldsymbol{\omega}}_{ibk}^b T_s - \tilde{\boldsymbol{C}}_{nk-1}^b\tilde{\boldsymbol{\omega}}_{iek}^n T_s - \tilde{\boldsymbol{C}}_{nk-1}^b\tilde{\boldsymbol{\omega}}_{ck}T_s)\times] \\ \tilde{f}_{sfk}^n = \tilde{\boldsymbol{C}}_{bk}^n\tilde{f}_{sfk}^b \\ L_k = L_{k-1} + v_{Nk}^n T_s/R_e \\ \lambda_k = \lambda_{k-1} + v_{Ek}^n T_s/R_e/\cos L_k \end{cases} \tag{4}$$

III. EXPERIMENTAL VERIFICATION

In order to verify the correctness of the damping algorithm, static base experiment, swing base experiment of triaxial turntable and vehicle simulation experiment are carried out. Due to the long time of the azimuth damping, SINS does not work in azimuth damping state. Therefore, the triaxial turntable experiment mainly verifies whether the external horizontal damping algorithm meets the expected target or not, and the vehicle simulation experiment is to further verify the correctness and reliability of the external horizontal damping algorithm in practical engineering application.

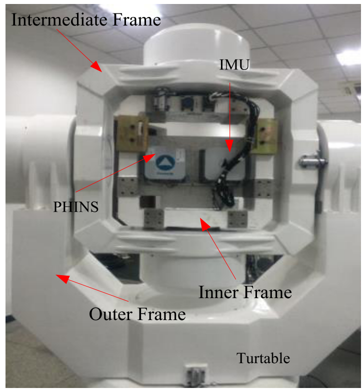

FIGURE 5. Triaxial turntable.

A. TRIAXIAL TURNTABLE EXPERIMENT

The triaxial turntable used in the experiment is shown in FIGURE 5. The rate control accuracy of the triaxial turntable is $\pm 0.0005°/s$ and the angular recalculation is $\pm 0.0001°$. The inner frame, middle frame and outer frame of the triaxial turntable are used to simulate the rolling, pitching and heading of the ship respectively.

In the turntable experiment, the gyro constant drift and random drift of the prototype of SINS are $0.02°/h$ and $0.006°/\sqrt{h}$ respectively. The zero bias of accelerometer is less than $50\mu g$, the update frequency of the turntable data and inertial measurement unit (IMU) data is 200 Hz.

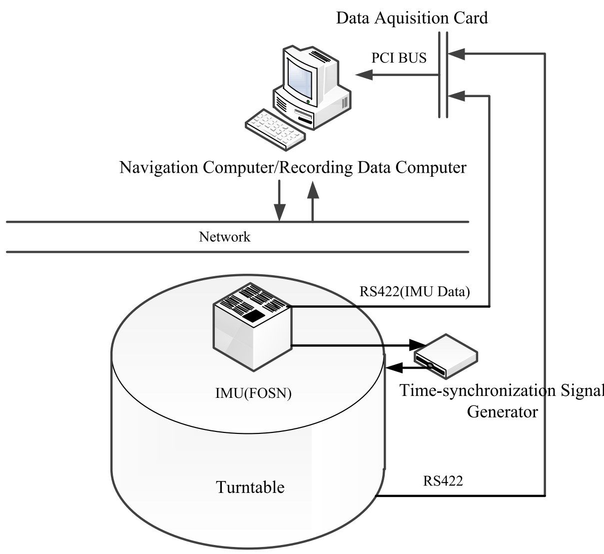

FIGURE 6. Schematic diagram of system turntable structure.

As shown in FIGURE 6, the experimental environment consists of a triaxial turntable, IMU, navigation computer/recording data computer, time synchronous signal generator, data acquisition card, local area network, serial communication port and so on.

Combined with the existing experimental equipment, the navigation information of the auxiliary navigation

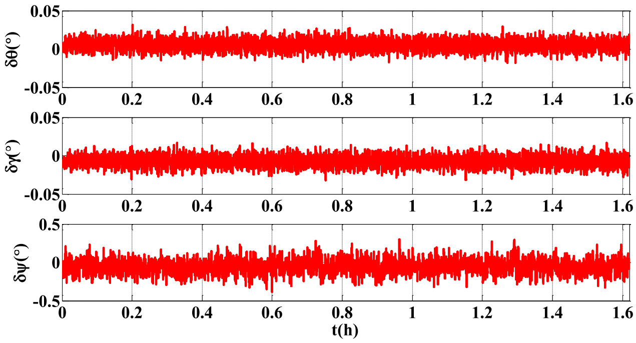

FIGURE 7. Attitude error of the static base.

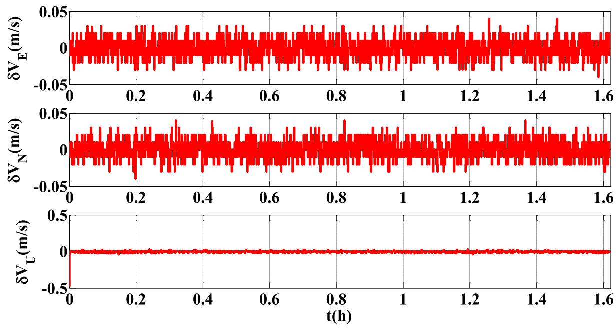

FIGURE 8. Velocity error of the static base.

equipment (electromagnetic log (EM log)) of the fiber-optic SINS is simulated by the following methods: the velocity information of EM log output is simulated by adding white noise with amplitude $0.2m/s$ on the basis of zero velocity [20].

1) EXTERNAL HORIZONTAL DAMPING EXPERIMENT OF THE STATIC BASE

In the external horizontal damping experiment of the static base, the triaxial turntable is set as: the inner frame is 8°, the middle frame is 6°, and the outer frame is 75°. The experiment time of static base lasts for approximately 1.5 h. At the beginning of the experiment, the prototype is first set up to carry out coarse alignment with inertial frame and compass fine alignment under the static base. After the alignment is finished, the prototype began to carry out the external horizontal damping under the static base. FIGURE 7, FIGURE 8 and FIGURE 9 are the curves of attitude error, velocity error and position error, respectively.

2) EXTERNAL HORIZONTAL DAMPING EXPERIMENT OF THE SWING BASE

In the experiment of the external horizontal damping on the swing base, the motion of the triaxial turntable on the swing base is set as follows: the swing center of the inner frame is 6°, the swing amplitude is 12°, and the frequency is 0.125 Hz. The swing center of the middle frame is 8°, the swing amplitude is 10°, the frequency is 0.2 Hz, the swing center of the outer frame is 75°, the swing amplitude is 6°, and the swing frequency is 0.15 Hz. The triaxial swinging motion is carried out simultaneously to simulate the moving state of a ship in mooring state under the action of surge. The turntable stops swinging after the swing base experiment is carried out for 1.5 h. At the beginning of the experiment, the prototype is first set up to carry out coarse alignment with inertial frame and compass fine alignment under the static base. After the alignment is finished, the prototype enters the working state of the external horizontal damping under the swing base. FIGUREs 10, FIGURE 11 and FIGURE 12 are the curves of attitude error, velocity error and position error of the external horizontal damping experiment on the swing base, respectively.

From triaxial turntable experiment result, it can be found that Schuler oscillation and Foucault oscillation disappeared.

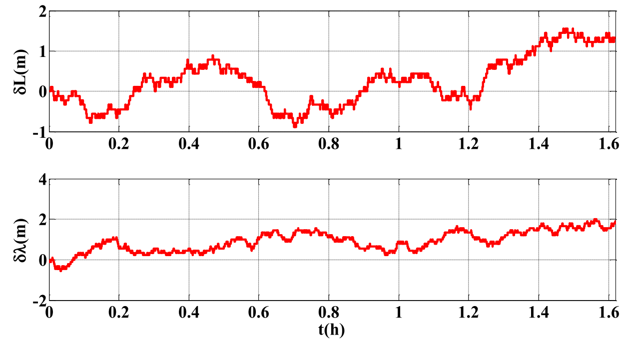

FIGURE 9. Position error of the static base.

TABLE 1. External horizontal damping turntable experiment error on static base.

Parameter Index		Mean Value	Variance
Attitude Error（°）	Pitch	0.0056	00068
	Roll	-0.0073	0.0069
	Heading	0.0468	0.0899
Velocity Error（m/s）	Eastward Velocity	8.5077×10^{-4}	0.0086
	Northern Velocity	2.3199×10^{-4}	0.0082
	Upward Velocity	-0.0032	5.4×10^{-6}
Position Error（m）	Longitude	0.9009	0.5135
	Latitude	0.2462	0.6012

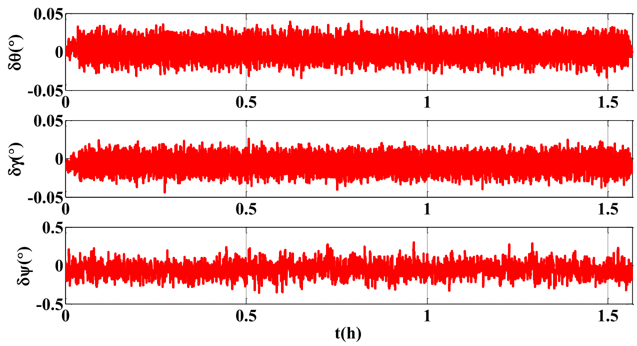

FIGURE 10. Attitude error of the swing base.

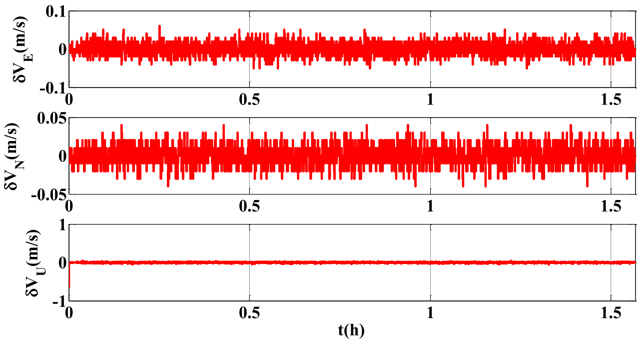

FIGURE 11. Velocity error of the swing base.

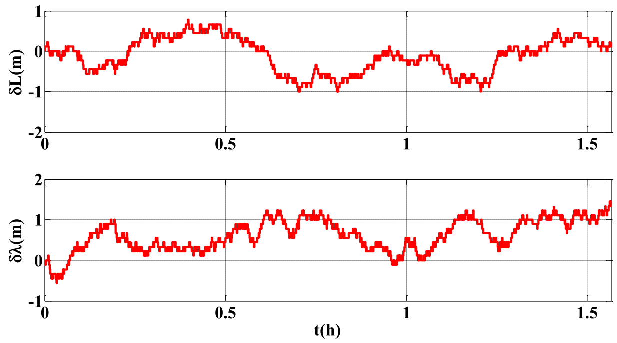

FIGURE 12. Position error of the swing base.

TABLE 2. External horizontal damping turntable experiment error of the swing base.

Parameter Index		Mean Value	Variance
Attitude Error (∘)	Pitch	0.0035	0.0114
	Roll	0.0149	0.0092
	Heading	-0.0532	0.0879
Velocity Error (*m/s*)	Eastward Velocity	1.494×10^{-4}	0.0112
	Northern Velocity	6.526×10^{-4}	0.0092
	Upward Velocity	-0.0039	3.8×10^{-6}
Position Error (*m*)	Longitude	0.6151	0.3872
	Latitude	-0.1091	0.4231

That is to say, the method put forward in this paper played a good role in damping the horizontal loop of the navigation system.

B. VEHICLE SIMULATION EXPERIMENT

In order to verify the reliability of the damping algorithm designed in this paper, vehicle simulation experiment is used. In the vehicle simulation experiment, the PHINS developed by iXBlue and the IMU of the prototype are fixed together through the overboard and placed in the interior of the vehicle. PHINS is set to the mode combined with global positioning system (GPS). The attitude, velocity and position information output by PHINS and GPS are used as reference for vehicle navigation information, and the accuracy of the damping algorithm is verified.

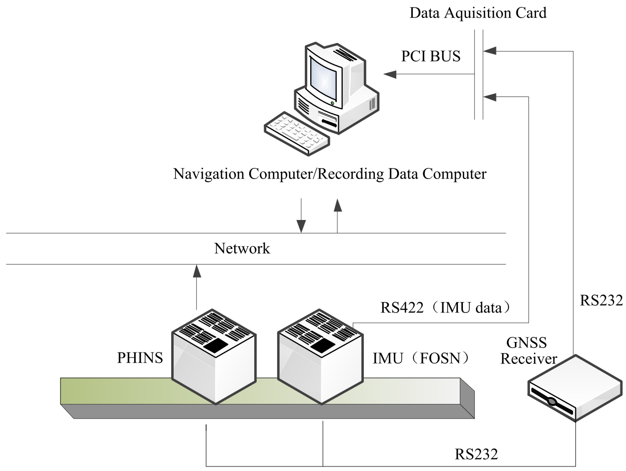

FIGURE 13. Structure of the vehicle simulation experiment.

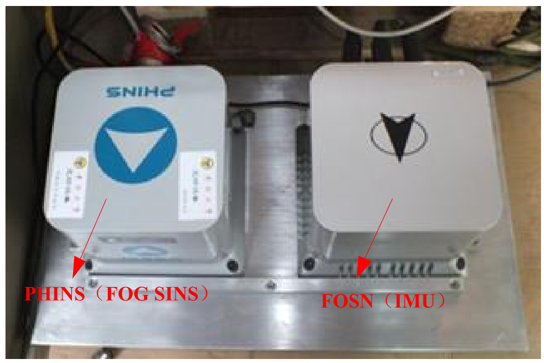

FIGURE 14. Installation of the vehicle simulation experiment equipment.

FIGURE 15. Interior environment of the vehicle.

The structure of the vehicle simulation experiment is shown in FIGURE 13, the installation of the vehicle simulation experiment equipment is shown in FIGURE 14, and the interior environment of the vehicle is shown in FIGURE 15.

1) PHINS PERFORMANCE

PHINS is developed and produced by France's iXBlue Company. It is a high-precision navigation equipment based on fiber optic gyroscope and quartz accelerometer.

FIGURE 16. Physical diagram of PHINS.

Meanwhile, PHINS has reserved interfaces with navigation equipment such as global navigation satellite system (GNSS), doppler velocity log (DVL), acoustic navigation, etc. Multi-sensor integrated navigation can be supported. The physical diagram is shown in FIGURE 16.

The main performance index of PHINS is shown in TABLE 3.

TABLE 3. The main performance of PHINS [21].

Main Technical Parameters		Technical Index
Positioning Accuracy（CEP）	GPS Stand-alone Assistance	5-15 m
	Differential GPS Assistance	0.5-3 m
	RTK Differential GPS Assistance	0.02-0.05 m
	No Assistance（five minutes）	20 m
	Pure Inertial Navigation	0.6 n mile/h
Heading Accuracy（RMS）	GPS Assistance	0.01°/cos L
	Pure Inertial Navigation	0.01°/cos L
Horizontal Attitude Accuracy（RMS）	GPS Assistance	0.01°
	Pure Inertial Navigation	0.01°

2) EXTERNAL HORIZONTAL DAMPING VEHICLE SIMULATION EXPERIMENT

Combined with the existing vehicle simulation experimental conditions, the navigation information of the auxiliary navigation equipment (EM log) of the fiber-optic SINS is simulated by the following method: the velocity information output by PHINS is converted from navigation system to body system and white noise with amplitude of 0.2 m/s is added, which is used to simulate the velocity information of EM log output [22].

When the prototype is used in the vehicle simulation experiment, the PHINS and GPS receivers are first started, and the PHINS is set to the dual-position alignment mode. After about 30 min, PHINS completes the alignment. At this time, let PHINS work at the state of combination with GPS, take the navigation information output from PHINS working at the integrated state as the reference datum for the vehicle simulation experiment of the prototype. Then start the navigation

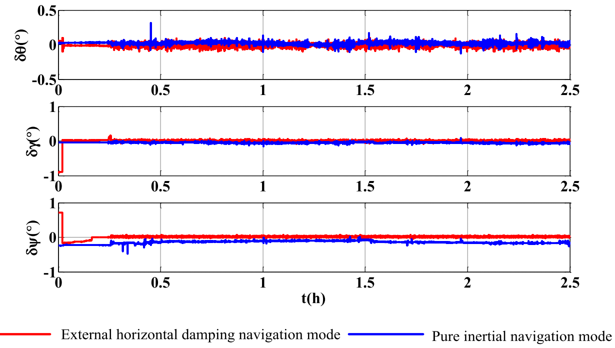

FIGURE 17. Comparison of attitude error between external horizontal damping and pure inertial navigation mode.

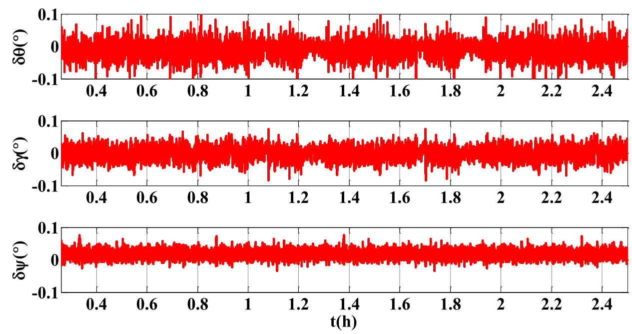

FIGURE 18. Attitude error curve of the external horizontal damping vehicle simulation experiment.

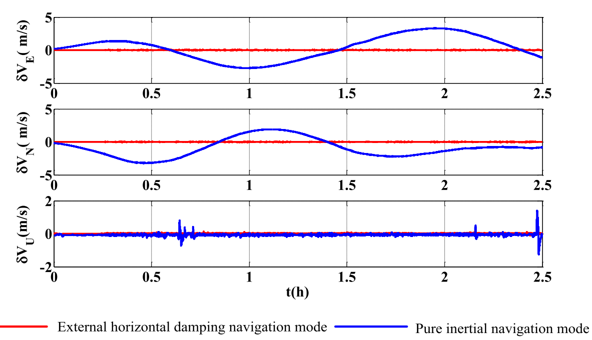

FIGURE 19. Comparison of velocity error between external horizontal damping and pure inertial navigation mode.

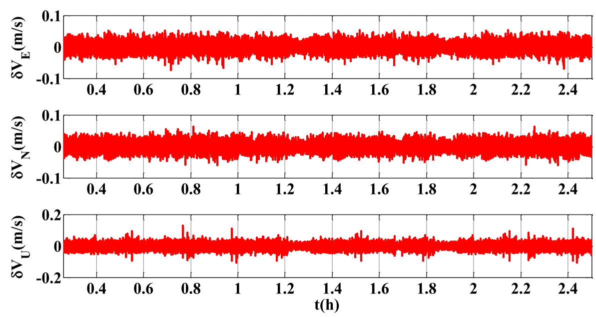

FIGURE 20. Velocity error curve of the external horizontal damping vehicle simulation experiment.

platform of the prototype of the experiment. The prototype is set into coarse alignment by solidification analysis method, fine alignment by compass method and navigation mode of

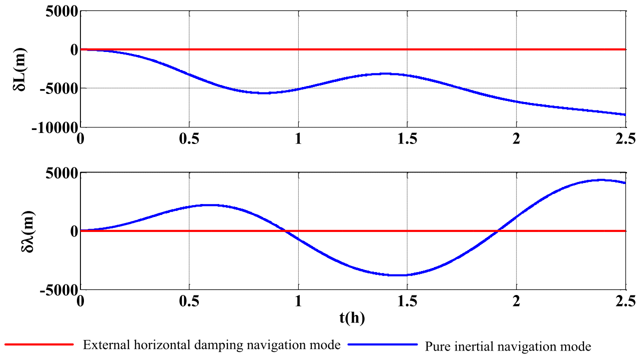

FIGURE 21. Comparison of position error between external horizontal damping and pure inertial navigation mode.

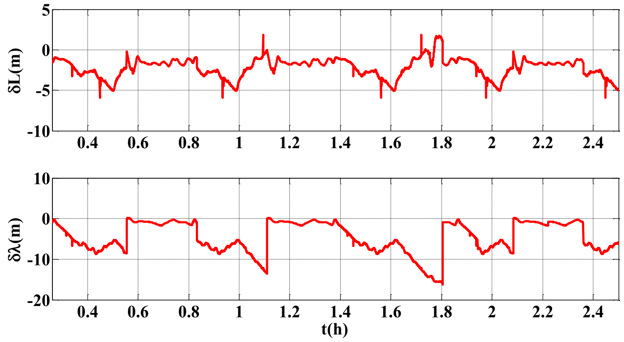

FIGURE 22. Position error curve of the external horizontal damping vehicle simulation experiment.

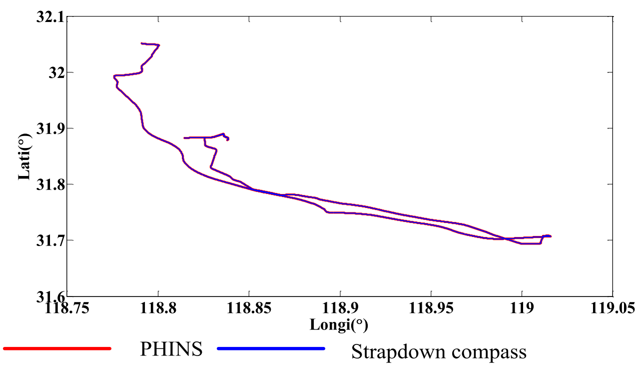

FIGURE 23. Horizontal position map of external horizontal damping vehicle simulation experiment.

the external horizontal damping. The alignment time is 600 s. During the alignment process, the motor engine is kept in normal operation without moving the experimental vehicle, and there is no restriction on the activities of the experimenters on the vehicle. After the alignment is finished, the vehicle is started. The vehicle starts from the south gate of Kowloon lake campus of southeast university, and stops recording along Shuanglong road for about 9000 s.

The output frequency of the navigation results of SINS is 200 Hz, and the attitude error, velocity error and position error curves compared with the pure inertial navigation mode are shown in FIGURE 17, FIGURE 19 and FIGURE 21, respectively. The attitude error, velocity error and position error

TABLE 4. Statistical results of synthetic error in vehicle simulation experiment.

Parameter Index		Mean Value	Variance
Attitude Error（∘）	Pitch	-0.0112	0.0167
	Roll	-0.0063	0.0832
	Heading	0.0137	0.0734
Velocity Error（*m/s*）	Eastward Velocity	0.0004	0.0123
	Northern Velocity	0.000005	0.0128
	Upward Velocity	-0.0017	0.0129
Position Error（*m*）	Longitude	-2.1172	1.1474
	Latitude	-4.2569	3.8084

curves of SINS are shown in FIGURE 18, FIGURE 20 and FIGURE 22, respectively. FIGURE 23 shows the track of the carrier based on the external horizontal damping navigation information of the prototype output and the position information of the PHINS output.

As observed from FIGURE 17 to FIGURE 22 and TABLE 4, when the system works in the mode of the external horizontal damping navigation, the system Schuler periodic oscillation error is effectively suppressed, the accuracy of the system attitude and velocity calculation is improved obviously, and the accuracy of the position calculation is also improved.

IV. CONCLUSION

In order to suppress the system Schuler periodic oscillation error, a novel damping method for SINS is given. Through comparing the damping network with the structure diagram of the compass alignment network, it can be found that the two networks are equivalent. Thus, the corresponding relationship of the parameters and coefficients in the damping network and the alignment network is deduced. And the horizontal damping network block diagram is designed; then the horizontal damping algorithm is derived based on the horizontal damping network and block diagram. Finally, the effectiveness of the algorithm is verified by the static base of the three-axis turntable, the swing base experiment and the vehicle simulation experiment. It shows that the external horizontal damping network designed in this paper can suppress the system Schuler periodic oscillation error and improve the accuracy of the system.

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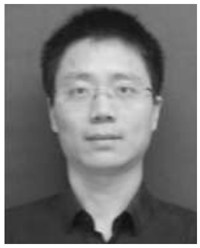

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