INS/CNS Integrated Calibration based on Speed Reference Information

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Abstract. CNS needs INS to provide horizon attitude information as the horizon reference. The non-damping INS on critical conditions is easy to cause error fluctuation and divergence when the accelerometer zero is changed, directly affecting horizon reference information precision of assistant CNS. Therefore, under on-board use conditions, the INS short-term high-precision characteristics are used in CNS/INS/LOG integrated system to design Kalman filter with horizontal speed damping and compensate dynamic error of INS. The calibration and readjustment technology of on-board CNS/INS integrated system is based on horizontal speed damping. The accurate reference information of CNS is used to finish correction of position error, misalignment angle and main gyro drift error. In this way, the readjustment period will be extended to realize long-time and high-precision navigation of the integrated system.

1. Introduction

For the characteristics of CNS/INS integrated system, this paper discusses the important correction link of navigation: integrated calibration. When solving integrated calibration problems of CNS/INS, the solutions suitable for on-board environment shall be sought. Under mooring status, INS is assigned by CNS attitude to finish rough alignment. Document [1] integrates data according to the CNS/INS alignment estimated by the recursive weighted least squares algorithm. In this alignment solution, CNS acquires high-precision attitude information according to the dock position, and no more requires INS to provide horizon attitude, avoiding transmission of INS horizon attitude error in the integrated system. The weighted least squares algorithm could reduce the impact of assignment error on alignment precision. For the problem of integrated calibration, this paper proposes the system readjustment plan to use electronic log as external speed reference, and introduce damping network to damp Schuler cycle oscillation caused by accelerometer error and gyro shift to the system, so as provide
favorable correction conditions for comprehensive calibration. For the damping problem of horizontal damping channel, this paper reasonably selects damping network parameters to infer damping system error equation, analyze damping error transmission rules, and design Kalman filter under horizontal damping conditions to finish integrated calibration.

2. Use of external speed reference information

The Schuler cycle oscillation error is mainly shown on horizontal channel. To damp the Schuler cycle oscillation error, the external speed is introduced to feed back to the system through damping network. Due to the arrangement in the geographical coordinate system, the selection of damping network and parameters could refer to the semi-analytical platform network mode and parameter selection method, as shown in Fig. 1.

In Fig.1, \( \left( f_x^p, f_y^p, f_z^p \right) \) is the projection of specific force outputted by accelerator to platform coordinate system (\( P \) system); \( C_p^n \) is the transformation matrix from \( P \) to \( n \); \( \left( \Delta a_x^n, \Delta a_y^n \right) \) is harmful acceleration; \( \left( v_{cx}, v_{cy} \right) \) is external speed introduced; \( \left( v_{cx}(0), v_{cy}(0) \right) \) is initial speed; \( \left( L_0, \lambda_0 \right) \) is initial position; \( \left( L, \lambda \right) \) is calculation position; \( \left( \omega_{nx}^n, \omega_{ny}^n, \omega_{nz}^n \right) \) is the projection of the inertial space rotation angle speed \( \omega_{in}^n \) of \( n \) system to \( n \) system;
is the project of inertial space rotation angle speed \( \omega^p \) of the \( P \) system to \( P \) system.

3. Damping network design

According to the block diagram, when \( H_1(s) = 1 \) and \( H_2(s) = 1 \), the block diagram will be changed to non-damping conditions. At that time, neither acceleration nor speed generates impact on the system. However, the disturbance variable of the gyro and accelerator will generate Schuler cycle oscillation error component to output volume of the system. When \( H_1(s) \neq 1 \) or \( H_2(s) \neq 1 \), a horizontal damping network is selected to offer damping effect to that system. Then, the oscillation error outputted by the system due to accelerator zero error, gyro drift and initial alignment error will be damped gradually; however, acceleration and speed will generate error component of navigation parameters caused by damping network introduction. Therefore, the horizontal damping network endows the system with damping effect, and meanwhile wishes \( H_1(s) \) and \( H_2(s) \) approaching to 1. In this way, the impact of ship movement on system error may be smaller \([2]\).

When selecting damping network, on the one hand, the root mean square value of error generated by gyro drift random component shall be reduced; on the other hand, the INS is required to be minimally sensitive to ship movement. The larger the damping coefficient is, the reduction of error generated by gyro drift random component will be. From the aspect of reducing impact generated by gyro drift random component on the system, it will be the better with larger damping coefficient. With the increase of damping coefficient, however, the error generated when the ship is moving will be larger. When the damping coefficient is increased again, the random drift component of gyro is not reduced obviously. Based on these two aspects, in the high-order transfer function of damping network in the system, the equivalent damping coefficient shall be 0.5 \([3,4]\).

The basic equation describes INS, accelerator output transformation and integral computing in the mathematical form. The correction of mathematical platform is replaced by mathematical model. In study on navigation system, in general the basic equation is used to describe changes between elements of the horizontal damping INS system.
\[
\begin{align*}
  f_{x}^p &= C_{a}^{p} - 11 \times f_{x}^p + C_{a}^{p} - 12 \times f_{y}^p + C_{a}^{p} - 13 \times f_{z}^p \\
  f_{y}^p &= C_{a}^{p} - 21 \times f_{x}^p + C_{a}^{p} - 22 \times f_{y}^p + C_{a}^{p} - 23 \times f_{z}^p \\
  f_{z}^p &= C_{a}^{p} - 31 \times f_{x}^p + C_{a}^{p} - 32 \times f_{y}^p + C_{a}^{p} - 33 \times f_{z}^p \\
  A_{nx} &= f_{x}^p - \Delta \alpha_{x} \\
  A_{ny} &= f_{y}^p - \Delta \alpha_{y} \\
  \dot{V}_{cs} &= A_{nx} + (2\omega_{n} \sin L_{e} + \frac{V}{R_{N}} \tan L_{e}) \times V_{cy} \\
  \dot{V}_{cs} &= A_{ny} - (2\omega_{n} \sin L_{e} + \frac{V}{R_{N}} \tan L_{e}) \times V_{cx} \\
  \begin{align*}
    \dot{L}_{c} &= \frac{V_{cy}}{R_{M}} H_{y} \\
    \dot{\lambda}_{c} &= \frac{V_{cx}}{R_{N}} \sec L H_{x} \\
    \omega_{int}^{n} &= -\frac{V_{cy}}{R_{M}} H_{y} \\
    \omega_{int}^{n} &= \omega_{n} \cos L_{e} + \frac{V_{cx}}{R_{N}} H_{x} \\
    \omega_{int}^{n} &= \omega_{n} \sin L_{e} + \frac{V_{cy}}{R_{N}} \tan L_{e} H_{y} \\
    C_{n}^{p} &= (\omega_{n}^{p} - C_{n}^{\alpha} \omega_{n}^{p}) C_{n}^{p}
  \end{align*}
\]

In the formula.

\[
C_{n}^{p} = \begin{bmatrix}
  C_{a}^{p} - 11 & C_{a}^{p} - 12 & C_{a}^{p} - 13 \\
  C_{a}^{p} - 21 & C_{a}^{p} - 22 & C_{a}^{p} - 23 \\
  C_{a}^{p} - 31 & C_{a}^{p} - 32 & C_{a}^{p} - 33 
\end{bmatrix}
\]

4. Damping system error equation

The error equation is used to study relationship between error sources and system output value of INS, and thus propose technical index requirements to INS components. After the precision indexes of components are confirmed, the precision of the system could be estimated so as to improve restriction and possibility of the entire INS precision. Therefore, the INS error is necessary for study on INS. The block diagram of horizontal damping error can be seen in Fig.2. The error equation of horizontal external speed damper and height damper system may be inferred according to the block diagram of damping system error \cite{5,6}.
In Fig. 2, $\Delta a^v_a$ is accelerator output error, $C_i$ is scale error transformation matrix, $\Delta M$ is accelerator zero offset, $C^w_r$ is the transformation matrix from $P$ to acceleration coordinate system $(a)$, $(\Delta f^v_x, \Delta f^v_y)$ is the projection of specific force outputted by accelerator to platform coordinate system $(P)$, $C^w_p$ is the transformation matrix from $P$ to $n$, $(\Delta a^v_x, \Delta a^v_y)$ is harmful acceleration, $(\Delta V^v_x, \Delta V^v_y)$ is external speed error, $(\delta V^v_x, \delta V^v_y)$ is horizontal speed of calculation, $K_i (i = 1, \cdots, 6)$ is damping coefficient, $(\delta V^v_{x0}, \delta V^v_{y0})$ is initial speed error, $(\delta L^v_0, \delta \lambda^v_0)$ is initial position error, and $(\delta L^v_x, \delta \lambda^v_x)$ is calculation position error.

The error equation of horizontal damping system shall be:
\[
\begin{align*}
\delta \dot{V}_x &= \frac{1}{R}(K_2 + (V_x \tan L - V_x)) - K_i + \frac{K_1}{K_2 + 1} \delta V_x + (K_2 + 1) \left(2\omega_0 \sin L + \frac{V_x \tan L}{R}\right) \delta V_x - (K_2 + 1)(2\omega_0 \cos L + \frac{V_x}{R}) \delta V_y \\
&
+(K_2 + 1)(2\omega_0 \sin L + 2\omega_0 V_x \cos L + \frac{V_x}{R} \sec^2 L) - (K_2 + 1) \Delta A_\phi \phi_x + (K_2 + 1) \Delta A_\theta \theta_x - (K_2 + 1) \phi_x \\
&
+(K_2 + 1) \Delta A_\phi \phi_x + (K_2 + 1) \Delta A_\theta \theta_x - (K_2 + 1) \phi_x \\
\delta \dot{V}_y &= -\frac{1}{R}(2\omega_0 \sin L + 2\omega_0 V_x \cos L + \frac{V_x}{R} \sec^2 L) - (K_2 + 1) \delta V_x - (K_2 + 1) \delta V_y - \frac{V_x}{R} \delta V_y \\
&
-(K_2 + 1)(2\omega_0 V_x \cos L + \frac{V_x^2}{R} \sec^2 L) - (K_2 + 1) \Delta A_\phi \phi_x - (K_2 + 1) \Delta A_\theta \theta_x - (K_2 + 1) \phi_x \\
&
+(K_2 + 1) \Delta A_\phi \phi_x + (K_2 + 1) \Delta A_\theta \theta_x - (K_2 + 1) \phi_x \\
\delta \dot{V}_z &= (2\omega_0 \cos L + \frac{V_x^2}{R}) - (K_2 + 1) \delta V_x + 2\omega_0 V_x \cos L + \frac{V_x}{R} \tan L + \frac{2\omega_0}{R} \delta h - \Delta A_\phi \phi_z + \Delta A_\theta \theta_z - z_i + \Delta A_\phi \phi_z + \Delta A_\theta \theta_z + \phi_z \\
\delta \dot{h} &= \frac{1}{R} \delta V_y - \frac{1}{R \cos L} \delta V_x \\
\delta \dot{L} &= \frac{1}{R \cos L} \delta V_x + \frac{V_x \tan L}{R \cos L} \\
\dot{\phi}_x &= \frac{1}{R} \delta V_x - \phi_x - \frac{\omega_0 \sin L + \frac{V_x \tan L}{R}}{R} \delta V_x - \frac{V_x}{R} \delta \phi_x + \epsilon_i \\
\dot{\phi}_y &= \frac{1}{R} \delta V_y - \phi_y - \frac{\omega_0 \sin L + \frac{V_x \tan L}{R}}{R} \delta V_y - \frac{V_x}{R} \delta \phi_y + \epsilon_i \\
\dot{\phi}_z &= \frac{1}{R} \delta V_z - \phi_z - \frac{\omega_0 \sin L + \frac{V_x \tan L}{R}}{R} \delta V_z - \frac{V_x}{R} \delta \phi_z + \epsilon_i \\
\dot{z}_1 &= \frac{K_2 + 1}{K_3 + 1} \delta V_y - \frac{K_1}{K_2 + 1} \delta V_y + (K_2 + 1) \delta V_x - \left(\frac{K_1}{K_2 + 1}\right) \delta V_y \\
\dot{z}_2 &= \frac{K_2 + 1}{K_3 + 1} \delta V_x - \frac{K_1}{K_2 + 1} \delta V_x + (K_2 + 1) \delta V_x - \left(\frac{K_1}{K_2 + 1}\right) \delta V_y \\
\dot{z}_3 &= \frac{K_2 + 1}{K_3 + 1} \delta V_y - \frac{K_1}{K_2 + 1} \delta V_y + (K_2 + 1) \delta V_x - \left(\frac{K_1}{K_2 + 1}\right) \delta V_y \\
\dot{z}_4 &= \frac{K_2 + 1}{K_3 + 1} \delta V_x - \frac{K_1}{K_2 + 1} \delta V_x + (K_2 + 1) \delta V_x - \left(\frac{K_1}{K_2 + 1}\right) \delta V_y \\
(\delta \dot{V}_x, \delta \dot{V}_y, \delta \dot{V}_z, \delta \dot{L}, \delta \dot{\theta}, \phi_x, \phi_y, \phi_z, z_1, z_2)^T
\end{align*}
\]

In the formula, \((\delta \dot{V}_x, \delta \dot{V}_y, \delta \dot{V}_z, \delta \dot{L}, \delta \dot{\theta}, \phi_x, \phi_y, \phi_z, z_1, z_2)^T\) are the speed errors along the geographical coordinate system, respectively latitude error, longitude error and height error, three intermediate variables of three attitude error angles and full external speed damping network on mathematical platform; \(R\) is earth radius, for the convenience of supposed \(R_m = R_n = R\) calculation; \(K_i (i = 1, \cdots, 6)\) is damping coefficient, input variables \((\Delta A_\phi, \Delta A_\theta, \Delta A_\phi, \epsilon_x, \epsilon_y, \epsilon_z, \delta V_y, \delta V_y, \delta V_y, \delta V_y, \delta V_y, \delta V_y)^T\) are respectively the axial components of accelerometer error \(\Delta A_\phi\) and gyro error \(\epsilon\) in the geographical coordinate system, external horizontal speed error and derivative, and height error.

5. Calibration design
Suppose the position reference information of CNS device is acquired at time \(t\). At that time, the position error is \(\Delta L(t)\); the heading error is \(H(t)\); geographical coordinate
The single-axle rotating strap-down INS may believe the horizontal gyro shift could be fully adjusted, i.e., \( \epsilon_x = \epsilon_y \approx 0 \); \( \alpha = \omega_{\text{ie}}(t - t_0) \), in which, \( \omega_{\text{ie}} \) and \( t_0 \) are respectively earth rotation angle rate and the end time of initial alignment \([6]\).

Under the horizontal damping status, according to the error transmission relationship of the system,

\[
\begin{bmatrix}
\delta L(t) \\
\delta \lambda(t)
\end{bmatrix} = M^{-1} \begin{bmatrix}
\epsilon_x \\
\epsilon_y
\end{bmatrix}
\]

\( M = \begin{bmatrix}
-\cos(L(t)) \sin \alpha & -\cos(L(t))(1 - \cos \alpha) \\
-\sin(L(t))(1 - \cos \alpha) & -\sin(L(t))(\alpha - \sin \alpha)
\end{bmatrix} \)

In the formula,

\[
\begin{align*}
\hat{e}_z &= b_2 \\
\hat{H}(t) &= \cos \alpha \hat{b}_1 + \sin \alpha \hat{b}_2
\end{align*}
\]

\section{6. Comprehensive calibration simulation based on horizontal damping}

The comprehensive calibration simulation conditions based on horizontal damping can be seen in Table 1:

| Simulation parameters                      | Value                                      |
|-------------------------------------------|-------------------------------------------|
| Initial position                          | \( L_0 = 39.181^\circ, \lambda_0 = 117.144^\circ \) |
| Initial speed                             | \( v_x = 0, v_y = 0 \)                     |
| Gyro constant value drift                 | \( \epsilon_x = 0.005^\circ / h, \epsilon_y = 0.006^\circ / h, \epsilon_z = 0.002^\circ / h \) |
| Gyro drift stability                      | \( \xi_\phi = \xi_\psi = \xi_\kappa = 0.006^\circ / h \) |
| X, Y, Z gyro installation error           | \((-12^\circ, 7^\circ), (-9^\circ, 10^\circ), (18^\circ, 6^\circ)\) |
| Accelerator zero offset                  | \( \Delta A_{x0} = 5 \times 10^{-7} \text{g}, \Delta A_{y0} = -6 \times 10^{-7} \text{g}, \Delta A_{z0} = 3 \times 10^{-5} \text{g} \) |
| Accelerator installation error           | \((-5^\circ, 12^\circ), (6^\circ, 9^\circ), (11^\circ, -7^\circ)\) |
| INS rotation method                      | Forward/backward halt speed 9°/s, halt time: 5s |
| INS output frequency                     | 400 Hz                                    |
| CNS output frequency                     | 1Hz                                       |
| CNS precision                            | Optical axis pointing error is 5” and horizontal axis pointing error is 7” |
| Filter period                            | 1s                                        |
| External speed error                     | 0.5Kn                                     |
The comprehensive calibration simulation can be seen in Fig.3–Fig.5:

7. Conclusion

Based on integrated calibration, this paper proposes the system readjustment plan to use electronic log as external speed reference, and introduce damping network to damp Schuler cycle oscillation caused by accelerator error and gyro shift to the system, so as provide favorable correction conditions for comprehensive calibration. For the damping problem of horizontal damping channel, this paper reasonably selects damping network parameters to infer damping system error equation, analyze damping error transmission rules and design Kalman filter under horizontal damping conditions, and finally carries out simulation analysis. Simulation results show: after repeated calibrations of CNS information, the speed error of INS is improved, the latitude and longitude error are corrected obviously, and INS position precision is improved obviously. The purpose of INS readjustment cycle extension is reached.
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