Study on Shafting Calibration Technology of INS/CNS Integrated Navigation System

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Abstract: As a high precision attitude measurement device, the INS/CNS integrated navigation system has error order of second and installation and calibration precision of minute. The calibration residue of installation error directly affects attitude determination and positioning precision. The paper discusses calibration method of sub-system installation error, and expounds calibration principles of INS/CNS integrated navigation system. According to overall technical solutions, this paper studies shafting calibration error transfer characteristics of INS/CNS integrated navigation system, and puts forward calibration solution for the system. It mainly analyzes impact of multiple error factors during system calibration such as installation error and measurement instrument error on the integrated system, models and analyzes countershaft inclination effect, coaxial error and zero position calibration, optimizes calibration method for the system and improves installation error calibration precision.

1. Introduction

INS/CNS integrated navigation system uses the heading and position information not accumulated with time provided by CNS to correct the INS error so as to realize high precision integrated navigation. It could be applied to platforms such as aircraft, ships, drone, missile and balloon [1,2]. The great military powers such as USA and Russia lay emphasis on research and development of the INS/CNS integrated navigation system, and apply this technology as an important navigation technical approach to each field extensively. According to different device forms, the INS/CNS integrated navigation system is divided to all-platform, semi-platform and strap-down system. The work modes of CNS navigation may be divided to star tracker and star sensor recognition as per different star identification modes [3]. The former finishes position measurement and vector conversion of carrier coordinate system and inertial coordinate system with photo-electronic imaging tracing method, which has unfavorable factors such as complex structure process, large size and complex sensor; the latter outputs conversion relationship between inertial and carrier coordinate system by means of star pattern.
identification and star matching. Under this mode, the project is easier to realize, configuration plan is more flexible and reliability is higher [4].

2. Principles and requirements of INS/CNS integrated navigation system calibration

2.1 Calibration principle

The calibration principle is to confirm conversion relationship of dichotomous system coordinate standard according to specific realization structure of CNS and INS devices. Different calibration approaches and programs will be selected for INS/CNS integrated navigation system with various integration modes. This paper proposes common-base coordinate calibration and operation process of INS/CNS integrated navigation system based on semi-platform INS/CNS integrated navigation system.

When calibrating CNS and INS devices separately, they have respective standards. When they are installed by common-base installation method, it is necessary to realize unified standard of branch devices through calibration, which is the precondition for normal operation of the integrated system. In INS/CNS integrated navigation system, the calibration purposes are different due to diversified functions to be realized: The INS device provides attitude and position information of ships in geographical coordinate system. INS is calibrated to make the benchmark and representative ship coordinate system consistent so as to guarantee attitude and position outputted could represent that in the geographical coordinate system; CNS is calibrated to keep the coordinate benchmark standard and CNS device consistent. The essence is to try to reduce transfer and introduction error of attitude information.

2.2 Calibration conditions and requirements

The calibration of common-base INS/CNS is to comprehensively calibrate each measurement device based on geodesic true horizon and azimuth mark so as to acquire high-precision mechanical zero position and shafting error data, and establish unified coordinate conversion relationship.

CNS is rigidly installed to the deck of ship by sharing one base of INS, and should acquire attitude information on the installation position when it is operating. Under the condition of common-base CNS/INS installation, the core of calibration solution is to acquire accurate electrical error of INS/CNS.

(1) The installation site shall provide the following conditions:
   ① Installation base provided on the installation position of ships shall be in complete conditions;
   ② The installation site shall provide space for installation, calibration and maintenance;
   ③ The environmental conditions on installation site shall meet requirements of equipment installation elements;
   ④ There should be no substance causing corrosion on the installation site;
   ⑤ The installation site shall provide suitable luminance;

   After the device is installed, corresponding protective measures shall be adopted according to specific environment on installation site.

(2) Requirements of equipment installation base:
   ① The installation base shall be designed by considering weight, gravity center of INS device and position of the ship, and calculating loads such as force and torque bore by installation base under
worse conditions of ships so as to guarantee normal operation of INS under carrier movement conditions;
② The flatness, roughness and horizontal precision of installation base shall comply with requirements of equipment installation requirements;
③ For installation base with stem-stern marking line, the marking line shall be in parallel with stem-stern level; the parallel deviation shall be no larger than alignment deviation, and installation base shall be clean.
④ The alignment of device shall comply with requirements of installation elements, which usually contain environmental conditions, standard, installation base and alignment deviation.

2.3 Calibration process
The calibration process of INS/CNS integrated navigation system is as follows:
(1) INS horizontal calibration, i.e., horizontal alignment between INS device and ship standard baseline; the measurement results shall comply with requirements of installation elements;
(2) INS stem-stern calibration, i.e., alignment between INS device and ship stem-stern baseline; the measurement results shall comply with requirements of installation elements;
(3) Repeated measurement, i.e., to reexamine the horizontal assignment calibration between INS and ship standard base line; the calibration will end if results comply with requirements of installation elements; if the error is out of tolerance, aforesaid steps shall be repeated till the measurement results meet requirements of installation elements;
(4) CNS declination calibration, i.e., measuring and recording horizontal deviation between CNS and INS and stem-stern line deviation;

3. Shafting calibration error analysis
The shafting error of INS/CNS mainly refers to the error between corresponding shafting when the rotating mechanism of orthogonal shafting has strict requirements for verticality of adjacent shafting but it could not reach the requirements completely due to restriction of process. In shafting transfer error, the azimuth axis of INS platform has different verticality degrees and coaxial error. Even if the mechanical zero of CNS and INS sub-systems has been calibrated strictly; with change in platform rotating angle, the inclination residue of installation error and non-verticality may be introduced to the integrated system [5]. The diagram of CNS/INS integrated navigation system shafting can be seen in Fig. 1.
When analyzing shafting transfer error, it is necessary to consider relationship between five elements closely related (non-verticality of INS azimuth shafting $\varepsilon_\beta$ and azimuth shaft rotating angle $\beta$; non-verticality of CNS pitch shafting $\varepsilon_\theta$ and rotating angle of pitch shaft $\theta$; non-verticality of CNS azimuth shafting $\varepsilon_\gamma$ and rotating angle of CNS azimuth shaft $\gamma$; calibration error between INS azimuth shaft and common-base standard surface at the mechanical zero position; calibration error between CNS shafting and main body coordinate system, common-base standard surface at the mechanical zero position).

Suppose in INS/CNS, the sub-system CNS’s rotating angle around the pitch shaft is $\theta$ and non-verticality of pitch shaft is $\varepsilon_\theta$, and the following formula can be acquired according to rotation cosine matrix:

$$C_{sp} = C_{sp}' C_{sp}$$

(1)

In the formula, $C_{sp}'$ represents the rotation relationship of CNS around pitch shaft, and $C_{sp}$ represents the rotation relationship caused by non-verticality of CNS around the pitch shaft. Their expression formulas are respectively:

$$C_{sp}' = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix}$$

(2)
\[
C^*_{p^s} = \begin{bmatrix}
1 & \varepsilon_\theta \sin \theta & 0 \\
\varepsilon_\theta \sin \theta & 1 & -\varepsilon_\theta + \varepsilon_\theta \cos \theta \\
0 & \varepsilon_\theta - \varepsilon_\theta \cos \theta & 1
\end{bmatrix}
\] (3)

According to aforesaid formula,
\[
C^*_{p} = \begin{bmatrix}
\cos \theta & \varepsilon_\theta \sin \theta & -\sin \theta \\
\varepsilon_\theta \sin 2\theta - \varepsilon_\theta \sin \theta & 1 & \varepsilon_\theta \cos 2\theta - \varepsilon_\theta \cos \theta \\
\sin \theta & \varepsilon_\theta - \varepsilon_\theta \cos \theta & \cos \theta
\end{bmatrix}
\] (4)

The rotating angle of CNS around the azimuth shaft is \( \gamma \) and the non-verticality of the azimuth shaft is \( \varepsilon_\gamma \). Similarly, the rotation relationship can be acquired:
\[
C^*_{H} = C^*_{p} C^H_{H}
\] (5)

In the formula, \( C^H_{H} \) represents the rotation relationship of CNS around the azimuth shaft, and \( C^*_{p} \) represents the rotation matrix caused by non-verticality of CNS around the azimuth shaft. Their expression formulas are respectively:
\[
C^H_{H} = \begin{bmatrix}
\cos \gamma & -\sin \gamma & 0 \\
\sin \gamma & \cos \gamma & 0 \\
0 & 0 & 1
\end{bmatrix}
\] (6)

\[
C^*_{p} = \begin{bmatrix}
1 & 0 & \varepsilon_\gamma \sin \gamma \\
0 & 1 & -\varepsilon_\gamma + \varepsilon_\gamma \cos \gamma \\
\varepsilon_\gamma \sin \gamma & \varepsilon_\gamma - \varepsilon_\gamma \cos \theta & 1
\end{bmatrix}
\] (7)

Put formula (6) and (7) into (5),
\[
C^*_{H} = \begin{bmatrix}
\cos \gamma & -\sin \gamma & \varepsilon_\gamma \sin \gamma \\
\sin \gamma & \cos \gamma & 2\varepsilon_\gamma (\sin \frac{r}{2})^2 \\
\varepsilon_\gamma \sin \gamma & 2\varepsilon_\gamma (\sin \frac{r}{2})^2 & 1
\end{bmatrix}
\] (8)

It is known that the non-verticality of azimuth shaft of INS sub-system is \( \varepsilon_\beta \) and azimuth shaft rotating angle is \( \beta \), the rotation matrix can be acquired:
\[
C^*_{A} = C^b_{A} C^d_{A}
\] (9)

In the formula, \( C^d_{A} \) represents rotation matrix of INS platform around the azimuth shaft,
and $C^b_{\alpha}$ represents the rotation matrix of INS platform non-verticality around the azimuth shaft. The formulas are respectively:

$C^b_{\alpha} = \begin{bmatrix}
\cos \beta & -\sin \beta & 0 \\
\sin \beta & \cos \beta & 0 \\
0 & 0 & 1
\end{bmatrix}$ \hspace{1cm} \text{(10)}$

C^b_{\alpha} = \begin{bmatrix}
1 & 0 & \varepsilon_\beta \sin \beta \\
0 & 1 & -\varepsilon_\beta + \varepsilon_\beta \cos \beta \\
\varepsilon_\beta \sin \beta & \varepsilon_\beta - \varepsilon_\beta \cos \beta & 1
\end{bmatrix}$ \hspace{1cm} \text{(11)}$

Put formula (10) and (11) into (9),

$C^b_{\alpha} = \begin{bmatrix}
\cos \beta & -\sin \beta & \varepsilon_\beta \sin \beta \\
\sin \beta & \cos \beta & 2\varepsilon_\beta (\sin \frac{\beta}{2})^2 \\
\varepsilon_\beta \sin \beta & 2\varepsilon_\beta (\sin \frac{\beta}{2})^2 & 1
\end{bmatrix}$ \hspace{1cm} \text{(12)}$

The conversion matrix of INS platform coordinate system toward common-base benchmark surface coordinate system (I system) can be expressed as:

$C^I_{\alpha} = \begin{bmatrix}
1 & \alpha_z & -\alpha_y \\
-\beta_z & 1 & \beta_x \\
\gamma_y & -\gamma_x & 1
\end{bmatrix}$ \hspace{1cm} \text{(13)}$

Similarly, the error of CNS during calibration with the common-base can be expressed as:

$C^p_{\alpha} = \begin{bmatrix}
1 & \alpha'_z & -\alpha'_y \\
-\beta'_z & 1 & \beta'_x \\
\gamma'_y & -\gamma'_x & 1
\end{bmatrix}$ \hspace{1cm} \text{(14)}$

Supposing inertial elements in INS have no installation error, the transfer process of horizon information toward CNS, i.e., the attitude information conversion process of INS can be shown simply in Fig. 2.

![Fig. 2 Attitude information conversion chart](image)

The conversion matrix of attitude transfer error $C^I_{\alpha}$ shall be:

$C^I_{\alpha} = C^p_{\alpha} C^s_{\alpha} C^l_{\alpha} C^{A}_{\alpha} C^{A}_{\alpha} C^{A}_{\alpha}$ \hspace{1cm} \text{(15)}$
4. Simulation of shafting transfer error

Supposing the shaft pendulum taper of INS azimuth shafting is 30” through process and processing, and the residual error is 6” generally after compensating through rotating shaft inclination calibration; the residual error of star sensor azimuth shafting through rotating shaft inclination compensation is 5”, and after-compensation residual error of pitch shafting is 7”; there is no calibration error on INS and common-base installation surface and star sensor and common-base installation surface. The star sensor pitch shafting is rotating from -80° to 80°, INS azimuth shafting is rotating from 0° clockwise, and star sensor azimuth shafting is rotating from 0° anticlockwise. When the carrier is static, the simulation of CNS horizon attitude errors transferred from INS shafts and INS heading error transferred from CNS shafts can be seen in Fig.3 and Fig.4. According to the simulation, for information transfer between INS and CNS, the horizon attitude of the former through shafting transfer may lead to the attitude error of the latter, as shown in Fig.5.

![Fig. 3 CNS horizon attitude errors transferred from INS shafts](image1)

![Fig. 4 INS heading error transferred from CNS shafts](image2)
5. Conclusion

INS and CNS have respective supporting shafting; during installation of the integrated system, it is easy to cause coaxial error between shafts, and meanwhile lead to rotating shaft inclination error when the shafting is rotating. Therefore, it is necessary to calibrate precisely the error relationship caused by rotation between the two sets of shafts through common base. The shafting error is easy to be transferred to CNS level by level, leading to attitude error of CNS. The shafting transfer error is not only related to current horizon attitude of carriers but also related to residual calibration error of its attitude error.

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