Design of airborne radar Attitude Test System Based on servo drive

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Abstract: This paper presents a design method of airborne radar attitude test system based on servo drive, which can realize the closed-loop test of servo system, the separate test of antenna drive module, the separate test of scanner base and the attitude test. The system adopts the attitude angle measurement method based on fiber laser gyroscope as the core, which can realize scanning angle: azimuth ±12° and pitch. By decoupling the disturbance and the measured, the small angle attitude algorithm is designed and corrected. The test results show that the scanning accuracy of the attitude determination system can be controlled ±0.3°, and through the modular instrument of PXI bus, the test efficiency and equipment fault maintenance ability of airborne radar can be improved.

1. Introduction:
The traditional airborne radar servo mechanism and attitude test are mostly manually tested by general instruments, which is inefficient and the error of data reading is relatively large due to the influence of objective conditions and operators. Therefore, testing through a test system built on modular characteristics or the virtual instruments of PXI equipment has become an important development direction of today’s test system.

In this paper, the modular instrument test system based on PXI bus is used to test the servo mechanism and attitude of airborne radar. Meanwhile, the signal conditioning box is used to realize the relevant test functions. In this way, the system becomes more reliable and expandable.

2. Principles of servo drive test system
The servo test system is mainly divided into three parts: antenna drive module test, scanner base test, antenna drive function test (antenna drive control module plus scanner base). In the antenna drive function test, the “inertial navigation unit” is installed on the scanner base to realize the detection of control angle. The hardware structure of the system is shown in Figure 1.
2.1 Test of scanner seat angle control:
As shown in Figure 2, the attitude measurement system is installed on the scanner base to measure the angle and angular velocity. When the scanner rotates in azimuth and pitch, the attitude measurement system can follow the movement, and detect the changes of the geomagnetic field and acceleration data in real time, process the data, and finally obtain the relevant data of the control angle of the scanner base.

3. Attitude determination system design

3.1 Hardware design of attitude determination system
The attitude measurement system is mainly composed of high-performance fiber optic gyroscope,
high-performance flexible inclinometer, silicon-based gyroscope and other sensors to realize the measurement of the square angle and pitch angle. The block diagram of the overall hardware composition is shown in Figure 3.

![Figure 3 composition block diagram of the attitude determination system](image)

3.1.1 Structure design of the attitude determination system

According to the sensitive direction of the measurement sensor, the system structure is shown in Figure 4.

![Figure 4 structure of attitude determination system](image)

3.2 Measurement and algorithm design

The coordinate transformation matrix from geographic coordinate system t to carrier coordinate system b will be used in the pitch and azimuth information measurement. According to the coordinate system transformation theory:

\[
C_t^b = \begin{bmatrix}
\cos \gamma & 0 & -\sin \gamma \\
0 & 1 & 0 \\
\sin \gamma & 0 & \cos \gamma
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \theta & \sin \theta \\
0 & -\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
\cos \psi & \sin \psi & 0 \\
-\sin \psi & \cos \psi & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

The pitch angle is measured by acceleration sensor and silicon-based gyroscope, and combined with the initial angle correction of high-performance level, the current pitch angle of scanner frame is output in real time. The acceleration sensor senses the change of the gravity field component caused by the platform pitching, and outputs corresponding analog signal ($\theta_\alpha$). As the rotation speed of the corresponding servo motor is high (45°/s), the interference of centrifugal acceleration on the inclinometer cannot be ignored, so a silicon-based gyroscope is added to measure the rotation speed ($\omega$).
which compensates the centrifugal acceleration caused by the rapid rotation of the motor, and corrects the measurement data of the tilt sensor. Two high-performance level meters, using electrolyte bubble as internal sensing unit, have high long-term stability and measurement accuracy, and can be used as horizontal zero reference ($\theta_0$) after the measurement system is powered on.

### 3.2.1 Algorithm design of the attitude angle measurement

#### a) Attitude angle calculation in small angle range

The relationship between accelerometer sensitivity $[a_x, a_y, a_z]^T$ and gravity field vector $[0, g, 0]^T$ is as follows:

$$
\begin{bmatrix}
    a_x \\
    a_y \\
    a_z
\end{bmatrix} =
\begin{bmatrix}
    \cos\psi & -\sin\psi & 0 \\
    \cos\theta\sin\psi & \cos\theta\cos\psi & \sin\theta \\
    -\sin\theta\sin\psi & \sin\theta\cos\psi & \cos\theta
\end{bmatrix}
\begin{bmatrix}
    1 & -\psi_0 & -\gamma_0 \\
    \psi_0 & 1 & \theta_0 \\
    -\gamma_0 & -\theta_0 & 1
\end{bmatrix}
$$

- $\psi_0$ is the misalignment angle matrix.

The result is as follows

$$
\begin{cases}
    \psi = \arcsin(-a_z/g) - \psi_0 \\
    \theta = \arcsin[a_x/g \cos(\psi_0 + \psi_1)] + \theta_0
\end{cases}
$$

#### b) Attitude angle correction

The acceleration sensor senses the change of gravity field component caused by platform pitching and outputs corresponding analog signal ($\theta_\alpha$). Because the rotation speed of the corresponding servo motor is fast (45°/s), a silicon-based gyroscope is added to measure the rotation speed ($\omega_\theta$), compensating the centrifugal acceleration caused by the rapid rotation of the motor, and correcting the measurement data of the tilt sensor.

Two high-performance level meters, using electrolyte bubble as the internal sensing unit, have high long-term stability and measurement accuracy, and can be used as horizontal zero reference ($\theta_0$) after the measurement system is powered on. It can be summarized as follows:

$$
\Theta = f(\theta_0, \omega_\theta, \theta_\alpha)
$$

Specifically, the centripetal acceleration produced by pitching: $a_\theta = w_\theta^2 r_\theta$

The component of the centripetal acceleration produced by azimuth rotation on the sensitive axis:

$$
a_\phi = g \sin \theta + a_\psi \cos \theta
$$

The component of the gravity acceleration on the sensitive axis:

$$
g \sin \theta = g \sin \theta + a_\phi \cos \theta
$$

$$
\theta = \arcsin([a_\phi + w_\phi^2 r_\phi + w_\phi^2 r_\phi \cos(\theta_{\phi\psi})]) / g
$$

In the above formula, $w_0$ is the angular velocity of the scanner frame around the local horizontal axis. $\theta$ is the angle between the inclination angle and the local horizontal plane. $w_\phi$ is the rotational angular velocity of the scanner frame around the local vertical axis. The above formula does not
consider the error caused by installation and the specific transformation of the corresponding sensors in the coordinate system of the attitude determination system. In order to achieve the corresponding test accuracy, the installation misalignment angle and coordinate transformation should be further considered and corrected.

Inclinometer misalignment correction:

The corresponding misalignment correction matrix is:

\[
\begin{bmatrix}
\cos \psi & \sin \psi & -\sin \gamma \\
-\sin \psi & \cos \psi & \sin \theta \\
\sin \gamma \cos \psi + \sin \theta \sin \psi & \sin \gamma \sin \psi - \sin \theta \cos \psi & 1
\end{bmatrix}
\]

The angle in the above matrix is the misalignment during installation. In the process of use, because there are strict restrictions on the position tolerance of the installation part, the corresponding \( \theta \) and \( \gamma \) are small amounts, and the correction matrix can be further simplified. \( \psi \) is the angle between the attitude determination system and the local due north direction. Therefore, the above matrix can be expressed as:

\[
\begin{bmatrix}
\cos \psi & \sin \psi & -\sin \gamma \\
-\sin \psi & \cos \psi & \sin \theta \\
\sin \gamma \cos \psi + \sin \theta \sin \psi & \sin \gamma \sin \psi - \sin \theta \cos \psi & 1
\end{bmatrix}
\]

Therefore, the acceleration of gravity after the correction of misalignment:

\[
a_y = \begin{bmatrix}
\cos \psi & \sin \psi & -\sin \gamma \\
-\sin \psi & \cos \psi & \sin \theta \\
\sin \gamma \cos \psi + \sin \theta \sin \psi & \sin \gamma \sin \psi - \sin \theta \cos \psi & 1
\end{bmatrix}
a
\]

\( a_y \) is the measurement of position \( a \), which is the component of the gravity acceleration projected to the coordinate system of the installed determination system. The corresponding angle of \( \theta \) and \( \gamma \) can be measured by level instrument, which has nothing to do with the angle \( \psi \) in the north direction. The specific transformation formula is: \([-G \sin \gamma \ G \sin \theta \ G \cos \gamma \cos \theta]\). The corresponding \( \theta \) and \( \gamma \) angles can be measured with a spirit level, which has nothing to do with the north included angle \( \psi \).

The measurement error correction of the silicon-based gyroscope is as follows:

The misalignment transformation of the silicon-based gyroscope measurement axis is (premise: the platform pitch rotation is parallel to the local horizontal plane):

\[
\begin{bmatrix}
\cos \psi & \sin \psi & -\sin \gamma \\
-\sin \psi & \cos \psi & \sin \theta \\
\sin \gamma \cos \psi + \sin \theta \sin \psi & \sin \gamma \sin \psi - \sin \theta \cos \psi & 1
\end{bmatrix}
\begin{bmatrix}
w_x \\
w_y \\
w_z 
\end{bmatrix} = \begin{bmatrix}
W_x \\
W_y \\
W_z 
\end{bmatrix}
\]

\( W_x \) is the actual measured value of the silicon-based gyroscope. In the above formula, \( \psi \) is defined as the included angle with north direction in b), but the yaw rotation of this project is carried out around the fixed vertical axis of the local coordinate system. And the pitch rotation and yaw rotation are always axially vertical, so they must be decomposed into two different rotations (RPY, Euler type). The azimuth rotation will not affect the orientation of the measurement axis of silicon-based gyroscope. Therefore, \( \psi \) in the above formula is the angle between the y-axis of the attitude determination system after installation and the y-axis of the scanning platform, which is a small angle. Therefore, the component projection of the actual pitch rotation of the scanner gantry on the measurement axis of the silicon-based gyroscope is:

\[
w_y \begin{bmatrix}
\cos \psi & \sin \psi & \sin \gamma
\end{bmatrix}
\]

The transformation relationship of the measured value of the inclinometer:

That is to say, for the pitch movement of the scanner frame, the overall effect is equivalent to the angular movement changes of \( \theta \) when \( \psi \) and \( \gamma \) are zero. The transformation matrix corresponding to each transformation is:
\[ \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{bmatrix} \]

So there is:

\[ \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} -G \sin \gamma \\ G \sin \theta \\ G \cos \gamma \cos \theta \end{bmatrix}_{\text{miss a target}} = \begin{bmatrix} -G \sin \gamma_{\text{shi}} \\ G \sin \theta_{\text{shi}} \cos \theta_{\text{shi}} + G \sin \theta_{\text{mav}} \sin \gamma_{\text{shi}} \\ -G \sin \theta_{\text{shi}} \sin \theta_{\text{mav}} + G \cos \theta_{\text{mav}} \end{bmatrix} \]

Therefore, the measurement accuracy of the adopted gyroscope is 0.1% FSR, that is, the final angle output accuracy is about 0.1% FSR under dynamic conditions. When the scanning table is at a large angle (> 9°), the compensation caused by the maximum centrifugal acceleration is less than 10% of the gravity component. When the error of centrifugal acceleration is 5%, the change rate of the ratio to gravity component is less than 1%. Therefore, when the measurement value exceeds 9°, the attitude angle can be measured in real time with the measurement value of the precision inclinometer, and the accuracy can reach 5‰.
5. Conclusion
In this paper, the servo drive mechanism and attitude test system of airborne radar are designed by using a virtual instrument system based on modular instrument. The design of attitude angle measurement algorithm based on fiber laser gyroscope (FOG) is mainly introduced. By changing the attitude of the tested platform in the inertial system, the disturbance and the measured can be decoupled, which can greatly reduce the influence of transmission clearance disturbance on the test results, and provides a good design idea for the design of radar automatic test equipment in the future.

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