Method for Decomposing Accuracy of Interferometer Based on Inertial Navigation Aid

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Abstract. In the complex electromagnetic countermeasure environment, in order to improve the detection ability is of great significance for aircraft application. Scientific and rational decomposition of direction-finding index plays an important role in system optimizing and product performance improving. In this paper, the direction-finding accuracy of passive detection device based on aided inertial information is calculated and analyzed. The accuracy demand of passive detection device is decomposed into accuracy of the attitude control algorithm, inertial device and structure installation. Through the calculation and analysis, the index of passive detection device will be 1.93°, when the direction-finding accuracy is 2°. The analysis results show that the index decomposition method is reasonable and effective, and can meet the requirements of the overall design, which provides a basis for the overall design.

1. Introduction
At present, with the rapid development of information technology, advanced electronic devices are gradually applied to aircraft, so consumer have more and more functional requirements for aircraft. Passive detection capability is an important function for aircraft. Therefore, the aircraft with passive detection ability will be increasingly favour with consumer[1]. The application of inertial information to the passive detection device is important for improving the accuracy of the direction-finding.

However, the aircraft system is complex and has more factors affecting the direction-finding accuracy[2]. Such as attitude control precision, inertial device precision, structure installation precision. How to decompose the accuracy of every influence factor scientifically and rationally, and allocate the direction-finding index for passive detection device, at present, relative researches are relatively few. The research of decomposition technology of direction-finding accuracy based on inertial information aided passive detection device is of great significance for optimizing the overall design and improving the detection ability. Based on the general direction-finding accuracy and the theoretical calculations and simulations, this paper presents the corresponding technical indicators for the direction-finding allocation of passive detection devices from the perspective of the aircraft's overall design.

2. Overall Direction Measurement Index
In the overall direction of direction measurement, part of the system in use, according to their own different purposes, the requirements of the accuracy are also different. From the perspective of index decomposition, this paper gives the total directional error as 2°.
3. Basic mathematics

3.1 The basic principle of passive direction-finding

The basic principle of passive direction-finding is to use a passive time-of-flight direction-finding system[3]. Using multiple antennas, the angle between the arrival signal and the antenna normal is calculated by calculating the phase difference between the signal and the antenna, and the phase information of the incident electromagnetic wave is obtained[4].

![Figure 1. Schematic diagram of passive detection](image1)

3.2 Coordinate system definition

3.2.1 Arrow coordinate system

Coordinate origin $o_1$ is the arrow centroid, $o_1x_1$ points forward along the main axis of the arrow; $o_1y_1$ is perpendicular to $o_1x_1$ and is upward in the longitudinal symmetry plane of the arrow. The $o_1z_1$ axis is determined by the Right hand rule [4].

3.2.2 Measuring coordinate system

The coordinate origin $o_c$ is the geometric center of the antenna array, $o_cx_c$ points to the rear along the main axis of the arrow; $o_cy_c$ is the normal direction of the antenna; the $o_cz_c$ axis is determined by the right hand rule.

3.3 Inertial Navigation Aided Direction-finding Principle

The basic mathematical principle of the interferometer direction-finding technology based on inertial information is to transmit the attitude information of the aircraft acquired by the inertial device in the arrow coordinate system to the passive detecting device[5]. The radiation source information acquired by the interferometer in the measurement coordinate system is framing, and the direction information of the radiation source is solved. Inertial devices and interferometers are generally mounted on different reference planes, taking into account the characteristics of the structural installation of the aircraft. Figure 2 shows the installation.

![Figure 2. Installation diagram](image2)

The coordinate conversion relationship between the arrow coordinate system($o_1 - x_1, y_1, z_1$) and the measurement coordinate system($o_c - x_c, y_c, z_c$) of the interferometer is shown in Fig. 3 [6].
Figure 3. Conversion relationship between measurement coordinate system and arrow coordinate system

See the formula (1) for the transformation matrix from the measurement coordinate system to the arrow coordinate system.

\[
B_c = M_z \begin{bmatrix} \gamma_c \\ \beta_c \\ \alpha_c \end{bmatrix} = \begin{bmatrix}
\cos \alpha_c & \sin \alpha_c & -\sin \beta_c \\
-\sin \alpha_c & \cos \alpha_c & \cos \beta_c \\
\cos \alpha_c & \cos \beta_c & \sin \alpha_c \cos \gamma_c - \sin \alpha_c \cos \gamma_c - \sin \beta_c \sin \gamma_c + \cos \alpha_c \cos \gamma_c & \cos \beta_c \sin \gamma_c \\
\cos \alpha_c & \cos \beta_c & \sin \alpha_c \sin \gamma_c - \cos \alpha_c \sin \gamma_c - \sin \beta_c \cos \gamma_c & \cos \beta_c \cos \gamma_c
\end{bmatrix}
\]

(1)

4. Error factor analysis and model construction

According to the basic principle of the inertial information assisted interferometer direction-finding on the aircraft, the error factors affecting the direction-finding of the interferometer are as follows:

- Interferometer direction-finding error \( (\sigma_1) \);
- Attitude measurement error \( (\sigma_2) \);
- Attitude control error \( (\sigma_3) \);
- Interferometer installation pitch/yaw error \( (\sigma_4) \);
- Interferometer installation torsion error \( (\sigma_5) \);
- Attitude measurement torsion error \( (\sigma_6) \);

According to the characteristics of the error factor, the model of the total direction-finding error is:

\[
\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2 + \sigma_5^2 + \sigma_6^2}
\]

(2)

According to the total direction-finding error, based on the analysis of each error factor, the accuracy index of the interferometer is given.

5. Direction error decomposition

5.1 Indicator decomposition steps

The indicator decomposition flow chart is shown in Figure 4.
5.1.1 Attitude measurement error
Attitude measurement error is affected by the accuracy of the inertial device gyro. According to the development status of inertial devices [7], the accuracy of common fiber optic gyros can generally reach 0.01°/h.

5.1.2 Attitude control error
The attitude control error is affected by the attitude control algorithm, which is typically 0.2°.

5.1.3 Installation error
Installation errors include pitch/yaw direction error and rolling direction error. Because the theoretical analysis of equipment installation error is not accurate enough, this paper gives the error index through the attitude measurement test combined with the small sample data statistical method.

5.1.3.1 Pitch/yaw direction error
The attitude measurement test results are shown in Table 1.

| Serial number | Pitch/yaw angle (") | Test status                             |
|---------------|---------------------|-----------------------------------------|
| 1             | -181                | Initial state                           |
| 2             | 88                  |                                        |
| 3             | -97                 | Fastening inertia device                |
| 4             | 25                  |                                        |
| 5             | -130                | Tightening interferometer               |
| 6             | 63                  |                                        |
| 7             | -200                | Fastening cabin                         |
| 8             | 97                  |                                        |
| Average value of absolute values | 110.125 | —                                      |
| Standard deviation | 58.3  | —                                      |
| Maximum       | 200                 | —                                      |
The total mean of pitch/yaw deviation $\xi$ obeys normal distribution and the total standard deviation is unknown [8]. The range of attitude deformation is calculated by interval estimation method [9]. The confidence interval of 99.8% is

$$
(\bar{\xi} - t_{\alpha}(n-1) \frac{\sigma}{\sqrt{n}}, \bar{\xi} + t_{\alpha}(n-1) \frac{\sigma}{\sqrt{n}})
$$

(3)

In the above formula $\alpha = 0.002$, you can see by querying the T distribution table.

$$
t_{\alpha}(n-1) = 4.785
$$

(4)

Therefore, according to formula (3) and formula (4), the upper limit of the confidence interval can be obtained. To ensure the reliability of the design, a certain redundancy design of the upper limit of the confidence interval can obtain a pitch/yaw deviation of 0.17°.

5.1.3.2 Torsional direction error
Torque direction measurement test results are shown in Table 2.

| Serial number | Torsional angle ("') | Test status               |
|---------------|----------------------|---------------------------|
| 1             | 100                  | Initial state             |
| 2             | -45                  | Fastening inertia device  |
| 3             | -274                 | Tightening interferometer |
| 4             | -89                  | Fastening cabin           |

Average value of absolute values 127 —
Standard deviation 100 —
Maximum 274 —

The overall mean $\xi$ of the torsional deviation follows a normal distribution, and the population standard deviation is an unknown quantity. In combination with the above method, the torsion deviation can be obtained as 0.2°.

5.1.3.3 Attitude measurement torsion error
According to the basic principle of the inertial information-assisted interferometer, when the aircraft is twisted, in addition to twisting its own error, it will cause additional errors to the antenna measurement, which is the attitude measurement torsion error. The schematic diagram of the coordinate change when the aircraft is twisted is shown in Figure 5.

![Figure 5. Torsion error geometry diagram](image)

It is assumed that the coordinates in the measurement coordinate system in which the radiation source M is not rotated are $(x_A, y_A, z_A)$, $\alpha$ is the azimuth angle and $\beta$ is the pitch angle. Can get the following formula:

$$
\tan \alpha = \frac{z_A}{x_A}
$$

(5)
\[
\tan \beta = \frac{y_A}{\sqrt{x_A^2 + z_A^2}}
\]  
(6)

It can be obtained from the above formula:

\[
y_A = \tan \beta \cdot \sqrt{1 + \tan^2 \alpha} \cdot x_A
\]  
(7)

\[
z_A = \tan \alpha \cdot x_A
\]  
(8)

Let the torsion angle be \(K\), and the coordinate of the radiation source \(M\) in the post-torsion coordinate system is \((x'_A, y'_A, z'_A)\). From the geometric relation of Fig.5, the coordinate transformation relation before and after torsion can be obtained as follows.

\[
\begin{align*}
x'_A &= x_A \\
y'_A &= y_A \cos K + z_A \sin K \\
z'_A &= -y_A \sin K + z_A \cos K
\end{align*}
\]  
(9)

By substituting formula (9) into a new coordinate system, the following formula can be obtained.

\[
\tan \alpha' = -\tan \beta \cdot \sqrt{1 + \tan^2 \alpha} \cdot \sin K + \tan \alpha \cdot \cos K
\]  
(10)

According to the accuracy of the inertial device and the installation torsion error, combined with the formula (10), \(\alpha - \alpha'\) can be calculated, which is the attitude measurement error caused by the torsion deviation.

If the technical index of the direction-finding range of the interferometer is \(\pm 45^\circ\), combined with the measurement accuracy of the inertial device and the twisting installation deviation of the interferometer, the attitude measurement torsion error of the interferometer antenna can be obtained to be about \(0.2^\circ\).

5.2 Interferometer accuracy calculation

Through the above analysis, the maximum allowable direction-finding error is \(2^\circ\). The attitude measurement error \(\sigma_2=0.01^\circ, \sigma_3=0.2^\circ\), the interferometer installation pitch/yaw error \(\sigma_4=0.17^\circ\), the torsion error \(\sigma_5=0.2^\circ\), the attitude measurement torsion error \(\sigma_6=0.2^\circ\). Combined with formula (2), the direction-finding accuracy of the interferometer can be calculated to be \(1.93^\circ\).

6. Conclusion

This paper starts from the direction-finding index of the interferometer and decomposes the direction-finding index by means of coordinate transformation, interval estimation and attitude measurement. The analysis results show that the decomposition method of this index is reasonable and effective, which can meet the requirements of the overall design of the system and provide an effective theoretical basis for the system design.

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