Influence of motion characteristics of dual stealth aircraft on monopulse radar performance

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Abstract. In view of the difficulties to effectively evaluate the influence of penetration of dual stealth aircraft formation on monopulse radar angle tracking error under different flight speeds, the dynamic track model of the dual stealth aircraft under different navigation speeds is established for the first time, and the acquisition method of the dynamic Radar cross section of the dual stealth aircraft formation under different navigation speeds is proposed; the dynamic signal-to-noise ratio of the dual stealth aircraft under different navigation speeds is used as a reference and the model of single pulse radar angle tracking error is established. This paper analyzes the influence of the formation motion characteristics of dual stealth aircraft on the angle tracking error performance of monopulse radar. It is the first time to conclude that the acceleration of the navigation speed of dual stealth aircraft will increase the angle tracking error of monopulse radar when there is no interference.

1. Introduction

The electronic warfare characteristics of dual stealth aircraft formation are particularly prominent in the actual combat, but before studying the electronic warfare between monopulse radar and stealth aircraft formation, it is necessary to understand the influence of different movement characteristics of stealth aircraft formation on monopulse radar angle tracking error performance without jamming.

This chapter mainly aims at solving the difficulty of establishing monopulse radar angle tracking error model caused by the diversity of the formation motion characteristics and the complexity of the combat style of the dual stealth aircraft. Referring to the parameter navigation speed which is easy to affect the dynamic parameters of the aircraft in the process of flight [1-3], the dynamic track model of the dual stealth aircraft under different navigation speeds is established for the first time. Because the angle tracking error of monopulse radar is affected by the variable dynamic RCS(Radar cross section) in real-time SNR(signal-to-noise ratio), the angle tracking principle of monopulse radar and the derivation and transformation idea of velocity influence factor in the references [3-7], using the dynamic SNR of two aircrafts at different navigation speeds as the parameter variable [8-13], a solution model of angle tracking error of monopulse radar suitable for the motion characteristics of two aircrafts is established.
2. The influence of the speed of dual stealth aircraft on the angle tracking performance of monopulse radar

2.1. Construction of navigation speed model.

The effective cooperative maneuver tactics of dual stealth aircraft in penetration operations can get rid of the real-time tracking of tracking radar. Generally, the basic change parameter of aircraft flexible maneuver is the real-time change of the navigation speed. The real-time change of the speed also causes the sharp change of the aircraft attitude angle and the different change characteristics of the RCS of stealth aircraft. In order to study the influence of the flight speed of the dual stealth aircraft on the angle tracking performance of monopulse radar, it is necessary to model the flight path. In order to effectively measure the influence of the flight speed, this paper adopts the level flight path as the penetration path model of the stealth aircraft to exclude the influence of different azimuth pitch angles of the formation on the attitude of the aircraft.

Without considering the disturbance of the flight attitude, the force analysis of the aircraft body is combined with the plane level flight model in Figure 1.

\[
\begin{align*}
\alpha(t) &= 0^\circ, \quad \theta(t) = 0^\circ, \quad \eta(t) = 0^\circ \\
\end{align*}
\]

(1)

Figure 1 Coordinate transformation between space and ground

Taking the time factor of real-time change into account, symbols a, B and C represent the corresponding pitch angle, azimuth angle and roll angle respectively. The real-time value of attitude angle is expressed by formula (1).
After the dynamic model of formation flying is built, the formation flying parameters in radar coordinate system are set. According to the navigation parameters of stealth aircraft in actual operation and the horizontal flight path and attitude angle model constructed, combined with the coordinate conversion relationship between ground air defense radar and air stealth aircraft in actual operation, and with reference to the setting of parameters related to horizontal flight path of dual aircraft formation, the corresponding track model is shown in Figure 2. Carefully observe the polar coordinate formula (2) and (3) under the conversion of the corresponding radar and the airframe. The change of the airframe attitude angle is determined by the flight speed, the navigation direction and the relative position of the airframe and the radar.

The transformation relationship between the two body space coordinate system and the monopulse radar coordinate system corresponding to the formation track is as follows [1-2]:

\[
\begin{bmatrix}
    x_{ST}(t) \\
    y_{ST}(t) \\
    z_{ST}(t)
\end{bmatrix} = I \times
\begin{bmatrix}
    x(t) \\
    y(t) \\
    z(t)
\end{bmatrix} + \begin{bmatrix}
    1 & 0 & 0 \\
    0 & 1 & 0 \\
    0 & 0 & 1
\end{bmatrix} \times
\begin{bmatrix}
    -x_{r}(t) \\
    -y_{r}(t) \\
    -z_{r}(t)
\end{bmatrix}
\]

(2)

In formula (2), \((x_{ST}(t), y_{ST}(t), z_{ST}(t))\) is the equivalent coordinate of \((x(t), y(t), z(t))\) in the dual body coordinate system; \((x(t), y(t), z(t))\) is the azimuth coordinate of any point in the monopulse radar coordinate system; \((-x_{r}(t), -y_{r}(t), -z_{r}(t))\) is the position coordinate of the equivalent point of stealth aircraft formation target in the monopulse radar coordinate system.

\[
I = \begin{bmatrix}
    \cos(\theta(t)) & 0 & -\sin(\theta(t)) \\
    0 & 1 & 0 \\
    \sin(\theta(t)) & 0 & \cos(\theta(t))
\end{bmatrix}
\]

(3)

\(I\) is the coordinate conversion matrix of dual body and monopulse radar. The coordinate origin \((0,0,0)\) of monopulse radar is substituted into formula (3). The coordinate of monopulse radar in dual plane coordinate system is \((x_{a}(t), y_{a}(t), z_{a}(t))\), and the pitch angle \(\alpha(t)\) and azimuth angle \(\theta(t)\) with time change are [12-13]:

\[
\begin{align*}
\alpha(t) &= \arctan \left( \frac{z_{ST}(t)}{\sqrt{x_{ST}^2(t) + y_{ST}^2(t)}} \right) \\
\theta(t) &= \arctan \left( \frac{y_{ST}(t)}{x_{ST}(t)} \right)
\end{align*}
\]

(4)

Using real-time pitch angle and azimuth angle, the dynamic RCS sequence of two aircrafts is extracted.

The parameters of the two aircraft level flight path are as follows: ① the roll angle of keeping the formation level flight is always \(\eta=0^\circ\); ② the aircraft elevation of keeping the formation level flight is \(\delta<5^\circ\); ③ the vertical height of the formation level flight from the ground is \(H=8km\); ④ when the distance between the two aircrafts is 150 meters, keep the formation track of the two stealth aircrafts unchanged, and the vertical distance between the projection line of the flight path of the stealth aircraft \(st1\) on the ground and the monopulse radar is \(L_2=5.15km\) respectively; ⑤ when the distance between the two aircrafts is 150 meters, keep the track of the stealth aircraft \(st2\) unchanged, and the vertical distance between the projection line of the flight path of the stealth aircraft \(st2\) on the ground and the
monopulse radar is $d=5\text{km}$; ⑥ the distance between the projection of the track starting point on the ground and the radar projection point on the track projection line is $R=20\text{km}$.

2.2. Setting of navigation speed parameters

In stealth aircraft penetration operations, the general penetration speed is kept at $0.8\sim1.7\text{Ma}$, and the subsequent corresponding simulation parameter settings are shown in Table 1 below.

| Speed of navigation | Corresponding speed ($m/s$) |
|---------------------|-----------------------------|
| 1 Ma                | 340                         |
| 1.2 Ma              | 408                         |
| 1.4 Ma              | 476                         |

2.3. Change of attitude angle under different navigation speeds

The real-time change of aircraft attitude angle will be generated by setting the same flight speed of the dual stealth aircraft under the same level flight path. The following simulation will be carried out by changing the aircraft attitude angle under the same formation flight speed in the same time period.

In Figure 3 (a) and (b) respectively represent the dynamic fluctuation of the body azimuth angle and the body pitch angle of the dual stealth aircraft in the same flight time interval at different flight speeds. Through careful observation, it can be found that the change trend of the attitude angle of stealth aircraft is the same as a whole at different level flight speeds. With the increase of flight speed, the real-time change rate of the corresponding body attitude angle increases, and the overall figure fluctuation is more intense.

2.4. Real time change under different navigation speeds

The time-varying simulation analysis of different formation flying speed models is carried out by using the static database of a certain type of foreign double stealth aircraft formation in the whole airspace and combining with the real-time dynamic calculation method of stealth aircraft formation in level flight path mode. The time-varying results are shown in Figure 4.
Through careful analysis of the figure, it can be seen that the fluctuation range of the real-time RCS under the time-varying speed model is generally $-31.57 \sim 38.72$ dBsm in the time-domain of $0 \sim 150s$. Due to different flight speeds, the attitude angle of the airframe changes, and the fluctuation of the corresponding RCS is also different. In the whole flight sequence, with the increase of the flight speed, the fluctuation of the real-time RCS jitter becomes more and more intense, and the attitude angle of the airframe changes more and more sharply and the visual range of the body is also increasing.

3. Construction of monopulse radar angle tracking model under the navigation speed model

The accurate real-time angular coordinates and distance information of dual stealth aircraft formation is the premise of monopulse radar effective tracking. Different flight speeds of stealth aircraft formation will cause the real-time coordinate information of the body to change, which will produce a certain angle tracking error to monopulse radar. At this time, since the influence of interference is not considered, the internal noise of the receiver shall be considered in combination with the flight speed of the aircraft. According to the radar equation, the instantaneous signal-to-noise ratio of the monopulse radar at different flight speeds of the two aircraft can be [8-9]:

$$
\frac{S_v}{N} = \frac{P_m \sigma_r(t)}{R_n(t)} \frac{G_m G_r \lambda^2}{(4\pi)^3 k T_b B M F L_z} \tag{5}
$$

In formula (5), the peak power of radar transmission is $P_m$; the gain of transmitting antenna is $G_m$; the gain of receiving antenna is $G_r$; the wavelength is $\lambda$; the RCS value of stealth aircraft at time $t$ is $\sigma_r(t)$ at different flight speeds; the bandwidth of receiver is $B_m$; the noise coefficient of receiver is $F_M$; the accumulated loss of radar is $L_z$, the fluctuation loss of target is $L_f$; the instant distance between stealth aircraft and radar at different flight speeds is $R_n(t)$.

The standard deviation of target azimuth error of monopulse radar when measuring the angle of stealth aircraft with different flight speeds can be expressed as [8-11]:

$$
\Delta \theta_{\text{ave}} = \frac{\theta_{\text{ave}}}{K_m} \sqrt{\frac{1}{B \tau N} \left[1 + \left(\frac{S_v}{N}\right)^2 \right]^{1/2}} \tag{6}
$$

4. Influence of navigation speed on angle tracking performance of monopulse radar

Refer to the relevant parameter settings of the active monopulse radar, and the corresponding specific parameters are shown in Table 2.

| Table 2 parameters setting of monopulse radar | Measurement |
|---------------------------------------------|-------------|
| Transmitting average output power /kw       | 100         |
| Transmit antenna gain /dB                   | 35          |
| Receiving antenna gain /dB                  | 35          |
| Effective temperature of noise /K           | 290         |
| Boltzmann constant / (kg \cdot m^2 \cdot s^{-2} \cdot K^{-1}) | 1.38 \times 10^{-23} |
| Radar receiver bandwidth /MHz               | 30          |
| Total system loss /dB                       | 12          |
| Minimum detectable SNR /dB                  | 20          |

4.1. Change of signal-to-noise ratio at different flight speeds

Combined with the definition formula 5 of the real-time RCS change trend and signal-to-noise ratio under the time-varying speed model of Figure 5, the real-time signal-to-noise ratio changes under different conditions of formation navigation speed shown in Figure 5 are comprehensively analyzed.
Compared with the change of time-varying signal-to-noise ratio under different flight speeds, although the flight speed is different, the trend of the overall real-time signal-to-noise ratio is the same. With the continuous improvement of the flight speed of two aircraft, the signal-to-noise ratio changes more obviously in the whole flight range, and the time-varying rate increases significantly. Combined with the real-time RCS under the time-varying speed model, it can be seen from Figure 5 that the change trend of the real-time SNR is roughly consistent with that of the real-time RCS. Combined with theoretical formula 5, it is also verified that the general trend of the real-time SNR proportional to the time-varying RCS.

4.2. Time varying analysis of angle tracking error of monopulse radar with different navigation speed

Using the formulas 5 and 6 derived in theory, combined with the related radar parameter setting and real-time signal-to-noise ratio simulation, the real-time change of monopulse radar angle tracking error under different navigation speed modes is obtained.

Figure 6 shows the time-varying simulation of the radar angle tracking error of the two stealth aircraft under different speed modes within 0 ~ 150s. It can be seen directly that different formation speed will cause some errors in some time nodes of radar angle tracking stage.

The comparative analysis can summarize the following points:
when the navigation speed is $340 \text{ m/s}$, the average error of monopulse radar angle tracking is $0.01017^\circ$; when the navigation speed is $408 \text{ m/s}$, the average error of monopulse radar angle tracking is $0.01023^\circ$; when the navigation speed is $476 \text{ m/s}$, the average error of monopulse radar angle tracking is $0.01226^\circ$; through comprehensive comparison, it can be found that the faster the navigation speed is, the more obvious the angle tracking error is.

In Figure 5 and Figure 6 (d), it can be found that the change trend of the overall angle tracking error of the time-varying monopulse radar is inversely proportional to the real-time signal-to-noise ratio. With the increase of the navigation speed, the real-time signal-to-noise ratio is smaller in some sections, which makes the angle tracking error increase continuously, and the error parameter is more obvious.

5. Summary
In this chapter, the angle tracking characteristics of monopulse radar are specifically analyzed based on the speed characteristics of dual stealth aircraft. By establishing the basic combat model and monopulse radar angle tracking error model close to the actual combat, and referring to the acquisition ideas and methods of dynamic RCS, the real-time signal-to-noise ratio is obtained on the premise of acquiring the dynamic RCS sequence of the airframe with different navigation speed and different aircraft speed respectively. The change of radar angle tracking error under the influence of different velocity parameters is obtained by the radar angle tracking model adapted to the flight of the dual stealth aircraft. The simulation results show that the dual stealth aircraft formation will generate a certain angle tracking error under different velocity parameters. With the acceleration of the navigation speed of the dual stealth aircraft formation, the angle tracking error of the monopulse radar tends to increase.

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