Simulation Research on Dynamic RCS Characteristics of Cruise Missile

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Abstract. The target radar cross section (RCS) is an important basis for air defense radar detection and tracking. Aiming at the influence of flight attitude change on the target RCS during the actual flight process, a dynamic RCS method based on the target static RCS database and the target motion track is proposed. The dynamic RCS characteristics of the cruise missile under the actual motion track are simulated, which is convenient for the air defense radar to accurately and quickly detect the target, and further provide operational advice for the best timing of the air defense weapon interception target. The simulation results show that the method can quickly and accurately obtain the dynamic RCS characteristics of the air target. The analysis of the simulation results can provide a theoretical reference for the air defense weapon to intercept the enemy’s incoming target.

Key words. FEKO; Dynamic RCS; Track simulation; Attitude angle; cruise missile.

1. Introduction

Radar cross section (RCS) is the most basic and important parameter to characterize the target characteristics, reflecting the target's ability to scatter electromagnetic waves [1]. In both static and dynamic aspects, dynamic scattering characteristics have a very high practical value in combat application research. The main way to obtain the dynamic scattering characteristics of a target is external field measurement. Since the external field dynamic measurement results can accurately reflect the actual scattering characteristics of the target, the world's military powers attach great importance to the construction and development of the target characteristic test field [2]. However, due to the high field dynamics measurement site requirements and high cost, the computer simulation technology is used to study the target dynamic RCS characteristics.

In Literature [3], based on the static measurement data of the motion attitude angle variation and the reduction ratio model, the dynamic RCS of the ballistic missile is obtained, but the accuracy of the model cannot be guaranteed, thus affecting the accuracy of the static RCS. In Literature [4], the typical target F-117 is taken as the research object. Based on the simulation of the previous electromagnetic scattering characteristics, the static RCS database of the target full airspace is obtained. The quasi-static method is used to simulate the dynamic RCS characteristics of the target maneuver. Stealth aircraft maneuvering provides simulation theory and experimental basis, but only studies the dynamic RCS under different
route shortcuts, and does not study the RCS under the changing track. Literature [5] based on FEKO software simulation calculation of fighter RCS, provides a data basis for the demonstration, design and application of fighters, has important practical significance, but the article only analyzes the target static RCS, research has certain limitations.

In this paper, the Tomahawk cruise missile is taken as the research object. Firstly, the 3D model of target electromagnetic calculation is established according to the actual size of the target. The target full-space static RCS sequence is obtained by FEKO software. Then, based on the kinematics of the target, the target is simulated based on the segmentation idea. Different flight paths are obtained. Finally, the attitude angle change value in the track simulation process is compared with the target static RCS database interpolation, and the typical air target dynamic RCS sequence is extracted. The electromagnetic scattering characteristics of different targets under different motion tracks are studied. The impact of weapon interception on the best timing.

2. Define the coordinate system and target attitude angle
(1) Radar coordinate system (n system)
The radar coordinate system generally uses the measured radar as the coordinate origin, with the north direction as the axis, the west direction as the axis, and the vertical direction as the axis.

(2) Body coordinate system (b system)
The body coordinate system is a coordinate system that is fixed to the body. The coordinate origin of the body coordinate system is located at the center of gravity of the aircraft, pointing forward along the longitudinal axis of the body, pointing to the right along the axis of the body, perpendicular to the axis, and pointing upward along the vertical axis of the aircraft, as shown in Figure 1. The orientation of the body coordinate system relative to the radar coordinate system is the target attitude angle.

\[ \alpha, \beta, \gamma \]

Figure 1. Positional relationship between radar coordinate system and body coordinate system

The target attitude angle is defined as follows: heading angle, pitch angle and roll angle, which constitute the target attitude angle. The angle between the projection line and the axis of the target vertical axis is the angle between the target vertical axis and the plane, which is the angle between the plane and the plummet face containing the axis. From the attitude angle heading angle, pitch angle and roll angle, the change of the attitude of the target during the movement can be completely determined [4].

3. Air target dynamic RCS value calculation
3.1. Dynamic RCS simulation method
The calculation steps of the RCS value in the air target maneuver process mainly include three processes: route generation, attitude angle calculation and RCS value calculation, as shown in Fig. 2. Firstly, the real-time position, velocity and flight attitude angle of the target in the radar coordinate system are
obtained. Then, the attitude angle calculation is realized by coordinate system transformation to determine the time-varying attitude angle of the radar line of sight in the body coordinate system. Finally, the obtained attitude is utilized. The angle is combined with the target static RCS sequence to calculate the RCS value of the target.

**Figure 2.** Target dynamic RCS simulation process

3.2. Build a target full airspace static RCS database
The target full airspace static RCS data is the basis of radar target dynamic RCS calculation. This paper uses FEKO software to obtain the target full airspace static RCS data. Specific steps are as follows:

**Step1:** Using the BGM-109 Tomahawk cruise missile as the object, use the SolidWorks to construct a three-dimensional model of a typical aerial target according to the actual size of the target, as shown in Figure 3;

**Figure 3.** Invasive target 3D model

**Step2:** Import the target 3D model into FEKO electromagnetic simulation software, and further mesh the model;

**Step3:** According to the search radar operating parameters in the air defense weapon system, set the radar operating frequency to 3GHz, the azimuth angle of the incident wave, the pitch angle, and the polarization mode as horizontal polarization, and perform full-space electromagnetic simulation on the incoming target;

**Step4:** Export and save the simulation results in a .txt format file;

**Step5:** Construct a full airspace static RCS database of the BGM-109 Tomahawk cruise missile, which is convenient for subsequent interpolation calls according to the simulation.

3.3. Radar attitude angle solution
The target static RCS database obtained by FEKO software contains data such as the azimuth and elevation angle of the radar measurement. Generally, the RCS data at the target viewing angle can describe the scattering characteristics of the moving target. The viewing angle is the relative angle of the radar in the body coordinate system. Therefore, in the dynamic RCS calculation, the coordinate system conversion is usually needed to obtain the body coordinate system. The RCS value corresponding to the viewing angle.

The radar attitude angle refers to the azimuth pitch angle of the incident wave of the radar relative to the target in the body coordinate, including the radar line of sight azimuth and the radar line of sight pitch angle. As shown in Figure 4, the radar azimuth is the projection of the aircraft's line of sight on the horizontal plane. The angle with the X-axis, the radar pitch angle is the angle between the line of
sight of the aircraft and the horizontal plane, and the distance \( R \) is the distance from the target to the measuring radar.

\[
\begin{align*}
\text{Figure 4. Radar attitude angle diagram}
\end{align*}
\]

When the position coordinates of the track point in the radar coordinate system are known, the positional coordinates of the track point in the geocentric coordinate system can be obtained first by the following conversion relationship:

\[
\begin{align*}
x_n &= (R_N + H) \cdot \cos B \cdot \cos L \\
y_n &= (R_N + H) \cdot \cos B \cdot \sin L \\
z_n &= (R_N (1 - f^2) + H) \cdot \sin B
\end{align*}
\]  

(1)

Where: \( R_N \) is the circle radius, \( f \) is the ellipse eccentricity, \( L \) is the target longitude, \( B \) is the target latitude, and \( H \) is the target height.

Set the position coordinates of the target track point on the radar coordinate system is \((x_n(t), y_n(t), z_n(t))\), the radar position coordinate is \((x, y, z)\), and the position coordinate on the radar coordinate system is converted to the position coordinate on the body coordinate system is \((x_b(t), y_b(t), z_b(t))\), then:

\[
\begin{align*}
x_b(t) &= C^b_a 
\begin{bmatrix}
x_n(t) \\
y_n(t) \\
z_n(t)
\end{bmatrix} \\
y_b(t) &= x - x_n(t) \\
z_b(t) &= y - y_n(t)
\end{align*}
\]  

(2)

Where: \( C^b_a \) is the change matrix of the radar coordinate system to the body coordinate system \([3]\):

\[
C^b_a = \begin{bmatrix}
\cos \beta \cos \alpha + \sin \beta \sin \alpha & -\cos \beta \sin \alpha + \sin \beta \sin \gamma \cos \alpha & -\sin \beta \cos \gamma \\
\cos \gamma \sin \alpha & \cos \gamma \cos \alpha & \sin \gamma \\
\sin \beta \cos \alpha - \cos \beta \sin \gamma \sin \alpha & -\sin \beta \cos \gamma - \cos \beta \sin \gamma \cos \alpha & \cos \beta \cos \gamma
\end{bmatrix}
\]

The real-time azimuth \( \phi(t) \) and elevation angle of the radar line of sight in the body coordinate system \( \theta(t) \) are:

\[
\phi(t) = \arctan \left( \frac{y_b(t)}{x_b(t)} \right)
\]
\[
\vartheta(t) = \arctan \left( \frac{z(t)}{\sqrt{(x(t))^2 + (y(t))^2}} \right)
\]  

(3)

Where: \( \varphi(t) \in [0^\circ, 360^\circ] \), \( \theta(t) \in [0^\circ, 180^\circ] \).

3.4. Target trajectory modeling

According to the basic motion state of the target described in [7], including stationary, uniform linear motion, uniform acceleration (deceleration), coordinated turning, and climbing (subduction), the equations of the attitude angle, velocity and instantaneous position of the target are derived. The target incoming motion trajectory is simulated in the coordinate system.

(1) Instantaneous attitude angle equation:

\[
\begin{align*}
\alpha_i &= \alpha_0 + \alpha T \\
\beta_i &= \beta_0 + \beta T \\
\gamma_i &= \gamma_0 + \gamma T
\end{align*}
\]  

(4)

Where: \( \alpha_0 \) is the initial heading angle, \( \beta_0 \) is the initial roll angle, \( \gamma_0 \) is the initial pitch angle, \( \alpha \) is the heading angular rate, \( \beta \) is the roll angular rate, \( \gamma \) is the pitch rate, and \( T \) is the target motion time.

(2) The velocity equation in the radar coordinate system:

\[
\begin{align*}
V_x^v &= (C_a^v)^T \times V_x \\
V_y^v &= (C_a^v)^T \times V_y \\
V_z^v &= (C_a^v)^T \times V_z
\end{align*}
\]  

(5)

Where: \( V_x, V_y, V_z \) is the speed in the target body coordinate system, \( C_a^v \) is the change matrix of the radar coordinate system to the body coordinate system.

(3) Instantaneous position equation:

\[
\begin{align*}
L_i &= L_0 + \frac{V_x^v}{(R_u + h_i)} \cos L_i T \\
B_i &= B_0 + \frac{V_y^v}{(R_u + h_i)} T \\
h_i &= h_0 + V_z^v T
\end{align*}
\]  

(6)

Where: \( R_u = R_x (1 + e \sin^2 L) \), \( R_N = R_x (1 - 2e + 3e \sin^2 L) \), \( e \) is the ellipticity of the earth, \( e = 1/298.257 \); \( R_x \) is the long semi-axis of the earth, with a value of 6378137m; \( L_0 \) is the initial longitude of the target, \( B_0 \) is the initial latitude of the target, \( h_0 \) is the initial height of the target, \( L_i \) is the instantaneous longitude of the target, \( B_i \) is the instantaneous latitude of the target, \( h_i \) is the instantaneous height of the target, and \( T \) is the target exercise time.
3.5. Cruise missile track simulation

Taking the radar coordinate system as the reference, (118°.32°,300) is the starting point of the target, \( \alpha = 90^\circ \) is the initial heading angle, \( \beta = 0^\circ \) is the initial roll angle, \( \gamma = 0^\circ \) is the initial pitch angle, the simulation step length \( T=1s \), the number of simulation steps \( N=3600 \), the polarization mode is horizontal polarization, \((125.5^\circ,31.997^\circ,500)\) is the radar deployment position, according to The motion characteristics of the target, respectively simulating the flight path of the aircraft and cruise missiles

Based on the radar coordinate system, a BGM-109C Tomahawk cruise missile is assumed to be attacked. According to the schematic diagram of the BGM-109 combat process proposed in the literature [8], the missile flight process is simplified to: climb, level flight, turn flight, Jumping and diving basic movements, by simulating the Tomahawk cruise missile attack trajectory by combining these simple trajectories. Figure 5(a) shows the flight path of the target in the radar coordinate system, and Figure 5(b) shows the attitude angle information of the target in the radar coordinate system.

![Cruise missile track simulation](image)

(a) Flight path in the radar coordinate system  (b) Change in attitude angle in the radar coordinate system

Figure 5. Cruise missile motion track simulation

4. Dynamic Analysis of Cruise Missile Dynamic RCS

Firstly, according to the target track, flight speed, radar position and sampling interval, and the attitude information of the target during flight, the apparent attitude angle in the body coordinate system is calculated. Then, the viewing angle angle at a certain moment is extracted, and the corresponding RCS value is retrieved from the static RCS sequence of the target, that is, the dynamic RCS value of the target at that time. Finally, the target dynamic RCS obtained by the simulation is analyzed.

The variation of the RCS amplitude of the cruise missile at the frequency \( F=3 \) GHz and horizontal polarization is shown in Fig. 6.

![Cruise missile RCS static measurement data](image)

Figure 6. Cruise missile RCS static measurement data
According to the simulation result of the cruise missile trajectory in Fig. 5, the azimuth angle of the target end striking section (jump-subduction section) is solved, and the RCS of the target under the target is interpolated with high precision, and the RCS of the corresponding azimuth is found, that is, the target dynamic RCS information. The variation of the target RCS amplitude during the observation time obtained by the simulation is shown in Fig. 7.

![RCS variation of cruise missile subduction zone](image)

It can be seen from Fig. 7 that in the subduction section of the cruise missile, the RCS of the missile changes greatly, and multiple peaks and troughs appear, and the RCS jumps to the maximum value during the 5~10s sampling time. This is due to the cruise missile. The jump flight results in a change in the viewing pitch angle. Therefore, for the end defense of cruise missiles, the search radar is easy to find targets in the cruise missile jump section, and the air defense weapons should start to take corresponding interception measures to deploy the firepower unit in advance.

5. Conclusion
With the increasing stealth performance of air strike weapons such as fighter jets and cruise missiles, higher requirements have been placed on the defense capabilities of air defense weapon systems that are responsible for protecting important targets and regional security. From the simulation analysis of this paper, it is known that for the target of high-speed motion, the flight trajectory affects the variation of the viewing angle in the body coordinate system. According to the scattering fluctuation of the complex target, the change of the viewing angle will cause the RCS to violently fluctuate. Through the combination of the track simulation results and the target static RCS data, the search radar can quickly and accurately grasp the changes of the scattering characteristics of the moving targets in advance, leaving sufficient time for subsequent operations.

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