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A Novel Simulation Approach of Aircraft Dynamic RCS

Ya-Qiang Zhuang*, Chen-Xin Zhang, and Xiao-Kuan Zhang

Abstract—The Radar Cross Section (RCS) of moving targets varies dramatically with aspect or time. The accuracy of simulated dynamic RCS is very important for radar system simulation. A novel approach to simulate the dynamic RCS of aircraft is proposed in this paper. Firstly, the electromagnetic (EM) model of aircraft is built and the all-space monostatic RCS database calculated. Secondly, the aspect angles (azimuth and elevation) in target coordinate system are calculated from flight path by coordinate transformation. Then dynamic RCS is obtained based on database and aspect angles by linear interpolation method. Account for the influence results from aircraft vibration in target motion, we use a white Gaussian distributed random series to modify the simulated results. The statistical characteristics of three kinds of dynamic RCS values are investigated, and the desirable agreement of results between modification and measurement shows the applicability of this simulation approach.

1. INTRODUCTION

In the radar target echo simulation field, the RCS of target is an important parameter to present the scatter properties of radar target. It is hard to obtain dynamic RCS characteristic of moving target especially non-cooperative target by dynamic measurement. The complex radar target usually consists of multiple scattering centers. The relative positions of the scattering centers change rapidly, and the target body vibrates randomly in its motion. In the dynamic situation modeling, aircraft vibrations should be considered, because every aircraft vibrates slightly during flight, and these vibrations are significant factors which affect aircraft RCS. Therefore, the dynamic RCS of moving target varies rapidly with aspect angle which brings difficulties to predict [1]. Fluctuation of RCS is random without regular pattern. It is significant to characterize RCS by statistical terms such as mean, median, variance and distribution models [2].

Much work has been done over the years in the field of dynamic RCS prediction. Dynamic RCS of F-117A stealth attacker's spiral flying was acquired based on aerodynamic theory and electromagnetic calculation [3]. For the influence of airflow, Su et al. adopted a random tremor model to analyze the effect of tremor on RCS [4]. Dynamic RCS of chaff clouds was estimated by generalized equivalent conductivity (GEC) method and modified trajectory tracking algorithm [5]. In order to obtain the dynamic RCS in real time, the all-space monostatic RCS database is calculated firstly in this paper. After that, an example of moving aircraft is given, and the aspect angles of radar line of sight (LOS) are calculated from flight path. Therefore, the dynamic RCS can be obtained in real time by linear interpolation based on RCS database. A white Gaussian distributed random series was used for modification. The excellent agreement in statistical characteristic between modified simulated RCS and measured RCS shows that this simulation approach is practicable.

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2. MONOSTATIC RCS CALCULATION

2.1. Target Modeling

As an example, a full-size EM model of an aircraft is shown in Figure 1. The aircraft shape is defined by CAD geometric modeling software using either a facets and wedges approximation or a parametric surface approach. With the help of NURBS curves, the accurate model can be built and then used for monostatic RCS calculation [6].

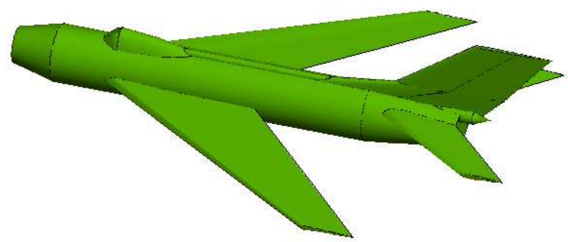


Figure 1. Aircraft target model.

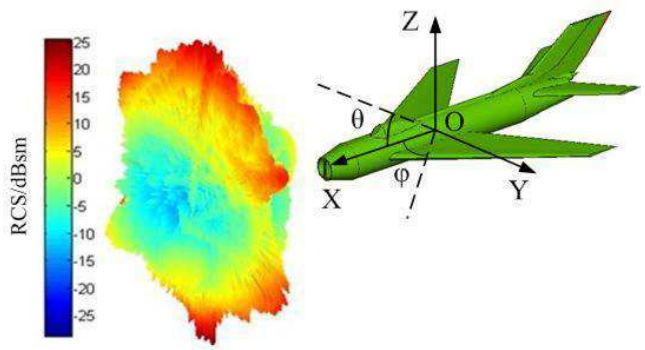


Figure 2. All-space monostatic RCS database.

2.2. Monostatic RCS Database

Physical Optics (PO) method [7–9] with Physical Theory of Diffraction (PTD) revision to edge diffraction is used to evaluate the monostatic RCS of the aircraft for VV polarization. PO is an efficient high frequency method to calculate the scattering of the electrically large target surface. PTD is adopted to calculate the diffraction of the boundaries [10, 11]. The body coordinate system $OXYZ$ is fixed in the aircraft as shown in Figure 2. The XOZ plane defines the plane symmetry of the aircraft, and it is convenient to arrange the OX axis so that it is parallel to the geometrical horizontal fuselage datum. The OY axis is directed to larboard, and the OZ axis is directed "upward". The origin O of the coordinate system is located at the centre of gravity for the aircraft. As shown in Figure 2, the incident wave direction of propagation (LOS) is described by the azimuth φ and elevation θ with respect to the aircraft body-fixed coordinate system. RCS value is calculated over the all-space ($-90° < \theta < 90°$, $0° < \varphi < 360°$) at step of 1° under 5.6 GHz. The configuration of all-space backscattering monostatic RCS is given in Figure 2.

3. DYNAMIC RCS SIMULATION

3.1. Aspect Angles

In this section, we use the actual flight path to calculate the aspect angles of LOS in target coordinate system. The aircraft is flying straight and level with slant range from 80 km to 10 km under velocity 180 m/s. It is known that there are two types of aircraft motion. The first is called rigid body motion and the second called individual motion. We only simulate translation rigid body motion in this paper. Rigid body motion refers to the entire aircraft vibrating, or moving, away from the intended path of flight as a rigid-body. In this case, there is no flexing of the aircraft at all. The aspect angles in radar coordinate system can be measured in the field dynamic measurement. Then the aspect angles in target coordinate system can be calculated by coordinate transformation from radar coordinate system. Projection of flight path and aspect angles in the target coordinate system are shown in Figures 3 and 4.

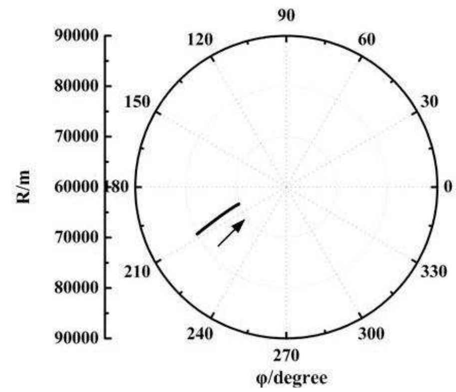
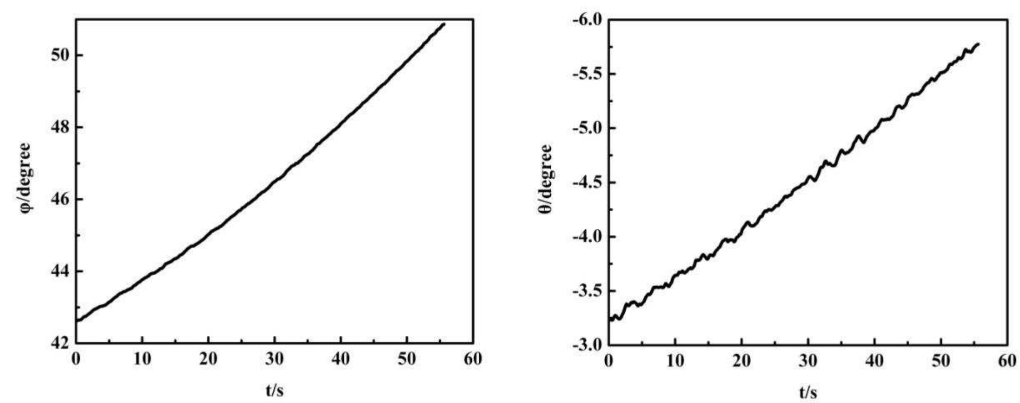


Figure 3. Projection of flight path.



(a) (b)

Figure 4. Aspect angles in target coordinate system, (a) azimuth; (b) elevation.

3.2. Linear Interpolation Method

Some RCS value of aforementioned aspect angles may not be calculated in database. We use the linear interpolation method to solve this problem. Figure 5 shows the principle of linear interpolation method.

In Figure 5, φ_H is the lowest one among angles higher than φ, and φ_L is the highest one among angles lower than φ. Similarly, θ_H is the lowest one among angles higher than θ, and θ_L is the highest one among angles lower than θ. The error of azimuth is calculated firstly by Eq. (1):

$$\Delta\varphi = \frac{\varphi - \varphi_L}{\varphi_H - \varphi_L} \tag{1}$$

Then, the maximum and minimum RCSs of azimuth are calculated by Eqs. (2) and (3):

$$\sigma_L = (\sigma(\varphi_H, \theta_L) - \sigma(\varphi_L, \theta_L)) \times \Delta\varphi + \sigma(\varphi_L, \theta_L) \tag{2}$$

$$\sigma_H = (\sigma(\varphi_H, \theta_H) - \sigma(\varphi_L, \theta_H)) \times \Delta\varphi + \sigma(\varphi_L, \theta_H) \tag{3}$$

At last, the error of elevation is calculated by Eq. (4), and RCS value is calculated by Eq. (5):

$$\Delta\theta = \frac{\theta - \theta_L}{\theta_H - \theta_L} \tag{4}$$

$$\sigma = (\sigma_H - \sigma_L) * \Delta\theta + \sigma_L \tag{5}$$

The dynamic RCS can be calculated using the quasi-stationary approximation, because the aircraft flight velocity is very much lower than the velocity of light. Therefore, the simulated dynamic RCS which

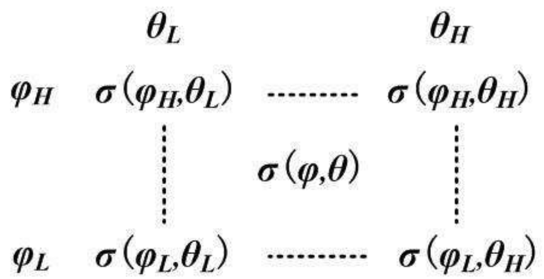


Figure 5. Plot of linear interpolation principle.

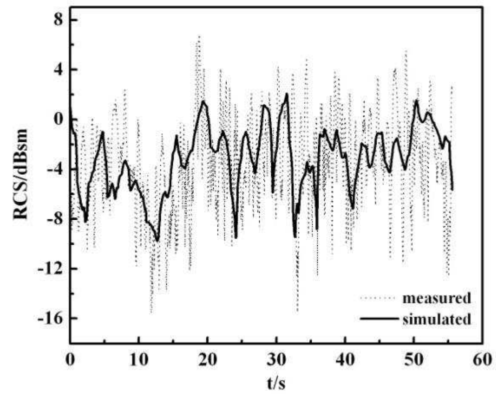


Figure 6. Comparison of measured and simulated RCS.

does not consider the vibration influence can be calculated in real time by linear interpolation method based on monostatic RCS database. Figure 6 shows the comparison between measured and simulated RCSs of moving aircraft.

Figure 6 displays the simulated and measured dynamic RCSs. As appreciated, an excellent agreement of results tendency between simulation and measurement is unambiguously observed except for higher fluctuation in the measurement case. It is considered that this higher fluctuation results from aircraft body vibration. Accordingly, the aircraft vibration influence should be added to the simulated dynamic RCS to better simulate a dynamic aircraft in flight, as discussed in the next section.

3.3. Aircraft Vibration Model

Although the aircraft vibrations are very small relative to the size of the target, they are significant factors which affect aircraft RCS and the driving factors behind angle error (glint) and Doppler shift. Thus, these perturbations, or vibrations, are modeled and described as follows. The error results from measured RCS minus simulated RCS. After statistical analysis of this error, we find that it obeys Gaussian distribution with zero mean as shown in Figure 7. Accordingly, we think about using a white Gaussian distributed random series for modification. The modified simulated RCS is given in Figure 8.

Following Figure 8, the modified result fluctuates more seriously than aforementioned simulated result. Though the error between modification and measurement still exists, a better agreement between

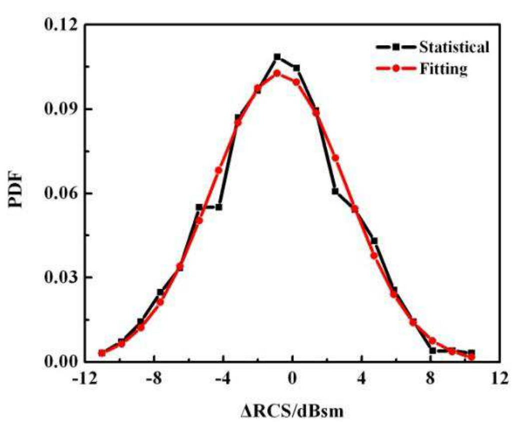


Figure 7. Aircraft vibration distribution.

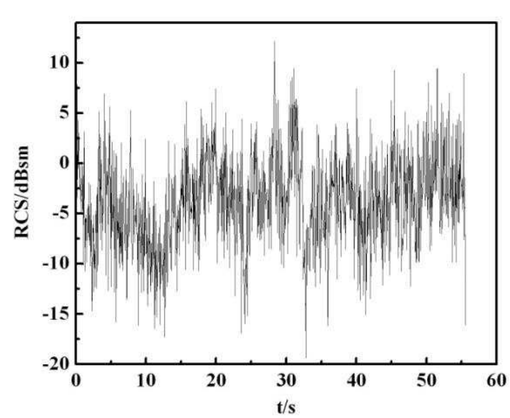


Figure 8. Modified result.

them is evident compared to the agreement between the simulation and the measurement. This error may attribute to the error of aircraft EM model or the error of measurement. The influence of these errors is neglected for they do not affect the RCS value observably.

It is concluded that the fluctuation resulting from random vibration can be described by white Gaussian distribution. With different flight paths and motion parameters, it may obey the Gaussian distribution with different standard deviations. So it is meaningful to conclude the relationship between the targets motion parameters and white Gaussian standard deviations. If the relationship has been concluded, it will be convenient to use the vibration model.

4. RESULT ANALYSIS

4.1. Statistical Parameters

The RCS of moving aircraft is a rather complicated phenomenon which depends on some factors whose values are often practically unknown and even time-varying. For these reasons, it has been advantageous to make a statistical analysis of target RCS. In this section, the statistical parameters of three kinds of dynamic RCS are provided in Table 1.

Following Table 1, an excellent agreement of mean and median results is clearly observed. The distinct deviation of variance results between measurement and modification is attributable to some extreme high RCS values in modification. This phenomenon cannot affect the whole simulation performance.

Table 1. Statistical parameters.

	mean/m^2	median/m^2	variance	minimum/m^2	maximum/m^2
Simulated	0.5678	0.5182	0.0968	0.1057	1.6135
Measured	0.6628	0.4763	0.3676	0.0277	4.8204
Modified simulated	0.7574	0.4185	1.2538	0.0115	16.3248

4.2. RCS Fluctuation Statistical Model

In radar engineering field, the RCS fluctuation statistical model is often used to analyze the characteristic of dynamic RCS. Chi-Square distribution is a conventional model often applied in radar detection field [12]. This distribution was introduced by Swerling assuming that the Probability Density Function (PDF) of the target RCS is a Chi-Square distribution provided by Eq. (6)

$$p(\sigma) = \frac{k}{\Gamma(k)\bar{\sigma}} \left(\frac{k\sigma}{\bar{\sigma}}\right)^{k-1} \exp\left(-\frac{k\sigma}{\bar{\sigma}}\right), \quad \sigma > 0 \tag{6}$$

where the statistical parameters in the model are

$$\bar{\sigma} = \text{ mean of } \sigma, \quad k = \bar{\sigma}^2/\text{variance of } \sigma$$

and $2k$ is called the "number of degree of freedom". k can be positive integer or non-integer, and it rules the depth of the amplitude fluctuation: the lower the k is, the higher the fluctuation spans. The Chi-Square distribution is simplified as the Swerling I-IV and Marcum distribution, corresponding to $k = 1$, N, 2, $2N$ and ∞.

After statistical analysis is conducted, we fit the PDF of RCS data with Chi-Square distribution. And the Least Squared estimation is used to fit the dynamic RCS because this method minimizes the sum of squared residuals. Error-of-fit is defined as Eq. (7)

$$E = \sum_i \left[P_e(i) - P_m(i)\right]^2 \tag{7}$$

P_e is the statistical result of RCS sample data and P_m the fitting result of Chi-Square distribution.

The fitting results are also evaluated by a Kolmogorov-Smirnov goodness-of-fit test (K-S test), which compare the data cumulative distribution function (CDF) with the CDF of the fitted Chi-Square distribution. The significance level is set at $\alpha = 0.05$ [13]. The test function is shown in Eq. (8), in which $F(x)$ is the statistical cumulative distribution of RCS data, and $F'(x)$ is that of the fitting results. If the test result is too high, it can be determined that the distribution used is not applicable to the data.

$$D = \max \left| F(x) - F'(x) \right| \tag{8}$$

The comparison fitting results are shown in Figure 9. The fitting parameters as well as error-of-fit and K-S test results are provided in Table 2.

From Table 2 and Figure 9, a desirable agreement of results between simulation and modification is evidently observed. The parameter k of modified simulated RCS is 1.1273 which approximates with 1.1704 of measured RCS. The parameter k of modified simulated RCS (1.1273) approximates with that of measured RCS (1.1704). This case also verifies that some extreme high RCS values do not affect the RCS distribution curve seriously.

Table 2. Fitting parameters, errors-of-fit and K-S test result.

	Simulated	Measured	Modified simulated
Fitting parameter	$k = 2.3918$	$k = 1.1704$	$k = 1.1273$
Error-of-fit	0.4987	0.0374	0.0865
K-S test results	0.1634	0.0545	0.0558

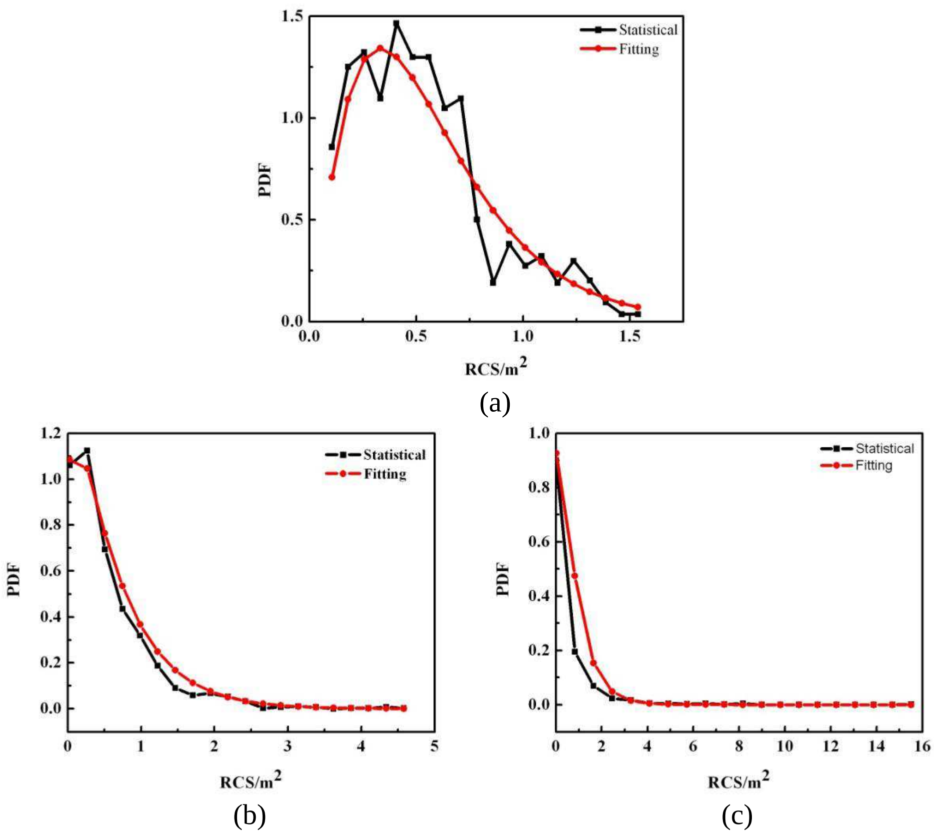


Figure 9. Fitting results of RCS distribution, (a) simulated RCS; (b) measured RCS; (c) modified simulated RCS.

5. CONCLUSION

A novel approach to simulate the RCS of moving target in real time is proposed in this paper. The aircraft EM model was built, and the monostatic RCS database was calculated. Then, the aspect angles of LOS in target coordinate system were calculated from flight path by coordinate transformation. The linear interpolation method was used to obtain simulated dynamic RCS. In addition, a white Gaussian distributed random series was used to simulated results for modification accounting for aircraft vibration. The reasonable agreement of statistical characteristic between modification and measurement indicates that this approach is practicable. When the relationship between motion parameters and white Gaussian standard deviations is acquired, the dynamic RCS of aircraft can be simulated directly.

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