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A New Method for Analyzing Integrated Stealth Ability of Penetration Aircraft

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Abstract

Taking into account the limitations of existing stealth performance analysis methods, a method termed as the integrated stealth performance analysis method is proposed for evaluating the stealth ability of the penetration aircraft. Based on various target radar cross section (RCS) scattering characters, this article integrates the relevant parameters needed for building up target circumferential RCS scattering model and proposes the RCS scattering controlling parameters to control the changing trends of the relevant model RCS scattering characters. According to the radar dynamic detecting characters during the whole penetration course, a dynamic stealth performance evaluating model is proposed accompanied by a series of stealth ability estimation rules. This new analysis method can enhance the integrality and dependability of the stealth analysis conclusions and summarize the relationship between the target RCS scattering characters and their effects on stealth performance. The rules indicated by this relationship can be used as the reference for designing new type of stealth aircraft and setting up specific penetration tactics.

Keywords: radar cross section; scattering; models; analysis; performance

1. Introduction

The conclusions based on a comprehensive and reasonable stealth performance analysis method are important references or guiding rules for modifying the design parameters of new type of stealth aircraft and setting up specific penetration tactics, which can greatly reduce the radar detect probability and enhance the survivability of aircraft. Due to the limitations of existing stealth performance analysis methods: just using the average radar cross section (RCS) value of the circumferential area of target or that of some important radar detecting areas under some important radar frequencies as the basis for stealth performance analysis. According to these analysis methods, the stealth aircraft with lower average RCS value has better stealth performance. So the analysis conclusions can just reflect several target RCS scattering characters. The target with the same average RCS value can have completely different circumferential RCS scattering characters. Besides, the conclusions derived from existing analysis methods do not have enough dependability for without combining with the combat missions and the actual detecting environment. So the existing stealth performance analysis methods can just reflect the target static stealth performance. In this article, for coping with these shortages of existing methods, a new method named the integrated stealth performance analysis method is proposed. This new method is suitable for analyzing the stealth performance of the aircraft, which carries out penetration mission. The new target circumferential RCS scattering model in this analysis method can satisfy various stealth ability analysis requirements, because this method can reflect various target RCS scattering characters well. Moreover, the new method takes the radar dynamic detecting characteristics and changing rules of the target dynamic RCS scattering characters into account, and the relevant analysis results can be more meaningful. Furthermore, the rules about how the target RCS scattering parameters affect its stealth performance can be learned from final stealth analysis results.

2. New Target Integrated Circumferential RCS Scattering Model

2.1. Relevant model parameters

There are several requirements which the model should meet for the new analysis method: 1) quantify-

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ing the overall and local RCS scattering characters of target, 2) setting up the relationship between each different radar detecting areas, and 3) controlling the RCS scattering changing trends of model through inducing several model RCS scattering control parameters. Considering that the RCS value can reflect the quantified target scattering characters and the differences between the RCS values may up to the magnitude order for the different target azimuths, the average RCS value of target circumferential area, $\delta_{\rm ave}$, is introduced as one of the RCS scattering characteristic parameters of model and its unit is dBsm[1].

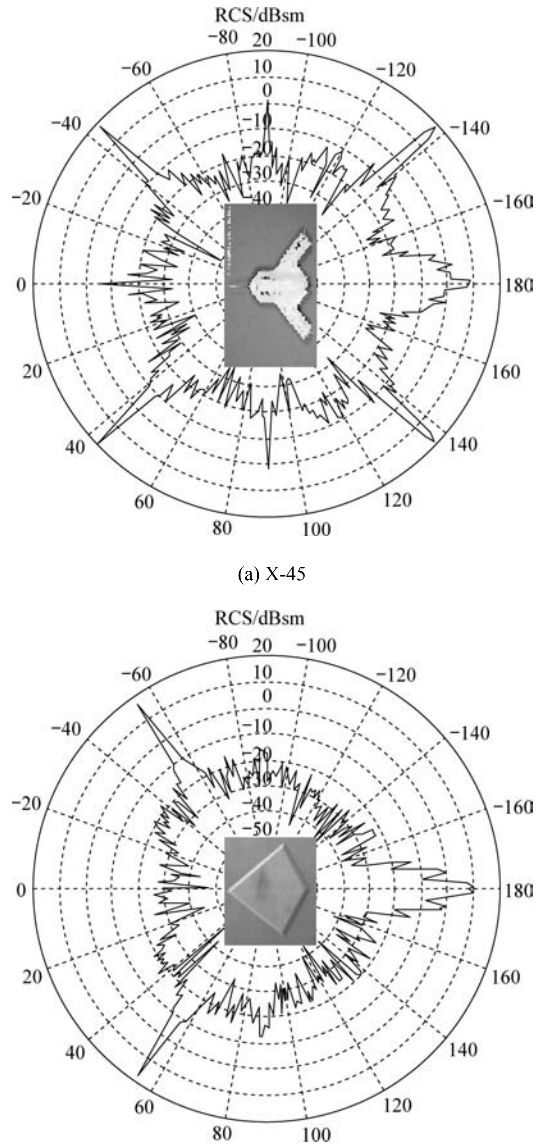
The existing analysis methods do not take the effects of the changing relationship between different important radar detecting regions on the target stealth ability into account. For example, the aircraft can be excellent in depth penetration mission, if it has lower RCS value at the front azimuth and higher RCS values at other azimuths. Moreover, if the stealth aircraft has lower RCS value at its two side azimuths compared with that for the rest azimuths, it can carry out penetration mission with a smaller horizontal distance arriving at the enemy bases. In order to build up the relationship between different target important detecting areas, the new analysis method uses the average RCS value of target front important radar detect area as the basis. Furthermore, the average RCS values of other radar detecting areas are introduced into the model as the target local RCS scattering characteristic parameters and the corresponding symbols are $\overline{\delta}_i$ (i=0,1,$\cdots$). The subscript i represents the sequence of radar detecting areas. For describing the relationship between the target front and other directions important radar detecting areas, the new model defines a set of relational parameters, and they can be written as

$$k_{\delta_i} = \overline{\delta}_i / \overline{\delta}_0 \quad (i = 0,1,\cdots) \tag{1}$$

where $\overline{\delta}_0$ represents the average RCS value of the target front important radar detecting area.

Because the unmanned combat air vehicles (UCAVs) X-45 and X-47 have different stealth design parameters, they have completely different RCS scattering characters. Their RCS curves differ much from each other, as shown in Fig.1.

So the same set of RCS scattering controlling parameters cannot be used to describe the dissimilar RCS curve patterns and control the RCS scattering changing trends of various new models well. There are two requirements for the RCS scattering controlling parameters: one is that it is not advisable to introduce too many RCS scattering controlling parameters, the other is the model can satisfy all kinds of stealth ability analysis requirements. For example, building up the target circumferential RCS scattering model with triangle pattern character as shown in Fig.1(b) needs two RCS scattering control parameters, which can meet the requirements of controlling RCS scattering changing



(a) X-45

(b) X-47

Fig.1 RCS curves corresponding to two types of stealth aircraft (under the S wave band).

trends and conducting target integrated stealth performance analysis. These parameters are K_L and K_A respectively, and they can be expressed as

$$K_L = L_a / L_b \tag{2}$$

$$K_A = A_{\rm F} / 360° \tag{3}$$

where L_a and L_b are the long and short sides lengths of model with triangle circumferential RCS scattering character. The parameter K_L can control the RCS scattering changing trends of target head and tail areas. By this way, it can satisfy the analysis requirements about the effects of different head and tail stealth performances on target integrated stealth performance. $A_{\rm F}$ represents the angular region of target front important radar detecting area. Likewise, the models with different $A_{\rm F}$ values can meet the analysis requirements about the effects of different front important radar detecting areas on target integrated stealth performance.

Fig.2 shows the models with various target circumferential RCS scattering characters and being built up by changing the values of K_L and K_A, when δ_{ave} is equal to −10 dBsm.

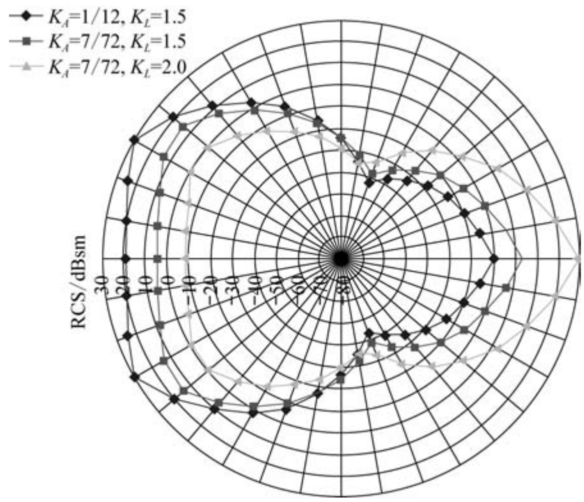


Fig.2 RCS curves of different target RCS scattering models (δ_{ave}= −10 dBsm).

2.2. *Building method of target circumferential RCS scattering model*

According to Fig.1(a), the detailed building steps of the new model are described in this section.

First of all, defining the suitable target overall and local RCS scattering characteristic parameters and introducing several model RCS scattering controlling parameters according to the different target RCS scattering characters are necessary. So as it is shown in Fig.1(a), the average RCS values of target circumferential area and the heading direction within the angular region of –30° to +30° are introduced as the target overall and local RCS scattering characteristic parameters respectively. The symbol of the latter is $\overline{\delta}_0$.

Secondly, different functions are used to describe the RCS curves of different radar detecting regions. The variable of curve function is radar detecting angle φ, its corresponding function value is length R. But in the target RCS curve, the corresponding value of φ is the target RCS value. Therefore, a transform between the coordinate length R and the target RCS value is needed. Based on this transform, RCS value in any direction of the target can be expressed by

$$\delta(\varphi)=\delta_{\text{ave}}+(R(\varphi)-\frac{1}{N}\sum_{j=1}^{N}R_j)\frac{\delta_{\text{ave}}+\delta_{\min}}{\frac{1}{N}\sum_{j=1}^{N}R_j} \tag{4}$$

where $R(\varphi)$ denotes the R value in any target azimuth, R_j one of the series values of R in any target important radar detecting areas, subscript j the sequence of these R values, and $\delta_{\min}$ the RCS value of the coordinate origin.

The stealth analysis about the target local RCS scattering character should be included in the conclusions of target integrated stealth performance analysis. So the last step is dividing the target RCS curve into several parts according to the target RCS scattering characters, then using different functions to describe these parts respectively. By this way, the analysis conclusion about how the target local stealth performance affects its integrated stealth ability can be reached. All the functions for every part of the curve can be written as

$$\delta_i(\varphi)=R_i(\varphi)\frac{(\delta_{\text{ave}}+\delta_{\min})}{\frac{1}{N}\sum_{j=1}^{N}R_j}-\delta_{\min} \tag{5}$$

where $\delta_i(\varphi)$ and $R_i(\varphi)$ are the target RCS values and R values corresponding to the target azimuth of φ respectively. The subscript i represents the sequence of target important radar detecting areas.

The functions corresponding to Fig.1(a) can be expressed as

$$\delta_i(\varphi)=\begin{cases}(\delta_{\text{ave}}+\delta_{\min})\dfrac{K_L}{2\cos\varphi}\cdot\dfrac{91^\circ}{\text{Sum}}-\delta_{\min} \\ \qquad 0\le\varphi\le\varphi_{\text{Limit}} \text{ or} \\ \quad 180^\circ-\varphi_{\text{Limit}}\le\varphi\le 180^\circ+\varphi_{\text{Limit}} \text{ or} \\ \quad 360^\circ-\varphi_{\text{Limit}}\le\varphi<360^\circ \\ (\delta_{\text{ave}}+\delta_{\min})\dfrac{1}{2\sin\varphi}\cdot\dfrac{91^\circ}{\text{Sum}}-\delta_{\min} \\ \quad 180^\circ+\varphi_{\text{Limit}}<\varphi<360^\circ-\varphi_{\text{Limit}} \text{ or} \\ \quad 360^\circ-\varphi_{\text{Limit}}\le\varphi<360^\circ\end{cases} \tag{6}$$

where $\text{Sum}=\sum_{\alpha=0}^{\varphi_{\text{Limit}}}\left|\dfrac{K_L}{2\cos\alpha}\right|+\sum_{\alpha=\varphi_{\text{Limit}}+1}^{90^\circ}\left|\dfrac{1}{2\sin\alpha}\right|$, α is the radar detect angle.

3. Dynamic Evaluation Model for Integrated Stealth Performance of Penetration Aircraft

3.1. *Dynamic evaluation model*

There are two kinds of relevant dynamic evaluation models for the integrated stealth ability analysis of aircraft: one is the radar dynamic detecting model, the other is target dynamic RCS scattering model which can satisfy various stealth performance analysis requirements.

Emphases of building up radar dynamic detecting model are simulating the changing process of radar detecting and calculating the radar detecting probability changing with time. The radar detect probability P_{d} can be written as[2-5]

$$P_{\text{d}}=1-B\int_0^{\infty}\mathrm{e}^{-t}\varphi(x)\left\{\frac{y_0-n_0\left[1+(S/N)t\right]}{n_0\left[1+2(S/N)t\right]}\right\}\mathrm{d}t \tag{7}$$

where $\varphi(x)=(\sqrt{2}\pi)^{-1}\int_{-\infty}^{x}\mathrm{e}^{-t^2/2}\mathrm{d}t$, n_0 is the radar accumulated scanning number, y_0 the threshold of radar false alarm, S/N the radar signal to noise ratio, and B one radar characteristic parameter.

The serial models with different RCS scattering characters are built up by changing relevant model parameters and these models can satisfy various stealth performance analysis requirements. For example, by analyzing the serial models with different target heading RCS scattering characters, which are built according to Fig.1(b), the conclusions about how the different heading RCS scattering characters affect target integrated stealth performance can be reached.

3.2. Integrated evaluation criteria for integrated stealth performance of penetration aircraft

The relevant stealth performance analysis methods and rules for one to one detecting condition are the basis for analyzing the target integrated stealth ability in a more complex detecting environment. This article will give the analysis conclusions of integrated stealth performance, according to the specific radar detecting results for the radars located in different azimuth of enemy base[6-7].

Considering the occurrence sequence of events during the whole penetration process and the effects of the radar detecting results on the aircraft survivability, this article uses five aspects of these radar detecting results as the basis for the evaluation criteria of integrated stealth:

(1) The time when the penetration aircraft is first found by radars, which decides how many times the aircraft will be attacked by enemy firepower. Its corresponding symbol is t_{First}.

(2) The distance to the enemy base when aircraft is first found by radars. Whether or not penetration aircraft can use the long range missile will be determined by this distance. Its notation is L_{Distance}.

(3) The total numbers of being found during the whole penetration period directly affect how many times the aircraft will be attacked by enemy firepower. Its notation is N_{Find}.

(4) The duration of the penetration aircraft in continuously radar found situation. The series notations are $t_{\mathrm{d},i}$ (i=1,2,$\cdots$, N_{Find})

(5) The recorded radar detecting probability values, since target is first found by radars until it is leaving away from the enemy base. The series notations are $P_{\mathrm{d},j}$ (j = 1,2,$\cdots$). The changing trends of these values can describe dynamic stealth performance of penetration aircraft in another form[8-12].

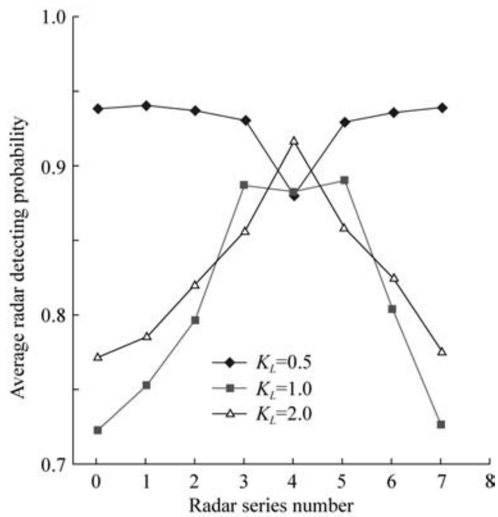
4. Examples and Discussion

In this section, the new kind of target circumferential RCS scattering models will be built according to Fig.1. Before that, disposing several radars in different azimuths of enemy base. Combing relevant dynamic models and integrated stealth analysis rules can give the detailed integrated stealth analysis conclusions. In these examples, aircraft flight altitude is 1 km and flight velocity is 500 m/s. The aircraft carries out the penetration mission along a straight flight course at the azimuth of 90°. The azimuths of these radars are 0°, 30°, 45°, 60°, 90°, 120°, 135° and 180° respectively. A comparison is made between the integrated stealth performance of these two serial models are given blow.

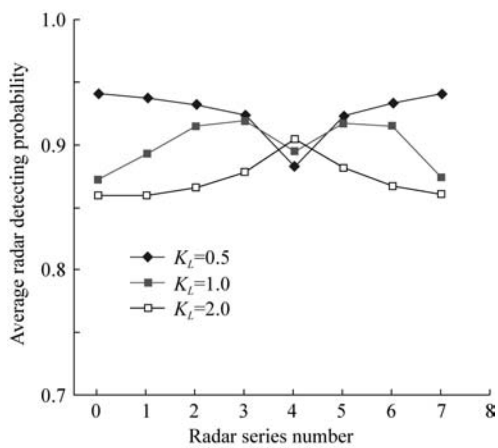
4.1. Rectangular RCS scattering models

Combining the new modeling methods described in Section 2.2 and the relevant stealth performance analysis requirements, the serial models with absolutely different RCS scattering characters are modeled.

The values of relevant model RCS scattering parameters are δ_{ave}= −10, 0 dBsm and K_L = 0.5, 1.0, 2.0 respectively. Fig.3 compares the average radar detecting probability of these serial models.



(a) δ_{ave}= −10 dBsm



(b) δ_{ave}= 0 dBsm

Fig.3 Comparison of radar detecting probability corresponding to serial models.

Fig.3(a) shows that the RCS scattering characters of these three models differ much from each other when δ_{ave} is equal to −10 dBsm. Among these models, the one corresponding to $K_L = 0.5$ has the highest average radar detecting probability. When $K_L = 1.0$, the corresponding model will have much lower average radar detecting probability. When $K_L = 0.5$, the radars located in the two sides of the enemy base will have much higher detecting probability than that for $K_L = 1.0$. So when δ_{ave} is around −10 dBsm, the condition of $K_L = 1.0$ can make the penetration aircraft with rectangular RCS scattering character have excellent sidewise stealth ability. Then the aircraft can carry out the penetration mission with a small transverse distance arriving at enemy base. The average radar detecting probability rises remarkably, when δ_{ave} goes up to 0 dBsm.

Tables 1-2 show the relevant radar detecting data of serial models when δ_{ave}=−10, 0 dBsm respectively.

Table 1 Relevant radar detecting data of serial models (δ_{ave}= −10 dBsm)

K_L	Radar series number	Lost target number	t_{First}/s	Stable tracking number	Tracking duration/s
0.5	0	1	289	1	315
0.5	1	1	201	1	291
0.5	2	1	174	1	263
0.5	3	1	161	1	225
0.5	4	1	167	1	159
0.5	5	1	162	1	223
0.5	6	1	175	1	261
0.5	7	1	290	1	313
1.0	0	2	194	1	139
				2	139
1.0	1	2	110	1	174
				2	174
1.0	2	1	87	1	436
1.0	3	1	79	1	389
1.0	4	1	89	1	315
1.0	5	1	81	1	385
1.0	6	1	89	1	433
1.0	7	2	196	1	141
				2	142
2.0	0	2	1	1	142
				2	300
2.0	1	2	1	1	105
				2	346
2.0	2	2	1	1	137
				2	399
2.0	3	2	1	1	197
				2	469
2.0	4	1	1	1	765
2.0	5	2	1	1	202
				2	474
2.0	6	2	1	1	142
				2	402
2.0	7	2	1	1	147
				2	304

Table 2 Relevant radar detecting data of serial models (δ_{ave}= 0 dBsm)

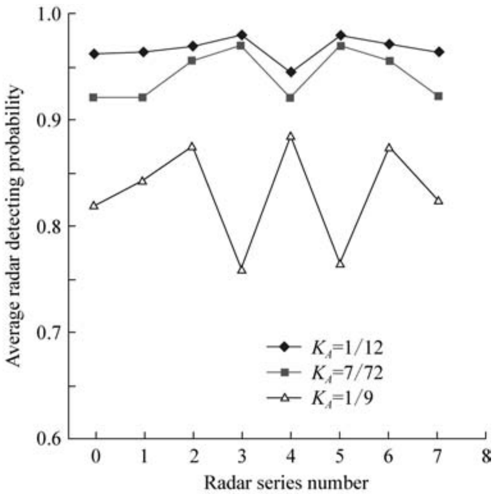
K_L	Radar series number	Lost target number	t_{First}/s	Stable tracking number	Tracking duration/s
0.5	0	1	242	1	409
0.5	1	1	156	1	381
0.5	2	1	132	1	347
0.5	3	1	122	1	303
0.5	4	1	131	1	231
0.5	5	1	123	1	301
0.5	6	1	133	1	344
0.5	7	1	244	1	406
1.0	0	1	86	1	721
1.0	1	1	4	1	685
1.0	2	1	1	1	626
1.0	3	1	1	1	569
1.0	4	1	1	1	509
1.0	5	1	1	1	568
1.0	6	1	1	1	625
1.0	7	1	88	1	717
2.0	0	2	1	1	250
				2	966
2.0	1	2	1	1	201
				2	1 003
2.0	2	1	1	1	221
				2	1 049
2.0	3	1	1	1	1 390
2.0	4	1	1	1	1 347
2.0	5	1	1	1	1 389
2.0	6	2	1	1	255
				2	1 053
2.0	7	2	1	1	255
				2	970

The data in Table 1 shows that when δ_{ave}= −10 dBsm, the lost target number will increase and t_{First} will decrease with the increase of K_L. Suppose that the aircraft will counter the threat of enemy firepower only when it is continuously found by radar more than a certain time threshold and the corresponding notation is t_{Limit}. If the time threshold is 200 s, when $K_L = 0.5$, 1.0, 2.0, the corresponding valid stable track number are 7, 5 and 9 respectively. So when $K_L = 1.0$, the model has the least chances of meeting with enemy firepower.

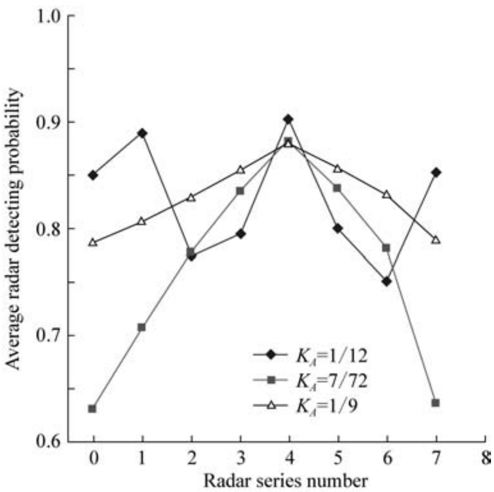
The data in Table 2 shows that when $\delta_{ave} = 0$ dBsm, the duration of aircraft being stable tracked rises obviously and the valid stable tracking number also increases. It is also learned from the data that the time of models first being found by radar corresponding to $K_L = 1.0$, 2.0 will be much earlier. Therefore, the data shows that the RCS scattering controlling parameter δ_{ave} has big effects on the integrated stealth performance of serial models.

4.2. Triangular RCS scattering models

The serial models with triangular RCS scattering characters are established according to the methods described in Section 4.1. The values of K_L and K_A are taken as K_L = 1.5, 2.0 and K_A = 1/12, 7/72, 1/9 respectively. Fig.4 shows the comparison of average radar detecting probability between these serial models.



(a) K_L=1.5



(b) K_L = 2.0

Fig.4 Comparison of radar detecting probability of serial models (δ_{ave}= −10 dBsm).

Fig.4(a) shows that when δ_{ave}= −10 dBsm and K_L = 1.5, the model with RCS scattering parameters K_A =1/9 has lower radar detecting probability than both the models for K_A = 1/12, 7/72 respectively. The radar detecting probability curves in Fig.4(b) show that compared with that of K_L = 1.5, the average radar detecting probability of all these serial models are decreased. Especially for the situation of K_A = 7/72, the decreasing range is the maximum one. Both the two models corresponding to K_A = 7/72, 1/9 respectively have lower radar detecting probability in their two sides than that in their heading direction. Especially when the RCS scattering controlling parameter K_A = 7/72.

Table 3 lists the relevant radar detecting data corresponding to the situation for the RCS scattering controlling parameters δ_{ave}= −10 dBsm and K_A = 7/72 and K_L adopts different values.

Table 3 Relevant radar detecting data of series models (δ_{ave}= −10 dBsm, K_A=7/72)

K_L	Radar series number	Lost target number	t_{First}/s	Stable tracking number	Tracking duration/s
1.5	0	1	1	1	378
1.5	1	1	1	1	299
1.5	2	1	1	1	279
1.5	3	1	1	1	269
1.5	4	1	1	1	684
1.5	5	1	1	1	270
1.5	6	1	1	1	281
1.5	7	1	1	1	380
2.0	0	2	120	1	161
				2	773
2.0	1	2	37	1	197
				2	1 020
2.0	2	2	16	1	224
				2	1 244
2.0	3	2	9	1	243
				2	1 476
2.0	4	1	17	1	2 097
2.0	5	2	10	1	243
				2	1 489
2.0	6	2	17	1	226
				2	1 259
2.0	7	2	121	1	165
				2	799

The data in Table 3 shows that when δ_{ave}= −10 dBsm, the models with RCS scattering parameter K_L = 2.0 will have more chances of being tracked by radar and the duration of radar stable tracking will be longer than the models corresponding to K_L=1. 5.

5. Conclusions

(1) By changing the relevant model RCS scattering controlling parameters, the new analysis method can build up serial models with different RCS scattering characters. These models can satisfy various integrated stealth analysis requirements of the new type or existing stealth aircraft, such as the effects of different important radar detecting angular region or various configuration designing parameters, etc. on the aircraft integrated stealth performance.

(2) The laws of the effects of different model parameters on aircraft integrated stealth ability and penetration efficiency are useful for developing new types of stealth aircraft and making specific penetration tactics.

(3) Analyzing the aircraft dynamic stealth performance reasonably based on the relevant dynamic analysis models and evaluation criteria can make the analysis conclusions to be the meaningful references for both developing new type of stealth aircraft and establishing some efficiency penetration tactics.

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