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Stealth evaluation and improvement of mast configuration in the preliminary design stage

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Abstract: The stealth performance of warships is directly affected by its mast; therefore, the analysis and evaluation of the stealth performance of the ship's mast in the preliminary design stage is the main research purpose of this paper. By taking a typical enclosed ship mast as the research model, the influences of several important parameters on the stealth performance are analyzed, with the major scattering characteristic of the mast being investigated. It is seen that most of RCS peak points are caused by the specular reflection, and the optimal adjustment of mast configuration is presented. When the ship is rolling, the dihedral angle effect caused by the affiliated platform and main structure would intensify. This paper provides a reference for the stealth performance evaluation and improvement of mast configuration in the preliminary design stage.

Keywords: warship mast; radar cross section; evaluation; stealthiness

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0 Introduction

Stealth technology is a kind of integrated technology which is developed to reduce the detection probability of the enemy's equipment by lowering the detectable signals of targets in a specific area[1-2]. Of all the detectable ship signals, radar reflection is one of the most grievous threats to ships on the water. Therefore, radar stealth performance of ships becomes one of the most important indicators to enhance ships' ability to strike and survive in the battles[3-4].

Restricted by the earth curvature, the design of mast configuration directly affects the radar stealth performance of the whole ship[5]. At present, Radar Cross Section (RCS) index allocation method is used for stealth design of ships. Mast is generally treated as an independent component to conduct stealth research[6-7]. When designing, for mast, its configuration must meet the allocated stealth indicator requirements, so it is necessary to specialize in the stealth performance of mast.

1 RCS high frequency computing method

The RCS level of ship is relatively high. Moreover, a great amount of computation is inevitable if the RCS high-accuracy computing method, which is supposed to apply to aircraft industry, is adopted. In the preliminary design stage of the enclosed ship mast, the designers pay more attention to the major reflection reason of mast radar signals and improvements of stealth performance, which allows the designers to balance the computation accuracy and the amount of work.

Feature sizes of mast are much larger than wavelengths of radar, and the RCS calculation problem is electrically large scale problem, which can be addressed by high frequency approximation method. This paper employs a geometrical/physical optics mixing method as the RCS computation method of mast.

Geometrical Optics (GO) method is derived from the traditional optical laws. GO assumes that radar

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wave mainly spreads along the special trajectory of ray path[8]. The incidence of radar wave on the object surface can be described by Snell's law. At this point, the backward RCS can be described as follows:

$$\sigma = \pi\rho_1\rho_2 \tag{1}$$

where, ρ_1 and ρ_2 are double curvature radii at the reflection point on the surface. When the curve radius is infinitely large, geometrical optics cannot be used.

Physical Optics (PO) method is derived from Stratton–Chu integral formula[9]. PO sets the current over the shadow borders as 0. Scattered field integrals of the places deviating at larger angles or in shadow areas are not accurate. When multiple reflection is calculated, each increase of reflection doubles integrals of physical optics, leading to a sharp increase of computing time. Thus, PO is not suitable for computing multiple reflections.

The geometrical/physical optics mixing method computes the areas illuminated by radar and the propagation path of radar along the target through geometric optics, and computes RCS of the illuminated areas through physical optics. Therefore, this method can avoid the major defects of both GO and PO.

2 Setting of evaluation parameters for the stealth performance of the ship's mast

The mast similar to the one on "Horizon" level destroyer is selected as a geometric model for shape stealth evaluation. When modeling, simplification of the mast is necessary, ignoring radar, communication and other electronic instruments installed on the mast (Fig. 1). Both the main body of the mast and the radar platform are tetrahedron, and the angles between most panels and vertical plane are 7°–8° . Steel and Frequency Selective Surface (FSS) materials are the main materials of ship's mast. Considering that shape stealth is the major research purpose of this paper, the mast should be seen as a perfect conductor, thus its internal electric field is 0.

Considering the application performance of anti–ship radar and early–warning radar, this paper takes the stealth performance of ship′s mast under center frequencies of L, S, C, X and Ku into consideration, with the corresponding radar wavelengths of 20, 10, 5, 3 and 2 cm. The detection condition that ships have to face is mainly from a single enemy ship or air armament platform, so single–station stealth

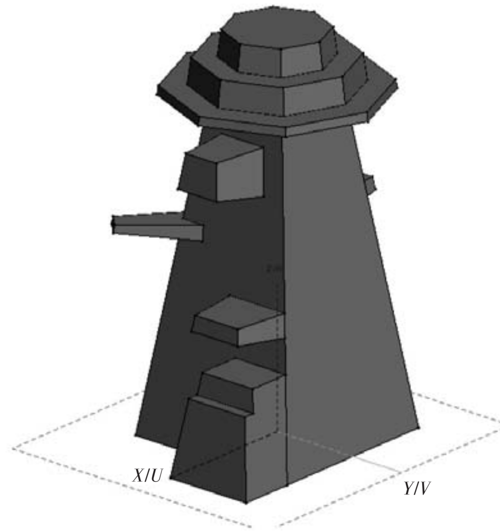


Fig.1 Geometric model of the mast

performance is more important in navy areas.

RCS of ships changes dramatically with the irradiation angle, and it is impracticable to realize radar wave stealth at all angles. The purpose of stealth design is to lower RCS in radar danger zone[10]. Therefore, the radar threatened area of mast is angled at 0° in elevation and at 0°–360° in horizon.

3 Analysis of the factors affecting the stealth performance of the ship's mast

3.1 Influence of radar wave parameters

The relationships between RCS and the frequency and horizontal angle of radar wave are studied. RCS distribution of the mast in different frequencies of radar waves (vertical polarization) is shown in Fig. 2, and the frequency interval is 1 GHz. As can be seen from Fig. 2, in different frequencies of radar waves, the "lightspot" of the mast remains unchanged; the higher the frequency is, the smaller the area where the RCS vlaue distribution exceeds 30 dBm^2 is, which means that the RCS peak regions decrease with the increase of frequency; mast's reflections of radar waves are always the biggest near 0° and 180°. If enemy's radar is located right ahead of or right behind the ship, the reflection energy of the mast is the strongest. When the angle of incidence is close to 90° or 270°, RCS intensity in any frequency is also high.

The relationships between RCS and the wavelength and polarization direction of radar wave are researched. The average and maximum curves of RCS in radar threatened areas under different polariza-

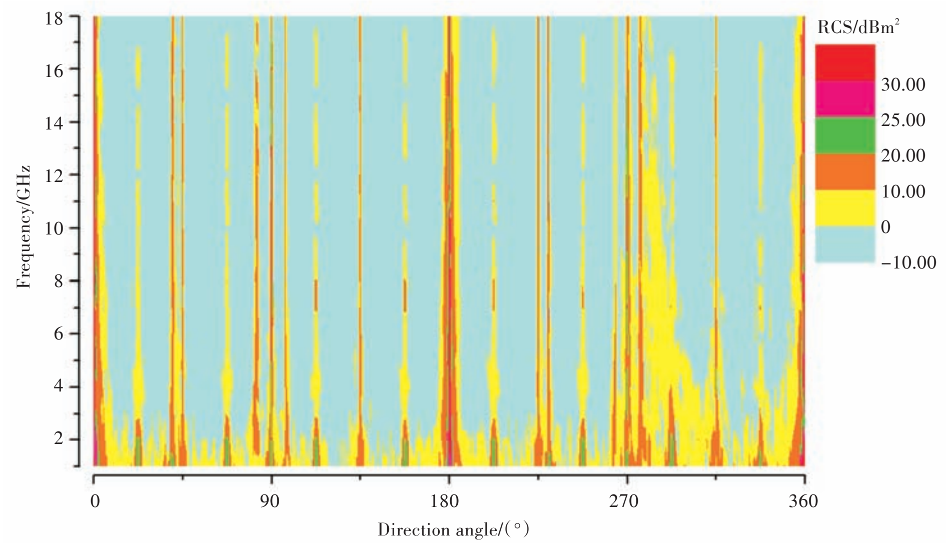
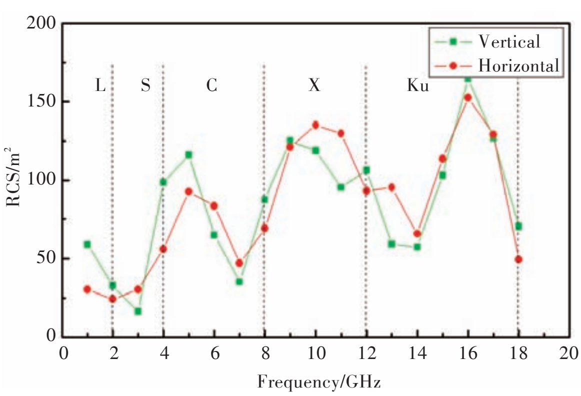
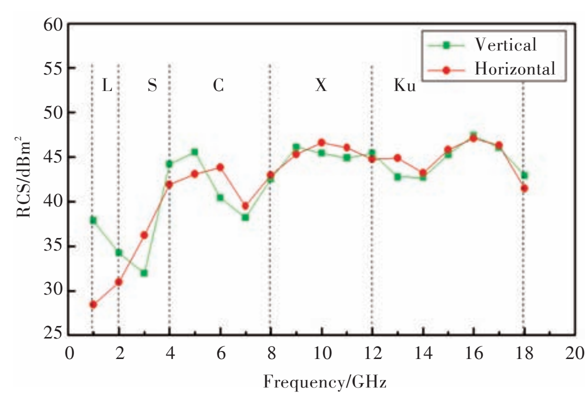


Fig.2 RCS distribution of mast in different frequencies and angles

tions are shown in Fig. 3. Whether in horizontal polarization mode or in vertical polarization mode, the variations of RCS with frequency in both modes are similar. However, polarization direction has greater influence on non-maximum angle.



(a) The average curves of RCS



(b) The maximum curves of RCS

Fig.3 Influences of wavelength and polarization

The change laws of the average and maximum RCS with frequency are complex, because even though the directions of polarization are the same, vibration still occurs. But the reason why the variations of the average and maximum RCS in both modes are similar is that the maximum RCS is usually much greater than the RCS at any other angle. Therefore, the maximum RCS takes up a large proportion in average RCS.

3.2 Influence of ship rolling

The ship rolling is inevitable due to waves and winds, so it is necessary to study the influences of rolling on mast's RCS[11]. The rolling range of the ship is set within ±30°, and the rolling angle is sampled every 5°. The RCS distribution of mast is shown in Fig. 4.

Despite rolling, the front or rear cross section of the mast almost remains unchanged, and the RCS values at 0° and 180° are basically stable. When the rolling angle is less than 10°, the RCS peak area almost remains unchanged, which means small-scale rolling has a small influence on mast's RCS. When the rolling angle is large, the RCS peak area changes obviously. Especially, under rightward rolling, a large scattering peak area is formed. Since the increase of RCS is regional, it can be judged that it is caused by multiple reflection. Compared with the geometric model, it can be told that these peak areas are caused by the dihedral angle which is formed by the overhang radar base of the mast and the main structure of the mast. So ship rolling can increase the dihedral angle effect of the mast.

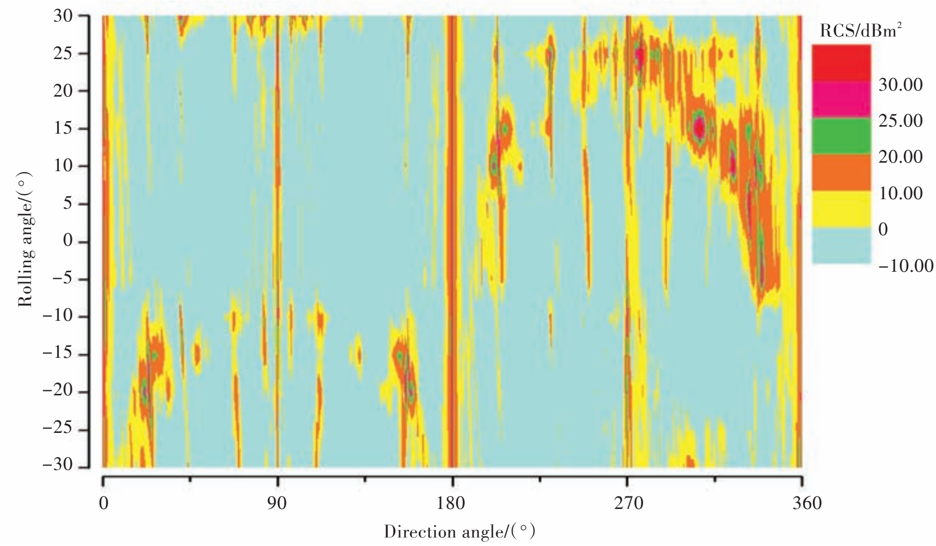


Fig.4 Variations of RCS with ship rolling

4 Analysis of radar reflection features

The main purpose of analyzing the features of radar reflection is to understand the main characteristics of radar waves reflected by the mast, which provides support for the evaluation and improvement of the stealth performance of mast. This purpose can be achieved by the analyses of reflection mechanism and the main reflection source. The evaluation radar wave used in this section is the X radar wave which is vertically polarized.

4.1 Analysis of radar wave reflection mechanism of the mast

The comparison between specular reflection and double reflection is shown in Fig. 5. After double reflection, there is no significant change in RCS peak values among most of the angles, and most RCS peak values are caused by specular reflection. When the angle of incident wave is 0°, the RCS value is the largest, reaching 22.5 dBm^2 at the specular reflection and 46.6 dBm^2 at the double reflection. In this incident angle, double reflection is stronger than specular reflection, because double reflection causes the RCS change of regional angle.

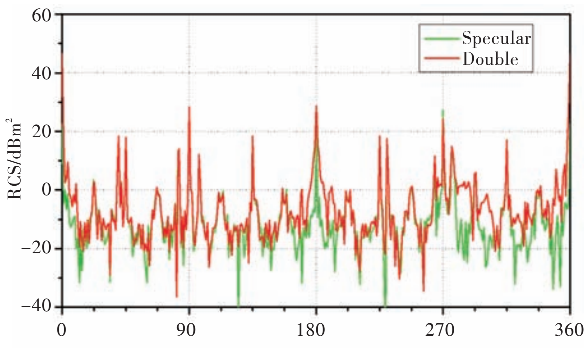


Fig.5 Comparison of the specular/double reflection

By contrasting the RCS peak angle and geometric model of the mast, a conclusion can be drawn: the double reflection is caused by the dihedral angle formed by the overhang structure of the mast and the main structure of the mast. This conclusion will also be proved in the next section.

The comparison between the double reflection and the triple reflection is demonstrated in Fig. 6. As can be seen from Fig. 6, only at a few angles can tiny difference be found between the two curves, and the difference can be ignored to some extent. In the threatened area, the third reflection is very small, indicating that the influence of the fourth reflection is even smaller. Generally speaking, when using the GO/PO method to compute the RCS of the mast, triple reflection results can meet the demands.

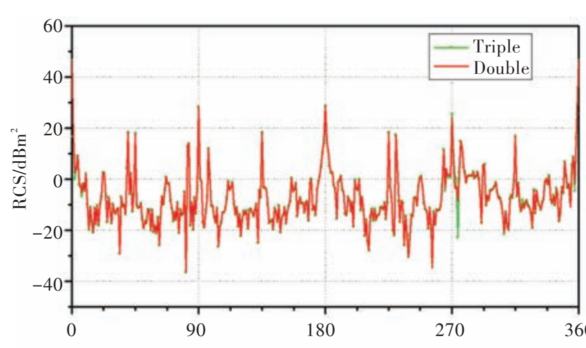


Fig.6 Comparison of the double/triple reflection

4.2 Analysis of the radar wave reflection source of the mast

To find the main reflection source of the mast, the subsidiary radar platform can be divided into six parts, and the labels are shown in Fig. 7. The computed RCS after six radar bearing platforms being removed is shown in Fig. 8. As can be found in Fig. 8(a), after the removal of #1 radar bearing platform, the peak points of the RCS near 23°, 67°, 111°, 157°, 202°, 243° and 337° disappear. But these peak points do exist in the RCS calculation results of specular reflection as shown in Fig. 5. In view of the geometric relations between these incident angles and #1 radar bearing platform, it can be deduced that these peak points are caused by the specular reflection of #1 radar bearing platform.

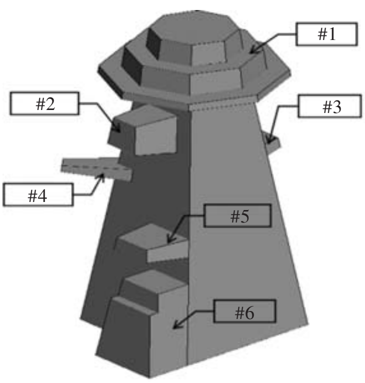
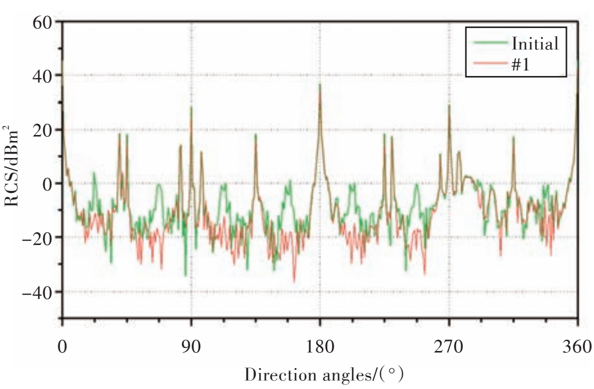
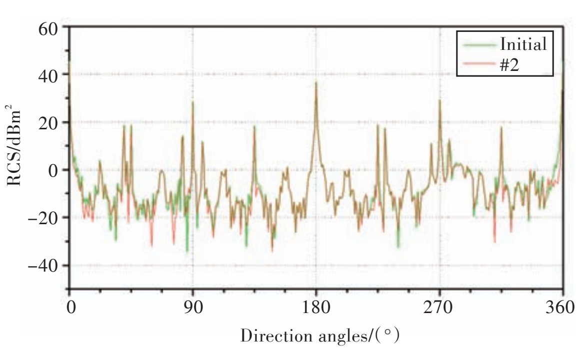


Fig.7 Schematic diagram of subsidiary radar base label

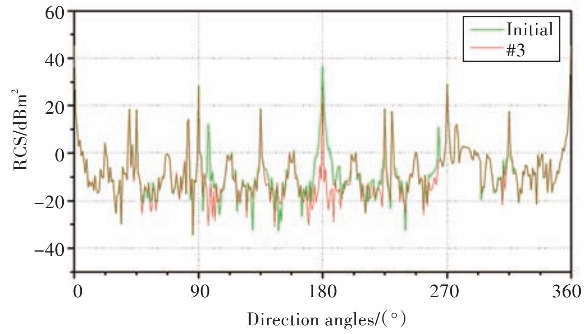
#2, #5 and #6 subsidiary platforms are rectangular blocks in the front of the mast. As can be observed from Fig. 8(b) and Fig. 8(e), #2 and #5 only affect the RCS value of mast's right front angle, and have no effect on other angles. After the removal of #5 subsidiary platform, the RCS peak value at 0° falls from



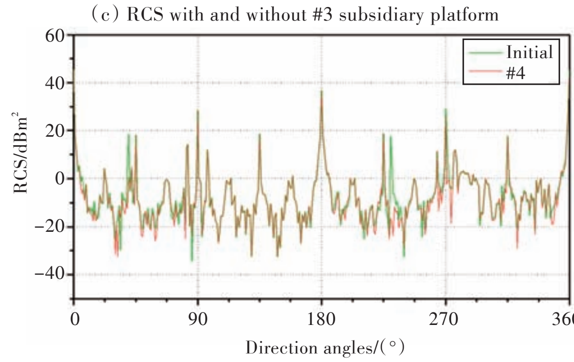
(a) RCS with and without #1 subsidiary platform



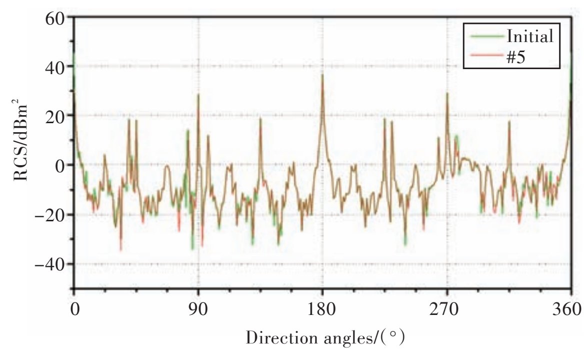
(b) RCS with and without #2 subsidiary platform



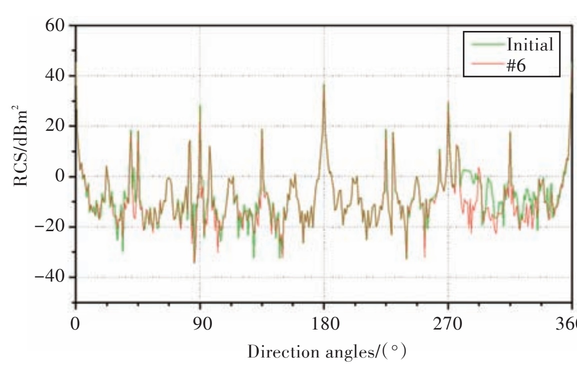
(c) RCS with and without #3 subsidiary platform



(d) RCS with and without #4 subsidiary platform



(e) RCS with and without #5 subsidiary platform



(f) RCS with and without #6 subsidiary platform

Fig.8 Comparisons of RCS computing results with and without subsidiary base, individually

45.5 dBm^2 to 30.9 dBm^2, which means #5 is a main reflection source at 0° for the mast. In Fig. 8(f), after the removal of #6 subsidiary platform, the RCS decreases significantly during 283°–344°, but the influences of other angles can be ignored. Compared with the geometric model, it can be deduced that this is caused by the dihedral angle, which is formed by the right-side plate of #6 subsidiary platform and the main structure of the mast. Therefore, it can be concluded that the design of #2 subsidiary platform is better, but the front-side plate of #5 subsidiary platform and the right-side plate of #6 subsidiary platform need to be adjusted. So the suggestion is that the angles between the above two plates and the main structure of the mast should be enlarged.

As can be seen from Fig. 8(c), after the removal of #3 subsidiary platform, when the incident angle is close to 97°, 180° and 223°, the RCS peak value falls significantly. It can be concluded that the designs of the front, left and right side plates are not good. So it is suggested that the angle between the front-side plate and the vertical plane should be enlarged, so does the angle between the front-side plate and the main structure of the mast.

It can be seen from Fig. 8(d) that the removal of #4 subsidiary platform significantly decreases the RCS at 40° and 230°, but has so little influence on other angles that can be neglected. Since multiple reflection is regional and compared with the geometric model, it can be concluded that these two peak values are caused by the specular reflection from the two side plates of #4 subsidiary platform. Thus, it is suggested that the angles between these two side plates and the vertical plane should be enlarged.

Since all the subsidiary platforms have little influence on the RCS peak values at 0°, 45°, 90°, 135°, 180°, 225° and 270°, it can be told that these peak values are caused by the specular reflection of the main structure of the mast. So these peak values can be improved by changing the inclination angle of the main structure of the mast.

5 Evaluation process analysis of mast's shape stealth

From the analysis and computing results of this paper, the basic process (Fig. 9) aiming at the evaluation and improvement of the stealth performance for ships that have exposed masts can be set as follows:

1) The evaluation range (single-station radar only) for the dangerous angles of the RCS is limited.

2) The RCS computing method should be selected according to the amount of calculation and the actual accuracy requirements.

3) A reasonable electromagnetic calculation model of the mast is established (equipments on the mast are not included generally), and the structure and material properties of the mast are simplified.

4) The RCS under different radar parameters is computed to get the variation laws of RCS with radar parameters.

5) A typical radar parameter is selected; the RCS under this radar parameter is computed and analyzed; the computing results between specular reflection and multiple reflection are compared and analyzed to figure out the main scattering features of the mast.

6) The main reflection source of the RCS is confirmed by comparing the RCS distribution in different mast models. Therefore, design quality of each part of the mast can be obtained and advice on shape adjustment can be proposed.

7) Preparation is made for the RCS evaluation in the next stage.

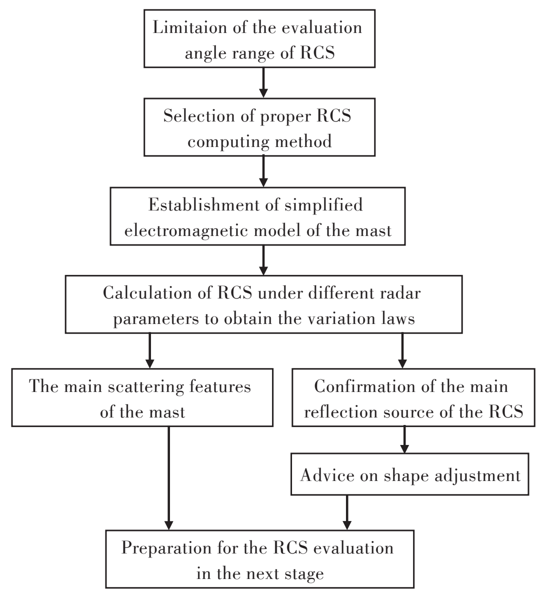


Fig.9 The evaluation process of stealth shape

6 Conclusions

As one of the important sources for radar reflection, mast has a great influence on the overall stealth performance of ships. After evaluation and analysis of the stealth performance of a typical enclosed mast shape, conclusions are made as follows:

1) Most RCS peak values are caused by specular reflection. Multiple reflection is weak and regional, which is caused by the dihedral angle formed by the radar platform and the main structure of the mast. Through adjusting the panel angles of #3, #4, #5 and #6 radar bearing platforms, better stealth performance can be obtained.

2) For horizontal and vertical polarization modes, with the increase of frequency, the average and the maximum RCS have the same changing trend, and what's more, the RCS peak zone is compressed. If the rolling angle is large, the RCS peak zone changes obviously, mainly because of the increased dihedral angle effect formed by the subsidiary platform and

the main structure of the mast.

Meanwhile, this paper also develops an evaluation and improvement process for the stealth performance of the mast, through which the stealth performance of the ship's mast in the preliminary design stage is instructed.

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初步设计阶段桅杆外形的隐身性评估与改进

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摘　要：桅杆作为重要的雷达波散射源，将直接影响到整个舰船的隐身性。在舰船设计初期，如何评估和改进桅杆的隐身性显得十分重要。以一个典型的封闭式桅杆为研究对象，分析评估参数对隐身性计算结果的影响，得到该桅杆的主要反射机制，识别出桅杆大部分RCS峰值是由单次反射引起，并给出桅杆外形隐身调整建议。结果显示，若发生横摇，附属平台和桅杆主体结构产生的二面角效应会增强，所得结论可为初步设计阶段舰船桅杆的隐身性评估和改进提供参考。

关键词：桅杆；雷达散射截面积；评估；隐身性