Structure Design And Optimization Approach For Low RCS Screws

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Abstract With the rapid development of radar stealth and detection technology, large numbers of screws and rivets have become a major factor that affecting the aircraft's invisibility. This is because these components have a significant impact on the overall radar cross section of the aircraft, when the electromagnetic scattering characteristic of strong scattering sources is greatly reduced. By analyzing the scattering contribution of the head and body to the screw, it has been obtained that the geometric structure of the head plays a primary role in influencing the overall radar cross section of the screw. According to the scattering mechanism and stealth principle, a shape design method for the low RCS screw is proposed, and then we investigated the scattering characteristic of the octagonal, hexadecagonal, and circular head screws respectively. Furthermore, a structure optimization approach for low RCS screws is introduced which takes the angle of the incident wave into account. This has resulted in the development of a corresponding triangular screw with low detection capabilities. The simulation results show that within the operating frequency band of radar, the triangular head screw has a maximum RCS reduction of approximately 30.1dB compared to a traditional round head screw in [-90°, 90°]. On average, there is a reduction of 12.6dB. The simulated results demonstrate the effectiveness and feasibility of the proposed design and optimization method for low RCS screw structures.

Keywords: Radar Cross Section; Screws; Structure design; Optimization; Invisibility.

1. Introduction

A rapidly expanding army of detection and regulation technology has revolutionized the weapons and equipment world to next generation, making the stealth crucial not only for improving aircraft survivability on the battlefield, but also as a key indicator of modern weapons and equipment [1]. In the medium or long-distance air combat, the stealth threat of aircraft mainly comes from electromagnetic detectors, and Radar Cross Section [2] is a significant index to judge the radar invisibility of aircraft. Conventional aircraft have numerous strong scattering sources, but the scattering proportion of screws or rivets [3] in the overall RCS increases significantly, especially at specific polarizations and incident angles, when the three strong scattering sources [1] are effectively reduced. [4] indicates that the scattering of ten round head screws with diameter of 10 mm can reach up to 1m2, greatly influencing the overall scattering of low-detectable aircraft. Therefore, the own RCS reduction of numerous electromagnetic discontinuities such as screws or rivets is of great to the scattering suppression of radar invisible aircraft. A series of work related to scattering analysis of screws or rivets had been developed.[4] using experimental measurements to obtain the relation between the electromagnetic scattering characteristics of screws and their polarizations and incident angles, taking into account the head types, distances and arrangements of the screws. [5] analyzed the stealth performance of rivets on the absorbing structures which using finite element numerical algorithm, and then derived the optimal distance between rivets through reflectivity optimization. [6] developed a method for extracting the scattering of ideal electromagnetic discontinuities targets, and analyzed the scattering characteristics of single or multiple steps and gaps. Through microwave chamber measurements, the scattering distribution of different types of discontinuities on the aircraft surface was studied, resulting in the identification of the influence patterns [7-9] of gap width, structure, and step height on the RCS distribution. While there has been significant research on weak scattering sources on aircraft, most of it has focused on the theoretical scattering analysis and experimental verification, with no references addressing the design of scattering reduction for screws or rivets.

In this work, a low RCS structure design principle of screws is proposed according to the theory of configuration stealth, and the scattering distribution and RCS reduction properties of octagonal, hexadecagonal and circular head screws is analyzed. Additionally, an optimization mechanism which aimed at scattering suppression for screws is given, and an optimal structure of screws head is also investigated. Finally, the corresponding simulation is implemented to prove the RCS reduction performance, the decrease in both VV and HH polarization at 8~10 GHz show that our proposed method is effective for low RCS structure design and optimization of screws.

2. Structure design of low RCS screws

According to the structural standards of screws [11], screws mainly consist of the head and the body [12]. The low RCS screw structure design in this paper is based on the standard screw. Fig.1 shows the schematic diagram of the standard screw with a slotted round head, featuring a radius of 0.72 mm and a thickness of 0.348 mm. The body of the screw is fastened into the aircrafts or other weapons, indicating that the head of the screw is the primary structure influencing the RCS of the screw. Therefore, our low-scattering structural design and angle analysis were primarily focused on the screw heads.

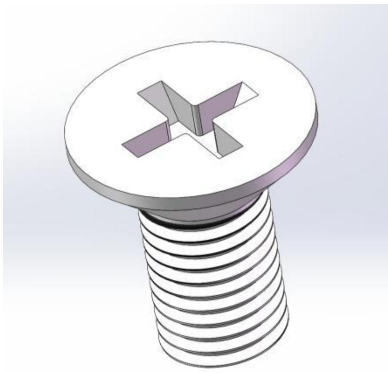
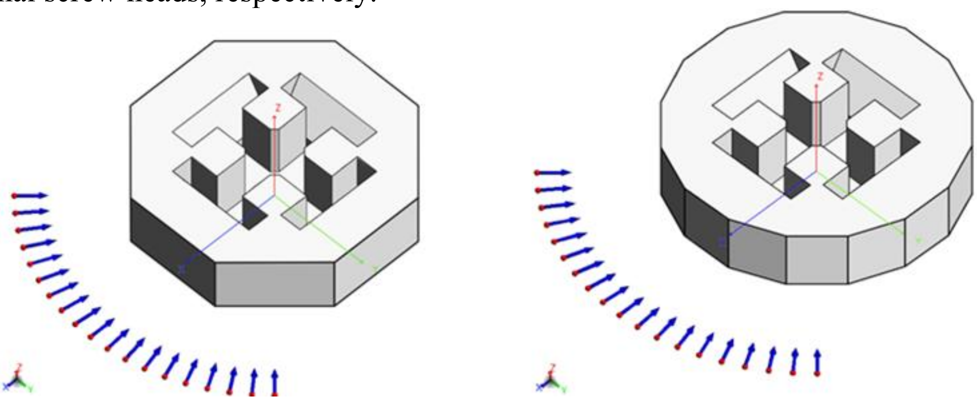


Fig .1 Geometry diagram of standard screw with slotted circular head

Taking the slotted circular head screws as a reference, we analyzed the scattering of the regular frustum screw head and circular screw head. The head of the screw with a cross gap is a frustum whose projection in the xoy plane forms a regular polygon. Fig.2 (a) and (b) show the octagonal and hexadecagonal screw heads, respectively.



(a) octagonal head (b) hexadecagonal head

Fig.2 Geometry diagram of low scattering screw head

As shown in Fig.2, the head of screws is placed on the xoy plane. The pitch and azimuth angles of the incident electromagnetic wave are θ=90°, = -45°~45°. The distance from the center to the vertex of an octagonal and hexadecagonal screw head is 0.768 mm, and the height is 0.348 mm. Fig.3 displays the simulated RCS results of octagonal, hexadecagonal, and circular screw heads at various incident angles under both vertical and horizontal polarization. It can be seen that the scattering field of the slotted round head is most concentrated at -19~-15 dBsm at -45° ~45° incident angles, the hexadecagonal screw head scatters at about -28~-16 dBsm, whereas that of the octagonal case is -32~-20 dBsm. Obviously, the RCS decreases gradually as the number of edges of the screw head projection polygon edges decreases. This is attributed to the decrease in the echo angle direction, which corresponds to strong mirror scattering. This conclusion provides ideas for the configuration design of low-scattering screws.

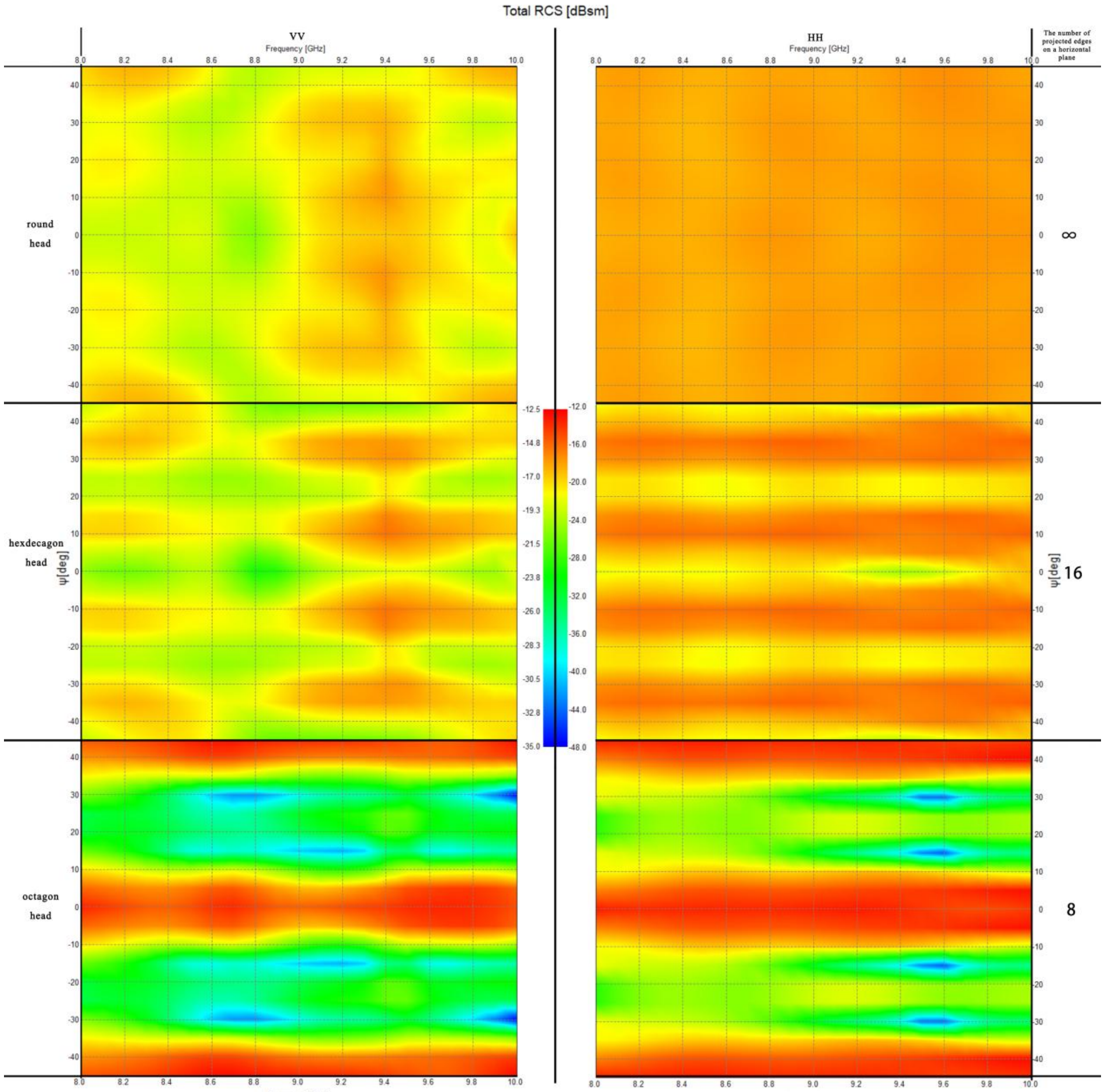
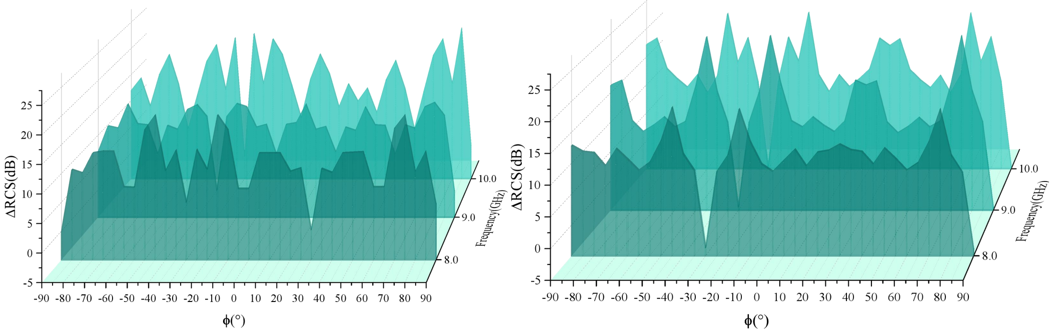


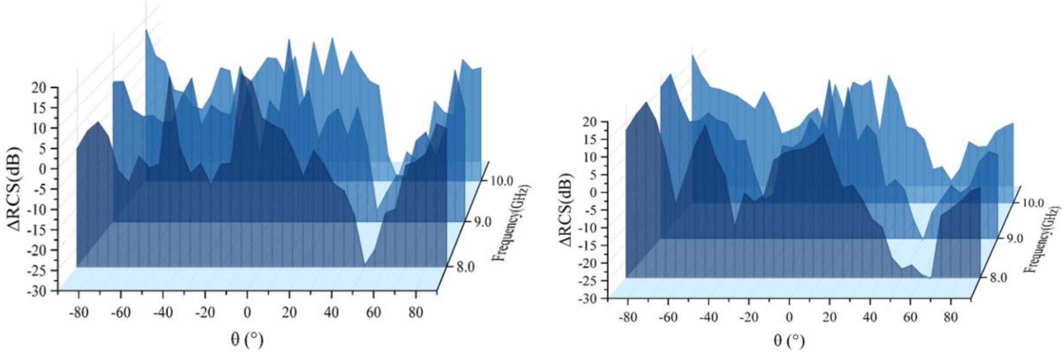
Fig.3 RCS distribution and edge projection of different screw head

Taking a further observation of the scattering distribution for the three types of screw heads, we can see that there is also a strong scattering region for the octagonal and hexadecagonal heads, although their RCS has a significance drop compared to the traditional slotted round head. As shown in Fig.4 and Fig.5, for the circular head, the RCS is relatively large within the incident angle of -45° ~-45° , however, the range for the hexadecagonal head has diminished to 5° ~20° , -20° ~-5° and 25° ~40° ,-40° ~-25° . Similarly, the scattering peak regions for the octagonal head are -10° ~10° , 35° ~45° , -45° ~-35° . This phenomenon occurs due to specular reflection when the incident wave within the specified range is almost perpendicular to the surface of the above head. Hence, according to the mirror scattering mechanism and the structure of the regular pyramid screw head, we can identify a range of positive and negative deviations of 10° with 0° and $180^\circ - \frac{(n-2)\cdot 180^\circ}{n}$ as centers that correspond to the angle regions of maximum scattering, where n represents the edge number of the screw head projection polygon.



（a）HH polarization （b）VV polarization

Fig.4 Angle distribution of triangular and round screw head under horizontal incidence



（a）HH polarization （b）VV polarization

Fig.5 Angle distribution of triangular and round screw head under vertical incidence

3. Structure optimization of low RCS screws

According to the RCS distribution characteristic of the octagonal, hexadecagonal and traditional round head screws, the optimal design method of the low scattering screw head structure is proposed in this section. In order to minimize the RCS of screw within the incidence angle which is taken into attention, the edge of polygonal screw head should meet:

$$180^\circ - \frac{(n-2)\cdot 180^\circ}{n} > \theta \tag{1}$$

A triangular head with the fewest number of edges is proposed and discussed. The angular domain of peak scattering can be organized according to low RCS optimization rules. The geometry of the triangular screw head is depicted in Fig. 6, the side lengths on the upper and lower surfaces were 0.932 mm and 1.879 mm, respectively, and the angle between the side and bottom of the triangular frustum head was 51.8°. Fig.7 draws the RCS curves of the triangular head and the traditional round head in θ=0° at 10GHz，and Tab.1 gives the RCS reduction of the triangular head at θ=-90° ~90° from 8 to 10 GHz compared to round head comprehensively analyzed the results of Fig.6 and Tab.1, it can be conclude the optimized triangular screw head has an average RCS reduction of 12.6dB, maximum of 30.1dB, in the incidence angle range of -90° ~90° at 8-10 GHz. The conclusion indicates that the optimized screw designed by Eq.(1) has significant low scattering characteristics compared to the traditional round head screws, which can provide a theoretical basis for further reducing the scattering of weak scattering sources of the aircraft.

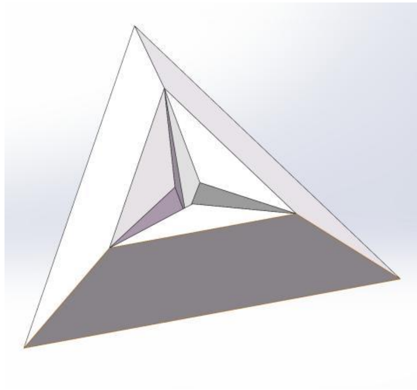
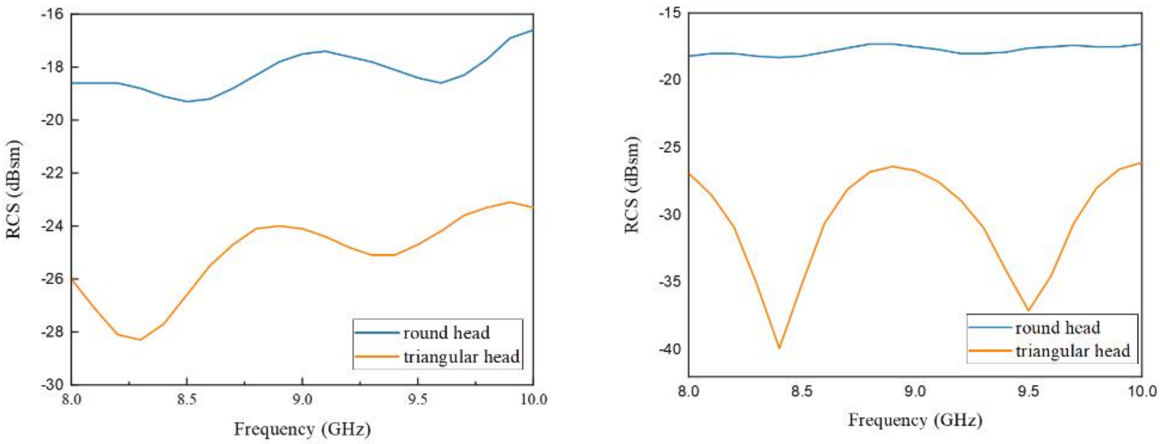


Fig.6 Geometry diagram of triangular screw head



(a) HH polarization (b) VV polarization

Fig.7 RCS comparison of triangular head and round head

Tab.1 RCS reduction of triangular head relative to round head at 8~10 GHz

入射角度 /°	最大缩减dB （HH/VV）	最小缩减dB （HH/VV）	平均缩减dB （HH/VV）
-90~-60	21.5 / 23.3	6.7 / 0.6	12.6 / 11.1
-60~-30	26.4 / 28.4	7.9 / 0.3	11.9 / 11.6
-30~0	26.5 / 28.6	7.8 / 0.3	11.9 / 11.5
0~30	21.6 / 23.3	6.7 / 0.2	12.6 / 11.1
30~60	21.5 / 22.1	6.7 / 0.2	12.6 / 11.2
60~90	26.5 / 30.1	7.9 / 0.1	11.9 / 11.5

4. Summary

Based on the geometry stealth theory, the paper proposed a design method of low scattering screws, and analyzed the electromagnetic scattering distribution of octagonal, hexadecagonal and traditional round screw head at different incidence angle from 8 to 10 GHz. Wherein the octagon, hex decagon head forms a strong mirror reflection in the incident range of -5° ~5° ,40° ~45° and 30° ~35° , 5° ~15° respectively, while the round head strongly scatters in all directions. Similarly, the scattering in the range is 30° ~35° and 5° ~15° . According to the low observable design of screw head, the corresponding shape optimization methodology of the screw head is further developed, and the triangular head is discussed accordingly. Taking the traditional round head as benchmark, the triangular head has a RCS reduction in -90° ~90° under both horizontal and vertical polarization from 8 to 10 GHz, which the average reduction is up to 12.6dB and maximum reduction is 30.1dB. The results illustrate the effectiveness and feasibility of the low-scattering screw design and optimization method, which can provide theoretical support for the weak scattering source RCS suppression of aircraft.

Acknowledgements

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