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OPTIMIZATION OF SCATTERING CHARACTERISTICS OF SUPPORT ROD BASED ON CST SOFTWARE

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Abstract: This paper addresses the problem of strong electromagnetic scattering from traditional diamond-shaped/cylindrical support rods in electromagnetic testing. Low-scattering optimization research is carried out based on finite integration software CST (Computer Simulation Technology) simulation. The scattering mechanism is analyzed by combining geometric diffraction and traveling wave theories, the "convex" water-drop-shaped cross-section is optimized, and a segmented coarse-fine alternating cylindrical structure is designed to disperse the scattering field. Simulations show that the designed water-drop-shaped cross-section segmented support rod has lower scattering intensity in the target frequency band, with significantly reduced scattering in high-frequency bands compared to traditional structures.

Keywords: Support rod; Low scattering; CST simulation

1 INTRODUCTION

With the rapid development of modern radar systems and electromagnetic compatibility testing technologies, the performance evaluation of precision testing environments such as anechoic chambers and compact ranges has raised measurement accuracy requirements to new heights. To support and position the object under test, specific low-scattering target support structures are often required, such as plastic foam brackets, wire rope suspension systems, and low-scattering metal brackets [1-3]. As a basic structure carrying key components like antennas and feeds in testing systems, the electromagnetic scattering characteristics of the support rod directly affect the measurement accuracy of the radar cross section (RCS) of the object under test. Traditional diamond-shaped or cylindrical cross-section support rods generate strong clutter interference in high-frequency bands due to edge diffraction and surface traveling wave coupling, becoming a major bottleneck restricting the improvement of the dynamic range and signal-to-noise ratio of testing systems [4]. Although existing studies have attempted to suppress scattering through absorbing material coating, problems such as narrow bandwidth and poor environmental adaptability persist, failing to meet the requirements of wide-band and high-stability testing [5]. Against this background, achieving low scattering of support rods through structural shape optimization has become a key technical problem urgently needing to be solved in the field of electromagnetic testing. This paper analyzes the diffraction scattering and traveling wave scattering equations of support rods, establishes a three-dimensional model of the support rod in CST, conducts scattering mechanism modeling based on geometric diffraction theory and traveling wave propagation theory, carries out water-drop-shaped cross-section shape optimization and segmented coarse-fine alternating cylindrical structure design, and verifies through simulation comparison. It solves the problem of strong scattering from traditional diamond-shaped/cylindrical support rods in electromagnetic testing and provides theoretical basis and technical support for the engineering application of low-scattering support rods.

2 SCATTERING MECHANISM MODELING OF SUPPORT RODS

2.1 Theoretical Analysis

The scattering contribution of the support rod mainly comes from two aspects: geometric diffraction scattering from edges and traveling wave scattering from the bracket surface.

For the geometric diffraction scattering from edges, according to geometric diffraction theory, the maximum diffraction scattering contribution from the front edge of the support rod with a given inclination angle can be calculated (taking vertical polarization as an example):

$$\sigma=\frac{1}{\pi f^2}\left[\frac{c}{(2-\beta/\pi)\pi\cot\boxed{f_0}\tau\sin\boxed{f_0}(\pi/(2-\beta/\pi))}\right]^2 \tag{1}$$

where:
σ: Radar cross section of the front edge of the support rod;
f: Frequency of incident electromagnetic waves;
β: Inner wedge angle of the front edge of the support rod;
τ: Inclination angle of the front edge of the support rod relative to the horizontal direction.

The diffraction from the front edge of the support rod decreases with the decrease of τ(inclination angle relative to the horizontal direction) and the decrease of β(inner wedge angle). This relationship still holds for horizontal polarization calculations.

For the traveling wave scattering from the bracket surface, according to the basic theory of surface traveling waves, extreme values of traveling wave scattering appear in specific directions, and the calculation formula for the angle between the extreme value direction and the oncoming wave direction is:

$$\phi=49.35\sqrt{\frac{\lambda}{L}} \tag{2}$$

where:
ϕ: Angle between the extreme value direction of traveling wave scattering and the oncoming wave direction;
λ: Wavelength of incident electromagnetic waves;
L: Distance of traveling wave propagation between the front and rear wedges of the bracket.
This angle decreases with the increase of L(distance of traveling wave propagation between the front and rear wedges of the bracket). When the inclination angle of the bracket relative to the horizontal direction decreases, if the difference in inclination angles between the front and rear wedges of the bracket remains unchanged, Lwill increase according to geometric relationships. Thus, the extreme value direction of traveling wave scattering is closer to the monostatic scattering direction of the bracket, increasing the total monostatic scattering. Since the trends of these two contributions with the change of bracket inclination angle are inconsistent, there should be a specific angle where the combined scattering contribution of the two is minimized, i.e., the optimized inclination angle. The bracket model for calculating traveling wave scattering is used to calculate its wedge scattering, and the two contributions are added together.

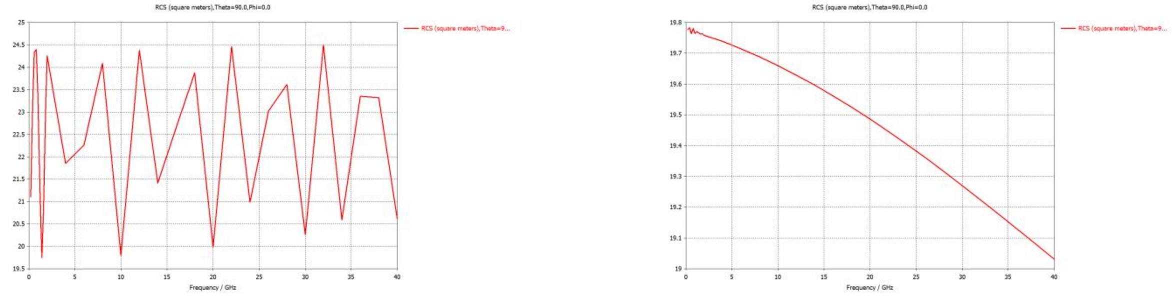
2.2 Model Construction

An electromagnetic simulation model of a diamond-shaped cross-section support rod is selected to simulate the scattering of the support rod. The length of the support rod is 15 m, and the maximum cross-sectional dimension is 1.24 m.
A diamond-shaped cross-section support rod model is established in the electromagnetic simulation software, including pure metal models and absorbing material-coated models [6], as shown in Figure 1.

(a) bare metal (b) coated with microwave-absorbing material

Figure 1 Models of Diamond-shaped Cross-section Support Rods

The electromagnetic signal reflection intensity of the diamond-shaped cross-section support rod model is simulated and analyzed using CST, and the results are shown in Figure 2.



(a) bare metal (b) coated with microwave-absorbing material

Figure 2 Reflection Intensity of Electromagnetic Signals from the Models of Diamond-shaped Cross-section Support Rods

3 SCATTERING SIMULATION ANALYSIS OF DIFFERENT STRUCTURES AND CROSS-SECTION FORMS

3.1 Optimization Design of Support Rod Cross-Section Shape

Unlike masking screens formed by direct metal sheet stamping, the support rod is a hollow structure with a certain wall thickness, so its cross-section shape is restricted by mechanical design and manufacturing. Symmetrical Gaussian curve cross-sections not only have large processing deformation but also leave little space for internal structure arrangement, limiting the target attitude adjustment capability of the support rod. The stress concentration area of traditional diamond-shaped cross-sections easily leads to structural deformation, thereby affecting scattering stability [7]. Therefore, the support rod should choose a "convex" cross-section shape to meet the above requirements, and optional cross-sections include oval, water-drop-shaped, etc. Under the premise of unchanged cross-section length and width dimensions, different cross-section shapes of the support rod will lead to changes in the inner wedge angle, traveling wave crawling distance, cross-section moment of inertia, and deformation amount.

3.2 Optimization Design of Support Rod Cylindrical Structure

Adopting a segmented coarse-fine alternating support rod structure is a periodically varying design, i.e., the support rod shows alternating coarse and fine changes along its length direction. Compared with traditional uniform-diameter support rods, this structure can break the periodicity of the scattering field, so that when incident electromagnetic waves undergo multiple reflections on the support rod surface, the scattering effect is dispersed into different frequencies and directions. It can effectively reduce resonance scattering and target-support coupling effects [8]. In addition, the coarse-fine alternating structure can form a frequency selective surface (FSS)-like effect, making electromagnetic waves of different frequencies produce different reflection intensities in different parts of the support rod. By reasonably designing the size and spacing of each coarse-fine segment, the scattering characteristics of the support rod in the working frequency band can be optimized, thereby reducing the reflection of electromagnetic waves at specific frequencies [9]. Especially in wide-band applications, this design can effectively reduce the scattering intensity at each frequency point, resulting in an overall scattering reduction.

4 STRUCTURAL OPTIMIZATION DESIGN OF LOW-SCATTERING SUPPORT RODS

4.1 Cross-Section Shape Optimization Simulation of Support Rods

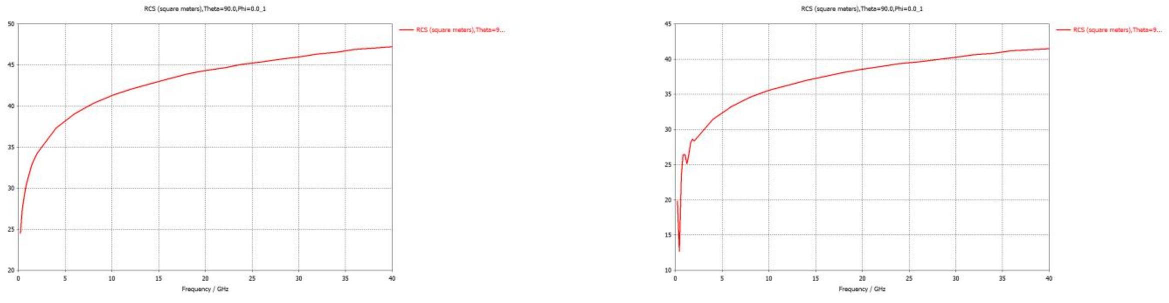
4.1.1 Elliptical cross-section support rod

An elliptical cross-section support rod model is established in the electromagnetic simulation software, including pure metal models and absorbing material-coated models, as shown in Figure 3.

(a) bare metal (b) coated with microwave-absorbing material

Figure 3 Models of elliptical cross-section support rods

The electromagnetic signal reflection intensity of the elliptical cross-section support rod model is simulated and analyzed using CST, and the results are shown in Figure 4.



(a) bare metal (b) coated with microwave-absorbing material

Figure 4 Reflection Intensity of Electromagnetic Signals from the Model of Elliptical Cross-section Support Rods

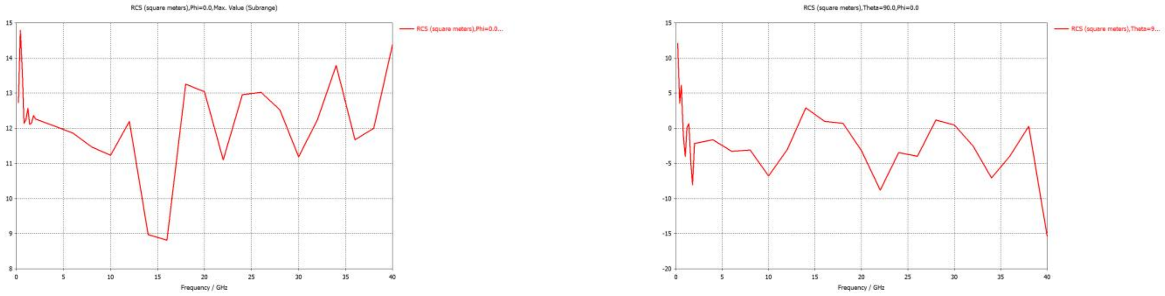
4.1.2 Water-drop-shaped cross-section support rod

A water-drop-shaped cross-section support rod model is established in the electromagnetic simulation software, including pure metal models and absorbing material-coated models, as shown in Figure 5.

(a) bare metal (b) coated with microwave-absorbing material

Figure 5 Models of Water-drop-shaped Cross-section Support Rods

The electromagnetic signal reflection intensity of the water-drop-shaped cross-section support rod model is simulated and analyzed, and the results are shown in Figure 6.



(a)bare metal (b)coated with microwave-absorbing material

Figure 6 Reflection Intensity of Electromagnetic Signals from Models of Water-drop-shaped Cross-section Support Rods

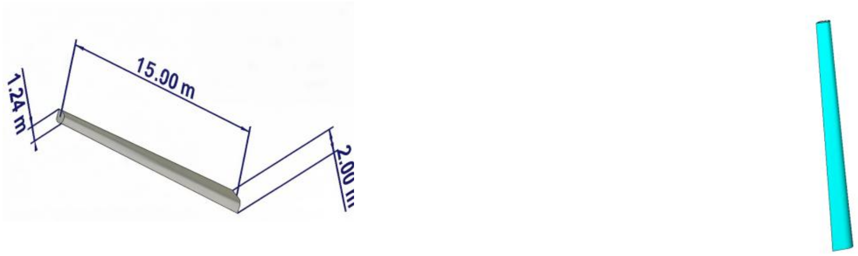
From the above results, it can be seen that when the cross-section of the low-scattering support rod model is water-drop-shaped, at 15 m, the signal reflection intensity of the entire support rod is lower than that of diamond-shaped and elliptical cross-section support rods, with lower reflection intensity. Moreover, adding absorbing materials can further reduce the signal reflection intensity at certain frequencies.

4.2 Cylindrical Design of Support Rods

In the above cross-section shape optimization simulation of support rods, all support rods have the same upper and lower dimensions. Now, the cylindrical structure of the water-drop-shaped cross-section support rod is designed.

4.2.1 Support rod with proportionally enlarged lower cross-section

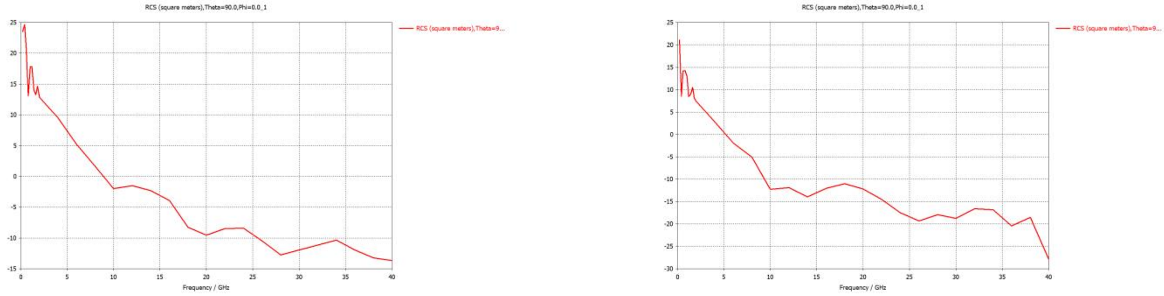
Based on the above simulation, the lower cross-section of the support rod is proportionally enlarged in the electromagnetic simulation software. The maximum dimension of the lower water-drop-shaped cross-section is set to 2 m, and the support rod model with a proportionally enlarged lower water-drop-shaped cross-section is obtained, including pure metal models and absorbing material-coated models, as shown in Figure 7.



(a) bare metal (b) coated with microwave-absorbing material

Figure 7 Models of lower cross-section equal-scale magnified water-drop-shaped support rods

The electromagnetic signal reflection intensity of the support rod model with a proportionally enlarged lower water-drop-shaped cross-section is simulated and analyzed, and the results are shown in Figure 8.



(a) bare metal (b) coated with microwave-absorbing material

Figure 8 Reflection intensity from models of lower scaled-up water-drop-shaped support rods

4.2.2 Segmented structure support rod with water-drop-shaped cross-section

Based on the above simulation, the support rod is segmented. Each segment consists of two parts, both with water-drop-shaped upper and lower surfaces. The lengths of the water-drop shapes are 1.24 m and 2 m respectively, with the shorter water-drop shape on top and the longer one below. The structure of a single segment is shown in Figure 9.

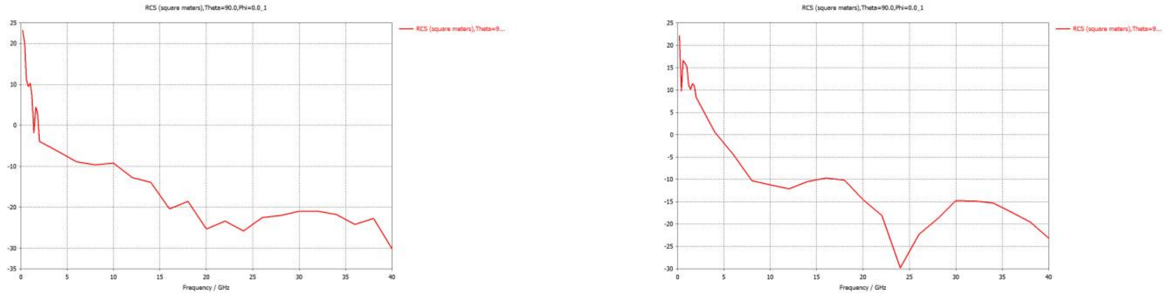
Figure 9 Single Segment Structure of Water-drop-shaped Sectional Support Rod Models

Extending the single-segment structure to 15 m, a segmented structure support rod model with water-drop-shaped cross-section is obtained, including pure metal models and absorbing material-coated models, as shown in Figure 10.

(a)bare metal (b)coated with microwave-absorbing material

Figure 10 Models of Water-drop-shaped Sectional Support Rods

The electromagnetic signal reflection intensity of the segmented structure support rod model with water-drop-shaped cross-section is simulated and analyzed, and the results are shown in Figure 11.



(a) bare metal (b) coated with microwave-absorbing material

Figure 11 Reflection Intensity from Models of Water-drop-shaped Sectional Support Rods

After analyzing the design of the above two cylindrical support rod models and comparing their electromagnetic signal reflection intensities, the segmented structure is selected to better reduce the electromagnetic signal reflection intensity of the support rod. Therefore, the low-scattering support rod model is a segmented structure with water-drop-shaped cross-section, and the simulation model of the support rod combined with the anechoic chamber size is shown in Figure 12.

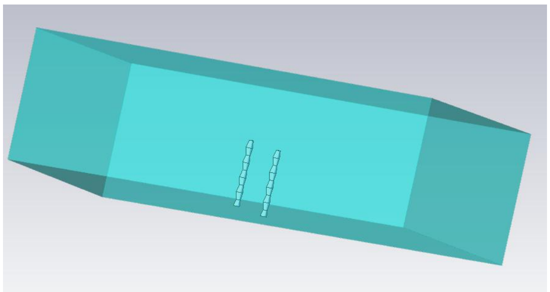


Figure 12 Simulation Models of Support Rods Combined with Darkroom Dimensions

5 CONCLUSIONS

This paper systematically studies and verifies the structural optimization of low-scattering support rods through the CST electromagnetic simulation platform. Based on geometric diffraction theory and traveling wave propagation theory, combined with optimization design methods, a "convex" water-drop-shaped cross-section segmented cylindrical structure design scheme is proposed, and its performance in different working frequency bands is comprehensively analyzed.

Simulation experiments show that within a certain frequency band, the water-drop-shaped cross-section support rod has lower scattering intensity compared to traditional diamond-shaped or cylindrical cross-section support rods. In further optimization design, dividing the support rod into multiple coarse-fine alternating segmented units can break the periodic propagation characteristics of the scattering field, effectively reduce resonance scattering phenomena at various frequency points, and thus achieve effective overall scattering reduction.

In practical application scenarios with anechoic chamber sizes, combined with water-drop-shaped cross-section and segmented structure optimization design, the electromagnetic scattering performance of the support rod meets the requirements of high stability and wide-band testing. Simulation analysis results show that for a 15 m long support rod with a maximum dimension of 1.24 m, the segmented cylindrical structure with water-drop-shaped cross-section has lower electromagnetic signal reflection intensity compared to traditional structures, and the scattering suppression effect of absorbing material coating is more significant in high-frequency bands.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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