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REVIEW ARTICLE

A Complementary Overview and Challenges in Radar Cross Section Modeling of Phased Array Antennas

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HIGHLIGHTS

- *Review of RCS modelling methods of array antennas*
- *Challenges of RCS computations*
- *Current RCS reduction techniques*

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ABSTRACT

The radar cross-section (RCS) is a critical factor in the design and performance of modern airborne weapon systems. These systems utilize phased array antennas due to their low profile, advanced beamforming, and angle measurement capabilities. The effect of phased array antennas on platform RCS can be crucial. Addressing the RCS of phased array antennas involves solving both structural and antenna mode scattering. Each component presents different challenges for computation and requires specific RCS reduction techniques. This short review delves into various existing methods for computing antenna and structural mode RCS and offers insights into their application. Simulating the RCS of large array antennas presents significant challenges due to the high demands on computing resources. Additionally, this review highlights existing solutions aimed at reducing the simulation times and memory usage in RCS modeling while maintaining accurate results. However, further advancements are necessary to simulate large scale array antennas more efficiently and accurately.

Keywords: *Radar Cross Section, Phased Array, Structural Mode, Antenna Mode RCS, Stealth*

I. INTRODUCTION

Radar Cross-Section (RCS) is an important metric for modern airborne weapon systems that depend on its electromagnetic features. RCS is basically the measure of scattered power when an electromagnetic wave is incident on a target, and is a function of parameters such as orientation of target relative to radar transmitter and receiver, target geometry and material, wavelength of the incident wave, transmitter and receiver polarization, and many more [1].

Today, most stealth aircraft platforms and missile systems have systems that uses phased array antennas such as datalink systems, electronic warfare systems, fire control radar, etc. This preference is due to their low profile compared to other types of antennas and their ability to be installed conformally without disrupting the stealth geometry of the platform. Additionally, their abilities such as electronically steer beams and precise angle measurement makes them ideal for most aircraft systems. Therefore, when designing stealth platforms, it is crucial to analyze and reduce RCS of this type of antennas.

Phased array antennas have two forms of scattering: scattering due their structure and scattering due to their radiation characteristics. These two terms are defined as structural mode and antenna mode scattering respectively [1]. Structural mode scattering is measured when the antenna system is match loaded. Therefore, antenna mode scattering is neutralized and scattering occurs only due to the antenna's geometry, materials and aperture size. Over the years many techniques have been developed to reduce antenna RCS. One of the most investigated methods of reducing the structural mode RCS of antennas involves the integration of metasurfaces (MSs) to antenna. MS usage is appealing because they can be designed to control the amplitude, phase, and polarization of scattered waves. These features are leveraged to achieve scattered field cancellation, and therefore effectively reducing the RCS of the antenna. Some of the MS types used in the RCS reduction are artificial magnetic conductor (AMC) with perfect electric conductor (PEC) [2], FSS [3], or checkerboard polarization conversion metasurface (CPCM) [4]-[7], electromagnetic bandgap (EBG) structure [8], etc. However, implementing MSs introduces additional structural components to the antenna array, which can lead to decrease on bandwidth and gain of the antenna. Another method for reducing structural mode RCS is through the use of the reflection cancellation technique [9]-[11]. This approach involves using different antenna elements designed to produce reflections that are 180 degrees out of phase. By arranging and tuning these different antenna elements, the reflected waves interfere destructively, effectively canceling each other out and thus reducing the overall RCS. The technique depends on precise control of the phase and spatial configuration of the antenna elements to ensure destructive interference occurs effectively within the antenna frequency band. While this method offers effective reduction of structural mode RCS without the bandwidth limitations and it does not introduce any additional structures. It presents challenges such as design complexity, as designing an array with different antenna elements that exhibits similar radiation characteristics can be challenging. Additionally, it is reported that reduction of RCS is only effective under normal incidence, with different incident angles RCS reduction is less efficient [9].

Antenna mode scattering, on the other hand, occurs when antenna load is not matched. In this case, scattering from antenna is the summation of both structural and antenna mode scattering. For phased array antennas, analytically computing RCS is particularly challenging because of their complicated feed networks, mutual coupling between antenna elements, and other complications [1]. All these complications affect the radiation characteristics of the antenna and, therefore, antenna mode scattering component. Figure 1 shows a simplified scenario of antenna scattering where a single antenna element of an array is connected to various circuit elements.

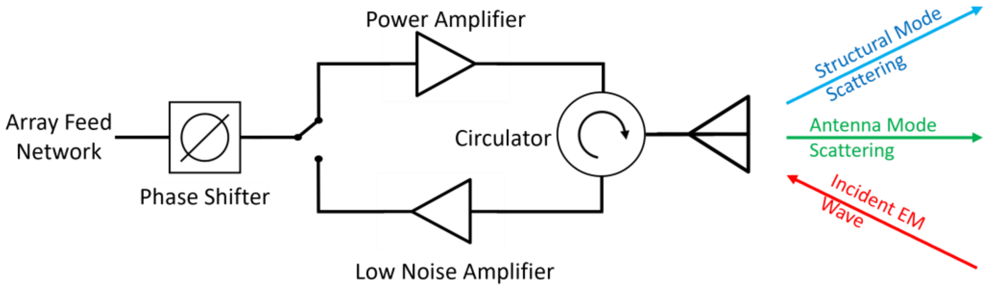

Figure 1. Scattering representation of phased array antenna

This study is organized as follows: Section II discusses the current analytical methods for computing antenna mode RCS, detailing their respective advantages and disadvantages. This section provides a comprehensive overview of techniques such as RCS with arbitrary loads, and gain-based reconstruction, among others. Section III addresses the challenges associated with computing the RCS of large phased array antennas. It also explores solutions to mitigate these challenges. Methods like GPU acceleration and the active element mode scattering pattern to enhance processing speeds and reduce memory requirements.

II. BACKGROUND INFO

There are several methods to compute and/or simulate the RCS of antennas. Solving antenna RCS purely through analytical methods can be impractical due to the numerous assumptions required. Solving RCS with analytical methods is more complex for array antennas, which often feature complex feed networks with devices such as phase shifters and couplers. These components contribute to transmission loss of the array antennas. Solving the antenna mode RCS of array antennas solely through a full-wave electromagnetic (EM) simulator is not possible without additional post-processing steps. Full-wave EM simulators (e.g., HFSS, CST Microwave Studio) are necessary for modeling array antennas and providing data such as far-field patterns and S-parameters. Structural mode RCS can be computed directly through these simulators by terminating the antenna with matched loads, thus ensuring the simulation computes only passive scattering. Antenna mode RCS requires further post processing steps.

A. Solving Antenna RCS with Arbitrary Loads

Antenna RCS can be expressed in terms of structural and antenna mode for an open circuited load as [12]

$$\sigma = \left|\sqrt{\sigma_s} + \sqrt{\sigma_{re}}e^{i\phi}\right|^2 \quad (1)$$

Where σ_s and σ_{re} are structural and antenna mode terms respectively, ϕ is the phase difference between the terms. To solve the unknown phase difference between these terms a model was proposed at [13]. With this model antenna RCS is obtained with full wave simulator by simulating the antenna scattering with open and short circuit loads. Antenna RCS under any arbitrary load can be obtained with

$$\vec{E}^s(Z_l) = \frac{(1-\Gamma_a)\vec{E}^s(\infty)+(1+\Gamma_a)\vec{E}^s(0)}{2} + \frac{\Gamma_l}{1-\Gamma_l\Gamma_a}\frac{1-\Gamma_a^2}{2}\left[\vec{E}^s(\infty) - \vec{E}^s(0)\right] \quad (2)$$

$\vec{E}^s(\infty)$ and $\vec{E}^s(0)$ is the scattered electric field when antenna load is terminated as open circuit and short circuit respectively. Γ_a and Γ_l represent the reflection coefficient of the antenna and the load, respectively. The first term of equation (2) corresponds to the structural mode scattering, while the second term corresponds to the antenna mode scattering field. Using this formulation, the scattered field of antenna RCS can be easily obtained with the aid of a full-wave simulator.

B. Reconstructed Antenna Mode RCS Based on Antenna Gain

Another method for solving antenna RCS is by using gain data of the antenna to reconstruct antenna scattering pattern. The relationship between antenna gain and antenna mode RCS has been long recognized. Appel-Hansen at [14] derives the relationship between antenna gain and antenna mode RCS for a hypothetical antenna for which all of the scattering is caused due to mismatch at the antenna load. If an antenna is terminated with a short circuit load there is a perfect reflection at the load [1] therefore total re-radiated power is equal to received power of the antenna.

Therefore, antenna mode RCS can be defined in terms of gain as;

$$\sigma_{re} = \frac{G^2\lambda^2}{4\pi} \tag{3}$$

This definition only represents the antenna mode scattering portion and completely ignores the structural mode RCS, which occurs due to the physical properties of the antenna. But with this definition antenna mode scattering pattern can be reconstructed using the gain pattern obtained with a full wave simulator. Structural mode RCS portion can be obtained separately with full wave simulations when antenna is terminated with a matched load. In this way, scattering from the antenna is independent of the antenna feed and occurs solely because of the structure of the antenna.

The authors in [15] modifies this definition for array antennas to compute the antenna mode RCS using the scattering pattern multiplication method. Although this method ignores mutual coupling, edge effects, and feed losses, it allows for the estimation of array RCS with reduced simulation time compared to other methods. An improved alternative for this method has been proposed in [16] called the active element mode scattering pattern, which is similar to the active element pattern [17]. The antenna mode RCS is estimated by superposition of the antenna elements active element mode scattering pattern. Simulation time is further reduced by assuming that the inner array elements have similar patterns to the middle element. It is reported that compared with the reference method, proposed method requires 88% less memory usage, while maintaining low relative error.

C. Antenna Mode RCS Calculation Through Directivity and Impedance of Each Array Segment

In [18], the authors propose a novel method for analytically estimating the antenna mode RCS. A patch antenna array is divided into sections, directivity and impedance of each segment is computed using a full-wave simulator. These values are then incorporated into the formulation of the antenna mode RCS for N-element linear patch arrays. The scattered field contributions from each component of the array and its feed network are described using reflection and transmission coefficients in the formulation. This method can be useful for RCS computations of more conventional arrays with reduced simulation times.

A summary of the existing studies on RCS computation is presented in Table I. From the results, it is evident that there is a trade-off between simulation time and accuracy. Active Element Mode Scattering Pattern seems to offer the best middle ground for computing RCS of large arrays.

TABLE I. Summary of RCS Computation Methods

Method	Advantage(s)	Disadvantages(s)	Reference
Antenna RCS with Arbitrary Loads	Uses full-wave simulator data for accurate RCS results under various loads	Requires computationally intensive simulations with different loads	[13]
Gain-Based Reconstruction	Simplifies antenna mode RCS calculation using the gain data obtained with a simulator	Ignores structural mode RCS	[14]

The Scattering Pattern Multiplication Method	Reduces memory usage and simulation time	Edge and mutual coupling effects are not considered	[15]
Active Element Mode Scattering Pattern	Reduces memory usage and simulation time; edge and mutual coupling effects are considered	Assumes inner array element patterns are the same	[16]
Directivity and Impedance Method	Useful for conventional arrays; reduces simulation time	Requires detailed segment-by-segment analysis of arrays	[18]

III. RESEARCH CHALLENGES AND DISCUSSION

Computing the RCS of large phased array antennas via full-wave simulators accurately can be very demanding on processing power and memory requirements. Detailed time-domain simulations can take a substantial amount of time. In order to increase processing speed, utilizing Graphical Processing Unit (GPU) acceleration can be very beneficial. Time-domain simulations heavily rely on the Central Processing Unit (CPU), resulting in memory bottlenecks and increased simulation times. The high memory bandwidth and parallel computing abilities of GPUs can significantly reduce simulation times compared to CPU computing alone.

New computational methods for simulating RCS of array antennas will likely focus on further optimizing existing methods to enhance time efficiency and accuracy. Hybrid methods that combine full-wave simulations with analytical approaches could be the key to more efficient and accurate RCS simulations.

IV. CONCLUSION AND FUTURE DIRECTION

In this study, as part of an ongoing research on the RCS estimation of large array antennas, a literature review was conducted to analyze the current methods of computing antenna RCS. The review goes through existing techniques to discuss their respective advantages and disadvantages. Challenges in computing RCS of large arrays along with proposed solutions are also discussed. The necessity of GPU acceleration in full-wave simulations to improve processing speeds and reduce memory requirements is emphasized and its potential to significantly improve simulation times. Furthermore, methods like the active element mode scattering pattern provide time efficient solutions for estimating RCS with reduced simulation times and memory requirements. Making this method a good option for large-scale phased array RCS analysis. This study aims to find the optimal methods for estimating the RCS of phased arrays by discussing the existing methods.

Our current focus is to apply the aforementioned methods to estimate the RCS of large active electronically scanned array (AESA) type antennas and investigate potential RCS reduction techniques for these systems. Given the popularity of AESA antennas in modern stealth aircraft and missile systems, accurately determining and mitigating their RCS is crucial. We will utilize a combination of full-wave simulators and analytical methods to model the structural and antenna mode scattering.

CONFLICTS OF INTEREST

They reported that there was no conflict of interest between the authors and their respective institutions.

RESEARCH AND PUBLICATION ETHICS

In the studies carried out within the scope of this article, the rules of research and publication ethics were followed.

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