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***Journal of Scientific and Engineering Research*, 2021, 8(4):90-98**

Review Article

ISSN: 2394-2630
CODEN(USA): JSERBR

A Study on the Radar Cross Section Prediction and Reduction for Unmanned Surface Vehicles

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Abstract We introduce the analysis of recent research trends on the prediction and reduction method of RCS (Radar Cross Section) for unmanned surface vehicles. The future trend of RCS reduction is predicted, including RCS basics and important scattering mechanisms, RCS prediction techniques, and RCS reduction techniques. In this review article, RCS prediction and reduction for unmanned surface vehicles are systematically summarized and analyzed with particular emphases on shaping and radar absorbing materials. In addition, we will focus on the shaping method and various RCS reduction methods using meta-material-based absorbers. Chapter 2 examines basic RCS prediction methods and important scattering mechanisms, and then introduces various RCS prediction methods in Chapter 3. And in Chapter 4, the shaping method and meta-material-based absorber are introduced among RCS reduction methods, and in Chapter 5, conclusions and future research plans are presented.

Keywords RCS (Radar Cross Section), Stealth, RAMs (Radar Absorbing Materials), Unmanned Surface Vehicle

1. Introduction

In the future battlefield, unlike simple bombardment with conventional weapons of the past, high-performance radar, sensors, and information technology will be applied to the precise and fast strike. In particular, efforts to avoid detection of the enemy have already been implemented in advanced countries through the development of stealth technology, and various studies have recently been conducted in Korea to implement detection technology. The ability of a radar target to reflect the signals in the transceiver direction is measured by its radar cross section (RCS) which is an important index in the radar system design. Efforts for radar detection can be solved through electromagnetic wave absorbers. The electromagnetic wave absorber is a device that prevents reflected waves or transmitted waves by maximizing loss by changing energy of incident electromagnetic waves as heat, and can be used for various purposes. However, it is difficult to make an absorber capable of absorbing electromagnetic waves of various frequencies by mixing electromagnetic wave absorbing materials. Therefore, a method of changing the structural shape of the absorber is also widely used.

However, the shaping method usually affects the aerodynamics and mechanical aspects of the object which limit its benefits. As a way to meet these technical requirements, a meta material-based electromagnetic wave absorber has been proposed, and various studies have been conducted. Radar absorbing materials (RAMs) are electromagnetic structures used to absorb the incident electromagnetic waves so that the reflected power as well as the transmitted power are reduced to a great extent [1-3]. Some of its applications such as RCS reduction [4], electromagnetic interference (EMI) shielding [5], stealth technology [6] etc. in contemporary times are more demanding, in the sense of reduced thickness [7], wide bandwidth [8], polarization insensitiveness [9,10], and ease of fabrication [11,12], in such a way that traditional Salisbury screen [13] and Jaumann absorbers [14] are set aside. Another promising method for the design of RAM is the circuit analog absorbers wherein conductors are patterned above the ground plane so that the combination acts as a high impedance ground plane (HIGP), which creates a magnetic wall and hence the maximum electric field intensity at a much lower thickness than quarter wavelength of the frequency of interest [15]. Lumped resistances or patterned resistive films are used to dissipate the resonating microwave energy in the patches [12]. In a similar fashion, there are capacitive circuit absorbers employing low pass square resistive patches instead of band stop frequency selective surface (FSS) resonators as that in circuit analog absorbers [16]. Both these techniques have resonant structures and require extensive optimizations and parameter analysis for achieving wideband nature for a higher wavelength to thickness ratio. They might need spacers which can lead to structural complexities that defy the very purpose of RCS reduction in core applications. The research in the field of 3D printable absorbers is a necessity when RCS from structures having complex geometries are to be reduced, which is getting attention in recent times particularly due to advancements in the additive manufacturing technology [17] and the advent of microwave materials with better absorption properties [18–25].

In this review article, future trend of RCS reduction is predicted, including RCS basics and important scattering mechanisms, RCS prediction techniques, and RCS reduction techniques. RCS prediction and reduction for unmanned surface vehicles are systematically summarized and analyzed with particular emphases on shaping and radar absorbing materials. In addition, the appropriate approaches will be introduced to design the above waterline structure with minimum echo through shaping, and then apply radar absorbing materials to remaining problem areas.

2. RCS Basics and Important Scattering Mechanisms

Radar Cross Section (RCS) is the measure of reflective strength of a target. RCS of a target is defined as the projected area of a metal sphere that would scatter same power in same direction as the target. RCS is formally defined as 4π times the ratio of the power per unit solid angle scattered in a specified direction to the power per unit area in a plane wave incident on the scatterer from a specified direction.

$$\sigma = \lim_{r\to\infty} 4\pi r^2 \frac{|E^{scatt}|^2}{|E^{inc}|^2} \quad (1)$$

where σ = RCS of the target, r = range between radar and target, E^{scat} = scattered electric field and E^{inc}= incident electric field.

RCS of a naval ship is a very important design factor for stealth to achieve surprise, initiative and survivability.It is important to understand scattering mechanisms on a naval ship for accurate RCS determination and effective RCS reduction. These mechanisms provide basic understanding of underlying physical process of scattering. Some scattering mechanisms are dominant compared to others. Scattering also depends on the target aspect angle. Important Scattering Mechanisms on Unmanned Surface Vehicles are shown in figure 1.Multiple bounce mechanism is very important on naval ships due to large above waterline structure with multiple components. Free space between parts of a single component also causes multiple bounce mechanism. Multiple bounce mechanism depends on above waterline geometry and general arrangements. Multiple bounce mechanism also occurs from interactions with water-surface. The presence of water-surface creates complexities. This problem is tackled by including the water-surface in RCS analysis and assigning dielectric properties to the water-surface. High frequency approximations such as geometric optics, Physical Optics, the geometric theory of diffraction, the uniform theory of diffraction and the physical theory of diffraction are used when the wavelength is much shorter than the target feature size.

In the design phase, it is often desirable to employ a computer to predict what the RCS will look like before fabricating an actual object. Many iterations of this prediction process can be performed in a short time at low cost, whereas use of a measurement range is often time-consuming, expensive and error-prone. The linearity of Maxwell's equations makes RCS relatively straightforward to calculate with a variety of analytic and numerical methods, but changing levels of military interest and the need for secrecy have made the field challenging, nonetheless. The field of solving Maxwell's equations through numerical algorithms is called computational electromagnetics, and many effective analysis methods have been applied to the RCS prediction problem. RCS prediction software are often run on large supercomputers and employ high-resolution CAD models of real radar targets.

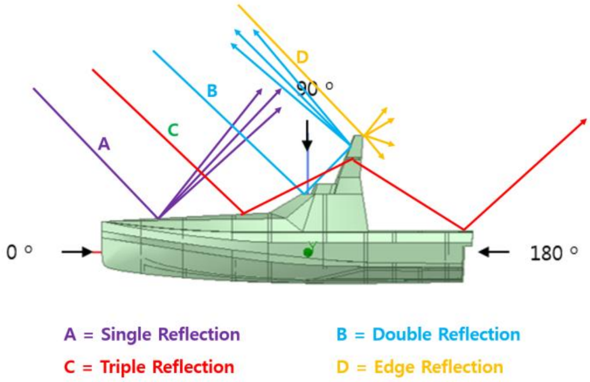


Figure 1: Important Scattering Mechanisms on Unmanned Surface Vehicles

3. RCS Prediction Techniques

In case of a naval ship, fabrication model of brass or a material suitable for RCS analysis is expensive. The model is also not very flexible to evaluating impact of change in above waterline structure to reduce RCS. Finally, RCS of an object can be determined using computational prediction techniques including exact methods and high frequency methods. Scattering objects are sorted into three regions based on their body size with respect to wavelength. Three regions based on their body size with respect to wavelength are shown in Table 1.

Table 1: Comparison of three regions based on their body size with respect to wavelength

Region	Size	Computational Prediction Techniques
Rayleigh region	Typical body size <λ	Exact Methods
Resonance region	λ< Typical body size < 3 λ	
Optic region	Typical body size > 3 λ	High Frequency Methods

The effectiveness of computational methods depends on the position of target in this size scheme. The exact methods are restricted to relatively simple and small objects in Rayleigh and Resonance regions. The high frequency analysis method is suitable for solving the scattering problem of structures that are very large compared to the wavelength, such as military targets, and it is a method of analyzing the electromagnetic wave scattering problem using the assumption that the characteristics of electromagnetic waves become similar to those of light when the frequency increases. Most computer codes in RCS prediction use Physical Optics (PO) and Physical theory of Diffraction (PTD) combined with Geometrical Optics (GO) and Geometrical Theory of Diffraction (GTD). The latter approaches are computationally cheaper and much more accurate for curved surfaces, but not applicable for the computation of the RCS of all surfaces of a complex object due to the presence of caustic problems in the analysis of concave surfaces or flat surfaces in the far field. In the case of unmanned surface vehicles with complex missions, design changes often occur during the construction phase, so RCS analysis and impact review for each design change are required. At this time, the time required for RCS analysis varies depending on the shape and size of the target, but is also greatly influenced by the analysis technique. Therefore, in order to successfully perform RCS analysis and reduction countermeasures for unmanned surface vehicles, an accurate and very fast analysis technique is essential. In this review article, the analysis was conducted using Ansys Electronics Tool [26], which provides an environment in which SBR (Shooting and Bouncing Rays) techniques can be used as an appropriate analysis technique. The SBR analysis method is one of the GO methods, which analyzes the characteristics of the propagation path and each reflective surface through ray tracing, and calculates the propagation phenomenon considering polarization.The SBR method is highly effective in the RCS prediction. For electrically large and complex targets, computing scattered fields is still time-consuming in many applications like range profile and ISAR simulation. At elevation 0-degree and azimuth 293 and 72-degrees, the mast and wall installed at the right and left rear of the unmanned surface vehicles form a corner reflection, and a relatively large RCS was found at the corresponding location.

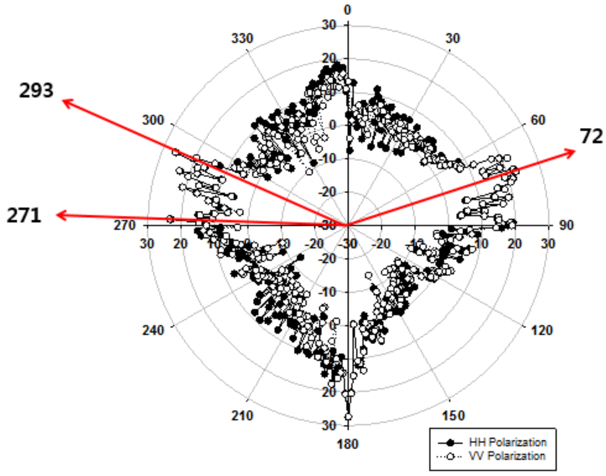
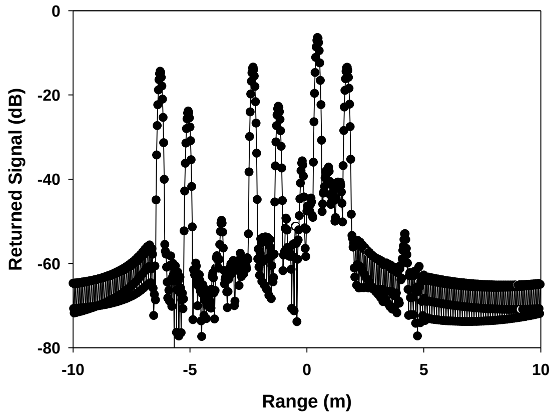
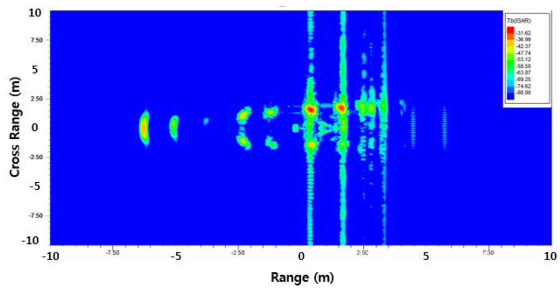


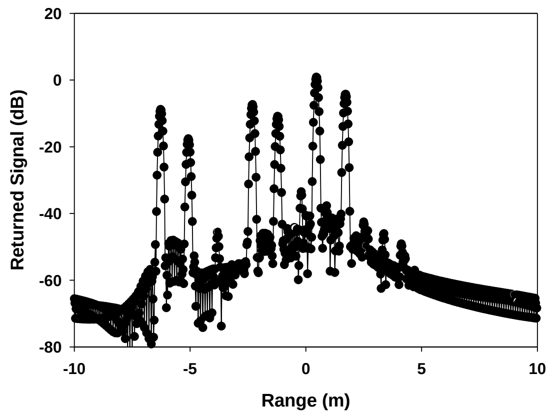
Figure 2: RCS Graph of Elevation 0 degree and selection of RCS Increment Location [27]



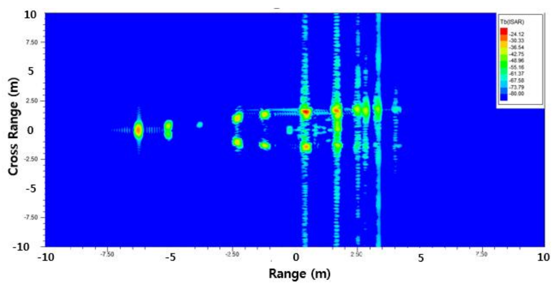
(a) Range Profile (4 GHz)



(b) ISAR Image (4 GHz)



(c) Range Profile (8 GHz)



(d) ISAR Image (8 GHz)

Figure 3: Analysis of Range Profile and ISAR Image [27]

4. RCS Reduction Techniques

Following four techniques are available for reducing RCS

1. Passive cancellation
2. Active cancellation
3. Shaping
4. Radar absorbing materials (RAMs)

Practically used RCS reduction methods on naval ships these days are shaping and radar absorbing materials. In current stealth designs, shaping techniques are first applied to create a design shape with low RCS in primary threat sectors. Radar absorbing materials are then applied to treat remaining problem areas whose shape could not be optimized to reduce RCS. In this review article, we focus on two main techniques (Stealth Technology) to reduce the RCS of unmanned surface vehicles.

4.1 RCS reduction design through shaping

The first is a shaping technique that transforms the geometric shape of an unmanned water crystal. This is due to the analysis of the main scattering sites and scattering mechanisms of the unmanned surface vehicles through RCS prediction and symptom analysis of the unmanned surface vehicles, and by appropriately changing the shape of the unmanned surface vehicles. It is a technique that prevents detection of unmanned surface vehicles. First, analyze the RCS of the unmanned surface vehicles design CAD model, analyze the RCS analysis results for the azimuth angle for each frequency/altitude, and then identify the location to increase the RCS. After confirming the scattering point on the CAD model or the structure generating high RCS, RCS reduction design is performed by applying RCS reduction measures such as model change.

The RCS of the unmanned surface vehicles is determined by the shape of the hull, the shape of the superstructure, and the shape of the mounted equipment. The shape of the hull is determined by the speed and stability of the unmanned surface vehicles, the load capacity, and the special mission, and since it is mainly in the form of a slope applied at sea level, it can be said that the impact of the RCS is lower than that of the superstructure shape or the shape of the mounted equipment. The following design guidelines should be applied if unmanned surface vehicles are to achieve the RCS reduction effect as in general traps.

1. Removal of corner reflective structure composed of vertical surfaces
2. The vertical plane should be inclined to have a certain inclination
3. Remove curved structure shape
4. Design the shape in a simple flat structure as far as possible

Table 2: Comparison of Analysis Results before and After Applying RCS Reduction Method (HH Polarization, dB Average) [27]

Elevation Angle	dB Average (4 GHz)			dB Average (8 GHz)		
	Model(A)	Model(B)	Difference(B-A)	Model(A)	Model(B)	Difference(B-A)
0	12.74	6.32	-6.42	13.12	6.88	-6.24
1	9.18	4.38	-4.8	11.28	6.34	-4.94
2	7.88	3.21	-4.67	9.35	4.72	-4.63
3	6.47	1.62	-4.85	8.62	4.35	-4.27
4	6.85	1.84	-5.01	7.74	2.64	-5.1
5	7.24	2.12	-5.12	6.82	2.12	-4.7
6	7.52	2.84	-4.68	6.05	2.05	-4
7	8.04	2.68	-5.36	5.84	1.56	-4.28
8	8.78	2.35	-6.43	6.26	2.34	-3.92
9	9.82	2.84	-6.98	6.57	2.78	-3.79
10	10.72	4.12	-6.6	7.12	2.84	-4.28

In overseas cases, the upper part of the unmanned surface vehicle takes the form of applying a slope to have a certain slope, and the RCS reduction range is mainly focused on the RCS reduction in the front part of the ship. In the case of general ships, the main threat targets can be seen as anti-ship missiles equipped with search radar and RF searcher, but in the case of unmanned surface ships, avoidance of search radars such as coastal search radars are prioritized. In the case of the rear part, when communication is cut off or power is lost in the carrier or base of the unmanned aerial vehicle, the tracking radar can be used to determine the movement trajectory of the unmanned surface vehicle or to ensure that the RCS appears relatively large at a specific location for smooth recovery.

4.2 RCS reduction design through RAMs (Radar Absorbing Materials)

Table 3: The radar frequency band [28]

IEEE band designation	NATO band designation	Frequency Range	Use of frequency
S	E/F	2 ~ 4 GHz	Mid-range detection / Air search radar
C	G/H	2 ~ 8 GHz	Long-range detection / homing, Sea search radar
X	I	8 ~ 12 GHz	Short-range detection / Shore radar
Ku	J	12 ~ 18 GHz	Missile base, missile seeker
K	K	18 ~ 27 GHz	Atmosphere attenuation

The second is a coating technique that prevents electromagnetic waves from being scattered by applying a material such as RAMs (Radar Absorbing Materials), which is an electromagnetic wave absorber, on the surface of the target [29-43]. The RCS depends on the radar's frequency and polarization, whether the transmission and reception timing is consistent (Monostatic/Bistatic), the shape and angle of incidence of the target, and the material of the target. The hull materials used in ships include mild steel, high tensile steel, high yield steel, aluminum alloy and composite materials. When selecting a hull structure material, in general, mechanical properties such as strength, stiffness, and specific gravity of the material, as well as workability such as weldability, workability, and water retention, corrosion resistance, fire resistance, and economy are considered together. High-strength steel is mainly used for ships where the weight reduction of the hull is important, such as high-speed boats and battleships, and the range of use is expanding. A typical ship made using FRP materials is the Swedish Navy's Visby-class patrol ship. For the Visby ship, the outer hull was inclined to reduce RCS, and most of the sensors were built into the conical Radom on the bridge, and the radio wave absorber was applied to the main part of the hull using carbon fiber reinforced plastic. The aforementioned Barracuda Stealth Boat is introduced not only to design for reduction of RCS by shape control, but also that the hull material was manufactured using FRP material, and Stealth Craft Company in the following figure also introduced a stealth boat using FRP material and absorber. In summary, as a result of confirming in overseas cases, the low RCS unmanned watercraft will be selected in consideration of the fact that much effort has been made to reduce the total RCS, and in the case of using RFP materials, it will be selected in consideration of issues such as the displacement of the box and the budget, but the RCS such as the radio wave absorber decreases. The material was used additionally in a state that was primarily based on shaping. Therefore, in order to reduce the RCS of the unmanned watercraft in which RCS analysis is performed, the shape design should be performed first, and if it is difficult to change the shape through additional analysis, it is necessary to determine the location where the radio wave absorber should be applied to reduce the RCS. Table 4 compares various metasurface specifications with the state of the art researches. It is found that the RCS reduction bandwidth is significantly wider [29] than the other works [31-43]. In more details, miniaturized artificial magnetic conductor (MAMC) structure by using non-resonant unit cells achieves more than 142 % RCS reduction bandwidth which has significantly wider rather than the best previous surface [29-43]. In addition, the start frequency of RCS reduction is low compared to the other works. Wide RCS reduction bandwidth, low cost and general design method are the main advantages of this work which proves its capability for practical applications. However, the application of the absorber is not easy to construct, and it is necessary to control the thickness of 0.1 mm in order to obtain the desired absorption performance, and it is very difficult to operate and maintain because strict manufacturing process management and post management are required.

Table 4: Comparison of meta-surfaces with state of the art references

Ref.	Structure	Frequency range (GHz)	10-dB Bandwidth (%)
[29]	Miniaturized artificial magnetic conductor(MAMC) by using non-resonant unit cells	5.22-30.85	141.8
[31]	Patch and Loop	13.25-24.2	58.4
[32]	Jerusalm Crosses	14.4-21.8	41
[33]	Non-absorptive miniaturized-element FSS (Patch-Patch and Loop-Cross)	9-15	50
[34]	Patch and Disk	5.9-12.7	73
[35]	Pixelated Cells	3.8-10.7	95
[36]	Artificial magnetic conductor	3.75-10	31
[37]	Uneven-Layered Coding Metamaterial Tile	6.2-25.7	122.3
[38]	Polarization Conversion Metasurfaces	9-40	126.5
[39]	Polarization Independent Metasurfaces	7.9-20.8	89
[40]	Random Combinatorial Gradient Metasurface	7.2-15.6	73
[41]	Multilayer Artificial Magnetic Conductor Metasurface	13.1-44.5	109
[42]	Low cost and thin metasurface	13.6-45.5	108
[43]	Checkerboard AMC structure	3.77-10.14	91.5

5. Conclusion

In this review article, RCS prediction and reduction for unmanned surface vehicles are systematically summarized and analyzed with particular emphases on shaping and radar absorbing materials. The future trend of RCS reduction is predicted, including RCS basics and important scattering mechanisms, RCS prediction techniques, and RCS reduction techniques. RCS analysis for unmanned surface vehicle was explained the process of analyzing and identifying the problem location through distance profile analysis and ISAR image analysis, and proposed RCS reduction methods that can solve the problem. In addition, by deriving and applying the RCS reduction method, a 3D CAD model to which the RCS reduction method was applied was produced, and RCS analysis was performed accordingly, and meta-surfaces with state of the art references were compared and analyzed. Practical RCS reduction methods for naval ships are shaping and radar absorbing materials. Shaping is very important in warships since significant advantages can be obtained by manipulating above waterline geometry and general arrangements. The appropriate approach is to design the above waterline structure with minimum echo through shaping, and then apply radar absorbing materials to remaining problem areas.

Acknowledgement

This paper was supported by Research Fund of LIGNex1 and Republic of Korea Naval Academy in 2021.

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