ANALYSIS OF STEALTH ENHANCEMENT DESIGN PROCESS AND METHODS FOR UNMANNED AERIAL VEHICLE

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Abstract

Unmanned aerial vehicles (UAVs) have outstanding advantages such as maneuverability, controlled costs, and no risk of personnel casualties, giving them a broad application market. Stealth enhancement design has become an important development direction in the overall and optimized UAV design. Conducting stealth enhancement design can effectively reduce the radar cross section of the aircraft, significantly improving its survivability and penetration capability. This paper introduces the basic principles of stealth design and builds the basic framework for stealth enhancement design from three aspects: strong scattering source localization and scattering mechanism analysis, construction of high efficiency and high fidelity aerodynamic and stealth parameterized model, and aerodynamic and stealth joint optimization. Simulation analysis and digital design practice have demonstrated the feasibility of the stealth enhancement design process and methods proposed in this paper.

Keywords: Unmanned aerial vehicles; radar cross-section; radar stealth; joint optimization; Pareto solutions

1. Introduction

From the birth of the F-117 to the service of the F-22 aircraft, stealth aircraft have gradually entered the public eye and had a disruptive impact. Radar stealth technology (hereafter referred to as stealth) has a profound influence on platform survivability and mission effectiveness, and it is gradually being applied to different types of aircraft [1-2]. Traditional UAVs did not prioritize stealth design, and their survivability faced severe challenges in high-threat adversarial environments. Therefore, enhancing the stealth capabilities of UAVs is increasingly valued by various countries. Strong stealth capability has gradually become an important feature of newly developed foreign UAVs, and notable stealth UAVs include [3-5]:

RQ-170 Sentinel: Developed by Lockheed Martin's Skunk Works, the RQ-170 is a flying wing UAV mainly used for penetrating reconnaissance in hotspot areas. It has a large wingspan, short fuselage, a high aspect ratio, and a high lift-to-drag ratio. It features a tailless design, a dorsal intake, and S-shaped ducts, providing excellent stealth performance.

X-47B: This experimental unmanned combat air vehicle is the first in history to be completely computer-controlled without human intervention. It is also the first stealth UAV capable of taking off from and landing on an aircraft carrier. The X-47B has a flat fuselage, tailless design, dorsal intake ducts, and internal weapon bays, offering good stealth performance across all radar bands.

XQ-58A: Originating from the U.S. Air Force's low-cost, expendable strike demonstrator program, this UAV requires no runway, is rocket-assisted for launch, and parachute-recovered. It features angled surfaces, a dorsal intake, and V-shaped tail fins for good stealth performance. It is suggested to be designed as a wingman for F-22/F-35 fighters, thus should possess excellent overall stealth capability.

MQ-25: The latest carrier-based UAV from the U.S. Navy, featuring a blended wing-body design with large V-shaped tail fins and a flat fuselage. Its slender wings provide high aerodynamic efficiency during cruise. The aircraft has a smooth fuselage and flush dorsal intake ducts, ensuring good stealth capabilities.

Enhancing the stealth capabilities of UAVs significantly increases the flexibility and robustness of the current aerial system. On one hand, UAVs like the RQ-170 can independently perform missions. On the other hand, UAVs like the XQ-58A can augment the capabilities of manned aircraft by executing a variety of tasks in coordination.

Additionally, the UK and France have also introduced different stealth UAVs. The BAE Systems Taranis demonstrator, developed under British leadership, aims to validate Unmanned Combat Air Systems (UCAS). It features a blended wing-body with a highly swept leading edge and rear edges parallel to the front edge, enhancing stealth performance while effectively providing lift. To minimize strong scattering sources, it uses a dorsal triangular intake and a beaver-tail exhaust, along with internal weapon bays.

Figure 1 The BAE Systems Taranis[4]

The Dassault nEUROn UAV is a European Unmanned Combat Air Vehicle (UCAV) technology demonstrator project, led by the French company Dassault Aviation. This aircraft features a flying wing design, straight-swept triangular wings, and a W-shaped tail. It has dorsal sawtooth intakes and is constructed entirely of composite materials, providing excellent radar stealth capabilities.

Figure 2 The nEUROn UAV[5]

2. Basic Methods of Stealth Design and the Challenges Faced

2.1 the basic radar stealth design methods

The core of stealth design is to reduce the Radar Cross Section (RCS) of the UAV. The smaller the RCS value, the harder it is for the UAV to be detected. Current aircraft stealth design mainly focuses on reducing the radar cross section from two aspects.

Firstly, there is the stealth design of the shape. Adjusting the shape can reflect radar waves away from the radar direction or use aircraft components to block major scattering sources, thus shaping plays a principal role in stealth design. Specific shape design principles include:

(a)Eliminating configurations that can form corner reflectors: Ensuring that the shape does not create strong radar reflections.

(b)Angled design: Converting backscattering into non-backscattering by angling surfaces.

(c)Shielding design: Using one component to shield another strong scattering component, such as employing dorsal intakes with the fuselage and wings blocking the intake.

(d)Parallel design: Arranging the edges of all wing surfaces in a few non-critical directions (greater

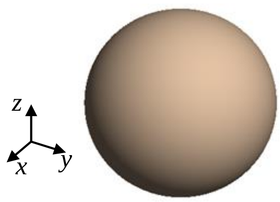
than 40° from directly ahead) so that radar reflection spikes overlap, reducing the number of strong spikes.
Another important method also contains internal weapons bays, by which weapons and other stores are carried inside the aircraft rather than on external pylons to maintain a smooth external shape and minimize RCS. the last but not the least, engine inlets and exhausts usually use S-shaped inlets and exhaust ducts to reduce radar visibility.
Secondly, the use of stealth coatings and stealth structural materials is essential. For some scattering sources that are difficult to fully reduce through shape adjustments, radar-absorbing materials can be used to absorb electromagnetic waves and convert them into internal energy. It can be seen that surface treatment special coatings and materials that absorb radar waves instead of reflecting them are applied to the aircraft’s surface, although maintenance of radar-absorbing materials and coatings is particularly challenging and requires frequent inspections and repairs.

2.2 The challenges faced by stealth design

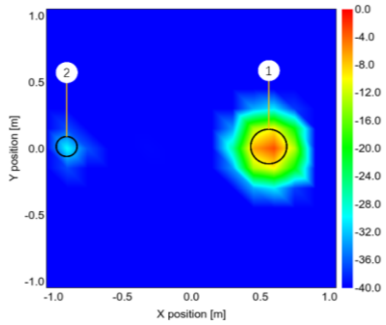
Traditional stealth design follows a forward design approach, combining various stealth methods to determine whether the stealth criteria are met. This design method is inefficient and cannot quantitatively estimate the UAV's stealth capability or clearly define the direction for optimizing stealth capabilities.
Compared to manned aircraft, UAVs have significantly simplified structures. UAVs that adhere to stealth design principles often have smooth fuselages and V-shaped tail fins, largely eliminating strong scattering sources caused by the aircraft's body. Based on such designs, the stealth design of UAV involves the quantitative detailing and trade-offs in comprehensive performance. Experience-based stealth treatments are no longer sufficient to effectively guide further reductions in radar signatures for UAVs.
Therefore, a systematic UAV stealth enhancement design technology is urgently needed. This includes precise assessment of electromagnetic scattering characteristics and identification of primary scattering sources (such as UAV inlets and exhaust nozzles, which may become major scattering sources). It requires determining the main geometric parameters of the scattering sources and performing joint optimization under multiple disciplinary performance constraints (since intake and exhaust systems affect the UAV's aerodynamic performance, pitch moment, and control performance, it is not feasible to drastically improve stealth performance at the cost of other performance aspects).
In summary, the stealth enhancement of UAVs urgently needs systematic research on key technologies and the development of a coherent design methodology to support the improvement of the overall radar stealth performance of UAVs.

3. UAV Strong Scattering Source Location and Scattering Mechanism Analysis

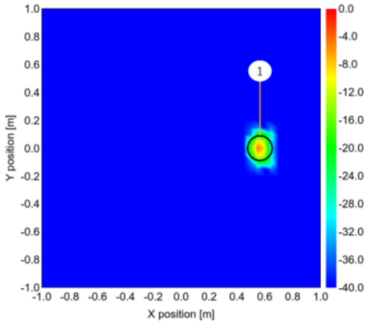
People are no longer satisfied with using one-dimensional RCS curves to evaluate the scattering characteristics of aircraft. Using radar imaging technology to perform detailed imaging of the aircraft can locate the main scattering sources and assess the size of the scattering points. Additionally, by analyzing the electromagnetic scattering mechanisms of typical aircraft structures, it is possible to understand the formation mechanism of scattering sources based on the distribution of scattering points, providing technical guidance for further suppressing RCS.
Regarding the main scattering mechanisms of aircraft under electromagnetic irradiation—specular reflection, surface wave scattering, edge diffraction, tip diffraction, and cavity scattering—we can analyze the two-dimensional imaging results of spheres, cylinders, cones, straight cavities, and S-bend cavities. This analysis established the relationship between scattering points and geometric bodies, preliminarily identifying the main electromagnetic scattering paths.
For the sake of brevity, the process of electromagnetic scattering analysis for spheres is as shown in Fig.3. Fig.3(a) is the shape of spherical model with radius is 560mm, Fig.3 (b) shows the Inverse synthetic aperture radar (ISAR) image of the spherical model. It is seen that two parts of scatters which named 1 and 2 is formed significantly. Specifically, the central frequency is 3GHz and the polarization model is HH, the two-dimensional resolution is 0.15mx0.14m. Fig.3 (c) shows the ISAR image of the spherical model in the condition that the central frequency is 10GHz and the two-dimensional resolution is 0.05mx0.04m. It is seen that the scatters named 1 is still apparent but the scatters named 2 is not obvious. It can be concluded that the scattering path according to scatters 2 is reduced apparently with the frequency increase. The scattering characteristics according to the spherical model is shown in Fig.3 (d). Similarly, the scattering characteristics according to other geometry such as cylinder, cone and intake duct can be obtained.



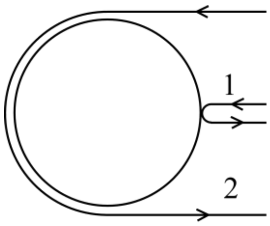
（a）Spherical model（radius is 560mm）



（b）3GHz HH polarization (resolution 0.15m x 0.14m)



（c）10GHz HH polarization (0.05m x 0.04m)



（d）Spherical scattering path characteristics

Figure 3 Analysis of Spherical Radar Images and Main Scattering Paths

For unmanned aerial vehicles, ISAR imaging technology can be used to obtain the primary strong scattering sources. By analyzing the scattering mechanisms, it is possible to understand the scattering principles, providing technical guidance for subsequent scattering suppression or RCS reduction treatments. For example, for a flying wing UAV, ISAR technology can be used to obtain its forward-facing imaging results as follows. Fig.4 shows the ISAR imaging results with the HH polarization for the initial shape of a fly wing layout UAV.

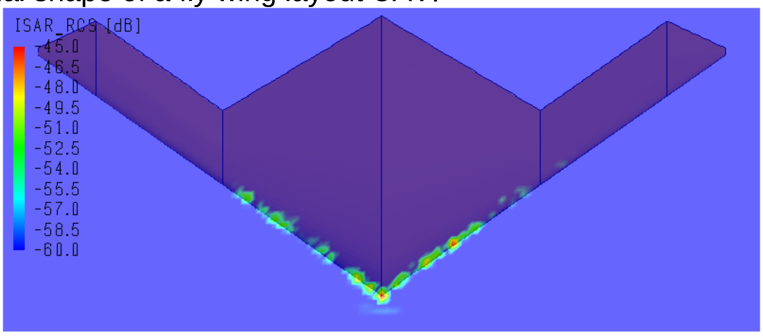


Figure 4 ISAR image with HH polarization conditions

In Fig.4, components such as the aircraft's intake, exhaust nozzle, and cockpit are not included, resulting in a relatively clean UAV shape. The strong scattering source analysis at this stage primarily evaluates the basic shape of the aircraft. As shown in the illustration, there are strong RCS scattering sources at the nose cone and the corresponding leading edge of the fuselage. This will guide us to focus on optimizing the RCS from the wing shape of the UAV.

4. The aerodynamic and stealth joint optimization of aircraft

4.1 Parametric Characterization of UAVs

Parametric modeling of UAVs is a necessary foundation for conducting shape joint optimization. The objects and dimensions of parametric modeling directly affect the quality of the aerodynamic and stealth joint optimization of the UAV.

Given the simple structure and simplified layout of flying wing UAVs, this paper adopts the basic approach of constraining the UAV's three-dimensional configuration through the wing surfaces.

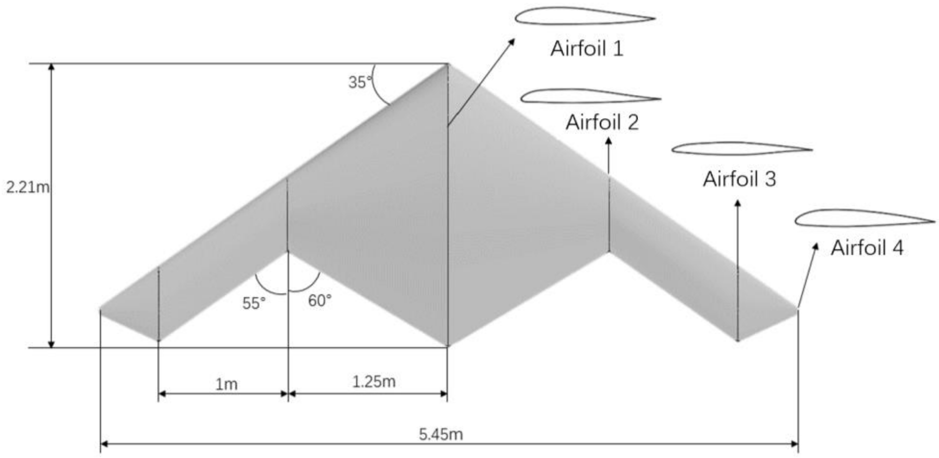


Figure5 Initial shape of a flying wing layout UAV

In figure 5, airfoils 1-4 are parameterized objects, the modeling method is to use class function/shape function transformation (CST) modeling to characterize the airfoil. After the airfoil 1-4 is determined, a three-dimensional configuration is formed through layout and stretching.

4.2 Introduction of Proxy Models and Joint Optimization Models

In the optimization design of aircraft, it is usually very time-consuming to obtain the evaluation of aerodynamic and electromagnetic characteristics by solving the aerodynamic equation and electromagnetic scattering equation. On one hand, some efficient calculation methods about RCS and aerodynamic analysis are suggested [6-7]. On the other hands, proxy model is an optional method. Fig.5 shows a typical flowchart of the proxy model.

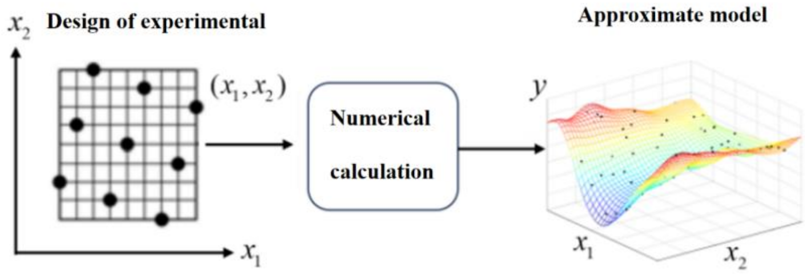


Figure 6 Schematic diagram of proxy model construction

The design of experiments (DOE) is the foundation of proxy method. The well-known surrogate models include polynomial surrogate models, Kriging surrogate models, neural network surrogate models, etc. The Kriging surrogate model has the advantage of providing variance of estimated values[8]. The Kriging surrogate model is widely used to evaluate the aerodynamic and stealth characteristics of aircraft.

Fig.7shows a schematic diagram of the process of aerodynamic and stealth joint optimization based on a proxy model.

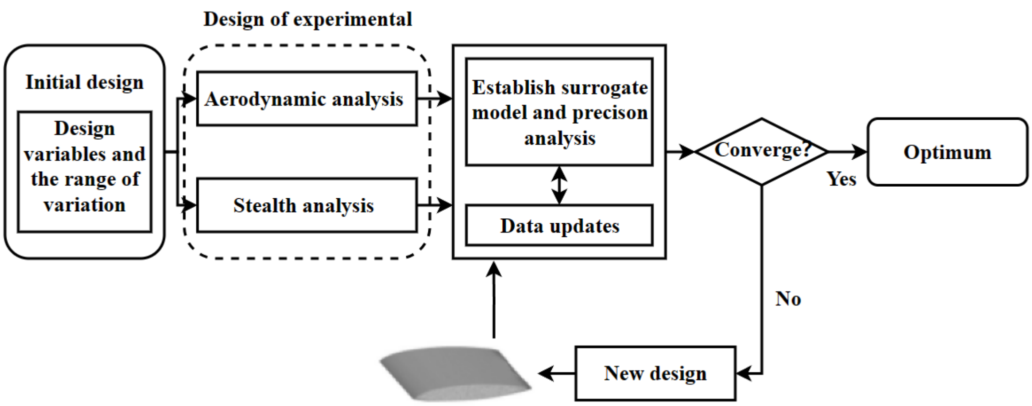


Figure 7 The joint optimization based on Proxy Model

In Fig.7 the basic procedures contain:
(a) Determine the design variables and their change range [9] with respect to the initial configuration.
(b) Conduct experimental design to obtain data from sample collection points; Based on sample point data, construct a proxy model and evaluate the fitting accuracy analysis.
(c) Build an iterative optimization process and set up a new design generation method if the iteration is not converged [10]. The converged iteration yields the optimization results.
In this paper, the objective function of joint optimization about the flying wing UAV is:

$$\begin{array}{ll} \text{Minimise} & \overline{\text{RCS}} \\ \text{Maximise} & \text{L/D} \\ \text{Maximise} & C_m \end{array} \tag{1}$$

in which $\overline{\text{RCS}}$ represents the average monostatic RCS according to the positive and negative 20 degrees of the aircraft's nose in the horizontal direction. L/D is the Lift to drag ratio of the UAV, C_m is the pitching moment coefficient.
Through joint optimization, the following optimization result was obtained. As the optimization objectives are three, the Pareto frontier solutions of the optimization results are presented in three-dimensional form, as shown by the blue dots.

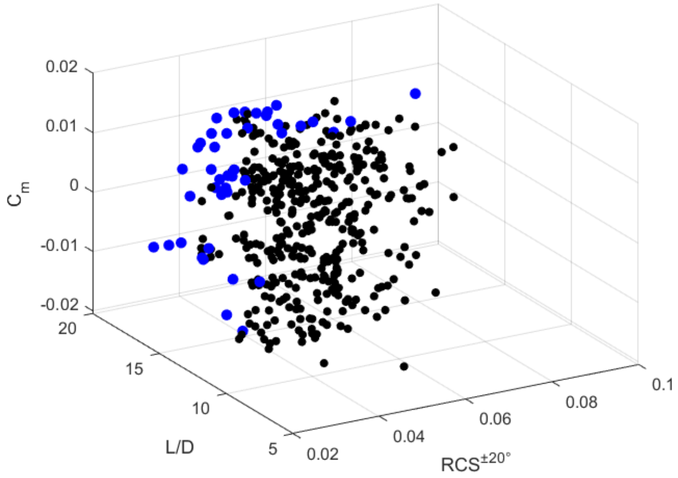


Figure8 Optimized data distribution map obtained by genetic algorithm
Select a sample point in the Pareto front solution and read its corresponding wing shape parameters. By stretching and laying out the four wings, the aircraft layout is obtained. Comparing the initial shape with the optimized shape, we find that the leading edge of the aircraft changes the most. Specifically, details shown in Fig.9.

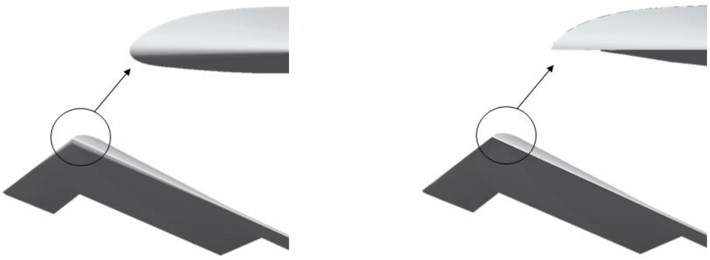


Figure9 Local comparison between the initial shape and the optimized shape
Intuitively, the radius based on the leading edge becomes smaller, in other words, the leading edge becomes sharper. From the electromagnetic scattering mechanism, it can be inferred that this optimization result is reasonable. A sharper leading edge helps to reflect radar electromagnetic waves in other directions, and then reduce the monostatic RCS. In addition, the ISAR imaging results corresponding to the jointly optimized UAV shape can also be obtained, Fig.10 shows a significant reduction in the intensity of the scattering source.

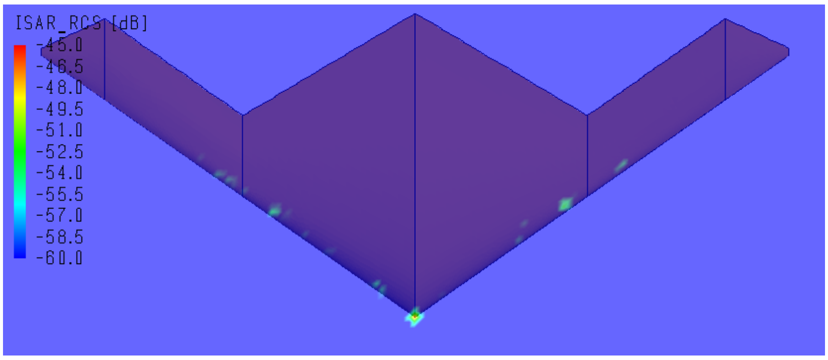
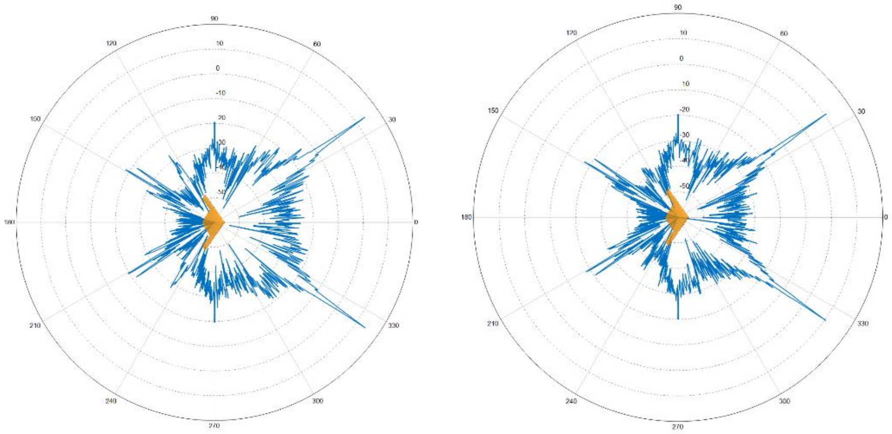


Figure10 ISAR imaging results of optimized layout with HH polarization

From a broader perspective, the optimized RSC also shows a significant decrease overall. The following figure shows the distribution of the omnidirectional RCS of the initial shape and the optimized layout, with an incident electromagnetic wave set at 10GHz and HH polarization mode.



(a) the initial (b) the optimized

Figure11 The comparison of RCS between the initial and optimized layout

Eventually, we should check the aerodynamic performance of the optimized shape, as we presented in the introduction part, the stealth enhancement should not decrease the aerodynamic characteristics. Table 1 shows the detailed information, contains lift coefficient, resistance coefficient, pitching moment coefficient and the lift to drag ratio, are not worse than the initial layout. It is noted that other sample points in the Pareto set could also be used, which will correspond different performance about the RCS, L/D, and pitching moment coefficient.

Table.1 The performance comparison between initial and optimized shape

	Lift coefficient	Resistance coefficient	Pitching moment coefficient	Lift to drag ratio
Initial shape	0.065648	0.004443	-0.004934	14.7741
Optimized shape	0.065649	0.004443	-0.004934	14.7743

5. Conclusion

This article proposes a stealth enhancement design method suitable for unmanned aerial vehicles, which mainly focuses on optimizing the structural shape. Using the basic architecture of aerodynamic and stealth joint optimization, it explores further enhancing stealth performance without loss of aerodynamic performance. The basic process of stealth enhancement includes the diagnosis of strong scattering sources, parameterized modeling for typical components of unmanned aerial vehicles, establishment of joint optimization models, and presentation of results.

The research method in this article has value for the stealth enhancement design of unmanned aerial vehicles and has certain promotional significance. Of course, the research in this article does not imply the significant potential of stealth coatings and electromagnetic modulation materials in stealth. In fact, after the proposed stealth enhancement design methods, the further stealth enhancement may require advanced stealth materials or electromagnetic modulation materials.

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