Integrated Design Optimization of Aerodynamic and Stealthy Performance for Flying Wing Aircraft

Yalin Pan, Jun Huang, Feng Li, and Chuxiong Yan

***Abstract*—Flying wing configuration has become an ideal configuration of the future unmanned aerial vehicles, and it has become the research hotspot of advanced aircraft in recent years. In this article, an optimization strategy is constructed to deal with the aerodynamic and stealthy multidisciplinary design optimization issue of double-swept flying wing aircraft. In order to describe the aircraft accurately, two methods are used to parametric the airfoil profiles of the aircraft CAD model with different leading edge shapes. For the two parametric approaches, geometric parameters of the airfoil are used to define its shape functions. It is analyzed that the parameters of the aircraft impact on aerodynamic performance and stealth capability, which is helpful to improve design. In applying the strategy, the optimization algorithm combining global optimization and gradient algorithm is adopted to search for the optimum design. The optimization results indicate that the optimization strategy can be implemented automatically, and reasonable results are obtained.**

***Index Terms*—aerodynamic, stealthy, parametric approach, optimization algorithm**

I. Introduction

Tailless flying wing configuration aircraft have potential benefits over conventional configurations in stealth capability and aerodynamic and structural efficiency [1, 2] because of their simple shape. Flying wing aircraft have attracted wide interest in both military and civilian fields, and they have become the research hotspot of advanced aircraft [3]. Several next-generation civil transport aircraft and unmanned air vehicles (UAVs) are of flying wing designs. Civilian flying wing aircraft include the Boeing X-48, the low noise transporter developed by Cranfield University, the flying wing aircraft in the studied by the Russian Central Aerohydrodynamic Institute (TsAGI), and the 250-seat flying wing concept in Beihang University. In the field of military aviation, several countries have developed UCAV with tailless configurations, such as the X-45, X-47B, nEURO, etc [4]. Flying wing configuration has become an ideal configuration of the future unmanned aerial vehicles [5].

The lack of statistics and practical experience about flying wing configuration aircraft posed great difficulties in aircraft conceptual design. Multidisciplinary design optimization (MDO) has been proved to be a promising method to solve this kind of problem, which has been widely used in conventional airplane design [6-9]. Flying wing aircraft have the characteristics of simple shape and blended wing body, which made it easily to parametric its CAD model shape.

The aim of this article is to propose a systematical method to deal with aerodynamic and stealthy MDO issue for double-swept wing configuration of an unmanned flying wing aircraft conceptual design.

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II. Parametric CAD Model

As for all optimization tasks, the complexity of the problem is directly coupled to the parameterization of the geometry. Of highest relevance is the number of parameters that are required to ensure valid modeling. The most important characteristic of the CAD model is to be highly flexible in order to be able to represent a variety of designs as large as possible. Secondly the model must be robust and reliable, since there will not be a specialist manually entering new parameters and supervising the update process [10]. Double-swept flying wing aircraft can be seen as a special wing which is connected together by three segments. The parameters defining this configuration can be grouped into three sets.

A. Parameters for Aircraft Outline

These parameters are used to describe the plane shape, including reference area of aircraft ($Sref$), wing aspect ratio (Ar), root chord length of inner wing (br), root chord length of outer wing ($b2$), semi span of inner wing ($l1$), leading edge swept angle of inner wing ($alpha1$), and leading edge swept angle of outer wing ($alpha2$), as shown in Figure 1. All the other outline parameters which are displayed in Figure 1 can be derived from the above mentioned parameters. The platform of the UAV is defined by these parameters.

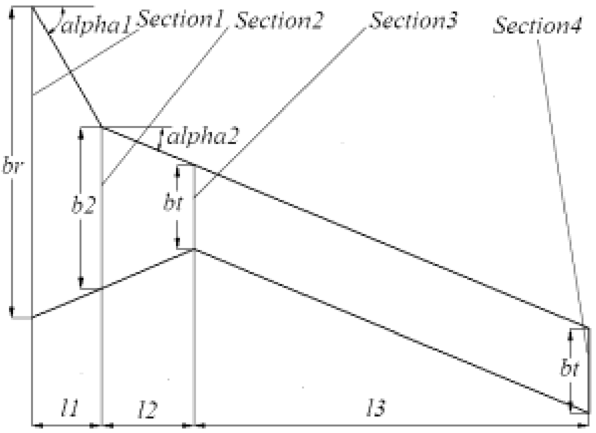

Fig. 1. Flying wing configuration platform.

B. Parameters for Master Sections

Master sections are referred to as the typical sections of flying wing along the streamline of airflow. Other sections can be fitted by these master sections [11]. The sections at inner wing root (Section 1), outer wing root (Section 2), turning of outer wing trailing edge (Section 3), and outer wing tip (Section 4) can be regarded as master sections, as shown in Figure 1. The parameters describing the profile of master sections are called the parameters for master sections. The parametric models for master sections are constructed using airfoil parameterization approach. These are several common airfoil parameterization techniques: Ferguson's curves, Hicks-Henne bump functions, B-Splines, PARSEC, and Class/Shape function Transformation [12-14].

A geometric parameterization method different from the PARSEC technique is used to describe master sections. The method uses eight geometric parameters which directly manipulate the shape of master sections as summarized in Table 1 and Table 2. The geometry profile is represented as the product of a camber function $f(x)$, and a thickness function $g(x)$. The coefficients of the camber function are determined by four camber parameters and the coefficients of the thickness function are determined by four thickness parameters [15].

TABLE I
DESCRIPTIONS OF CAMBER PARAMETERS

Camber Parameters	Descriptions
C	relative camber
XC	relative camber location
AlphaLE	the angle between leading edge of camber line and chord line
AlphaTE	the angle between trailing edge of camber line and chord line

TABLE II
DESCRIPTIONS OF THICKNESS PARAMETERS

Thickness Parameters	Descriptions
T	relative thickness
XT	relative thickness location
R	leading edge radius
BetaTE	the angle between trailing edge of thickness line and chord line

The airfoil camber function is defined as formula (1):

$$f(x) = c_1 \cdot \sin(\pi \cdot x) + c_2 \cdot \sin(\pi \cdot x^{1.5}) + c_3 \cdot \sin(\pi \cdot x^2) + c_4 \cdot \sin(\pi \cdot x^{2.5}) \tag{1}$$

The airfoil thickness function is defined as formula (2):

$$g(x) = t_1 \cdot x^{0.5} + t_2 \cdot x + t_3 \cdot x^2 + t_4 \cdot x^3 + t_5 \cdot x^4 \tag{2}$$

This parameterization technique can only be used to describe the airfoil with round leading edge. The section at the root of inner wing is of the airfoil with tip leading edge, so the above method is invalid to it. The above camber function and a new thickness function are adopted to describe section1 profile. Four thickness parameters are used to derive the coefficients of the new thickness function. The parameters and their descriptions are shown in Table 3.

TABLE III
DESCRIPTIONS OF THICKNESS PARAMETERS

Thickness Parameters	Descriptions
T	relative thickness
XT	relative thickness location
BetaLE	the angle between leading edge of thickness line and chord line
BetaTE	the angle between trailing edge of thickness line and chord line

The new thickness function for the tip leading edge airfoil is defined as formula (3):

$$g(x) = t_1 \cdot x^4 \cdot (1-x) + t_2 \cdot x^3 \cdot (1-x)^2 + t_3 \cdot x^2 \cdot (1-x)^3 + t_4 \cdot x \cdot (1-x)^4 \tag{3}$$

In the UAV conceptual design, CJ4 airfoil is used as the initial profiles of master sections except section 1and the parameterized airfoils with above method are presented in Figure 2 and Figure 3.

Fig. 2. The profile of section 1.

Fig. 3. The profile of other master sections.

C. Other Parameters

These parameters include torsion angle and dihedral angle which are used to describe the segments position of wing.

All the parameters are used to generate the geometric model of UAV in an automated fashion in CATIA. The parameters for every section are independent of each other,

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and they could change freely. A different CAD model will be generated along with the change of the parameters. The generated model of flying wing aircraft is shown in Figure 4.

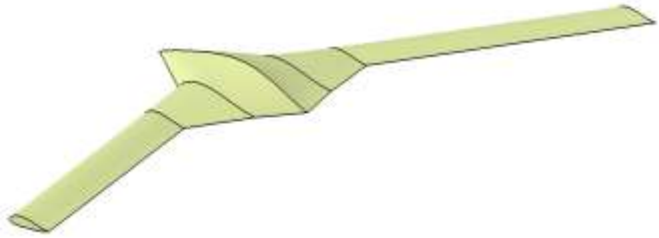

Fig. 4. The CAD model of flying wing aircraft.

III. Sensitivity Analysis

Too many parameters are used to describe the CAD model. If all the parameters are defined as design variables to optimize will cost a lot of computing time and the efficiency of MDO will be very low. This section analyzed the sensitivity of various parameters to design target through design of experiments (DOE).The results of DOE can be used to analyze how the parameters influence optimization goals, and it can help us to determine which parameters should be as variables and estimate the results of optimization preliminarily.

C. DOE Processes

Lift coefficient (Cl), drag coefficient (Cd), and radar cross section (RCS) are computed to evaluate the aerodynamics and stealth performance of UAV in this section. A panel code (Panair), which was developed by The Boeing Company and NASA, is adopted for aerodynamic analysis. Panel codes are numerical schemes for solving (the Prandtl-Glauert equation) for linear, inviscid, irrotational flow about aircraft flying at subsonic or supersonic speeds [16, 17]. Lift coefficient, pitching moment coefficient and induced drag coefficient are computed by Panair. Compared to CFD codes, Panair has advantages of the computing speed and meshing. A MATLAB procedure based on the boundary layer theory was written to compute aircraft friction drag coefficient. Another MATLAB program which is based on the physical optics method, is used to predict the RCS of the UAV. The aerodynamic analysis and RCS computation require the surface mesh information of the UAV configuration. At the moment, Pointwise software is used to get quad mesh and triangle mesh. Several numerical codes were written to generate data which was used by CATIA and the files which were transmitted into Panair and stealth calculation program. Once the data files for aerodynamic and RCS analyses are generated, the aerodynamic characteristics and RCS for the given UAV geometric model can be predicted directly by executing the Panair code and the RCS calculation program.

Lift coefficient, drag coefficient and RCS are computed through the following steps: (1) the data for CATIA are calculated; (2) the CAD model is generated in CATIA; (3) the quad mesh file is generated by Pointwise; (4) the file which is transferred to Panair is generated; (5) executing Panair program; (6) calculating friction drag coefficient; (7) the triangle mesh file is generated by Pointwise; (8) the mesh file is converted to the data format suitable for RCS analysis; (9) computing radar cross section; (10) deleting the files have been generated during the procedure.

In order to automate the process of DOE, Isight software is used to integrate all the application programs [18]. The DOE process is shown as Figure 5. Optimal Latin hypercube technique is adopted to extract points in the design space to calculate aerodynamic and stealth performance of the aircraft.

D. Results Analysis

The Pareto graphs of DOE results are presented in Figure 6-8.These histograms not only show the main effect factors in design space but also display their effect direction. Interaction effect between different parameters plays an important role in the key factors.

Outline parameter $alpha1$ is the major factor for response drag coefficient. Other CAD model parameters such as Ar, $alphaTE$, XC, T and XT have some impacts on Cd too. All these parameters except Ar are positively correlated with drag coefficient. The main factors which affect lift coefficient include outline parameters and camber parameters of master sections. Outline parameters except Ar have the same influence on Cl, it's disadvantage to improve lift coefficient by increasing these parameters. There is a positive correlation between lift coefficient and some master sections parameters such XC and $alphaLE$. Compared with other parameters, the thickness parameters of master sections have less effect on Cl. In radar threat sectors, master sections parameters have a greater impact on the average RCS than outline parameters. In the main factors, only one outline parameter $alpha1$ plays a positive effect on enhancing stealth property of UAV.

All the CAD model parameters have impacts on UAV performance more or less, and the correlations between them are complex. For instance, lift coefficient will reduce along with the decrease of Cd and RCS by increasing $alpha1$. As

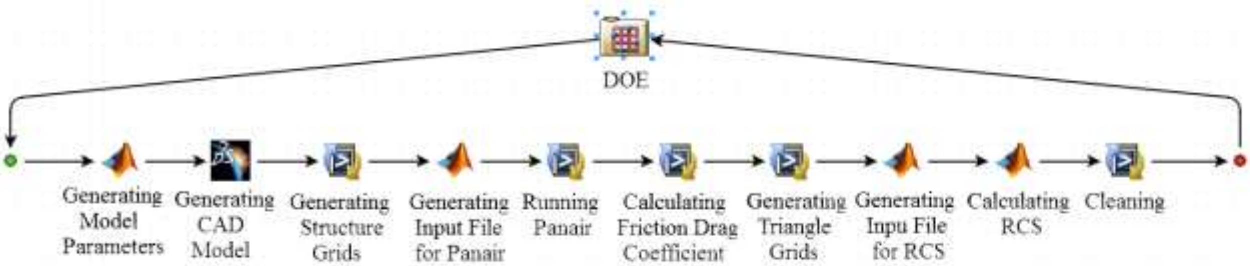

Fig. 5. DOE Flowchart of UAV.

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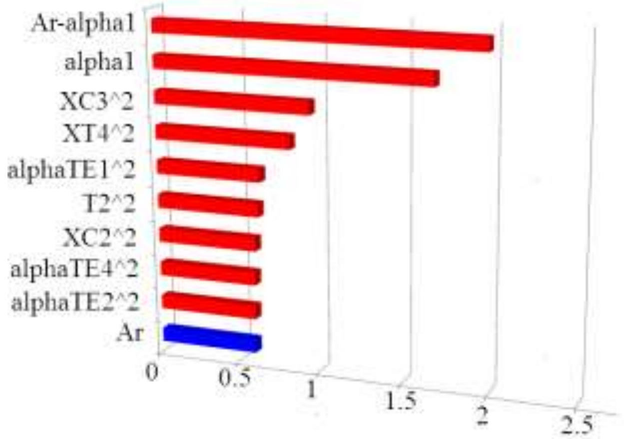

Fig. 6. Pareto graph for response Cd.

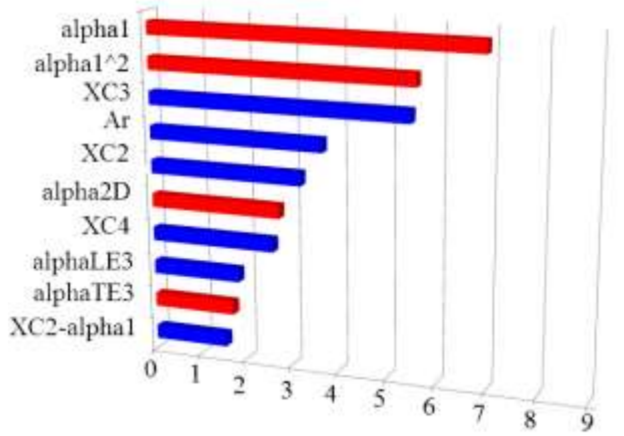

Fig. 7. Pareto graph for response Cl.

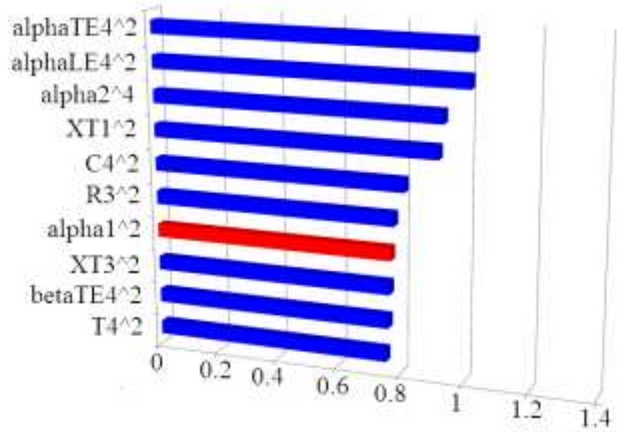

Fig. 8. Pareto graph for response RCS.

another example, the correlation between $alphaTE$ of Section 4 and Cd is different from the correlation between $alphaTE$ of Section 4 and RCS .

IV. Optimization

Based on the results of DOE, since aerodynamic performance and stealth property of flying wing aircraft integrate highly, the parameters influence both the aerodynamic performance and stealthy. Aerodynamic performance always has a higher priority than the stealth capabilities in aircraft design. In the optimization strategy, aerodynamic performance is defined as the optimization goal and stealth performance is defined as the constraints.

A. Optimization Strategy

In order to meet the requirements of internal space, the thickness parameter of master sections are not included in design variables in optimization. Some extra parameters such as reference area, torsion angle, and dihedral angle are not design variables too. The formulation of aerodynamic and stealthy optimization problem is as follows:

Given conditions: Cruise Mach number is 0.8, cruise altitude is 18 km, flight attack angle $2°$, and radar threat sectors: $0°$—$30°$ (measuring from the nose of the UAV).

Objective: Minimized aerodynamic drag coefficient Cd .

Design variables: Outline parameters (Ar , $alpha1$, $alpha2$), master sections parameters (C , XC , $AlphaLE$, $AlphaTE$, XT , $BetaLE$, $BetaTE$).

Constraints: (1) Design lift coefficient, $Cl \geq 0.362$; (2) The average RCS within the threat sector of radar, $\overline{\sigma} \leq -21 dBm^2$.

The optimization result may be the local optimal solution by using gradient methodology because of the characteristics of multiple solutions in aircraft design and characteristics of multimodality in aerodynamic optimization. The algorithm combining global optimization algorithm and gradient optimization algorithm is used in the article. Searching for global optimization through the multi-island genetic algorithm is the first step. Then the global optimal solution is transmitted to next step as initial value for local optimization. The overall process of the multidisciplinary design optimization is executed automatically. The MDO process is shown in Figure 9 and the global optimization and local optimization have the same components to DOE.

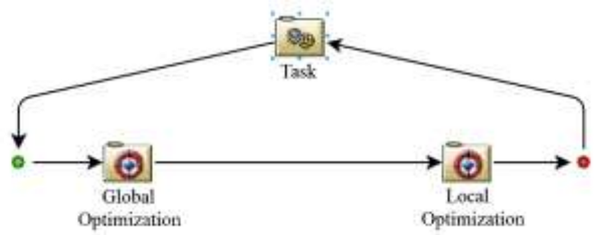

Fig. 9. MDO flowchart of UAV.

B. Optimization Results

The comparison before and after optimization in the UAV outline is shown in Figure 10. In optimized scheme, the outline parameters such as aspect ratio (Ar), swept angle of inner wing ($alpha1$), and swept angle of outer wing ($alpha2$) are larger than the origin configuration. The changes of master sections profiles are presented in Figure 11. The camber parameters of master sections have the same changing trend. The relative camber (C), the angle between trailing edge of camber line and the chord line ($alphaTE$) are increasing, while the relative camber location (XC), the angle between leading edge of camber line and chord line

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($alphaLE$) are decreasing. In thickness parameters, relative thickness location parameters (XT) are all larger, and other thickness parameters have the different tendency.

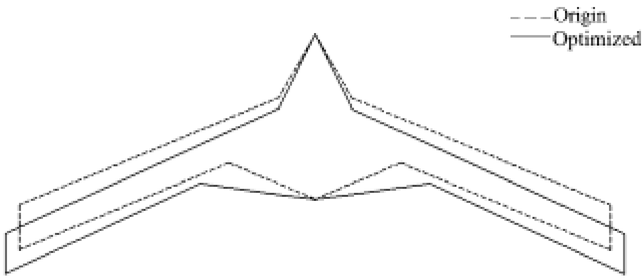
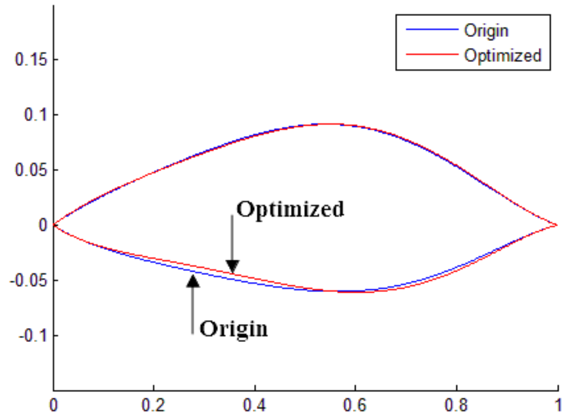
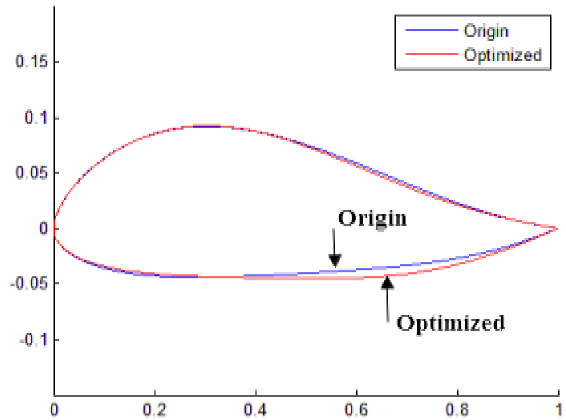


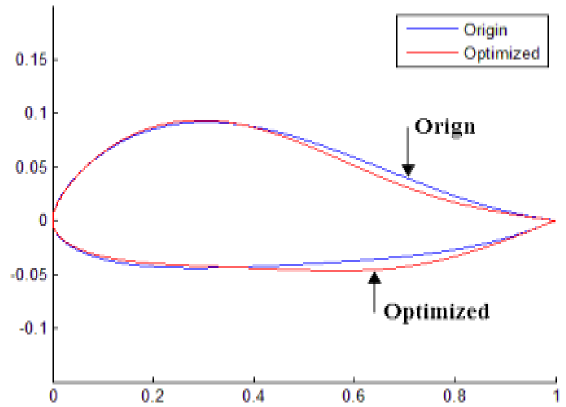
Fig. 10. Comparison of the aircraft outline between initial and optimized.



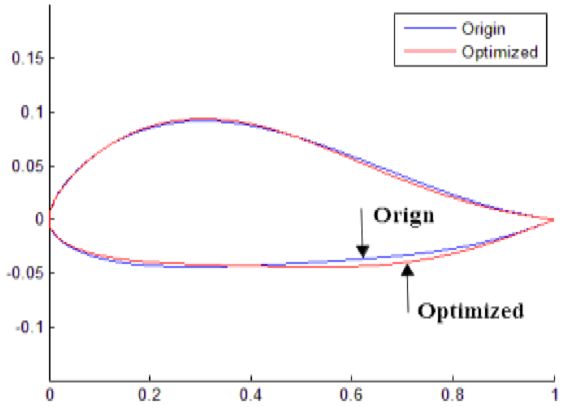
(a) Section 1



(b) Section 2



(c) Section 3



(d) Section 4

Fig. 11. Profiles comparison of master sections.

The comparison of aerodynamic performances of flying wing aircraft before and after optimization is shown in Figure 12 and Figure 13. The slope of lift curve has no change in optimized configuration, and zero-lift angle of attack is reducing slightly. The friction drag coefficient after the optimization is lower than initial scheme in the range of calculated angles of attack. The RCS distribution is displayed in Figure 14. The average RCS within the threat sector of radar is lower and a peak is missing in the distribution map after optimization.

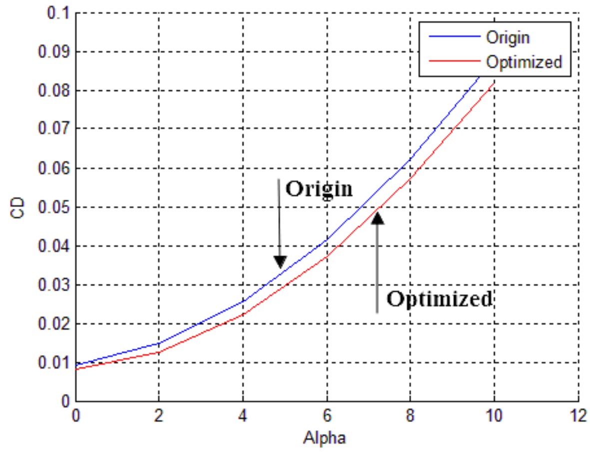


Fig. 12. Drag coefficient comparison of UAV.

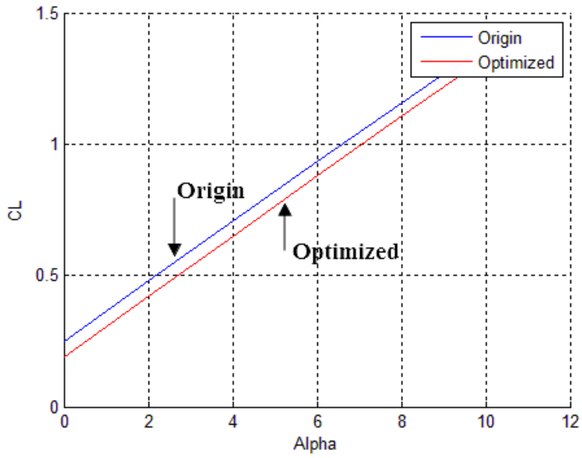


Fig. 13. Lift coefficient comparison of UAV.

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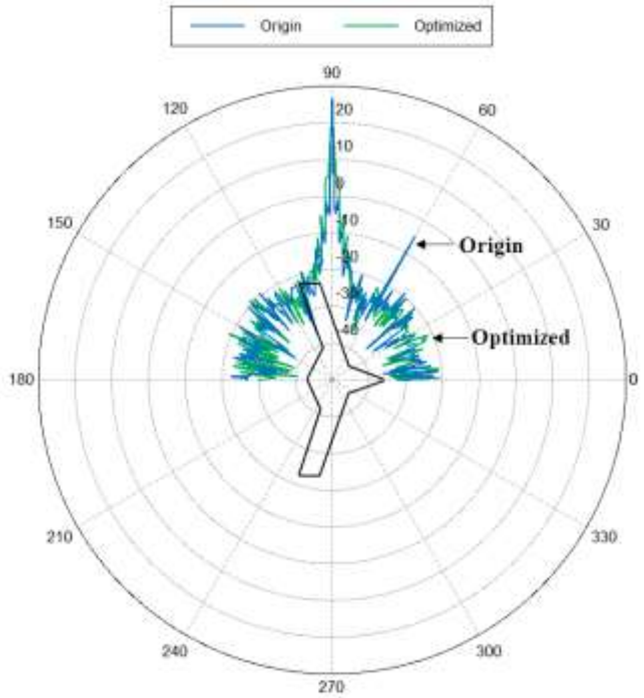

Fig. 14. Distribution comparison of UAV RCS.

Table 4 shows the values which present aerodynamic and stealth performance of the UAV. The Drag coefficient is reduced by 17.3 percent, lift drag ratio is increased by 3 percent, and the average RCS is decreased by 4 percent after optimization. The optimized UAV has a higher performance in aerodynamic and stealthy than origin configuration.

TABLE IV
COMPARISON BEFORE AND AFTER OPTIMIZATION

	Cd	*Cl/Cd*	*RCS*
Origin	0.01484	32.27	-21.891
Optimized	0.01265	33.25	-22.765

V. CONCLUSION

In this paper, investigation has been made to study aerodynamic and stealth optimization of flying wing aircraft, the conclusions as follows:

(1) The new parameterization method for describing the section with tip leading edge is effective, and it makes geometric model of UAV more flexible.

(2) The results of DOE show that how model parameters affect aerodynamic and stealth performance of the UAV in design space, and it's helpful to improve aircraft performance by changing these parameters.

(3) The optimization strategy which improved aerodynamic and stealth performance of flying wing aircraft shows that combination of global optimization algorithm and gradient method is useful.

(4) Optimization strategy in the paper used is an effective method, which is suitable for optimization in flying wing aircraft conceptual design.

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