# THE INVESTIGATION OF MULTI-DISCIPLINARY AND MULTI-OBJECTIVE OPTIMIZATION METHOD FOR THE AIRCRAFT CONFIGURATION DESIGN

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## Abstract

*The shape design of the aircraft involves multiple objectives of multiple disciplines, which are interactional. In this paper, based on system decomposition approach, applying linear combined weighted object optimization method and simple genetic algorithm, a multi-disciplinary and multi-objective optimization method is built. As an example, an aerodynamic-stealth integration optimization design for a wing-body is carried out by using the method. Compared with original configuration, the aerodynamic and stealth performances of optimized configuration are improved, which showed the method is applicable and feasible.*

## Introduction

The shape design of the aircraft is an important phase of its develop process. It involves multiple objective of multiple disciplinary, which are interactional. With the fast development of modern aircraft technology, the subsystems are more and more complex and so do the couple of them. So, requirements of integrated design were brought forward. For example, improving the integrated performance of supersonic and subsonic aerodynamic performance and stealthy performance becomes a crucial problem of the shape design for modern fighters.

Since the subsystems of the aircraft are more and more complex, if analysis modules and optimization modules of multiple disciplines are integrated to compute, the problem is too complicated. So, in this paper, from the point of multi-objective and multi-disciplinary integrated optimization, the approach of system decomposition is discussed. From the point of engineering problem, an integration optimization of aerodynamic configuration and stealth for a wing-body is done.

## 1 Multi-objective and Multi-disciplinary Optimization Method

### 1.1 Optimization Model

Consider the multi-objective optimization problem of the following mathematical programming statement: search design variables $X=(x_1,x_2,\cdots,x_n)^T$ to

$$\begin{array}{llll} & \min: \ [f_i(X)] & i=1,\cdots,s & \\ \text{Subject to} & h_k(X)=0, & k=1,\cdots,m & (1) \\ & g_j(X)\geq 0, & j=1,\cdots,p & \end{array}$$

where *n,s,p,m* are the number of design variables、objective functions 、inequation and equation constrains， $X$ is a vector composed of the design variables, the analysis of constrains $h_k$ 、 $g_j$ and objective function $f_i$ involves multiple disciplines.

In the shape design, first of all, the objective functions representing the deferent performance requirement should be decided. Then, aiming at the influence factors on the objective feature, the geometry parameters characterizing the configuration are chosen as the design variables. At last, according to structure, intensity, the feature of the objective functions and the engineering limits, the constrains should be decided reasonable.

The aerodynamic and stealth performances of the aircraft involve two disciplines. For such complex configurations as aircrafts built-up with many components, the configuration parameters influencing on the aerodynamic and stealth performances are intricate. So, the optimization method for the integration design of aerodynamic configuration and stealth should be study at the point of multi-objective and multi-disciplinary optimization. For configuration optimization problem of such complicated system made up with many subsystems as aircrafts, they frequently become too costly and unmanageable, and can easily saturate even the largest computers available today or in the foreseeable future. Generally, the objectives conflict with each other, which means that there is not an optimal design point to make every objective optimal simultaneously. A proper optimization method should be chosen to make the whole performance decided by multiple objectives optimal and to meet the requirement of the constraints. The well-known multi-objective optimization methods are value function method, interactive programming method [1], etc.

In this paper, the system decomposition approach is used firstly to turn the multi-objective and multi-disciplinary optimization problem of the integration design of aerodynamic configuration and stealth to several multi-objective problems of several subsystems. Based on this, the linear combined weighted object optimization method is used to deal with the corresponding multi-objective optimization problems.

## 1.2 System Decomposition Approach

The decomposition approach [2] is natural in an engineering organization: to decompose a complex system into several coupling subsystems. It can reduce the complexity of the system not by increasing the analysis speed but by changing the organizational structure of the optimization design problem. In the process of decomposing the system, some smaller and simpler subproblems are brought. The total workload of those subproblems is less than that of the primary system. Moreover, those subproblems keep collaborative and can be analyzed parallel, which reduce the cost and time of the optimization problem.

Decomposing the system, the design variables and the constraints are distributed according to the system levels. The diagram in Fig. 1 shows a system decomposed into several levels of subsystems. Every rectangle box represents the analysis and optimization of a subsystem. The analysis information is transmitted from the top level to the bottom level while the optimization order is reverse. When a subsystem is optimized, the parameters transmitted from the superior levels are regarded as constant while the design variables optimized belong to the subsystem, so the optimization is carrying out inside the subsystem.

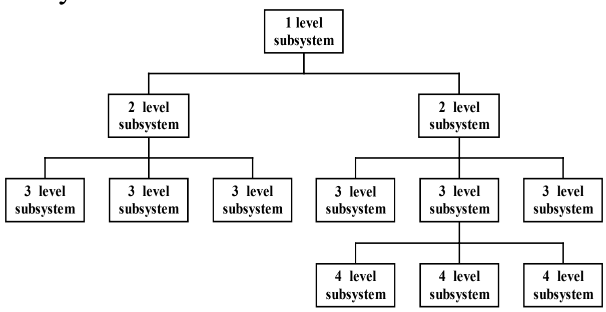


Fig.1 Level of the system

The decomposition of the system makes the transmit of the information occurring not directly among the subsystems of the same level but only among the subsystems of deferent levels. So, the parallel analysis and optimization of the same level can be achieved.

Considering the integration optimization design of aerodynamic configuration and stealth, the deferent design variables have deferent influence on the deferent objectives. From the analyzing the stealth performance of the wing-body, the maximum of RCS is in the side direction (the incident angle is about 90 degree), which means that the primary scatter source is the body and the influence of the wing on the whole RCS is less except on the peak value. A conclusion can be drawn that the stealth performance is more sensitive to the change of the body while aerodynamic performance is to the wing.

From the above analysis, the whole system is decomposed into two subsystems, showed as Fig. 2. In this way, the number of the design variables and the computational expense of the optimization for a single subsystem are reduced while the total number of the design variables is kept unchanged. Furthermore, since the influencing factors turn to be more simplex, the chose of the weighted coefficients are easier. After the parallel optimization of the subsystems, for analysis and dispose, the optimization results are transmitted to the upper system, which is the wing-body system. Then the analysis information from upper system is transmitted to the subsystems as constant and initial condition for the next parallel optimization. The process is iterative till the optimal result is convergent, which considering the interaction and the tradeoff of deferent subsystems. Applying this idea to multi-disciplinary and multi-objective optimization problem, the optimization result is satisfying, the optimization process is simplified and the efficiency is kept.

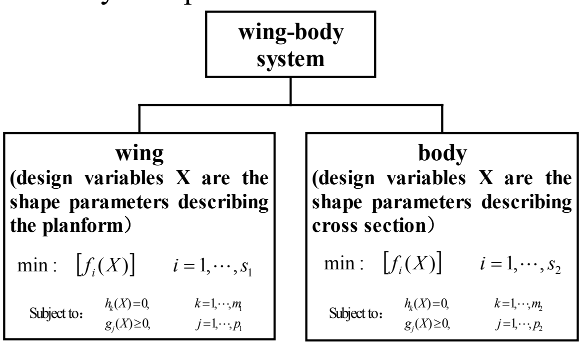


Fig. 2 Decomposition of the wing-body system

## 1.3 Linear Combined Weighted Object Optimization Method (LWO)

According to the important degree of the deferent objectives in the problem, parameters are assigned separately to them as the weighted coefficients, and then the objective functions together with their coefficients are added to form a single objective function. Then, the multi-objective problem is turned to a single one. It can be described as follows: search design variables $X=(x_1,x_2,\cdots,x_n)^T$ to

$$\min : \sum_{i=1}^{s} w_i f_i(X)$$
$$\text{Subject to} \quad \begin{matrix} h_k(X)=0, & k=1,\cdots,m \\ g_j(X)\ge 0, & j=1,\cdots,p \end{matrix} \qquad (2)$$

Where the definition of *n, s, p, m* is the same as (1), $w_i$ are the weighted coefficients, $\sum_{i=1}^{s} w_i = 1$.

In the shape design, if considering the aerodynamic and stealth performances, the objective functions can be described, for example, the objective function representing aerodynamic performance $f_{qi}$, the objective function representing stealth performance $f_{yi}$, where the objective functions $f_{qi}$、 $f_{yi}$ are nondimensioned. $w_{qi}$、 $w_{yi}$ are corresponding weighted coefficients, $\sum_{i=1}^{s1} w_{qi} + \sum_{i=1}^{s2} w_{yi} = 1$. Then, the integration optimization design of aerodynamic configuration and stealth can be stated as: search design variables $X=(x_1,x_2,\cdots,x_n)^T$ to

$$\min : \sum_{i=1}^{s1} w_{qi} f_{qi}(X) + \sum_{i=1}^{s2} w_{yi} f_{yi}(X)$$
$$\text{Subject to} \quad \begin{matrix} h_k(X)=0, & k=1,\cdots,m \\ g_j(X)\ge 0, & j=1,\cdots,p \end{matrix} \qquad (3)$$

where the definition of *n, s, p, m* is the same as (1), *s1*， *s2* are the number of aerodynamic and stealth objective functions.

As for LWO, choosing the weighted coefficient is very important. Generally, the weighted coefficients are decided according to the important degree of the deferent objectives or engineering experience. Whereas, the disadvantage of the constant weighted object optimization method (CWO) is that in general, the optimal solution is very sensitive to the weighted coefficients distribution, which is mainly determined by designer's experience. Moreover, once the weighted coefficients are determined, the influence of deferent subsystems on the optimization of deferent design variables is kept unchanged. So, in this paper, an auto-adjusting weighted objective optimization method (AWO) [3] is suggested, in which the weighted coefficients are adjusted according to the information about the improving rates of individual objective function during the optimization process, to avoid the future optimization of other objective functions being hampered due to the too fast optimization of some individual functions, thus multi-objective functions can be optimized at almost same speed. The weighted coefficients will be adjusted as:

$$\begin{aligned} W_{better} &= W_{better} - \delta_w \\ W_{worse} &= W_{worse} - \delta_w \end{aligned} \qquad (4)$$

Where $W_{better}$ and $W_{worse}$ are the corresponding weighted coefficients for individual objective function of the better and worse improving rates, $\sum_{i=1}^{s} w_i = 1$, $\delta_w$ is the adjusted step size.

### 1.4 Optimum Search Algorithm

Nowadays, the traditional search algorithms in general of the shape design are gradient and second derivative method, sequential quadratic programming method and constraint variable method, etc. Although these methods are ripe, the primary disadvantage of them is that the optimization result is apt to be local optimal. Since the local optimal feature of the optimization result is decided by the characteristic of the search algorithm itself, the stochastic methods, such as genetic algorithms, simulated annealing methods and Monte-Carlo methods, which are global search approaches should be used to improving the globality of the optimization result. In this paper, the simple genetic algorithm [4] is used.

Simple genetic algorithm (SGA) is a typical scheme among the genetic algorithms. SGA implements the evolution of population through the operations of reproduction, crossover and mutation based on binary encoding and decoding. In this paper, the selection strategy is the elitist strategy based on the roulette wheel selection, the one-point crossover is taken as the crossover operator and the one-point mutation is adopted as mutation operator [5].

## 2 Analysis and Computation Method

Since the Simple genetic algorithm is taken as search algorithm, it usually requires thousands of analysis runs to search the design space for even fairly simple cases. In order to keep the efficiency of the optimization, Green's function method is adopted as the analysis method for aerodynamic performance. Green's function method with strict theoretical proof is applicable to the aerodynamic analysis of complex shape, the analysis result is exact and the computational expense is less [6]. The analysis method for RCS in this paper is based on physical optics method. Considering that the aircraft often with deferent wings, which are the stronger edge diffraction source, while physical optics method does not deal with edge diffraction, the equivalent current method is adopted to computing the influence of the edge diffraction [7,8].

## 3 Results and Discussion

To validate the feasibility of the decomposition of the system, computational analysis of a simple example for the design of a wing is carried out firstly. The objective functions are the ratio of the lift and the drag for aerodynamic performance and the maximum of RCS for the stealth performance. The design variables are the shape parameters describing the planform, including the length of the root, the tip, and the span and the value of the sweepback, etc. A constant weighted object optimization method (CWO) and an auto-adjusting weighted object optimization method (AWO) are applied to the wing design. There are two projects:

① $w_q = 0.5 \quad w_y = 0.5$ ② $w_q = 0.8 \quad w_y = 0.2$,

The result is as follows:

| | CWO | | AWO | |
|---|---|---|---|---|
| | $f_q$ (Δ%) | $f_y$ (Δ%) | $f_q$ (Δ%) | $f_y$ (Δ%) |
| ① | 1.66% | -0.17% | 1.67% | -0.145% |
| ② | 20.9% | -0.144% | 20.93% | -0.154% |

The result shows that when $w_q$ is close to $w_y$, the optimization rate of aerodynamic performance is low; while when $w_q$ is ascendant, the optimization rate of aerodynamic performance is high. Further more, whatever the project is, the optimization rate of stealth performance is low. These results explain the theoretical analysis above and show the decomposition of the system is applicable.

Then, the optimization design of a wing-body is carrying out at Mach number of 0.6, flight height of 1000m, and attack angle of 4°. The level of the optimization system is showed as Fig. 3:

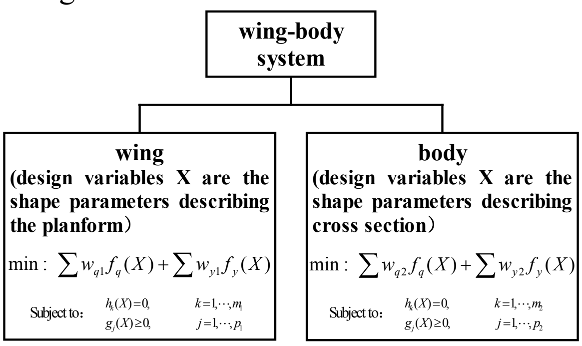

Fig. 3 Level of the optimization system

Parameters describing the shape of the planform of the wing and the cross section of the body are decided as the design variables. The original shape of the cross section is a circle while the optimal result is the combination of an arc and a line. The location relation between the center of the arc and the center of the circle is characteristic as the longitudinal and the lateral parameters and the tangent point of the arc and the line is characteristic as location parameter of the cross section.

The objective functions are the ratio of the lift and the drag for aerodynamic performance and the maximum of RCS for the stealth performance. According to the requirements of engineering experience and structure, the constrains are decided: the low and up bounds of the design variables; the range of the area of the planform of the wing; the range of the area of the cross section of the body; the low bound of the lift coefficient.

The ranges of design variables of the wing-body are listed in table.1.

| design variables | low | up |
|---|---|---|
| sweep angle (° ) | 0 | 60 |
| wingspan(m) | 0.8 | 1.4 |
| root(m) | 0.1 | 0.6 |
| wingtip(m) | 0.1 | 0.5 |
| lateral parameter (m) | 0.15 | 1.0 |
| longitudinal parameter (m) | 1.0 | 7.0 |
| location parameter | 0 | 15 |

Table.1 Range of design variables

The comparison of design variables and performances corresponding to final results and the original values are listed in table.2 and table.3. The Taper ratio and the aspect ratio of the optimal wing increase and so the ratio of the lift and the drag are improved. The maximum value and the average value of RCS are reduced and so the stealth performance is improved. The aim of the optimization is achieved. The comparison between the performances is showed as Fig. 4.

| design variables | original value | optimal result |
|---|---|---|
| sweep angle (° ) | 45.0 | 14.5 |
| wingspan(m) | 1.138 | 1.398 |
| root(m) | 0.551 | 0.57 |
| wingtip(m) | 0.446 | 0.268 |
| lateral parameter (m) | 0.0 | 0.334 |
| longitudinal parameter (m) | 0.0 | 5.796 |
| location parameter | 0 | 13 |

Table.2 Comparison of design variables

| performance | Original shape | Optimal shape | rate |
|---|---|---|---|
| ratio of the lift and the drag | 7.783 | 9.861 | 26.7% |
| maximum RCS (dBsm) | 11.96 | 1.176 | 90.2% |
| average RCS (dBsm) | -25.23 | -27.62 | 9.5% |

Table.3 Comparison of the performances

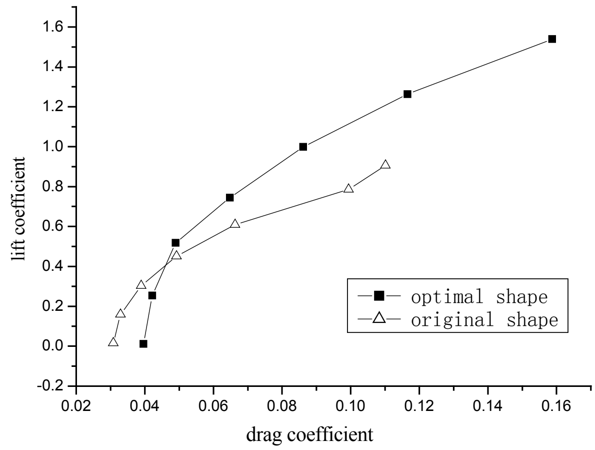


Fig. 4.1 Comparison of aerodynamic performance

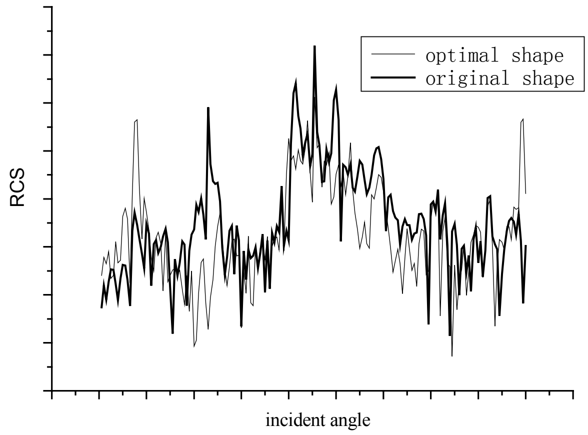


Fig. 4.2 Comparison of stealth performance

## 4 Conclusions

Deferent optimization methods have deferent influence on the optimization result and the efficiency for deferent optimization problems. In the actual design, the result of the optimization are related to not only the feature of the optimization method but also the deferent of the chose of the design variables, the constrains and the objective functions. So, the build of the optimization model is important. In this paper, the system decomposition approach is used to change the original model. This transform simplifies the optimization problem.

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