THE RESEARCH OF STRUCTURAL OPTIMIZATION WITH THE CONSTRAINTS OF AERODYNAMICS AND RADAR CROSS SECTION (RCS) OF AIRCRAFT

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Abstract

The development of structural optimization calls for considering the influence of aerodynamics and radar cross section (RCS) of aircraft. So models and software's flow charts for structural optimization based on Concurrent Subspace Optimization(CSSO), with the constraints of aerodynamics and radar cross section (RCS) are presented and studied. The response surface technique is adopted to simulate the single disciplinary model, including structure disciplinary, aerodynamics disciplinary and radar detection and the dimension of input variables for response surface is decreased by distinguishing system variables which explicitly impact more than one subsystem from local variables which explicitly impact only one subsystem. The new constructing response surface method is integrated a two-level optimization frame, to solve complex engineering systems, in which system level optimizer optimizes system design variables and subsystem level optimizers optimize local design variables. These measures will reduce the times of single disciplinary re-analysis greatly. The effectiveness of the framework for improving optimization process in this paper is shown by an example, which is about design optimization of a flying-wing layout structure.

1 Introduction

Aircraft design is relative to many provinces such as structure, aerodynamics and RCS etc. which couple each other. Conventional structural optimization does not consider the constraints of aerodynamics and RCS and usually only adjusts the layout and size of structure elements after the aerodynamics design and RCS design. Thus it can not be considered in structural optimization whether the parameters of aerodynamics design and RCS design are appropriate. Also it is not easy to feed back the influence of structure design to aerodynamics or RCS design. We see a design example of wing aspect ratio. When the wing aspect ratio changes, not only the aerodynamics performance but also loads and form of acting loads of structure change at the same time. For better aerodynamics performance, the aerodynamics specialist will select high aspect ratio wing, but this may be unacceptable because high wing aspect ratio will cause "bad" form of acting loads and higher structural weight. Structural optimization, without constraints of aerodynamics and RCS , does not know about the influence of structural design to aerodynamics and RCS, too. As a result, obtaining appropriate wing aspect ratio is difficult. If we can consider constraints of aerodynamics and RCS in structural optimization, we can get minimum structural weight design with appropriate aerodynamics performance and minimum RCS by utilizing the interaction of disciplinary. Another disadvantage of conventional structural optimization is that it is a sequence design. We have to execute aerodynamics design firstly and then structural optimization. If structural design is incompatible with aerodynamics design or RCS design, all foregoing work will be wasted.

Thus long design cycle is ineluctable. This also calls for considering the influence of aerodynamics and RCS in aircraft structural optimization.

However, considering the influence of aerodynamics and RCS in aircraft structural optimization will brings large numbers of structure, aerodynamics and RCS re-analysis. Because of huge computation amount, conventional structural optimization methods have no ability to solve such problems. In general, aerodynamics analysis at least needs several hours one time and structural and RCS analysis at least need several minutes, too. Thousands re-analysis of conventional optimization methods are unacceptable. In order to solve similar problems, many methods such as Concurrent Subspace Optimization (CSSO) and Collaborative Optimization (CO) [1][2][3] are developed. In these methods Response Surface Method is the major measure to reduce computation burden. By these methods, MDO problems with a few design variables are solved perfectly, but for MDO problems with large numbers of design variables, it is still difficult to solve. The reason for this is that the needed re-analysis numbers for constructing Response Surface Model (RSM) increase rapidly with the increasing of the dimension of input variables[4][5][6][7]. Assuming using Orthotropic Experimental Design (OED) to plan experiments, if the dimension of input variables is 4 (Assuming only 3 levels), 9 times experiments are needed and if the dimension of input variables is 13, at least 27 times experiments are needed. We can believe that more experiments will be required with the increasing of the dimension of input variables and the number of levels. Thus if we want to consider constraints of aerodynamics and RCS in practical structural optimization, we must decrease the price of constructing RSM, that is to say, to decrease the dimension of input variables of RSM.

Aiming at aircraft structural optimization problem with large number of design variables , in order to decrease computation cost, a two-level structural optimization frame based on CSSO, with the constraints of aerodynamics and RCS , is presented and studied. The Response Surface technique is adopted to simulate the single disciplinary model, including structure disciplinary, aerodynamics disciplinary and radar detection disciplinary and the dimension of input variables for response surface is decreased by distinguishing system variables which explicitly impact more than one subsystem from local variables which explicitly impact only one subsystem. The new constructing response surface method is integrated the optimization frame, to solve complex engineering systems, in which system level optimizer optimizes system design variables and subsystem level optimizers optimize local design variables. These measures will reduce the times of single disciplinary re-analysis greatly. The effectiveness of the frame for improving optimization process in this paper is shown by an example, which is about design optimization of a flying-wing layout structure.

2 Two-level Optimization Frame with Constraints of Aerodynamics and RCS

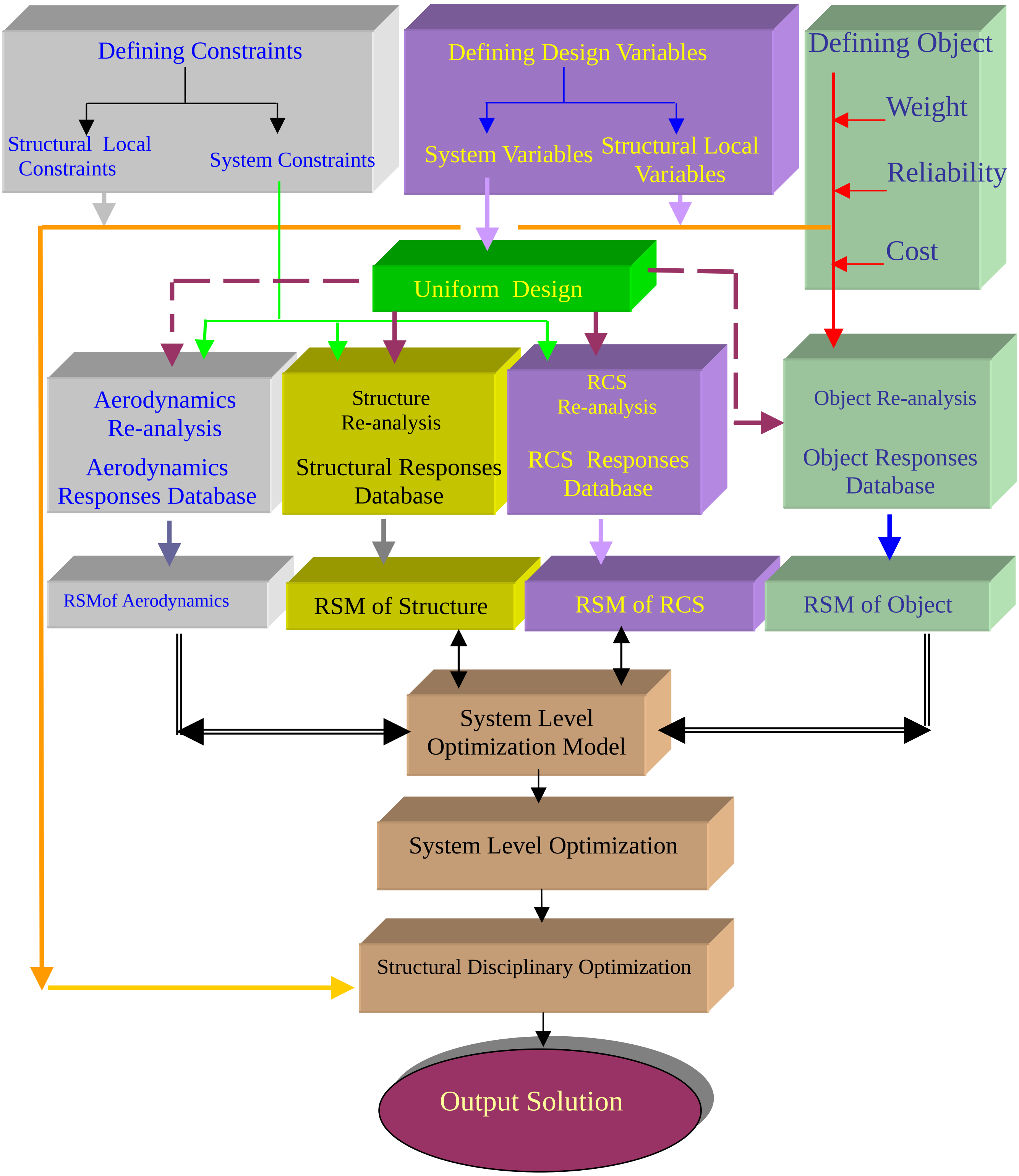
This frame firstly distinguishes system design variables from local design variables, then at each experimental point of system design variables combination with Uniform Experimental Design (UED) system analysis including structure, aerodynamics and RCS analysis is executed. The results of system analysis are stored into a database and each disciplinary constructs its RSM with the data of the database. Next, system level optimizer optimizes system design variables based on RSM. At last structure disciplinary optimizer optimizes local design variables with the fixed system design variables values.

3 Analysis of the Frame's Components

3.1 Distinguishing the Design Variables

We divide design variables into system design variables and local design variables. System variables explicitly impact state variables more than one subsystem or

Fig. 1 the Two-level Structural Optimization Frame with Constraints of Aerodynamics and RCS



disciplinary of structure, aerodynamics and RCS. Local variables explicitly impact only one subsystem. For example , the wing length is a system design variable because it is relative to structural weight, stress etc. and constraints of aerodynamics and RCS. The web thickness of beams is the local design variable because it influences only state variables of structural disciplinary. In general, parameters of shape can be classified into system design variables and size of structural elements can be classified into local design variables.

In this paper, the system design variables are optimized in the system level optimizer and the local design variables are optimized in structural disciplinary optimizer. We have two reason to do this. Firstly, the influences of system and local design variables to the design object are not at the same magnitude, thus the combination of all design variables is unreasonable . Secondly, the number of system design variables is small relative to local variables and the cost to construct RSM of system level optimization based on Experimental Design will be decreased greatly.

3.2 Defining the Constraints and Object

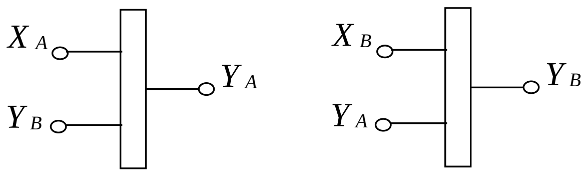
Before constructing single disciplinary RSM, we must list the constraints of system level optimization and structural disciplinary level optimization. Then we can confirm the state variables to analysis and build the system optimization model and structural disciplinary optimization model.

In this paper, the optimization object is structural weight, but in the frame defining object is listed individually and we can define other object such as structural reliability etc.

3.3 Experimental Design of System Variables and Single Disciplinary RSM

The first step to construct RSM is to define the input variables, then based on Experimental Design to plan experimental points to analyze state variables. Just as we mentioned before, the cost of system analysis increases greatly with the dimension of input variables, so we must reduce the number of input variables.

Fig. 2 Coupled Problem with Two Disciplinary



A coupled problem with two disciplinary is illustrated in figure 2. Conventional RSM constructing methods select the union set of two disciplinary design variables as the input variables[4]. The status is shown in figure 3. However, practical engineering optimization problems maybe have thousands of design variables and in order to get RSM, all variables' combination is needed. It is impossible to execute system analysis at each experimental point.

Fig. 3 Conventional Methods of Constructing RSM

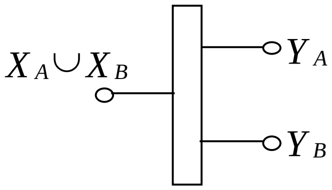
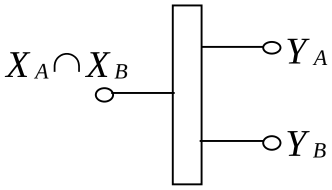


Fig. 4 Advised Method of Constructing RSM



Pay attention to such a reality that the number of system design variables is much smaller than the number of local design variables (size of structural elements) in actual engineering structural optimization. In order to reduce the number of disciplinary re-analysis and improve the efficiency of design optimization without losing RSM precision, this paper only defines system design variables as input variables of RSM and analyzes at each UED combination point of system design variables. This is shown in figure 4. We give another example here. If aerodynamics disciplinary has 5 parameters of shape and structural disciplinary has 5 parameters and 100 size parameters, the dimension of input variables of RSM is 105 with the method of reference [3]. With this paper's method, the dimension is only 5. We can see that the burden to construct RSM with proper precision is decreased greatly and the optimization based on RSM becomes a reality.

The frame has a disciplinary response database, so the constructing of RSM and the system analysis can be separate. Each design point's state variables values are put into the database, and the RSM was constructed based on information stored in the database. Another advantage of disciplinary response database is that we can utilize not only the analysis data but also experimental data and estimating data. The only thing we have to do is to store the information into the database.

3.4 System Level Optimization

This paper selects the Updated Concurrent Subspace Optimization(UCSSO) [9] as the system level optimizer. UCSSO optimizes system design variables based on RSM approximation model and does not directly calls for disciplinary analysis module except to update the RSM approximation model. Optimization of the system design variables with UCSSO is an iteration progress and the iteration result each time is re-analyzed as an updated point. New values of state variables are stored into database to update the RSM. If the results of close iterations almost have no difference, the optimization progress is convergent and the system optimization is accomplished.

3.5 Structural Local Variables Optimization

The former part has pointed out that state variables values of aerodynamics and RCS disciplinary analysis don't change with the local variables. Thus in order to reduce the computation amount of system level optimization, we optimize structural local variables in structural disciplinary optimization. The process of structural local variables optimization is similar to the conventional structural optimization and we can utilize appropriate structural optimization method.

4 the Analysis of Computation Amount of the Frame

This part gives a simple analysis to the computation amount of the frame. Firstly only system design variables are input variables of RSM and because of relatively small number of system design variables, the times of structure, aerodynamics and RCS re-analysis will be decreased greatly in constructing RSM. Secondly the optimization of system design variables bases on single disciplinary approximation model: RSM . Thus all state variables are apparent function of design variables and so the optimization cost almost can be omitted. Thirdly this paper selects UED to plan experimental points. On the one hand this guarantees that information stored in the database is abundant and the RSM based on the database is robust, on the other hand this guarantees the low computation cost attributing to small numbers of experimental points. At last, after system level optimization, disciplinary of structure, aerodynamics and RCS have no couple and the structural local variables optimization becomes a single disciplinary optimization problem. So we can utilize appropriate structural optimization method to solve it. All these measures will reduce the times of single disciplinary re-analysis greatly and make the structural optimization with constraints of aerodynamics and RCS be a reality.

5 Design Optimization of a Flying-wing Structure

The effectiveness of the frame for improving optimization process in this paper is shown by an example, which is about design optimization of a flying-wing structure.

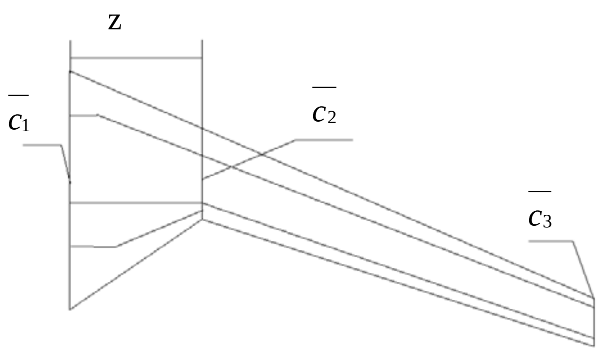
5.1 Introduction of the Optimization Problem

- The object is the structural weight of flying-wing
- Having 15 design variables divided into two classes

System design variables : the inflexion location between inner and outer wing z and the aerofoil relative thickness of the root, inflexion and tip wing $\bar{c}_1$, $\bar{c}_2$, $\bar{c}_3$ (Other parameters of shape are defined as constant values). They are shown in figure 5.

Structural local design variables: the area of beam stringer located in the root, inflexion and tip wing A_{11} , A_{12} , A_{13} ;the area of the stringer of enhanced rib A_{21}; the thickness of beam web located in the root, inflexion and tip wing T_{11} , T_{12} , T_{13} ;the thickness of wing skin located in the root, inflexion and tip wing T_{21} , T_{22} , T_{23} and the web thickness of enhanced rib T_{31} .Other parameters are interpolated linearly according to these variables. The figure is omitted.

Fig. 5 System Design Variables



- constraints

the constraints of system level optimization:

the structural displacements of some points are no more than permitting values;

the structural stress of some points are no more than permitting values;

the twist angle of wing is no more than permitting values;

the structural inherence frequencies are larger than frequencies of corresponding exciting forces;

the wing lift/drag ratio L/D is larger than the permitting minimum value;

the RCS of some directions are no more than permitting values;

the bounds of system design variables.

the constraints of structural disciplinary level optimization:

the structural displacements of some points are no more than permitting values;

the structural stress of some points are no more than permitting values;

the twist angle of wing is no more than permitting values;

the structural inherence frequencies are larger than frequencies of corresponding exciting forces;

the bounds of Structural local design variables.

It must be pointed out that the constraints here are only to illustrate the frame and in actual application of optimization more constraints must be defined.

5.2 the Uniform Design of System Variables and the Constructing of RSM

We select experimental points with UED, each variable having five levels. The selected Uniform Design table is $U_{15}(5^4)$ [8] and the table is omitted here.

Based on the selected table, we can compute the performance parameters of structure, aerodynamics and RCS by system analysis. Three disciplinary call for analysis software to get the state variables values of the 15 points, including L_i / D_i , RCS values $RCS(j)_i$ (apposed having P directions and j presenting the jth direction), maximum stress values $\sigma(j)_i$ (apposed considering Q points and j presenting the jth point), maximum displacement values $\delta(j)_i$ (apposed considering S points and j presenting the jth point), twist angle θ_{zi} and weight w_i . At last according to these data, we can construct the RSM of all the three disciplinary state variables. The exhaustive process is also omitted in this paper.

5.3 System Level Optimization Model

Based on RSM of constraints and object, we can get system level optimization model:

$$\text{Min} \quad W(Z, \bar{c}_1, \bar{c}_2, \bar{c}_3)$$

$$\begin{aligned}
\text{S.T.} \quad & L/D > [L/D] \\
& \text{RCS(j)} \le [\text{RCS(j)}], \quad \text{j=1,2,…P} \\
& \sigma(j) \le [\sigma(j)], \quad \text{j=1,2, …Q} \\
& \delta(j) \le [\delta(j)], \quad \text{j=1,2, …S} \\
& \theta_z \le [\theta_z], \\
& f_j > [f_j], \quad \text{j=1,…4} \\
& G^L \le G \le G^U
\end{aligned}$$

where $G = (Z, \bar{c}_1, \bar{c}_2, \bar{c}_3)^T$

In this model, all constraints and object are RSM ,that is to say, they are apparent function of design variables, so we can solve it with Nonlinear Programming[10].

5.4 Structural Disciplinary Level Optimization Model

Based on described constraints and object, we can get structural disciplinary level optimization model:

$$\text{Min} \quad W(A_{11}, A_{12}, A_{13}, A_{21}, T_{11}, T_{12}, T_{13}, T_{21}, T_{22}, T_{23}, T_{31})$$

$$\begin{aligned} \text{S.T} \quad & \sigma(j) \le [\sigma(j)], && j=1,2,\dots Q \\ & \delta(j) \le [\delta(j)], && j=1,2,\dots S \\ & \theta_z \le [\theta_z], && \\ & f_j > [f_j], && j=1,\dots 4 \\ & T^L \le T \le T^U && \end{aligned}$$

where $T = (A_{11}, A_{12}, A_{13}, A_{21}, T_{11}, T_{12}, T_{13}, T_{21}, T_{22}, T_{23}, T_{31})^T$

This is a conventional structural optimization problem and can be solved by conventional structural optimizer[11][12].

After building up the system level optimization model and structural disciplinary level optimization model, we can begin the iteration process shown by figure 1. In this example, the number of structure, aerodynamics and RCS re-analysis of system level optimization is 15 adding the number of system level iteration. Relative to the combination of all variables, at least requiring （15×15+3×15+2）/2=136 system analysis (with quadratic RSM), the frame reduces the times of aerodynamics and RCS analysis greatly. If a problem has more structural local variables, the frame in this paper will has more advantage.

6 Conclusion

1) The two-level structural optimization frame in this paper greatly decreased the high computation cost of structural optimization with constraints of aerodynamics and RCS, making the practical engineering structure optimization with constraints of aerodynamics and RCS be a reality.

2) The “optimum” solution of this frame is a satisfactory solution in fact because the structural responses are relative to not only system design variables but also structural local design variables. Thus the sequential optimization in the frame is not fully equivalent to the original problem.

3) It is necessary to research the influence of the results of structural disciplinary optimization to the system level optimization.

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