Research on Global Optimization Algorithm for Multidiscipline Design Optimization

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***Abstract* — Multidisciplinary design optimization (MDO) is a systematic design methodology based on subject analysis and optimization. To study the complexity of multi discipline system, the research on the collaborative optimization algorithm based on multi discipline design optimization algorithm is proposed, which is based on the existing cooperative optimization algorithm. Through the re-allocation of design variables, the decoupling process of the coupling variables is simplified, and the purpose of the optimization process is achieved. Firstly, the research introduces the key technologies of MDO, system mathematical modeling, decomposition and organization technology and multidisciplinary design optimization algorithm. This research discusses the problems and development trend of multi discipline design optimization. Based on the global convergence of evolutionary particle swarm optimization algorithm, the problem is solved. This method is very suitable for the multidiscipline design.**

Keywords - Multidisciplinary Design Optimization, Global Optimization Algorithms, Collaborative Optimization (CO), Complex Engineering System, Particle Swarm Optimization Algorithm (PSO)

I. INTRODUCTION

With the continuous development of science and technology, engineering systems are becoming more and more sophisticated and complex, and the interaction among the components of the system is becoming more and more obvious. From this point of view, today's engineering system has obvious characteristics of multi discipline. The traditional design method is often to each subsystem (subject) to optimize, in an attempt to combine a number of optimal sub system into one is also the optimal system. The design method neglects the inter relationship among the subsystems, and can't meet the needs of the development of engineering technology. The contradiction between engineering system and design method is particularly evident in the field of aviation and spaceflight. On one hand, the theory of structure, power, control and so on, the development of the theory of structure, power, control and so on. For example, the use of finite element method for structural analysis, the use of computational fluid dynamics for flow field analysis, and so on, but the above progress is basically in the range of specific disciplines or subsystems, and no direct benefits for the overall design. On the other hand, with the development of the overall design method of aerospace engineering system, the theory and methods of aerospace engineering system have been stagnant[1]. However, these theories and methods have played an important role in the development of aviation and space industry. However, they are not suitable for the development of aerospace technology in the new period.

Multidisciplinary design optimization is an effective method to solve complex system design. The complex system is composed of many subjects or subsystems, which are coupled with each other. The traditional design method is very difficult to find the optimal solution of the system, and the design cycle is longer. By taking full advantage of the synergy between the various disciplines or subsystems, the overall optimal solution of the system is obtained by using the synergy effect between the MDO and the system.

Multidisciplinary design optimization method is the most important and the most important research direction in the field of multidisciplinary design optimization technology. NASA senior fellow, American born mathematician J.Sobieski in the direction of the development of the initiative to make a groundbreaking contribution. He first proposed the full sensitivity equation analysis method for complex system, and uses the output of each subsystem to create the global sensitivity equation of the whole system [2]. This method not only reflects the mutual coupling effect of each subsystem in large system, but also realizes the parallel processing, so it has wide application prospect in the design of complex system[3]. Subsequently, Sobieski proposed a seed space optimization method, namely, the connection between the sub space, artificially for the sub space allocation constraints and design variables, so that the sub space in their own design variables to optimize the space, and then through the system coordination problem to adjust the system to obtain the optimal solution of the whole system[4]. The two important theories of Sobieski have laid a solid foundation for the research on the multi discipline design optimization method[5]. On the basis of this, other scientists have developed more and more multidisciplinary design optimization method, and applied it to engineering design, and achieved fruitful results. Renaud and Batill have improved and developed the subspace optimization method. The parallel subspace optimization method was applied to the design of mechanical components, and the satisfactory results were obtained. Sellar et al [6]. Based on the response surface of the parallel subspace optimization method is applied to simplify the general aviation aircraft and the initial design of the rotor, not only reduce the number of system analysis, but also improve the probability of finding the global optimal solution. Bloebaum et al introduced the expert system into the parallel subspace optimization method[7]. The design variables were optimized by using the expert system to deal with the distribution of design variables and the change of design variables. The optimization method was improved. Braun et al.

In comparison, the research results of the other two directions in the field of multidisciplinary design optimization technology are less [8]. Various disciplines in design oriented analysis method and software integration research, Livne was developed for the analysis of the design of the software LS-CLASS, for active control of wing structure / control / pneumatic integrated optimization; NASA Langley Research Center of Townsend proposed the CAD system and multidisciplinary design optimization framework combines the specific means; research in multidisciplinary design optimization of distributed network computing environment, the olds and established the analysis and optimization of an integrated network environment.

At present, MDO is regarded as an integrated system design methodology based on subject analysis and optimization. The main idea of MDO is to integrate the knowledge of various disciplines (sub system) in the whole process of complex system design, and to design and manage complex systems with effective design optimization strategy and distributed computer network system[9]. By making full use of the synergy effect of the interaction between the various disciplines (sub systems), the overall optimal solution or the engineering satisfactory solution is obtained.

To study the complexity of multi discipline system, the research on the collaborative optimization algorithm based on multi discipline design optimization algorithm is proposed, which is based on the existing cooperative optimization algorithm. Through the re-allocation of design variables, the decoupling process of the coupling variables is simplified, and the purpose of the optimization process is achieved. Firstly, the research introduces the key technologies of MDO, system mathematical modeling, decomposition and organization technology and multidisciplinary design optimization algorithm.

II. DESCRIPTION OF MDO PROBLEM

The MDO problem can be described as follows.

$$min\ \ f(x,\mu(x)) \tag{1}$$

$$s.t.\quad g_i(x,\mu(x)) \geq 0,\ \ i=1,2,\cdots,m \tag{2}$$

In the formula, x is the design variable vector, f is the objective function, and G is the constraint function, $\mu(x)$ can be decided by the system analysis equation $A(x,\mu(x))$.

$$A(x,\mu(x)) = \begin{bmatrix} A_1(x,\mu_1(x),\cdots,\mu_N(x)) \\ \cdots \\ A_N(x,\mu_1(x),\cdots,\mu_N(x)) \end{bmatrix} = 0 \tag{3}$$

In the equation, the number of MDO for the N subsystem. The equation (3) is a MDA (Multi-disciplinary Analysis) equation, in which the N sub system analysis equation is determined by the subject analysis and cross disciplinary coupling relationship, state equation $\mu(x)$ is generally described by coupled differential equations[10]. It is assumed that the multi-objective function of the system can be transformed into a single objective function of the equation (1) by the weighted method and the constraint method f.

The general solving process of MDO is to design variable vector set x (MDA) system, and the state vector μ, which is a multi discipline system, is obtained by the formula (2). Only when the design variables x meet MDA, can further obtain the constraint and objective function, the design scheme called consistentdesign (feasible design). When the consistency is designed to meet the requirements of the state equation, and meet the explicit constraint set formula (2), then it is known as the feasibility design. When the feasibility design through the qualitative evaluation of the best performance, it is called optimal design.

The main research contents of MDO can be summarized as 6 aspects, that is, the system modeling, decomposition and organization technology, system sensitivity analysis, approximation techniques, MDO algorithm or optimization method, man-machine interface. The model of the optimization method of MDO must meet the requirements of the model: the mathematical structure of the problem, the compatibility with the present design principle and the style. And it can be used to carry out the work of the existing analysis tools. Due to space limitations, this research focuses on modeling, decomposition and organization, as well as MDO algorithm and technology.

Simultaneous analysis and design (SAD) is the result of MDF. The parameters x, $\boldsymbol{s}$ and $\boldsymbol{t}$ should be regarded as independent parameters with each other and unknowns, so that the overall reformulation to be calculted as follows.

$$
\begin{aligned}
&\min_{x} \hat{f}\left(\boldsymbol{x},\boldsymbol{s}(\boldsymbol{x}),\boldsymbol{t}(\boldsymbol{x})\right)\\
&\quad g_0\left(\boldsymbol{x},\boldsymbol{s}(\boldsymbol{x})\right)\geq 0\\
&\quad g_1\left(x_0,x_1,\boldsymbol{s}(\boldsymbol{x})\right)\geq 0\\
&\quad \ldots\\
&\quad g_p\left(x_0,x_p,\boldsymbol{s}(\boldsymbol{x})\right)\geq 0\\
&\quad W_1\left(x_0,x_1,s_1,t_2,\ldots,t_p\right)=0\\
&\quad \ldots\\
&\quad W_p\left(x_0,x_p,s_p,t_1,\ldots,t_{p-1}\right)=0\\
&\quad t_1=C_1\left(s_1\right)\\
&\quad \ldots\\
&\quad t_p=C_p\left(s_p\right)
\end{aligned}
\tag{4}
$$

where W_i is the set of PDEs. It can be seen that the number of unknown parameters for simultaneous analysis and design is larger than MDF. The structure of simultaneous analysis and design is an OD/ODA/OIC reformulation.

Collaborative optimization is a multi-level optimization problem. Here, the different roles played by the system level and the level of discipline strong comments. In particular, it is allowed that the two design variables and state variables of interdisciplinary restrictions. Integral nonlinear program is introduced as the so-called surrogates $y_1, y_2, \ldots, y_p$ of vector x_0. Each subject was observed, which is unknown to defcouple upper and the lower, they play a role similar to that of vector $\boldsymbol{t}$.

$$
\begin{aligned}
&\min_{x,\boldsymbol{t}} \hat{f}\left(x_0,x_1,\ldots,x_p,\boldsymbol{t}\right)\\
&\quad \left\|t_i-C_i\left(y_i-x_0,s_i\left(y_i,x_i,\boldsymbol{t}\right)\right)\right\|_2=0, i\leq p
\end{aligned}
\tag{5}
$$

$$
\begin{aligned}
&\min_{y_i,x_i}\frac{1}{2}\left[\left\|y_i-x_0\right\|^2+\left\|s_i\left(y_i,x_i,\boldsymbol{t}\right)-t_i\right\|^2\right]\\
&\quad g_i\left(y_i,x_i,s_i\left(y_i,x_i,\boldsymbol{t}\right)\right)\geq 0, i\leq p
\end{aligned}
\tag{6}
$$

III. THE SYSTEM MATHEMATICAL MODELING

System mathematical modeling is the premise of the establishment of multidisciplinary design optimization. System modeling generally refers to the characteristics of the system design level definition or system geometry, functional characteristics of the mathematical description. New model for physical model and physical model, including model for the analysis of aerodynamic, structure analysis and other traditional disciplines, and maintainability, reliability and cost budget discipline analysis model, and in the mathematical model but also to express each subject mutual influence relations. Mathematical modeling is helpful to find the optimal path from the initial point to the best advantage in the design space. The mathematical modeling of the system can be divided into MDF (multidisciplinary feasible approach), IDF (individual feasible approach) and AAO (all-at-once approach). And the MDO and implicit constraints are classified:

(1) Fully Integrated Optimization (FIO) is a MDF, which is sometimes referred to as a one-time (all-in-one) optimization, which is mainly used to simplify the use of variables. The disadvantage is that the efficiency is low.

(2) Parallel analysis and design (Simultaneous Analysis and Design, SAD) modeling, namely AAO, Cramer, the proposed method can find the optimal solution in the feasible space, but it is lack of robustness.

(3) Distributed optimization analysis (Distributed Analysis Optimization, DAO) IDF modeling method is one of the methods. In this method, the consistency constraint is introduced to improve the autonomy of the discipline optimization, but it is difficult to find the initial auxiliary design variables of the subject design variables.

(4) Collaborative optimization (CO) modeling. The method is non convex, nonlinear second level optimization method and system level constraints is the interdisciplinary consistency constraints, and strive to make section input and output to minimize the difference. But in fact there are still conflict.

IV. A GENERALIZED PSO SCHEME FOR GO

As described before, PSO is an iterative heuristics for the optimization solution. It generates the continuous solvers of points in N dimensional space. And it possibly close to a stationary point of $f(x)$ eventually. Aiming at the current iteration k, the PSO algorithm creates the P sequences $\left\{x_j^k\right\}, j=1,2,\ldots,P$. The algorithm and the calculation process are based on the following equations.

$$
\begin{aligned}
&v_j^{k+1}=\hbar\left[\lambda^k v_j^k+c_j r_j\left(p_j^k-x_j^k\right)+c_g r_g\left(p_g^k-x_j^k\right)\right]\\
&x_j^{k+1}=x_j^k+v_j^{k+1}
\end{aligned}
\tag{7}
$$

PSO belongs to the wide class of evolutionary algorithms and follows the natural paradigm of a bee swarm, where the trajectories of the bees (so called particles) are represented by the P sequences $\left\{x_j^k\right\}$. On the other hand, the vector $v_j^{k+1}\in^n$ represents the speed of the j-th particle at iteration k. Finally, the n-real vectors p_j^k and p_g^k, for any k, satisfy the conditions:

The particle swarm optimization algorithm is an evolutionary optimization algorithm, which is based on the evolution of the particle swarm and the individual. And it follows the natural form of the ant colony, where the ant (so-called particle) trajectories are represented by the P sequences $\left\{x_j^k\right\}$. On the other hand, the vector

$v_j^{k+1} \in \mathbb{R}^n$ representation is the so-called j -th particle velocity at iteration k in the iterative process. Finally, for any value of k , the n real vector, p_j^k and p_g^k , are should be satisfied the following case and situation:

$$\begin{cases} p_j^k \in \left\{x_j^l\right\}, l \leq k, j = 1,...,P \\ f\left(p_j^k\right) \leq f\left(x_j^l\right), \forall l \leq k, j = 1,...,P \end{cases} \tag{8}$$

and

$$\begin{cases} p_g^k \in \left\{x_1^l,...,x_P^l\right\}, l \leq k \\ f\left(p_g^k\right) \leq f\left(x_j^l\right), \forall l \leq k, \forall j = 1,...,P \end{cases} \tag{9}$$

What's more, the parameter $\hbar, \lambda^k, c_j, r_j, c_g, r_g$ are real coefficients which have the limitation and boundary. It can be seen that the parameter j is used to represent the number of the calculation sequence. In addition, the superscript k is adopted to calculate the iterate number in the subsequences $\left\{x_j^k\right\}$. And p_j^k indicates the best solver of one local particle in the j -th sequence. And p_g^k is the best solver among all the particles. The coefficients of the calculation are selected by the users and decided by the detailed optimization problem. And the coefficients can be changed with the calculation process. And they are often problem dependent. Specially, the parameters r_j and r_g are often the value from 0 to 1 which are parameters decided randomly.

Among the equations above, the speed v_j^{k+1} is decided only by the vectors $p_j^k - x_j^k$ and $p_g^k - x_j^k$. But for the updating calculation of j -th particle, the process of the iteration is shown in the following:

$$\begin{aligned} v_j^{k+1} &= \hbar_j^k \left[w_j^k v_j^k + \sum_{h=1}^{P} c_{h,j} r_{h,j} \left(p_h^k - x_j^k\right) \right] \\ x_j^{k+1} &= x_j^k + v_j^{k+1} \end{aligned} \tag{10}$$

where the speed v_j^{k+1} is decided by the P vectors $p_h^k - x_j^k$, $h = 1,...,P$.

In the course of the movement, the particle's motion range is more than the given constraint range, and the general processing method is to re-assign the boundary position to the current position of the particle.

At the same time, to the frequency response also constraint on the response, it is mainly dealt with through the penalty function, by penalty function the fitness values decrease and eliminate inappropriate particles.

In the early iterations, the search process tends to be dominated by a few super particles that have an absolute advantage over the fitness value. If the target function is multi peak, the particle cannot lead the population to the global optimum in the long run. In this research, the objective function is used to select the roulette wheel, so that the initial optimal individual is chosen as the global extreme value p_g , which is used to calculate the target function of all particles.

V. PSO ALGORITHM IN A DAO FORMULATION

According to the introduction above, the DAO formulation is open to design variables and cross disciplinary consistency constraints. The latter once which meet the method is to optimize the design variables of the collection. In fact, if we consider a small change in the design, it can be assumed that the value of the variables of the cross discipline will not change dramatically.

If we are also able to get a little change in the designing parameters of a design object, it is needed for us to search for the optimization solution of the optimal solution is more than the natural optimization algorithm to explore the design space. This is not a normal calculation process for a global optimization algorithm. So, in the MDO, it is found that many problems are changing the different objective functions into a single value function with several constraints. And this problem has been solved by using gradient which is based on the optimization algorithms.

Considering every particle swarm particle in the DAO agreement, cross disciplinary constraints convergence we can separate. PSO algorithm is also suitable for multi objective optimization problem. Penalty function is generally introduced to deal with multi-objective optimization problems, or the existing multi-objective function is integrated to form a new objective function. At this point, the algorithm uses the algorithm to solve the multi-objective problem, where the objective function is not to be changed into a single merit value function, but can be operated. In this case, the complete Pareto problem can be determined, rather than a single objective function of the optimal solution of the objective function.

VI. NUMERICAL EXPERIMENTS AND DISCUSSION

In the experiment, the optimization for a fin is taken into discussion. It is moving at the speed of 5 m/s which has an attack angle of 8 degrees. The objective function is the work fin efficiency which is decided by the relationship between vertical and longitudinal forces. This function is needed to get the maximum value.

The convergence characteristics of the multidisciplinary design constraints are checked in this research. And the value of the objective functions are calculated based on the MDA.

TABLE 1. CONVERGENCE HISTORY OF THE MDA OF THE ORIGINAL DESIGN

Iteration	1	2	3	4	5	6	7	8	9	10	11	12
u	75	19	9.5	5.8	1.5	1.3	1.0	0.8	0.7	0.45	0.21	0.08
Objective function	-0.472	-0.583	-0.532	-0.563	-0.541	-0.551	-0.559	-0.549	-0.550	-0.552	-0.553	-0.550

In Table. 1, for the initial structure, the convergence parameter u and the objective function are both regarded as a function of the iteration number. It can be se en that 12 inner steps are required for MDA. In the following calculations, a limitation of 10-3 is used to help and decide the MDA converged.

At the trailing edge, the contour is thicker and the trailing edge is thin. Efficiency improvement is from 0.445 (the original configuration file) to 0.564 (best profile) profile. The final yield is about 20%. It is remembered that the development was taken into account in the entire calculation process of the actual efficiency of the fin under the hydrodynamic loading and forces.

The conclusion can be gotten that the elastic reaction of the fin trends to be increased which is obviously shown in Fig. 1. If not considering the impact on the configure of the loading, then the optimization is achieved and calculated by the flow around. The efficiency of the original file will be 0.697, which will be 0.925 of the best configuration file. This implies that the development is not achieved by reducing the deformation of the fin: the larger part of the improved water power performance is improved by enhancing the shape.

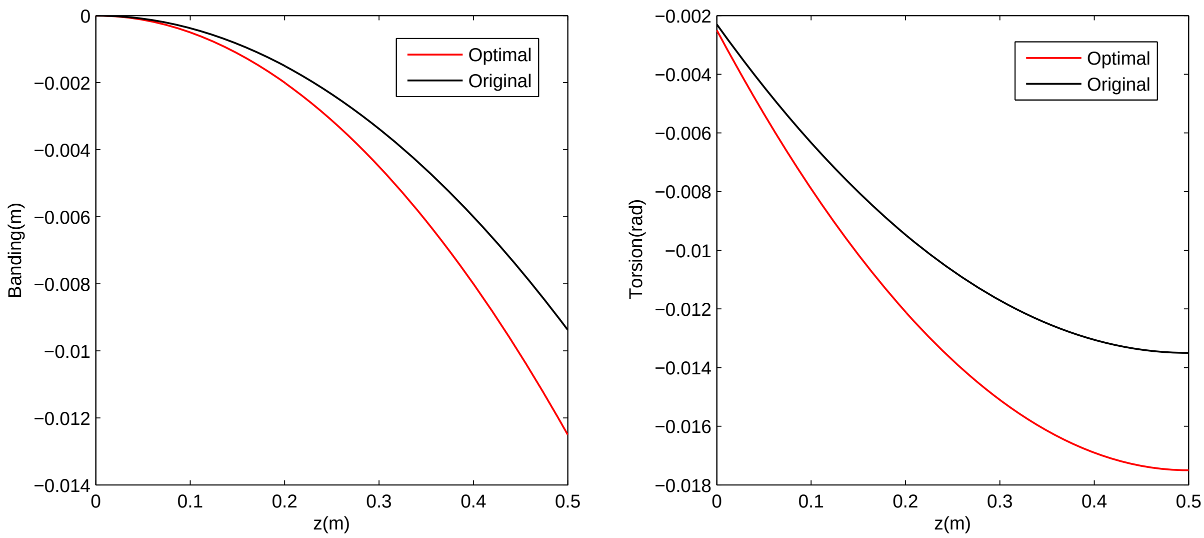

Fig. (1). Comparison of Bending and Torsion of the Fin for the Original and Optimal Shape

VII. CONCLUSION

The problems of complex engineering systems are very difficult to be solved or solved. Therefore, the study of MDO method and its system has become the focus of people's attention. Computational difficulty lies in the coupling between disciplines. It is difficult to coordinate the relationship between subjects in the process of optimization. The ideal MDO algorithm can find the global optimal solution in a large probability. It can be decomposed into multiple sub systems, which can be decomposed into a number of parallel subsystems, which can reduce the number of system analysis, and integrate the existing disciplines and design software easily.

Optimization problems in which the solution depends on more disciplines may be tackled with MDO. In this research, the results are presented for the MDO optimal shape of a vertical fin travelling across the free surface, simultaneously accounting for hydrodynamics and elasticity. The optimal design problem is dealing considering a Global Optimization (GO) problem within a MDO framework. Future work will include the application of this technique to multi-objective problems and a more articulated reshaping of the profile.

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