Numerical Simulation for Composite Wing Structure Design Optimization of a Minitype Unmanned Aerial Vehicle

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Abstract: To improve the structure performances of minitype unmanned aerial vehicle (UAV) wing, numerical simulation and optimization design principle was carried out for designing the best composites wing structure. Thus tradeoff can be obtained between the general performance and the weight of the wing. Advanced composite material has its own outstanding features, such as high specific strength, high specific modulus, designable performance and integral forming easily. The application of advanced composite material on the aerocraft structure can significantly reduce the weight, and improve the aerodynamic and flight performances. In this paper, the parametric finite element model is established using parametric modeling technique for stress and stain analysis. Given any set of geometric parameters, the geometric modeling, meshing, strain and stress analysis can be automatically carried out in sequence. The global optimal solution is guaranteed by the proposed two-step optimization search strategy combing genetic algorithm (GA) and sequential quadratic programming (SQP). Comparative studies show that the optimization efficiency can be greatly improved with the two-step optimization search strategy.

Keywords: Advanced composite material, structure design, parametric finite element modeling, optimization design.

1. INTRODUCTION

As a kind of new material, the advanced composite material brings about great revolution to the aerocraft industry since it was introduced in the 1960s. With its wide application in aerospace structure, the advanced composite material is named as "the four main materials of aerospace structure" along with aluminum alloy, titanium alloy, and alloy steel. The advanced composite material has its own prominent features, such as high specific strength, high specific modulus, designable performance and integral forming easily, etc. With the application of the advanced composites, the weight of the aerocraft structure can be reduced by about 25% ~ 30% compared to the conventional metal structures. Moreover, the aerodynamic and flight performances can be improved to the levels that the conventional materials can hardly achieve. The extensive application of advanced composites is also able to promote some further technology development of structure stealth and intelligent structure design. The aerocraft structure performance is significantly dependent on the part and quality of the advanced composites used in aerocraft. However, it is difficult to achieve good designs of the composites in aerocraft structure to guarantee requirements for different missions. Therefore, to fully explore the directional properties of composites, the designable ability of structure performance and the excellent manufacturability of large component integral forming, it is necessary to introduce the principle of optimization to the composite structure design [1-6].

In this paper, the optimization design and numerical simulation for composite structure of wing on a UAV is implemented. By using parametric modeling technique, the parametric finite element model is established to conduct stress and strain analysis of the wing. Given any set of geometric parameters, the geometric modeling, meshing, strain and stress analysis can be automatically carried out in sequence. To ensure the optimal solution can be obtained, a two-step optimization search strategy which combines genetic algorithm (GA) and sequential quadratic programming (SQP) is proposed during optimization. It is concluded that this two-step optimization search strategy can greatly enhance the efficiency of finding the true optimal solution through comparing this method with GA.

2. THE PARAMETRIC FINITE ELEMENT MODELING OF UAV

2.1. Geometric Modeling and Meshing

Wing box is the main load bearing structure of airfoil surface, including skin panels, beams and core sandwich panel, etc. Aerofoil B-8306-b 5 depicted in Fig. (**1**) is considered in this work [7]. Fig. (**2**) displays the geometric model with mesh of the minitype UAV wing. The parameters involved in the geometric modeling process are: the quality of UAV W=5kg, reference area of wing s=0.16 m2, taper ratio $\lambda = 0.8$, aspect ration A=8, wing span b, length of root chord c_r, length of tip chord c_t, sweepback angle (leading edge sweepback angle L_{LE}, a quarter chord sweepback angle $L_{c/4} = 10^{\mathrm{o}}$) and b, c_t, L_{LE} ($A = \dfrac{b^2}{s}$, $c_t = \dfrac{2s}{b(1+l)}$,

$$\tan L_{LE} = \tan L_{c/4} + \frac{1-l}{A(1+l)}).$$

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on the stiffness and strength of the wing structure, the maximum deformation and the largest torsion angle of the wing. Generally, to trade off between minimizing the structure weight and optimizing the structure performance, the number of layers of carbon fibers is considered to be smaller than 7 in the literature. So x_3 can vary among the six integral (1 to 6). $x_4 \in [1-5]$ represents the materials of the five most common carbon fiber/epoxy resins (G814NT/3234, G803/5224, G827/55, G803/QY891, G827/QY891) used in this work correspondingly [10].

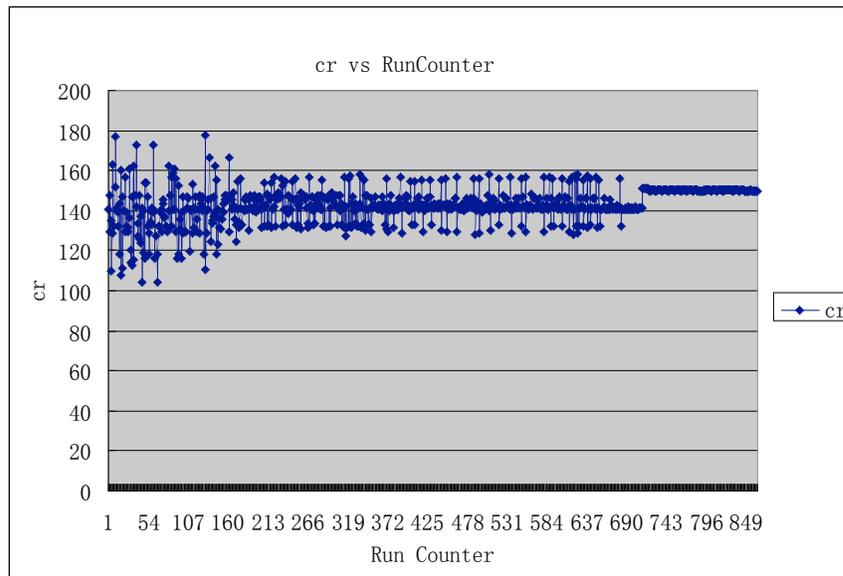### 3.2. Realization of Optimization

iSIGHT is a software which can carry out system integration, design optimization and automation processing. Through a graphical interface, this software is able to integrate simulation code and provide intelligent support.

The product design period can be significantly reduced; meanwhile, the product quality and reliability can be improved. Therefore, iSIGHT is applied to realize design integration and optimization in our work. The optimization is accomplished in the iSIGHT software.

Genetic algorithm (GA) is applicable to optimization problems with both continuous and discrete design variables. The global optimal solution can be achieved with high possibility. However, it may converge to the vicinity of the optimal point causing inaccurate solution [11-14]. What's more, it suffers heavy calculation burden and slow convergence rate because of too many searching times. Sequential quadratic programming (SQP) is only applied to continuous problems. With fewer reanalysis, it converges quickly, and the accurate optimal solution can be achieved in high efficiency [15].
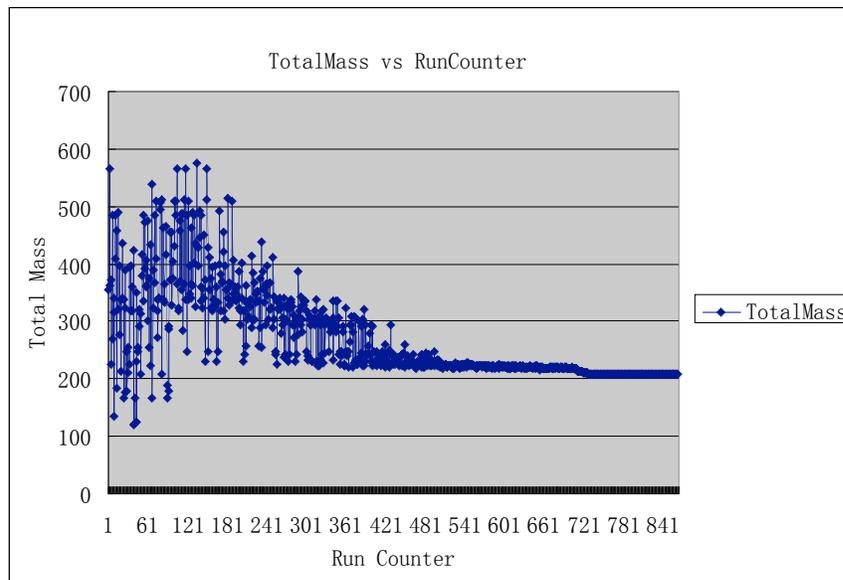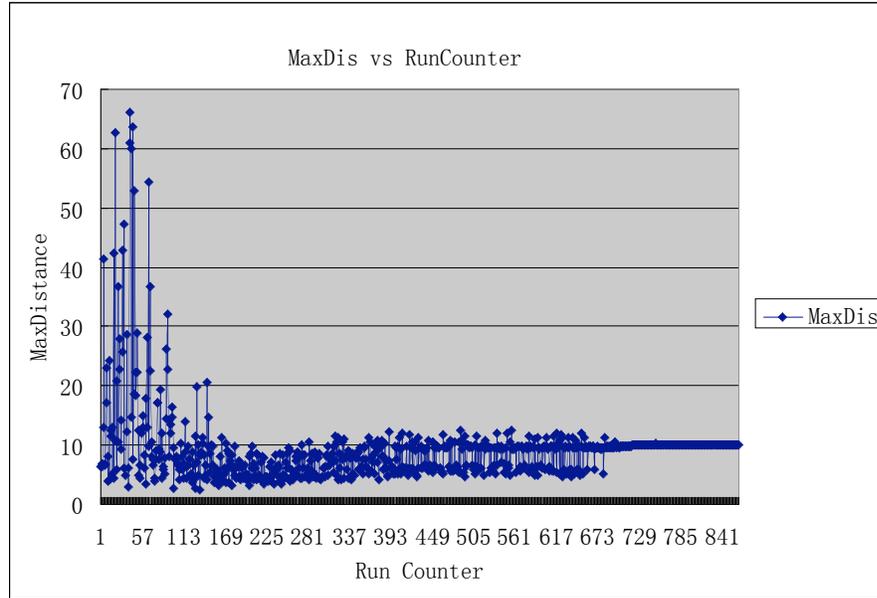

a. Convergence plot of optimization parameter Total Mass.

b. Convergence plot of optimization parameter c_r.

(Fig. 6) Contd…..

c. Convergence plot of optimization parameter d_{max}.

Fig. (6). Convergence plots of optimization parameters (Total Mass, c_r, d_{max}).

Table 2. Design Variables and System Performances

	Design vars. $X \begin{cases} x_1, x_2, x_3, x_4, x_5, \\ x_6, x_7, x_8, x_9 \end{cases}$	**Total Mass**	c_r	c_t	d_{max}	σ_1	τ_1	R_{max}
Init.	0.8,10,5,4,45, 0.15,0.8,5,5	355.243	140.5457	112.44	6.3302	0.0072	0.0041	-0.1036
GA	0.78,9.92,3,3,2.596, 0.01,0.95,0.101,0.1	208.979	143.0193	110.93	9.9922	0.0319	0.0184	-0.2892
GA+ SQP	0.64,10.59,3,3,45, 0.017,0.95,0.1,0.14	208.582	149.9999	95.858	9.9999	0.0225	0.013	-0.2404

Since both continuous and discrete design variables are involved in this optimization problem, GA is applied. Considering the slow convergence rate and stochastic properties of GA, SQP is used to conduct further optimization search to guarantee the true global optimal solution and improve the convergence rate. GA is first applied to obtain a sub-optimal design point, and then SQP is used to conduct the second round of optimization search with the sub-optimal design point from GA as the initial start point. During this second round, the discrete variables x_3 and x_4 are fixed at the values of the sub-optimal design point. In order to investigate the efficiency of our numerical simulation model, another method is carried out for a detailed comparison, in which GA is alone applied to obtain the optimal design point.

3.3. Optimization Results Analysis

In order to verify the effectiveness of our approach, the wing structure performances at the initial start point are also calculated for comparison. Both the initial design variables and optimal ones of these two methods are plugged input into the FEA model to estimate the structure performances. The convergence plots for optimization parameters (Total Mass, c_r, and d_{max}) are depicted in Fig. (**6**). The design variables and the system performances generated by our approach and those at the initial points are shown in Table **2**. To more clearly show the improvement of the optimal design solutions, the stress and displacement distribution at initial point (P0), the optimal point of GA (P1), and the final optimal point of GA+SQP (P2), are also illustrated in Figs. (**7**, **8** and **9**), respectively.

From Table **2** and Figs. (**7**, **8** and **9**) three noteworthy results are drawn below:

(1)   The mass of wing is greatly reduced at the optimal design. The Total Mass at the final optimal design point P2 is 208.582g, which is reduced by 41.3% compared to that at the initial design point P0 (355.243g).

(2)   The material can be fully utilized with optimal design. Although, the constraints at both the initial design point P0 and the final optimal design point P2

b. Stress tensor distribution at P1.

Fig. (8). Stress and displacement distribution at the GA optimal point (P1).

a. Displacement distribution at P2.

b. Stress tensor distribution at P2.

Fig. (9). Stress and displacement distribution at the GA+SQP optimal point (P2).

are satisfied, the latter show smaller gap to the constraints upper bound. Just take the maximum deformation as an example, the initial design and the optimal design respectively produce values of 6.3302mm and 9.9999mm (see in columns 6 in Table **2**). It is clear that the optimal design is much closer to the constraint upper bound (10mm), which indicates that the material utilization ratio is greatly increased through composites optimization design by our approach. The maximum deformations in Figs. (**7a**) and (**8a**) show the same trend.

(3)   The Total Mass at the final optimal design point P2 is 208.582g compared to that at the point P1(208.979g). The run time for the GA simulation method was around 12 CPU hours on a Pentium IV 3.0G machine as the data of the optimal point was achieved, and that for our two-step simulation method was only 2.5 CPU hours on the same machine. Moreover, take the length of root chord as an example, the values at P1 and the final optimal design point P2 are respectively 143.0193mm and 149.99mm (see in columns 4 in Table **2**). It is clear that the final optimal design is much closer to the constraint upper bound (150mm). The final optimal results are significantly improved compared to that of GA, which indicates the effect-iveness of our two-step optimization search.

4. CONCLUSIONS

The application of the advanced composites plays an important role in improving the aerocraft structure perfor-mances. In this work, the parametric finite element model is established to accomplish the stress and strain analysis for UAV composite wings. In the process of optimization, the combination of GA and SQP algorithms ensure that the global optimal solution can be obtained. The optimization results show that the mass of the wing is greatly reduced using our proposed approach, and the utilization rate of material is evidently increased compared to that of the initial design. Meanwhile, the optimization efficiency can be greatly improved with the two-step optimization search strategy.

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