Structural Modelling and Optimization of the Double-Ducted Fan UAV

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Abstract. This paper aims to model and optimize the structure of a double-ducted fan UAV (unmanned aerial vehicle). The structural model of the UAV is established based on main technical requirements. Aluminum alloy is selected in UAV structure. The static analysis of UAV is performed using finite element method. The section thicknesses of UAV are optimized by a feasible direction method. The optimized structure weight of the UAV is reduced by 18%. This paper provides some useful reference for the structural modelling and optimization of double-ducted fan UAV.

1. Introduction
The UAV plays an important role in military, police and civilian filed, and more and more applications are used due to its flexibility, endurance property, safety performance and low cost [1]. Zhang Weize proposed a new transition method of a ducted-fan unmanned aerial vehicle [2]. Zhang Qiao established an aerodynamic mathematical modelling of the ducted fan and wings [3]. Zhang Qi modelled and optimized a testing cabin of the thin-walled structure by FEM and SQP [4].

The overview of UAV is shown in Figure 1. The main technical parameters of double-ducted fan UAV are shown in Table 1.

![Figure 1. The overview of double-ducted fan UAV](image)

Table 1. Main Technical Parameters of Double-Ducted Fan UAV

| Parameter                        | Value              | Units |  |
|----------------------------------|--------------------|-------|---|
| Length × width × height          | 6300 × 2100 × 1500 | mm    |   |
| Maximum takeoff weight           | 600                | kg    |   |
| Single side lift                 | 300                | kg    |   |
2. Modelling and analysis

2.1. Structural model
Truss structures are selected to simulate the double-ducted fan UAV with large section size and a symmetrical shape. With large bending and torsional stiffness, truss structures have larger loading capacity [5].

Frames, longitudinal beams, transverse beams, columns and oblique beams are included in double-ducted fan UAV. Axial force caused by the bending moment of fuselage is mainly carried by transverse beams. Frames and columns are used to maintain the cross-sectional shape of fuselage. Lift load is mainly carried by oblique beams. Transverse beams, columns and oblique beams are supported by longitudinal beams.

The geometrical model of double-ducted fan UAV is shown in Figure 2.

| Length of lift arm | 1900 mm |
|-------------------|--------|
| Center of gravity (X-Y-Z) | 2380×0×340 mm |

Figure 2. The geometrical model of double-ducted fan UAV

2.2. Finite element model
In UAV finite element model, shell elements are selected to simulate thin-walled structures. Extracting mid-surfaces, meshing, and section properties assigning are performed in the Hypermesh pre-processing software. Grid size is 10mm approximately and 220,660 elements are included in this model. The finite element models of UAV structure are shown in figure 3, figure 4, figure 5, figure 6 and figure 7.

The aluminum alloy with low density, excellent corrosion resistance and low cost is selected to be used in the UAV structure. Mechanical properties of aluminum alloy are shown in Table 2 [6] [7].

Figure 3. Full grid model of UAV structure
Figure 4. Connections between bottom beams
Figure 5. Connections between longitudinal beams and columns

Figure 6. Connections between trusses and frames

Figure 7. Connections between oblique beams and fuselages

Table 2. Mechanical Properties of Aluminum Alloy

| Material          | Poisson's ratio | Density   | Yield strength | Elastic modulus |
|-------------------|-----------------|-----------|----------------|-----------------|
| Aluminum alloy    | 0.33            | 2.8g/cm³  | 270MPa         | 68GPa           |

Five integration points are used in shell elements, and shell element thicknesses of different parts are shown in table 3. Section properties of UAV structure are shown in figure 8.

Table 3. Section Property Settings

| Number | Component                  | Color | Thickness / mm |
|--------|-----------------------------|-------|-----------------|
| 1      | Oblique beams, longitudinal beams | Red   | 5               |
| 2      | Beams and columns           | Green | 3               |
| 3      | Other parts                 | Blue  | 1               |
2.3. Static analysis

Static analysis of double-ducted fan UAV is performed using ABAQUS software. A reference point is set at the central gravity position. The nodes on symmetrical plane are coupled to this reference point. The reference point is fixed with $U_1=U_2=U_3=U_{R_1}=U_{R_2}=U_{R_3}=0$.

The lift generated by propeller and duct applies on the outer end of the duct arm, which is symmetrical about middle plane. Lift force of each side is 300kg; gravitational acceleration is $9.8\text{m/s}^2$; overload factor is 1.25 and safety factor is 1.2, as a result, the lift load with value of 4410N is obtained by calculating.

The stress contour of UAV structure is shown in Figure 9. The maximum Von-Mises stress is 48.40 MPa, occurring at the connecting position of oblique beam and longitudinal beam, which is smaller than the yield stress of aluminum alloy.

The displacement contour of UAV structure is shown in Figure 10. The maximum displacement is $1.82\text{mm}$, which appears at the outer end of oblique beam.

3. Weight optimization

3.1. Optimization method

The optimization method contains numerical methods and global methods. Numerical methods are used to search for the maximum value fast and effectively. Global method is used to avoid the local optimal solution [8].

Feasible direction method is a direct numerical optimization method, which will search in nonlinear design space directly [9]. It can constantly find optimal solutions with a certain direction in search space. The mathematical equation can be described as follows:

$$\text{Design } i = \text{Design } i-1 + A \times \text{Search Direction } i$$

In the formula above, $i$ represents a loop variable, and $A$ represents a constant determined at the time of a certain space search.

3.2. Optimization of UAV structure

Feasible direction method is used to optimize UAV structure weight. Design variables consist of the thickness of section 1 and section 2. Oblique beams and longitudinal beams are included in section 1;
beams and columns are included in section 2. The range of design variables are shown in table 4. Stress constraint and displacement constraint are applied in the optimization process. The optimization objective is to get the smallest weight. Table 5 shows constraint and objective. After 52 iterations, optimal solutions are obtained, which are shown in Table 6.

| Table 4. Design Variable |
|--------------------------|
| Design Variable | Section | Minimum / mm | Initial Value / mm | Maximum / mm |
| 1 | 1 | 1 | 5 | 5 |
| 2 | 2 | 1 | 3 | 3 |

| Table 5. Constraint and Objective |
|-----------------------------------|
| Constraint | Value | Objective | Target |
| Maximum Von-Mises stress | ≤200Mpa | Total structure weight | Minimum |
| Maximum displacement | ≤3mm |

| Table 6. Optimization Result |
|------------------------------|
| Design variables | Calculated value / mm | Final value / mm | Objective | Total mass / kg | Reducing weight percent |
| 1 | 3.95279 | 4 | Initial value | 125.782 | 18% |
| 2 | 1.95279 | 2 | Final value | 103.492 |

3.3. Optimization results check
Optimization results are checked by substituting into original finite element model. As shown in table 7, it is verified that the maximum Von-Mises stress of UAV structure is 72.92 MPa and the maximum displacement is 2.84 mm. Both of stress and displacement are consistent with optimization results.

| Table 7. Optimization results check |
|-----------------------------------|
| Constraint | Optimization | Value |
| Maximum Von-Mises stress | 72.92Mpa | ≤200Mpa |
| Maximum displacement | 2.84mm | ≤3mm |

4. Conclusion
Truss structures are selected to establish the model of double-ducted fan UAV. Static analysis is performed using ABAQUS software. The displacement and stress of UAV structure in the flying condition are obtained. Feasible direction method is used to optimize UAV structure weight. After optimization, the UAV structure weight is reduced by 18 percent. The maximum Von-Mises stress is 72.92Mpa and maximum displacement is 2.84mm, which meet design requirements. This paper provides a powerful basis for the modelling and optimization of double-ducted fan UAV.

5. References
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