Lightweight design of aircraft truss based on topology and size optimization

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Abstract. Truss structure is widely used in aircraft design. In this paper, the lightweight design of a certain type of aircraft truss structure is carried out through topology analysis and size optimization to improve the performance of the aircraft. The original truss model is established based on ABAQUS, and its static strength is checked and analyzed. According to the design domain of the original model, a topology optimization method is used to obtain a new material distribution. Then the section size of each truss member is taken as the optimization variable, the maximum deformation of the structure is taken as the constraint, and the overall model volume is the minimum as the optimization goal, the genetic algorithm is used to obtain the new structure size. The results show that the truss members after the second optimization can meet the requirements of use and have a 75.15% reduction in mass compared to the original structure, which verifies that the method is feasible and provides a new idea for the lightweight design of truss structures.

1. Introduction
Truss structure is widely used in the structural composition of aircraft fuselage and wings. In recent years, the optimal design of aircraft structure is an important research and development field in the modern aviation industry. The so-called optimal design of the structure means that the weight of the designed structure is the lightest or the cost of the material is the lowest under the condition of satisfying a certain use performance. Traditional structural optimization algorithms often have certain limitations, such as the need for gradient information, convex programming, unimodal problems, etc [1]. The applicable engineering problems are relatively simple, and the results have poor convergence. With the development of aviation industry technology, engineering structural problems that need to be solved in actual structural applications also tend to be more complicated. Therefore, designing a new application optimization method on the basis of the existing structural optimization theory is of great significance for optimizing and reducing the structure of modern aircraft.

Topology optimization algorithm is a commonly used optimization algorithm for truss structures. It was first proposed by Dorn [2] in 1964 and applied to the field of structural optimization. After that, Achtziger and Bendsøe et al. [3-4] studied the topology optimization design of discrete structures. Regarding the topological optimization calculation method of the continuum, it was proposed by Bendsøe and Kikuchi [5] in 1988 using the homogenization method. Since then, topology optimization has been widely used in structural design. Mljenk [6] and Xie [7] proposed the relative density method and the progressive structure optimization method to expand the topological mechanism. Zhao, Z. et al. [8] established a tree-structured intelligent design algorithm system by integrating topology optimization with form-finding algorithm and component length. Topology optimization has also been widely used
in modern aircraft manufacturing. Xing, G. et al. [9] designed the external support structure of a certain type of aeroengine based on the topology optimization technology of the variable density method to make the engine structure more in line with actual work requirements. Wang, K. [10] et al. carried out the topology design of the anti-torsion arm structure of the landing gear of a certain type of aircraft, which effectively reduced the mass of the mechanism and significantly enhanced the strength performance. Zhou, C. et al. [11] optimized the topology and shape of the plane structure of a helicopter rotor blade to reduce the local stress concentration to find a reasonable layout position of the structural boundary nodes. It can be seen that most of the research at this stage is mainly aimed at the lightweight design of aircraft structures, and is mostly based on the parameter optimization of the topology optimization algorithm of the traditional variable density method. With the continuous development of intelligent algorithms, it is particularly important to further improve the optimization results by applying intelligent optimization algorithms to the optimization design of aircraft structure and size, and to improve the performance of the aircraft.

This paper takes the truss structure of a certain type of aircraft as the research object. Based on ABAQUS, the stress and strain analysis of the truss structure is carried out. The topology optimization method is used to obtain the optimal distribution of materials, and the new truss design structure is determined after changing the conditions and constraints. Then through the use of genetic algorithm, the optimized new structure is further optimized for the shape and size of the truss section. In this way, the optimal model of the truss under this working condition is found through topology optimization and size optimization based on genetic algorithm.

2. Optimization method and model establishment

2.1. Topology optimization method

Topology optimization is to continuously modify the material properties (element density and stiffness) of the elements in the specified optimization area under the premise of satisfying the optimization constraints (such as the minimum volume or maximum displacement) based on the initial model in the optimization iteration loop. Remove the element from the analysis model to obtain the optimal design [12]. In the process of optimizing the structure, the main consideration is the load condition of the structure, the node displacement constraint and the minimum construction size constraint, etc. Its mathematical model can be described as:

$$\text{Find: } X = [x_1, x_2, x_3, ..., x_n]^T$$

$$\min f(x) = f(x^*)$$

$$s.t. \begin{cases} f = \frac{v - v_1}{v_0} \leq f_{\text{max}} \\ 0 \leq x_{\text{min}} \leq x_i \leq x_{\text{max}} \end{cases}$$

In the formula, $X$ represents the structural topology optimization variable; $x_i$ represents the relative density of the $i$ unit; $f(x)$ is the objective function of structural optimization; $x^*$ is the optimal value of the optimization result; $v$ is the volume of the structure before optimization, $v_0$ is the volume of the structural design area; $v_1$ is the volume with density less than 1; $f_{\text{max}}$ is the volume constraint parameter. $x_{\text{min}}$ is the relative lower limit of cell density, $x_{\text{max}}$ is the relative upper limit of the cell density. Generally, in order to avoid the singularity of the stiffness matrix, $x_{\text{min}} = 0.001$.

2.2. Shape optimization algorithm based on genetic algorithm

Genetic algorithm is a brand-new random search and optimization algorithm that has developed rapidly in recent years. Its basic principles are Darwin's theory of evolution and Mendel's theory of genetics. It was first proposed by Holland et al. [13] in 1975. Currently, genetic algorithms have been successfully applied in industrial design and part shape structure optimization [14-15]. In the process of solving specific problems, it is mainly used by evaluating the adaptive function to perform iterative calculation
to find the optimal solution. In this paper, the truss structure is optimized by the genetic algorithm framework mainly based on the sko module provided by Python. Its mathematical model can be described as:

\[
\begin{align*}
\min f(x) &= \min (M) \\
\text{s.t.} & \begin{cases}
\sigma_{\max} \leq \sigma \\
U \leq U_{\max} \\
A = [A_1, A_2, \ldots, A_N]^T
\end{cases}
\end{align*}
\]

In the formula, (4) represents the optimized objective function, which requires a minimum optimized truss mass, (5) is a constraint, that is, the maximum equal effect force is the allowable stress of the material, and the maximum node displacement cannot exceed the set displacement. (6) represents the variables requiring optimization, the value corresponding to the section radius size of each truss.

3. Topology optimization of the model

3.1. Model building

The truss structure and shape size used in this article are shown in figure 1 below, and the nodes of the front and rear optimization displacement quantity requiring the comparison results are also indicated in the figure. The nodes 0 and 5 of the truss are hinge supports, and the other end node 11 can be moved in a horizontal direction.

![Figure 1. Original truss structure and dimensions.](image)

Topological optimization belongs to a hydrostatic analysis problem. In this model, material density is $7.85 \times 10^3 \text{kg/m}^3$, elastic modulus is 200 GPa, poisson ratio is 0.3, cross-sectional area is $200 \text{mm}^2$. At node 1, nodes 2 and 7, nodes 3 and 9, nodes 4 and 10 are applied with concentration forces of -500N, -425N, -375N, -200N, at nodes 4 and 5, and nodes 10 and 11, a concentration force of 300N and -300N in the horizontal direction is applied. The truss model established in ABAUQS and the model of the design domain are shown in figure 2 below.

![Figure 2. Optimization model establishment.](image)

Submit the job in ABAQUS, and the obtained stress cloud diagram and the stress cloud diagram in the Y direction are shown in figure 3 below:

![Figure 3. ABAQUS calculation results of the original truss.](image)
3.2. Topology optimization results of different volume fractions

According to the mathematical model description of the topology optimization method above, in ABAQUS, the element density of the design area is set as the optimization variable, the volume fraction response of the design model and the strain energy response, the volume constraints are defined, and the optimal strain energy is minimized as the goal function to optimize the design domain. In the model used in this paper, the constrained volume fraction of topology optimization is set to 0.2. The resulting topology optimization results under the constraint of the volume fraction and the truss structure established under the results are shown in figure 4 below.

![Topology optimization Results](image1)
(a) Topology optimization Results

![Optimized truss structure](image2)
(b) Optimized truss structure

Figure 4. Topology optimization calculation results and optimized truss structure.

The stress cloud diagram obtained by static analysis of the new truss structure under the original working conditions, and the displacement cloud diagram in the Y direction is shown in figure 5 below.

![Stress cloud diagram after topology optimization](image3)
(a) Stress cloud diagram after topology optimization

![Displacement cloud diagram of Y direction after topology optimization](image4)
(b) Displacement cloud diagram of Y direction after topology optimization

Figure 5. ABAQUS calculation results of truss after topology optimization.

Since the truss model after topology optimization only obtains a relatively irregular shape, it is difficult to guarantee the specific dimensions of each truss member. Therefore, this paper uses genetic algorithm to further optimize the section size of each truss member.

4. Dimension optimization of the aircraft truss

4.1. Construction of Finite-element Solving Function Based on Genetic Algorithm

In this paper, Feon, a third-party module of Python, is used to build a finite element solution framework. Feon is an open source and free finite element calculation framework based on Python developed by Pei, Y. et al. [16] of Hubei University of Technology in China. The working conditions of the truss model are established through this architecture, and a simplified model of the truss is obtained. The section radius of each member in the following figure 6 is used as the optimization parameter, and the structure is optimized with the genetic algorithm of the sko module in Python.

![Schematic diagram of truss label](image5)

Figure 6. Schematic diagram of truss label.
4.2. **Optimization results of genetic algorithm**

By limiting the radius of each truss to within $4mm - 10mm$ and the maximum displacement within $0.04mm$, the results obtained are 7 types of pipe fittings. The optimized radius is shown in table 1. Taking into account the requirements of actual processing, the radius is rounded and calculated the corresponding cross-sectional area of the truss. The iterative process of the genetic algorithm and the model diagram established on the basis of the optimized truss radius is shown in figure 7.

| Label | Optimization radius (mm) | Rounding radius (mm) | Cross-sectional area ($mm^2$) |
|-------|--------------------------|----------------------|-----------------------------|
| 1     | 7.42                     | 7                    | 153.86                      |
| 2     | 4.31                     | 4                    | 50.24                       |
| 3     | 6.04                     | 6                    | 113.04                      |
| 4     | 4.15                     | 4                    | 50.24                       |
| 5     | 8.97                     | 9                    | 254.34                      |
| 6     | 6.22                     | 6                    | 113.04                      |
| 7     | 4.25                     | 4                    | 50.24                       |

(a) Genetic algorithm iterative process  
(b) Dimension-optimized truss structure diagram

**Figure 7. ABAQUS calculation results of truss after topology optimization.**

The truss structure that has undergone topology optimization and genetic algorithm optimization is modeled in ABAQUS, and static analysis is performed to impose preset working conditions. The established model and the results of the analysis are shown in Figure 8 below.

(a) Stress cloud diagram after secondary optimization  
(b) Displacement cloud diagram of Y direction after secondary optimization

**Figure 8. ABAQUS calculation results of truss after secondary optimization.**

5. **Optimization result comparison**

The strength analysis results of the pre-truss model, the model after the topology optimization and the model after the secondary optimization are listed in table 2 below.
Table 2. Comparison of the results of the different optimization methods

| Variables                        | Original truss | Topology optimized truss | Secondary optimization truss |
|----------------------------------|----------------|--------------------------|-------------------------------|
| Maximum displacement (mm)        | 0.00966        | 0.01861                  | 0.03577                       |
| Displacement of node 1 (mm)      | 0.00501        | 0.00365                  | 0.00456                       |
| Displacement of node 2 (mm)      | 0.00854        | 0.00646                  | 0.02740                       |
| Displacement of node 3 (mm)      | 0.00851        | 0.01861                  | 0.03130                       |
| Displacement of node 4 (mm)      | 0.00490        | 0.00995                  | 0.02484                       |
| Truss mass (kg)                  | 16.74          | 9.04                     | 4.16                          |

It can be seen from Table 2 that the truss structure after the second optimization is compared with the original truss. Although the displacement of the node concerned has increased compared with the original truss, the displacement is still in an acceptable range, and the mass of the truss is reduced by 75.15% compared to the original truss rod. Therefore, although the optimization result sacrifices certain mechanical properties, it further reduces the self-weight of the structure.

6. Conclusion

This paper uses the truss structure of the truss structure of the plane and the new type of the plane truss. Then, the optimal size of the truss is obtained under the node displacement constraint, and finally the obtained structure is compared with the original structure. According to the comparison results, the support frame structure obtained by topology and size optimization has a lighter structural weight than the original structure. Therefore, it shows that the structural lightweight design method based on topology and size optimization is feasible, providing new ideas for aviation structure lightweight design, and providing theoretical basis and technical support for similar truss structure optimization.

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