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Application of Topology Optimization in the Design of Composite Fuselages of Civil Aircraft

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Abstract. Due to the many problems in the traditional design scheme of civil aircraft, such as low structural efficiency caused by traditional material distribution, contradiction between lightweight and airworthiness requirements, limitations of complex structure manufacturing process, and full life cycle cost control, this paper proposes to use topology optimization method to design lightweight composite fuselage structure, combine advanced manufacturing technology with structural optimization, and promote the engineering application of composite materials. In this paper, the method of literature analysis and review is mainly studied to study the topology optimization method of civil aircraft composite fuselage structure oriented to manufacturing constraints, and analyzes the synergistic optimization of ply parameters and topological configuration and the feasibility verification of its application to engineering. After analysis, this paper finds that the aircraft fuselage designed with this scheme takes into account both strength and fatigue resistance. Specifically, by collaboratively optimizing the material distribution and fiber laying direction, the weight of the fuselage structure can be reduced under the premise of meeting the core requirements such as strength, stiffness and fatigue performance, thereby reducing fuel consumption and carbon emissions.

Keywords: topology optimization, composites, civil aircraft, structural optimization

1. Introduction

In recent years, with the development of the aviation industry in the direction of lightweight and high-performance, the application of composite materials (such as carbon fiber reinforced polymers) in the fuselage structure of modern civil aircraft has increased year by year (such as Boeing 787 up to 50% and Airbus A350 up to 53%). However, the anisotropic properties of composites are inherently contradictory to traditional design methods (such as empirical analogy and parametric optimization), making it difficult to break through structural efficiency [1]. The topological design theories of traditional metal structures (such as homogenization method and variable density method) cannot be directly applied to the optimization of the playing direction and the control of mechanical behavior between layers of composite materials, which makes the composite body face bottlenecks in the manufacturing process (such as automatic wire laying path planning), structural performance (such as damage tolerance) and cost control (such as material utilization). In addition, airworthiness certification imposes strict requirements on the static strength (FAR 25.303), fatigue

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life (FAR 25.571), and fire resistance (FAR 25.853) of the airframe structure, further exacerbating design complexity. Previously, many people have conducted research on this phenomenon, designing electromagnetic shielding technology for composite structures and the technology for arranging the opening of the lower wall plate of composite wings of civil aircraft, while the application of topology optimization in civil aviation aircraft can be traced back to 2022 when Gu Xiaojun et al. combined it with additive technology [2]. It can be seen that topology optimization is becoming more and more important in the technological development of civil aviation aircraft.

The mechanical properties of composites are strongly dependent on the angle, thickness and sequence of the layers, and topological description methods considering anisotropy (such as tensor-based material interpolation models) need to be developed. The automatic laying (AFP) and automatic tape laying (ATL) processes require continuous curvature of the fiber path, and the traditional 0-1 topology needs to be converted into a manufacturable continuous fiber trajectory. This study aims to break through the limitations of traditional topology optimization theory in the field of composites and establish a multiphysics co-optimization framework for manufacturing constraints. It is hoped that a mathematical model for topological optimization of composite fuselage can be established to realize the synchronous optimization of the layering angle, thickness and topological configuration. At the same time, this study proposes a topology optimization solution strategy considering the constraints of the manufacturing process to ensure that the design scheme can be realized by the AFP/ATL process, and verify the structural performance of the optimization scheme under typical load conditions, and compare the weight reduction effect and cost-effectiveness of traditional design methods. For the aviation industry, the research in this paper can help design lighter, safer and lower manufacturing fuselages, which not only meet the development needs of green aviation, but also enhance the competitiveness of the industry. For subsequent researchers, the optimization framework and verification methods constructed by it can provide practical reference for design and research in related fields, reduce repeated exploration, and promote the further development of technology.

2. Theoretical basis of topology optimization of composite materials

2.1. Basic principles of topology optimization

Topology optimization is a mathematical method that optimizes the distribution of materials in a given area according to given requirements, and is a kind of structural optimization. The core is to find the optimal arrangement of materials through calculations, mathematical reasoning and other methods in a given space. It can be understood that in a given space, to find the most reasonable distribution of material structure, use topological optimization to analyze it. First, set the optimization goal, and at the same time add some additional conditions, and then optimize, through calculation, analyze each microelement in a given space, leave the key part of the force, remove the elements that have no impact on the overall performance, and make the structure more concise. After several iterations like this, there will be a huge change in the overall performance after removing these units, and at this time, the last unit needs to be "added back". At this point, the whole process of topology optimization is realized. At this time, the remaining area is the most critical and concentrated area. In terms of appearance, the structure is simple, and in terms of performance, it can meet all requirements.

In general, topology optimization does not rely on the designer's experience to preset the structural shape, but uses mathematical and mechanical logic to "filter" the optimal layout of materials from a wide space, so as to achieve a balance between performance and efficiency. This

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technology is widely used in the design of aviation and bridge components and thermal generators[3-5].

2.2. Mechanical properties of composites

Composite materials are materials obtained by combining different materials, and have some advantages in structure and function that a single material does not have, which is why they have more applications in industrial production.

Firstly, composite materials exhibit flexible properties in both strength and stiffness. For example, carbon fiber composites (CFRP), which are often used in aviation manufacturing, have a lower density than metal materials and can greatly reduce the weight of the structure. The specific strength and specific modulus are higher than those of traditional materials, so they have advantages in terms of bearing capacity and stiffness. It is suitable for the design and production of aerospace components [6]. Second, composites are anisotropic. Materials will have excellent mechanical properties in specific directions, so the material can meet specific mechanical requirements in different directions by adjusting the laying method of the structure [7]. In addition, composite materials have unique advantages in fatigue and damage resistance. The combined structure of fibers and substrates can disperse stresses, and when microcracks appear, fibers can organize the propagation of cracks and extend the life of the material [8]. At the same time, the damping characteristics are also particularly good, which can absorb vibration energy and help absorb shock.

3. Key technologies

3.1. Multivariate coupling optimization model

The multivariate coupling optimization model is the core framework of composite topology optimization, which "simulates" the interrelationship between several properties of composite materials using mathematical formulas, computer programs, and other methods, so as to achieve multi-objective collaborative optimization and make the material have better performance [9-10].

According to the structure type of composites, it is divided into two common models: first, the hierarchical coupling model, which is suitable for laminated composites, treats each layer as an independent design space, optimizes the topological variables and material attribute variables of each layer respectively, and then ensures the interlayer collaborative work through interlayer constraints; Then there is the continuous attribute model, which assumes that the material properties change continuously in the design space, describes the spatial distribution of the attribute variables through functions, and optimizes them synchronously with the topological variables, which is suitable for the overall molded composite structure. By establishing a mathematical correlation between each variable, the topology and material properties are adapted to each other.

3.2. Performance interpolation method for anisotropic materials

The core of the performance interpolation method for anisotropic materials in topology optimization is to correlate the topological variables with the anisotropic properties of the material through mathematical functions, while retaining the directivity characteristics of the material, and the common methods include the following categories: The extension method based on the solid isotropic material penalty model (SIMP) is the most commonly used, which decomposes the anisotropic stiffness matrix into the product of the reference stiffness and the density function on the basis of the density interpolation of traditional SIMP [11]. The other is the direction-dependent

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interpolation method, which directly incorporates the material directionality parameters into the interpolation function, which is suitable for scenarios where the fiber direction and topology need to be optimized simultaneously; In addition, there is also an interpolation method based on material property tensor, which ensures that the symmetry and physical meaning of the tensor remain unchanged during the interpolation process by interpolating the elastic tensor components of anisotropic materials, and avoids non-physical material properties caused by interpolation. For laminated composites, the hierarchical interpolation strategy is also adopted, that is, the anisotropic properties of each layer are individually interpolated, and then the overall performance is integrated through the lamination theory, and the coordination of interlayer properties is considered to meet the hierarchical design requirements of laminated structures. The common goal of these methods is to achieve a smooth correlation between material existence and anisotropic properties under the premise of ensuring numerical stability, and to provide a reasonable mathematical basis for the topological optimization of anisotropic materials.

4. Practical application of topology optimization in civil aircraft design

4.1. Optimization of the load-bearing structure of the fuselage

The challenge faced by civil aviation aircraft is how to reduce fuel consumption as much as possible while ensuring the safety of fuselage load-bearing performance (including cabin pressure, aerodynamic load and own weight). By using topology optimization technology, the key load-bearing parts of the fuselage (frame, bulkhead, etc.) can be analyzed, and the optimal distribution of materials and material structures can be found by combining the stress distribution of the aircraft at different stages of the entire flight process (takeoff, cruise, landing, etc.) [12].

Traditional designs have problems such as excess material, increased weight and fuel consumption. Topology optimization can retain sufficient materials and support structures in high-stress areas, while designing lightweight forms such as honeycomb hollows or mesh in low-stress areas. According to research, this design greatly reduces material consumption and fuel consumption while ensuring that strength and stiffness meet the requirements. At the same time, topology optimization can be combined with acoustic requirements to adjust the distribution of materials to achieve a noise reduction effect and complete functions. Therefore, topology optimization is widely used in the fuselage design of civil aviation aircraft, which can improve the economy and environmental protection of the aircraft, and improve the comfort of passengers while ensuring complete functions.

4.2. Engine nacelle and suspension structure design

The engine nacelle is the key component that wraps the engine, which not only has to withstand the huge thrust, vibration and aerodynamic resistance generated by the engine when the engine is running, but also provides space for engine maintenance, heat dissipation, etc., and the design space is very limited. The application of topology optimization in this field focuses on balancing spatial constraints with structural performance [13]. By establishing a three-dimensional design space model of the nacelle and inputting parameters such as engine weight, thrust, and vibration frequency, the algorithm can automatically optimize the shape of the support frame and connecting structure, so that the material can be distributed along the path of load transfer and avoid wasting material in the non-stressed area. Taking the engine suspension structure of the Boeing 787 as an example, the topology-optimized structure adopts a complex curved support beam, which not only

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avoids the installation space of engine pipelines and cables, but also evenly transmits the load of the engine to the wings, which reduces the weight of the structure by 15% compared with the traditional design, and reduces the vibration response by 20%, which greatly improves the stability and safety of the engine.

4.3. Optimization of landing gear and cabin structure

The landing gear is the core load-bearing component of the aircraft during taxiing, takeoff and landing on the ground, which needs to withstand the impact load brought by the full weight of the aircraft, and at the same time needs to be stored in the landing gear compartment during flight, which requires extremely high structural compactness. In the landing gear design, topology optimization can optimize the distribution of materials for key components such as struts and shock absorber connections under the premise of meeting strength and shock absorption performance. For example, in the design of landing gear struts, topology optimization increases the material thickness in stress-concentrated areas such as the roots of the struts according to the impact force distribution during landing, while designing hollow or grid-like structures in areas with less stress such as the middle, which not only reduces weight but also ensures rigidity [14]. In the design of the landing gear compartment door frame of the Airbus A320neo, the topology-optimized structure not only perfectly adapts to the storage space of the landing gear, but also reduces the weight of the door frame by 12%, and at the same time, by optimizing the stress transfer path, it avoids the problem of local cracking caused by the compact structure in the traditional design, and extends the service life of the components.

4.4. Lightweight interior components of the cabin

Although the seat frame, luggage rack, floor support and other components inside the cabin are not part of the core load-bearing structure of the aircraft, their total weight has a non-negligible impact on the fuel consumption of the aircraft. These components are designed with a focus on lightweight while meeting functional requirements and safety standards. Taking the seat frame as an example, the traditional metal seat frame is mostly a solid structure and weighs a lot, while the topology-optimized seat frame adopts a bionic structure similar to the human bone, retaining sufficient support materials in the main stressed parts such as the backrest and cushion, and designing hollow or thin-walled structures in other parts, which not only ensures the safety of passengers (such as the ability to withstand impact loads), but also significantly reduces the weight [15]. The seat frame of an airline's Boeing 737 passenger aircraft has been topology optimized, reducing the weight of each seat by about 1.5 kg, and the total weight of the entire aircraft is reduced by 270 kg based on 180 seats, saving hundreds of thousands of yuan in fuel costs per year, while also improving passenger comfort.

5. Conclusion

In summary, the application of topology optimization in the design of civil aircraft composite fuselages is of great value: by collaboratively optimizing the material distribution and fiber laying direction, the weight of the fuselage structure can be reduced under the premise of meeting the core requirements such as strength, stiffness and fatigue performance, thereby reducing fuel consumption and carbon emissions, and at the same time improving the comprehensive performance of the structure such as impact resistance and vibration resistance, which provides key technical support

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for the lightweight and economic performance of the new generation of civil aircraft. In the fuselage partition frame and stiffener design of Airbus A350, Boeing 787 and other models, this technology has proven its engineering feasibility and has become an important tool for innovative design of composite structures.

However, there are still obvious shortcomings and limitations in this article. This study only systematically discusses the feasibility of topology optimization in civil aircraft composite materials, and does not enter the laboratory for experimental verification, nor does it provide more detailed data and information. In future scientific research, experiments can be carried out and more applications can be explored, such as embedding composite layer angle limits, minimum wall thickness, molding process constraints, etc. into topology optimization algorithms to directly generate manufacturable optimization results and reduce the cost of later process adaptation. It is believed that more breakthroughs can be made in the future, and topology optimization will be more applied to the application of civil aircraft design.

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