Topology Optimization Design of Aero-Engine Auxiliary Bracket under Additive Manufacturing Constraints

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Abstract

Aiming to address the issues of redundancy and insufficient lightweight design in traditional engine auxiliary brackets, this study integrates the characteristics of additive manufacturing (AM) technology to conduct a lightweight design for engine auxiliary brackets under AM constraints. With the objective of maximizing bracket stiffness, material distribution optimization was performed on the initial bracket while comprehensively considering manufacturing constraints. Based on the topology optimization results, a novel AM-compliant engine auxiliary bracket structure was developed through geometric reconstruction and local feature reinforcement. Finite element analysis (FEA) was employed to compare the maximum displacement, stress distribution, and mass of the structure before and after optimization. The results demonstrate that the optimized bracket achieved a 25.68% ↓ reduction in mass, 68.53% ↓ decrease in maximum displacement, and 53.20% ↓ reduction in maximum stress. This research validates the effectiveness of the synergistic design combining topology optimization and additive manufacturing in lightweighting complex load-bearing components, providing theoretical foundations and engineering references for innovative designs of similar bracket structures.

Keywords

Bracket; Lightweight; Topology Optimization; Additive Manufacturing.

1. Introduction

With the rapid development of additive manufacturing (AM), its advantages in the design and manufacturing of complex structural components have become increasingly prominent [1-4]. Topology optimization, as a core methodology for achieving structural lightweighting, enables the creation of innovative configurations with superior performance through optimal material distribution. The additive manufacturing process effectively overcomes the limitations of traditional manufacturing techniques in fabricating topology-optimized structures. In the aerospace sector, engine auxiliary brackets, serving as critical load-bearing components, hold significant importance for enhancing aircraft performance and fuel efficiency through lightweight design. Xing Guangpeng et al. [5] conducted topology optimization-based structural design for an engine bracket with the objective of minimizing total compliance under multiple working conditions. The final model achieved a mass reduction to merely 7.3% of the initial design while satisfying strength, vibration, and contour requirements. Wang Yongheng et al. [6] designed a biomimetic bracket structure for aircraft based on structural bionics principles. Finite element analysis demonstrated a 7.35% reduction in mass for the biomimetic structure. Liu Lei et al. [7] performed shape and structural optimization on a diesel engine bracket, resulting in a 19% mass reduction while maintaining functional performance. Existing research predominantly focuses on structural optimization under traditional manufacturing processes, necessitating further exploration into topology optimization methodologies and engineering applications under additive manufacturing constraints.

This study addresses the lightweighting requirements of an engine auxiliary bracket by conducting topology optimization design tailored for additive manufacturing. A mathematical model for bracket topology optimization is established with stiffness maximization as the objective, incorporating volume constraints and manufacturing constraints. Material distribution is solved using the variable density method. The topology optimization results are analyzed and geometrically reconstructed to form a bracket structure compliant with additive manufacturing characteristics. Static finite element analysis is performed on both the original and optimized brackets to validate the effectiveness of the lightweight design.

2. Model and Methods

2.1 Mathematical Model for Topology Optimization

Topology optimization is now widely used in the lightweight design of aerospace structures, effectively seeking the load transmission paths and removing excess material. To achieve the lightweight design of the engine auxiliary bracket, this paper establishes a stiffness maximization objective function with volume constraints applied to the structural design domain. The optimization model is formulated as follows[8]:

$$\begin{cases} \min C(X) F^{T} * U(X) \\ \text{subject to} \begin{cases} V(X)/V_0 \le f \\ 0 \le X_i \le 1, i = 1, \cdots, N \end{cases} \end{cases} \tag{1}$$

where X is the vector of design variables (pseudo-density in this case), $C(X)$ represents the structural compliance, F denotes the nodal load vector, $U(X)$ is the nodal displacement vector, $V(X)$ signifies the effective volume of the optimized structure, V_0 is the original volume of the structure, f stands for the volume constraint percentage, and N is the number of design variables.

2.2 Optimization Design Process of Aero-Engine Auxiliary Bracket Structure

The topology optimization design process for an aero-engine auxiliary bracket structure primarily consists of five stages: pre-optimization structural static analysis under extreme operating conditions, initial optimization model construction of the bracket, computation of multiple topology optimization schemes, optimization result screening, model reconstruction, and validation analysis, as illustrated in Fig.1.

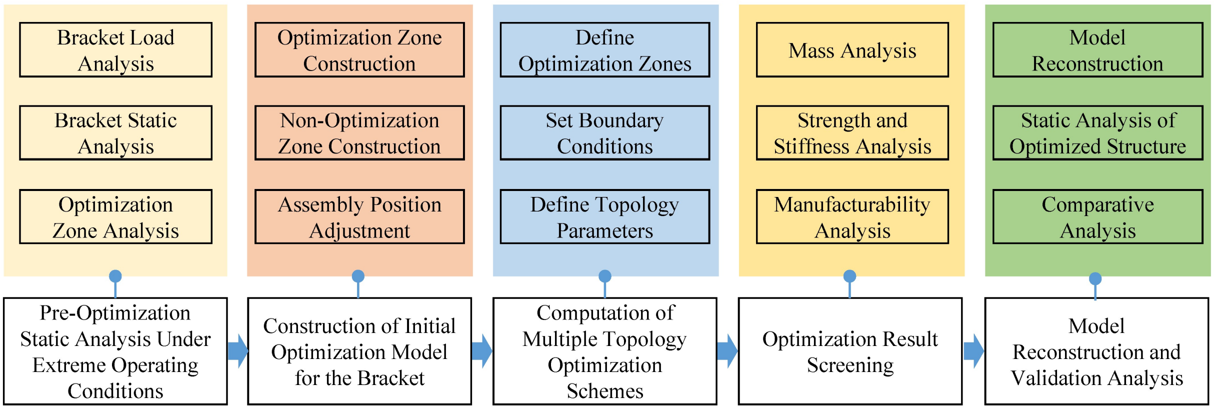

Fig. 1 Optimization Design Process of Aero-Engine Auxiliary Bracket Structure

2.2.1 Pre-Optimization Static Analysis under Extreme Operating Conditions

Analyze the load distribution of the bracket, select its most critical operating condition as boundary conditions for static analysis, and determine the maximum equivalent stress and displacement. Based on the component’s load distribution and applied boundary conditions, define topology optimization regions and non-optimizable regions.

2.2.2 Construction of Initial Optimization Model for the Bracket

By analyzing the static analysis results of the bracket, regions with lower stress are filled and designated as optimization zones. Concurrently, critical areas such as load-bearing contact surfaces and assembly interfaces are preserved and segmented as non-design domains for topology optimization. Additionally, the quantity and positions of mounting holes are adjusted based on the component’s load distribution to enhance load-bearing efficiency. Following these principles, the initial optimization model is created in CATIA and subsequently imported into the topology optimization module for preprocessing.

2.2.3 Computation of Multiple Topology Optimization Schemes

Configure the initial optimization model by assigning topology optimization zones and non-optimizable regions, defining material parameters, and applying extreme operating loads and constraints. Subsequently, establish topology optimization objectives and constraints. To achieve the optimal structural configuration, conduct independent topology optimization solutions with varying manufacturing constraints and parameters, generating multiple optimization results. These results are then screened to identify the most suitable candidate for model reconstruction. To ensure post-weight-reduction reliability meets design requirements, all optimization objectives prioritize stiffness maximization. Based on the bracket’s structural characteristics, four topology optimization schemes are defined:

30% volume fraction constraint with no manufacturing constraints;

20% volume fraction constraint with symmetry manufacturing constraints;

15% volume fraction constraint with symmetry manufacturing constraints;

20% volume fraction constraint with bidirectional draft angles and symmetry manufacturing constraints.

Topology optimization calculations are executed according to these schemes.

2.2.4 Optimization Result Screening

Through the computation of four topology optimization schemes, four bracket optimization results are obtained. To reduce time spent on structural validation, comparative analysis is directly performed on the optimization outcomes to identify the optimal solution. The evaluation criteria include:

a) Mass Analysis: The optimized structure’s mass must be reduced by ≤10% compared to the original design to achieve lightweight objectives in subsequent reconstruction.

b) Strength and Stiffness Analysis: Key performance metrics (e.g., stress, displacement) must improve relative to the pre-optimized structure to meet design requirements.

c) Manufacturability and Aesthetics:The geometry must be feasible for manufacturing processes (e.g., additive manufacturing).Minimize overhangs to reduce support structures, lowering production time and costs.Ensure aesthetic coherence in final design.

Based on these criteria, the optimal topology optimization result is selected for model reconstruction.

2.2.5 Model Reconstruction and Validation Analysis

Based on the optimal topology optimization result, the model is reconstructed by retaining non-optimized regions, ensuring smooth transitions between optimized and non-optimized zones. The load transfer paths in optimized areas are refined through geometric smoothing to minimize unnecessary overhangs, while appropriately thickening overly thin material paths to ensure structural integrity. Post-reconstruction, static analysis is performed on the optimized structure using identical boundary conditions and mesh settings as the original model. The results are then validated against the original design by comparing key parameters: mass, maximum equivalent stress, and maximum displacement.

2.3 Static Analysis of Original Bracket Structure

The engine auxiliary bracket originally features a typical machined frame-and-beam configuration, consisting of webs and flanges on the webs. The structural dimensions are approximately 200×100×30 mm, and the material is 7050 aluminum alloy (material parameters listed in Table 1). Under extreme loading conditions, the center of the upper-left end joint on the bracket must withstand a vertically downward force of 3200 N. After processing minor features such as rounded corners, the bracket was meshed using tetrahedral elements with a defined element size of 3 mm. The resulting mesh contains 23,886 elements and 46,283 nodes.A static analysis was performed by applying loads to the bracket and constraining its assembly connection locations. The finite element model and boundary conditions are illustrated in Fig. 2a, while the maximum equivalent stress and maximum displacement of the bracket are shown in Fig.2b.

Table 1. Material parameters of 7050 alloy

Mechanical properties	Assigned value
Elastic Modulus (GPa)	71
Poisson’s Ratio	0.33
Density (g/cm^3)	2.74
Yield Strength (MPa)	455

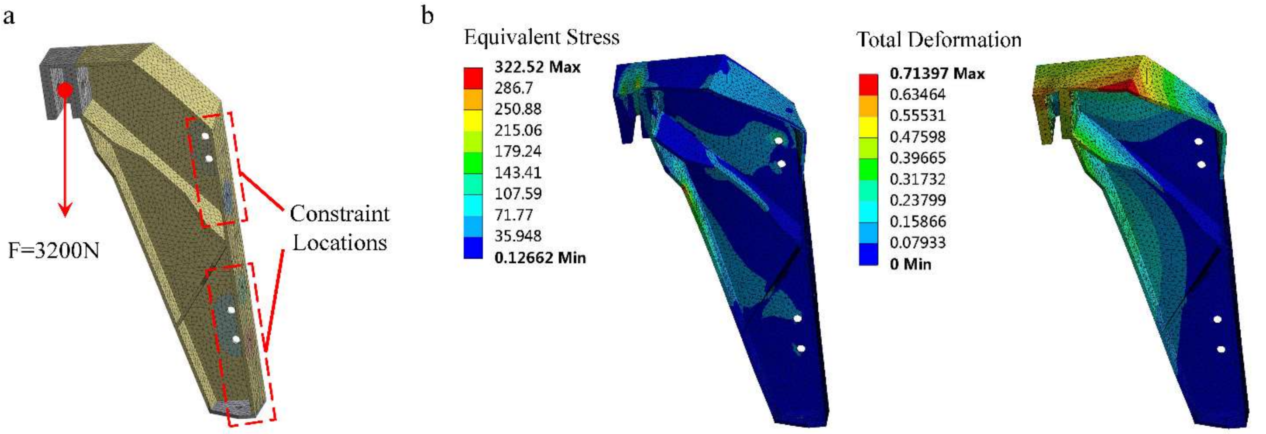

Fig. 2 (a) Finite Element Model and Boundary Conditions of the Original Bracket Structure;(b) Maximum Equivalent stress and Deformation of the Original Bracket Structure.

The analysis results indicate that under extreme operating conditions, the auxiliary bracket exhibits a maximum equivalent stress of 322.52 MPa and a maximum displacement of 0.71397 mm. The primary load-bearing area is concentrated around the upper-left end joint of the bracket, while the stress in the web stiffener region of the component is significantly lower. Consequently, the web region is designated as the design area for optimization, whereas the upper-left end joint zone and the assembly connection regions of the bracket are defined as non-design areas.

2.4 Topology Optimization Analysis of the Bracket

Following the aforementioned approach, the initial optimization model was established in CATIA. The web region of the bracket was filled as the design area. To distribute the load from assembly holes, additional symmetrical assembly holes were incorporated into the filled region to ensure balanced force distribution. The assembly holes were then separated from the load-bearing hole positions at the top, defining them as non-design areas, as illustrated in Fig.3.

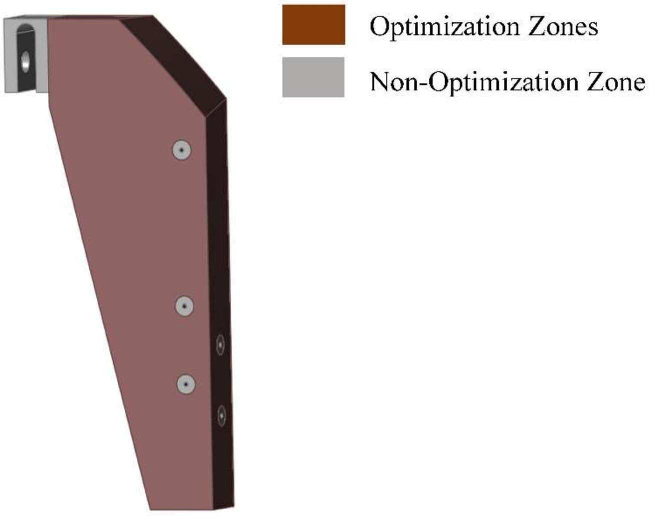

Fig. 3 Topology Optimization Regions and Non-Design Regions of the Bracket.

After defining the design area, the material was specified as AlSi10Mg for additive manufacturing. The model was meshed using tetrahedral elements with a size of 3 mm. Following meshing, the extreme load conditions were applied to the bracket, and constraints were imposed on its connection regions to complete the static analysis. Topology optimization parameters were then configured, with the objective set to maximize stiffness. Calculations were performed according to the four topology optimization schemes outlined in Section 2.2.3. Upon completing these optimizations, the resulting material distribution patterns for the four bracket designs are illustrated in Fig.4.

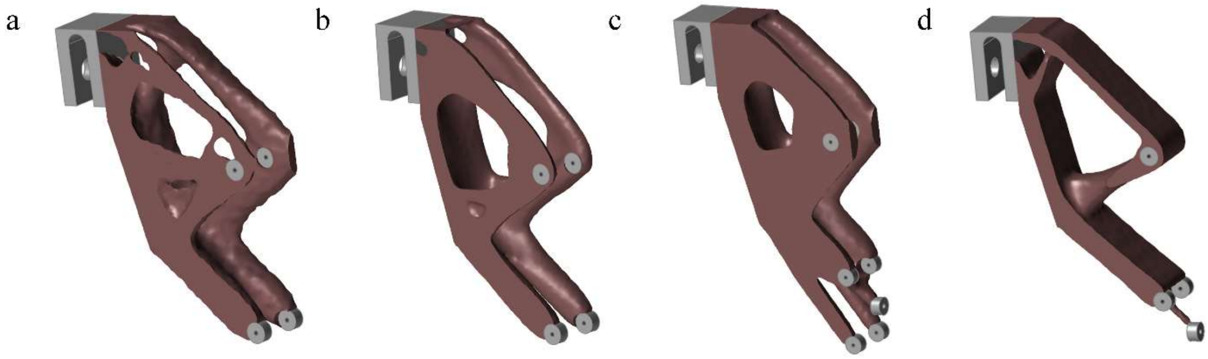

Fig. 4 Topology Optimization Results Under Different Manufacturing Constraints: (a) No manufacturing constraints, volume fraction constraint: 30%; (b) Symmetry constraint, volume fraction constraint: 15%; (c) Symmetry constraint, volume fraction constraint: 20%; (d) Bidirectional draft and symmetry constraint, volume fraction constraint: 20%.

Based on the evaluation criteria outlined in Section 2.2.4, the four optimization results were analyzed as follows:

(1) Mass Analysis: Designs b and d exhibit comparable mass values, both achieving a weight reduction exceeding 10% while maintaining the lightest overall mass.

(2) Strength and Stiffness Analysis: Design b demonstrates the most significant reductions in stress and displacement among the four configurations, fully meeting the design requirements.

(3) Geometric Feasibility: Designs a and b feature fewer overhanging surfaces, reducing the need for support structures during manufacturing. However, design b adopts a symmetrical configuration, offering enhanced aesthetic appeal and even fewer overhanging surfaces compared to a.

Through comprehensive analysis, design b was selected for geometric model reconstruction.

2.5 Geometric Reconstruction and Validation

Building upon the topology-optimized Structure b, a smoothing processing of the optimization result was conducted in accordance with the model reconstruction principles outlined in Section 2.2.5. The reconstructed new bracket configuration is illustrated in Fig.5a. The redesigned configuration removes redundant material under non-load-bearing conditions while preserving critical load-bearing paths. Additionally, superfluous mounting points are eliminated, resulting in a clear force transmission layout. The smoothed surfaces further enhance suitability for additive manufacturing, ensuring both structural efficiency and manufacturability.

A static analysis was performed on the new bracket configuration, with the material defined as AlSi10Mg. The meshing strategy and boundary conditions were kept consistent with those applied to the original bracket structure in Section 2.3. The finite element model of the new configuration, shown in Fig.5b, consists of 63,421 elements and 108,695 nodes.The analysis results, presented in Fig.5c and Fig.5d, reveal the following:

Maximum equivalent stress: 151.2 MPa, which is below the material’s yield strength.

Maximum displacement: 0.22466 mm, representing a reduction of 68.96% compared to the pre-optimized design.

Mass: 136 g, achieving a 25.68% weight reduction relative to the original structure.

A comparative summary of the performance metrics between the original and optimized brackets is provided in Table 2.

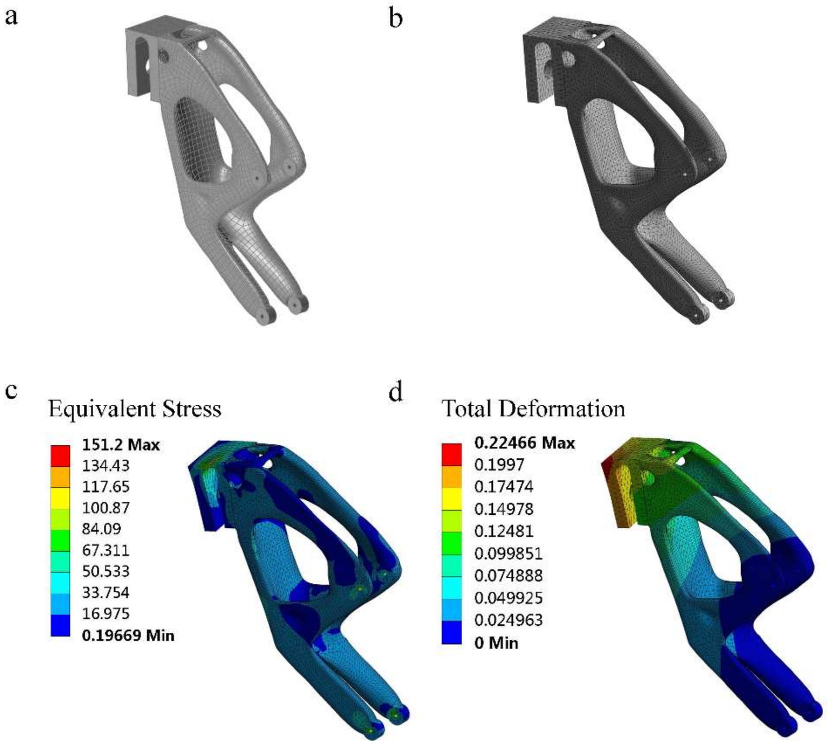

Fig. 5 (a) Topology-Optimized Structure of Engine Auxiliary Bracket; (b) Finite Element Model of the New Bracket Configuration; (c) Maximum Equivalent Stress of the New Bracket Configuration; (d) Maximum Displacement of the New Bracket Configuration.

Table 2. Performance Comparison Between Pre- and Post-Optimization

	Mass	Maximum equivalent stress	Maximum displacement
Pre-optimization	183	322.52	0.71397
Post-optimization	136	151.2	0.22466
	25.68%↓	53.20%↓	68.53%↓

3. Conclusion

Based on the research on topology optimization design of engine auxiliary brackets under additive manufacturing constraints, this study addresses the limitations of traditional brackets in terms of insufficient lightweight performance and redundant load-bearing paths. By integrating topology optimization algorithms with additive manufacturing process constraints, a novel structural design methodology tailored for additive manufacturing is proposed. The following conclusions are drawn:

(1) Synergy Between Topology Optimization and Additive Manufacturing. By combining topology optimization with additive manufacturing constraints, this study effectively resolves the issues of structural redundancy and inadequate lightweight characteristics in traditional brackets. The proposed method achieves a 25.68% reduction in mass while preserving structural integrity, demonstrating the potential of synergistic integration between computational optimization and advanced manufacturing technologies.

(2) Significant Performance Enhancements. Finite element analysis reveals substantial improvements in mechanical performance:

Maximum displacement decreased by 68.53%, indicating a notable enhancement in stiffness.

Maximum stress reduced by 53.20%, ensuring safety margins remain within the material’s yield strength limits.

These results validate the effectiveness of the optimized design in balancing lightweight objectives with load-bearing requirements.

(3) Methodological and Engineering Contributions. This study establishes a systematic framework for additive manufacturing-oriented structural design, encompassing topology optimization, geometric reconstruction, and localized feature reinforcement. The methodology not only provides theoretical guidance for lightweight design of complex load-bearing components but also offers practical engineering references for innovative designs in aerospace, automotive, and related fields, advancing the industrial application of high-performance lightweight technologies.

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