

Study on Lightweight Design Strategies and Advanced Manufacturing Technologies for Aero-Engines

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Abstract. Facing stringent global carbon neutrality targets, the aviation industry urgently requires technological advancements, and consequently, lightweight design has become a key strategy for improving aero-engine fuel efficiency and reducing emissions. This paper examines the application of lightweight, high-strength structures in aero-engines, addressing the extreme operational environments and multifaceted design constraints. It focuses on achieving mass reduction while preserving structural integrity and lifespan, highlighting the important contributions of advanced approaches such as topology optimization and damage-tolerant design. Moreover, the paper examines the enabling role of advanced manufacturing technologies, especially additive manufacturing (AM), in realizing these designs. Emerging trends, including intelligent materials and AI-assisted design, are also discussed, offering insights into the future of sustainable aviation propulsion. The study finds that lightweight design can not only effectively reduce the structural mass of aero-engines but also enhance fuel efficiency and lower emissions without compromising performance, underscoring the significance of integrating new materials, precise design, and innovative manufacturing technologies for next-generation aero-engines.

Keywords: Aero-engine, Lightweight Design, Additive Manufacturing, Structural Integrity

1. Introduction

The performance of aero-engines, which are central to modern aircraft, directly determines overall efficiency and safety. Driven by increasing global pressure for energy conservation and emission reduction, as well as the demand for higher flight efficiency, lightweight engine design has become a key development direction. It is estimated that reducing structural weight by 1 kg can save about 0.1 ton of fuel over the engine lifecycle, and support the International Air Transport Association (IATA) 2050 net-zero carbon emissions goal [1]. At present, significant progress has been made in aero-engine lightweight design. For instance, ceramic matrix composites (CMCs) cut structural weight while enhancing high-temperature load capacity, topology optimization achieves 25-35% weight reduction in critical load-bearing structures, and additive manufacturing (AM) increases design freedom and structural performance by enabling part integration and complex geometries [2-4]. However, current research is limited by unclear long-term reliability of new materials under thermo-mechanical fatigue, challenges in controlling microstructure during AM, and the absence of integration between lightweight design, lifespan, and manufacturing constraints. This study aims to

investigate design constraints, materials, structural optimization, and AM technologies to identify methods for lightweight design that maintain performance and lifespan. Particular attention is given to optimizing materials and structures under multi-physics coupling, improving reliability through manufacturing and quality control, and advancing lightweight design via smart materials and digital tools. As such, through literature review and case analysis, design strategies, materials, structural optimization methods, and manufacturing processes are evaluated for performance and feasibility. In addition, the opportunities and limitations of smart materials and digital design are analyzed for future applications, informing lightweight aero-engine design and supporting improved efficiency and component performance.

2. The design requirements and constraints for lightweight structures

2.1. Multi-field coupling in complex environments

There are highly complex conditions, governed by coupled multiphysical interactions, under which aircraft engine components must operate [5]. Among these, thermal loads are the primary challenge. The turbine inlet can reach temperatures above 1700 °C, far exceeding the melting point of nickel-based superalloys, which requires advanced cooling strategies to keep the blade surfaces within safe limits [6]. Besides, high-pressure turbine blades experience temperature gradients as steep as 300 °C per centimeter during startup, which causes significant thermomechanical fatigue (TMF). Moreover, there are frequent thermal shocks that combustion chamber liners must withstand while operating at temperatures ranging from 800 to 1100 °C [7].

Mechanical loads are equally demanding. The high-speed rotors, with rotational speeds greater than 10,000 rpm, induce substantial centrifugal forces, which lead to stresses near 800 MPa at the root of an individual 200 g turbine blade. And unsteady aerodynamic loads produce high-frequency vibrations between 50 and 3000 Hz, which are the main cause of high-cycle fatigue (HCF). Fan and compressor blades can also be damaged by foreign objects (FOD) [8-10].

In service, materials are subjected to high-temperature oxidation, hot corrosion, stress corrosion cracking, and microstructural evolution, including γ' coarsening [11]. Each flight cycle imposes low-cycle fatigue on critical components like disks, which ultimately determines their service life. Engine designs must also ensure that catastrophic failures are prevented under extreme events, such as fan blade loss. Thus, thermal, mechanical, and environmental factors are closely interconnected, including thermomechanical and fluid-structure interactions, which place strict demands on lightweight structural design. Consequently, designs must optimize structural mass while ensuring safety and durability, providing necessary constraints for subsequent lightweighting strategies [12].

2.2. Manufacturing constraints of performance materials

Lightweight design must be carried out within the limits of material manufacturing capabilities while also ensuring structural performance and reliability. The main manufacturing constraints of materials relate to physical machinability, production processes, and cost pressures. Additive manufacturing (AM) has become a key method for achieving lightweight structures in modern aircraft engines, but its minimum feature size is around 0.1 mm, imposing strict requirements on complex structural designs [13]. In addition, limitations on part dimensions, hole sizes, and wall thicknesses during manufacturing can affect the feasibility of the final structure.

The inherent properties of materials also influence manufacturing feasibility. Requirements for high specific strength, high-temperature strength, and creep resistance restrict the range of suitable

materials. For instance, Ti-6Al-4V and certain nickel-based superalloys are suitable for low- and intermediate-temperature structures, while high-temperature turbine blades or load-bearing critical components may still require composites or specialized manufacturing processes [14]. Meanwhile, materials with high damage tolerance can be more difficult to shape or may incur higher processing costs.

Physical space and design constraints further complicate manufacturing. Radial space in turbine disks is limited (with aspect ratios typically below 0.15), vibration clearance must exceed 15%, and cooling flow restrictions affect blade geometry and structural layout [13]. These factors partially constrain both material selection and the achievable level of lightweighting. In practical design, the use of MDO methods enables the resolution of competing manufacturing and material constraints, achieving a balance between manufacturability, lightweighting, and performance requirements.

3. Lightweight design strategies and technological implementation

3.1. Design strategies and service life balancing

In order to boost overall efficiency, lightweight design targets a reduction in structural mass while safeguarding component lifespan. Traditional methods of thinning structures can reduce weight, but they often lead to increased local stresses, significantly lowering fatigue life. For example, a 20% increase in stress may result in a reduction of life by more than 50% [15]. To address this challenge, topology optimization is a common strategy used to achieve an optimal balance between structural stiffness and weight by rationally distributing material. In regions where local stress concentrations may occur, surface enhancement techniques, such as laser shock peening (LSP), can be applied to introduce deep residual compressive stresses, thereby improving fatigue performance and damage tolerance. This approach allows components to withstand higher local stresses under limited weight conditions while extending service life. Equally important, the concept of damage tolerance plays a critical role during the design process. Designs may allow for certain initial defects, but through monitoring and control, these defects are ensured not to grow to critical sizes during service. By integrating structural health monitoring (SHM) and digital twin technologies, the structural state can be evaluated in real time, hence providing a scientific basis for life prediction and condition-based maintenance. Furthermore, MDO offers systematic support for balancing lightweight and lifespan objectives. Through the integration of mechanics, materials, and design constraints, MDO enables designers to examine the influence of different design options on weight and lifespan at preliminary stages, realizing optimal lightweight design while adhering to safety and performance criteria [16].

3.2. Material selection and performance improvement

Lightweight aero-engine design depends on selecting materials with appropriate high-performance properties. Accordingly, the working conditions and functions of each component set the material selection criteria [14]. High-pressure turbine blades employ third-generation nickel-based single-crystal superalloys (e.g., CMSX-10) to ensure creep strength and long-term load-bearing capability at high temperatures. Combustion chambers typically use solid-solution strengthened alloys (e.g., Haynes 230) to resist high-temperature oxidation and corrosion. Compressor components utilize Ti-6Al-4V, offering both high specific strength and superior high-cycle fatigue performance. Low-pressure turbines are gradually incorporating TiAl intermetallics, which have roughly half the density of nickel-based alloys while providing higher high-temperature load capacity. Besides, polymer matrix composites (PMCs) and ceramic matrix composites (CMCs) require strict control of

environmental conditions like humidity and temperature, to ensure long-term service performance. Beyond material selection, performance enhancement methods can further improve structural durability and reliability. Environmental barrier coatings (EBCs) not only mitigate high-temperature oxidation and thermal corrosion but also form a stable protective layer on CMC surfaces, reducing thermal stress concentrations. Microstructural control techniques, including phase composition optimization, grain refinement, and precipitation strengthening, can greatly boost creep strength and high-temperature fatigue performance. By creating deep compressive stresses, LSP and mechanical rolling slow crack growth and enhance fatigue life under low- and high-cycle loads. To perform optimally, coatings and microstructure control should integrate with design, cooling channels, and manufacturing [7,12].

3.3. Structural optimization and weight reduction

In order to achieve lightweight design in aero-engines, structural optimization techniques are widely employed. Through topology optimization, biomimetic design, and integrated design, weight can be minimized while maintaining stiffness and integrity [3,4]. In particular, topology optimization is one of the fundamental methods for lightweight design. This approach achieves an optimal balance between weight and stiffness by rationally distributing material within a predefined design space. Prior studies have indicated that topology optimization can reduce weight by approximately 30% to 40% while maintaining or improving overall stiffness and vibration characteristics. This method is applicable to turbine blades, casings, and other critical components, thus providing a foundation for efficient lightweight design. Moreover, biomimetic design enhances material efficiency by drawing inspiration from natural structures. For example, hollow fan blades use truss structures modeled on bird bones, hence reducing weight by approximately 20% while preserving buckling resistance. This design approach not only optimizes mechanical performance but also offers innovative ideas for complex lightweight components. Integrated design reduces weight and assembly complexity by decreasing the number of parts. For instance, Blisk (blade-integrated disk) technology combines blades and the disk into a single component, thereby removing traditional blade root connections. This integration can reduce rotor weight by about 30% while eliminating stress concentrations and potential fatigue crack sites. In addition, integrated design simplifies component manufacturing and maintenance processes, providing systematic support for overall lightweight design [2,3].

3.4. Manufacturing processes and quality control

The complexity, weight, and performance of aero-engine components are directly determined by their manufacturing processes [17]. In particular, AM has emerged as a key technique for producing intricate lightweight components. Laser Powder Bed Fusion (L-PBF) can fabricate intricate internal cooling channels that are unattainable by traditional methods, improving cooling efficiency by about 40% while reducing component weight by about 25%. Electron Beam Melting (EBM) is well suited for high-melting-point alloys such as TiAl. Despite its unprecedented design freedom, AM requires strict quality control measures, such as in-situ monitoring and Hot Isostatic Pressing (HIP) post-processing, to ensure component consistency and integrity. For large and complex structures, conventional manufacturing remains essential. Superplastic Forming/Diffusion Bonding (SPF/DB) produces hollow titanium alloy fan blades, while Automated Fiber Placement (AFP) optimizes fiber paths in composite fan casings to control stiffness and protect blades.

Quality control and performance assurance are critical to meeting design objectives. Specifically, secondary processes like LSP induce residual compressive stresses to improve fatigue life, while

microstructural control approaches, including directional solidification and single-crystal growth, enhance blade creep performance [18]. Through real-time monitoring and process optimization, digital manufacturing systems uphold process stability and repeatability, significantly reducing performance variability. As such, component manufacturability, performance, and service life in lightweight structures are governed by manufacturing processes and quality control. The selection of suitable processes and the implementation of effective monitoring and optimization are essential for achieving high-performance lightweight aero-engine designs.

4. Future trends in lightweight engine design and technologies

The adoption of smart materials offers new possibilities for future lightweight design. In particular, through reconfigurable geometries, shape memory alloys facilitate adaptive vibration control, which strengthens component stability under demanding conditions. By repairing micro-cracks during service, self-healing materials exhibit exceptional performance in composites, and helps extend the lifespan of critical components and reduce maintenance demands. These materials not only reduce structural weight but also demonstrate unique advantages in terms of reliability [14].

Meanwhile, digitalization and artificial intelligence are transforming the evolution of lightweight design methodologies. For example, generative design leverages algorithms to explore vast design spaces and discover optimal solutions, thus enabling highly efficient geometries that are difficult to achieve through traditional design approaches. By integrating high-fidelity physical models with machine learning, intelligent digital twins provide dynamic prediction of structural performance and lifespan and allow real-time adjustments during operation. In addition, the application of real-time optimization technologies in manufacturing can improve dimensional accuracy and consistency of complex components, enhancing the manufacturability of advanced designs.

Therefore, smart materials and AI-driven digital tools will become key directions in advancing lightweight design. The former expand the application boundaries of material systems via improved structural functionality and damage tolerance. The latter provide quantitative support across the full lifecycle of design, manufacturing, and service management. Future research should address the stability of smart materials under extreme environments, as well as improve the verifiability and interpretability of digital twin and AI methods, to secure their practical application in aero-engines.

5. Conclusion

This paper analyzes the constraints, material selection strategies, structural optimization methods, and advanced manufacturing technologies for lightweight aero-engine design. The results show that topology optimization, surface enhancement, and damage-tolerant design not only reduce structural weight but also ensure service life, while high-temperature alloys, composites, and coatings with controllable microstructures provide material reliability, and biomimetic design, integrated design, AM, and precision composite processes further reduce weight without compromising performance. In addition, smart materials and AI-driven digital tools offer new potential for lightweight design. However, this study lacks systematic experiments and service data, and the long-term reliability of new materials under extreme conditions, the fatigue performance of AM components, and the practicality of digital twin methods remain poorly quantified. Future research should focus on experimental assessment of long-term material behavior, refinement of lifespan prediction models for lightweight structures, improving the verifiability and interpretability of AI and digital twin tools in design and manufacturing, and exploring the application potential of smart materials under

extreme conditions, to further advance the scientific and reliable development of lightweight aero-engine design.

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