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# Multidisciplinary Review on FEA, Topology Optimization and AI-Based Analysis of Aero-Engine Turbine Blades

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**Abstract**: The design and analysis of turbine blades for aero-engines, especially those in the high-pressure turbine stage of turbofan engines, represent some of the most intricate challenges in aerospace engineering due to the intense thermal, aerodynamic, and mechanical stresses they face. Recent developments in computational methods, additive manufacturing, topology optimization, and artificial intelligence have significantly propelled research in turbine blades forward. This review paper delves into notable advancements in areas such as turbine blade modeling, computational fluid dynamics (CFD), finite element analysis (FEA), fatigue analysis, material optimization, lattice structures [2], [3], [4], fluid-structure interaction [13], and AI-driven defect detection [1]. The review is based on an analysis of twenty-three research papers from journals, conferences, and reports that concentrate on gas turbine blade performance design and CAE (Computer Aided Engineering) applications. The gathered studies were organized according to aerodynamic analysis [5], [6], [7], [8], thermal analysis, structural analysis, topology optimization, vibration behavior, and material selection. The literature review reveals that CFD and FEA continue to be the predominant tools for forecasting stress, deformation, heat transfer, and aerodynamic performance in turbine blades. Recent research has highlighted that topology optimization [1], [9] and lattice-based internal structures can significantly decrease blade weight while enhancing structural integrity and vibration resistance. Moreover, deep learning techniques [1], [10] have shown great promise for the automated detection of defects and predictive maintenance of aero-engine blades. The review's findings indicate that future turbine blade systems are likely to incorporate lightweight structures, additive manufacturing, advanced cooling techniques, and AI-assisted monitoring systems. This paper offers a comprehensive understanding of current research trends and pinpoints future opportunities for interdisciplinary research on turbine blades.

**Keywords:** Gas Turbine Blades, Finite Element Analysis, Topology Optimisation, Fluid Structure Interaction.

## I. INTRODUCTION

In the aerospace sector, especially in aviation, gas turbine blades or aero-engine turbine blades of a turbofan engine are among the most crucial elements. These blades endure continuous high pressure, significant temperature fluctuations, centrifugal forces, and aerodynamic stresses. The efficiency and lifespan of the turbine largely depend on the performance of these blades. As a result, researchers have concentrated on improving the materials used for blades, their structural integrity, aerodynamic efficiency, and thermal resistance. Traditionally, the creation of turbine blades relied heavily on experimental testing and iterative manufacturing processes. However, modern engineering practices are increasingly adopting computational modeling techniques such as CFD and finite element analysis. These approaches not only reduce development time but also improve accuracy and help engineers optimize blade geometry under realistic operating conditions. The reviewed literature indicates a strong trend toward multidisciplinary optimization. Studies involving topology optimization, additive manufacturing, lattice structures, and AI-based defect detection are gaining momentum.

## II. LITERATURE REVIEW

The literature review on aero-engine turbine blades underscores the increasing adoption of multidisciplinary methods, including Finite Element Analysis, Topology Optimization, Computational Fluid Dynamics, and Artificial Intelligence, to enhance blade performance, longevity, and efficiency. Numerous studies have concentrated on Finite Element Analysis (FEA) to assess stress distribution, vibration characteristics, deformation, and thermomechanical fatigue behavior under extreme conditions. Biradar [7], Jabbar et al. [10], and Orah et al. [11] illustrated that FEA is crucial for forecasting the structural reliability and fatigue life of turbine blades. In the realm of topology optimization, Antorkas et al. [4], Abdulhameed [2], and Hussain et al. [3] investigated lightweight lattice-based blade structures that can minimize material usage while preserving structural integrity and vibration stability. Najafabadi et al. [9] enhanced turbine blade cooling efficiency by optimizing internal cooling channel designs through conjugate heat transfer analysis. Abbott [8] highlighted the significance of blade design and airflow properties in enhancing aerodynamic performance. Additionally, Abdulrahman et al. [1] explored deep learning methods for the automated detection of blade defects, while Zhang and Janeway [5] combined neural networks with CFD to optimize aerodynamics. Collectively, the research suggests that integrating FEA, CFD, topology optimization, and AI-driven approaches can greatly advance the creation of lightweight, efficient, reliable, and intelligent aero-engine turbine blade systems.

## III. MATERIALS AND METHODS

The review paper was developed by examining twenty-three sources of literature concerning turbine blades in aero-engines. The chosen documents comprised journal articles, conference papers, review articles, and technical reports published from 1936 to 2026. The literature was categorized into key areas such as aerodynamic analysis, structural analysis, thermal behavior, fatigue analysis, topology optimization, additive manufacturing, material selection, and AI-based defect detection.

Keywords like CFD, FEA, turbine blade optimization, fatigue analysis, topology optimization, lattice structures, machine learning, and aero-engine defect detection were employed to classify the reviewed documents. The gathered data was critically assessed and arranged based on the objectives and outcomes of the respective studies.

### Fundamentals of Gas Turbine Blade Systems

Gas turbines function on the Brayton cycle, where compressed air is combined with fuel and ignited to produce high-temperature gases. These gases expand through turbine stages, transferring energy to the rotating blades.

Research into gas turbine fundamentals indicates that turbine blades are subjected to significant thermal and mechanical stresses. Selecting appropriate materials is essential, as the blades must demonstrate high creep resistance, robust fatigue strength, and thermal stability. Nickel-based superalloys, titanium alloys, and ceramic coatings are often explored for their effectiveness in high-temperature settings. The literature also underscores that aerodynamic efficiency has a direct impact on thrust generation and fuel consumption. Elements such as blade geometry, cooling passages, leading edge profiles, and pressure distributions contribute to the turbine's overall performance. CFD-Based Aerodynamic Analysis Computational Fluid Dynamics has become a pivotal tool for studying the aerodynamics of turbine blades. CFD provides engineers with the ability to visualize velocity distribution, pressure changes, and the dynamics of turbulence and flow separation around turbine blades. Numerous studies have confirmed that CFD simulations are crucial for refining blade geometry without solely depending on physical prototypes. Aerodynamic parameters such as drag force, lift coefficient, pressure ratio, and flow separation have been thoroughly investigated.

Research incorporating neural-network-assisted CFD optimization has demonstrated that artificial neural networks can significantly reduce computational time while maintaining acceptable accuracy. These techniques are particularly beneficial in large-scale optimization scenarios where thousands of simulations might otherwise be necessary.

Fluid Structure Interaction modeling has also become a significant area of research. FSI methods integrate aerodynamic loads derived from CFD with structural deformation predicted through FEA. This integration enhances prediction accuracy and aids in assessing aeroelastic instability, deformation, and stress distribution.

### Structural and Thermal Analysis using FEA

Finite Element Analysis (FEA) is extensively employed to assess the stress, strain, deformation, and thermal characteristics of turbine blades. The majority of the studies reviewed utilized ANSYS and CATIA for both modeling and structural simulations. The literature reviewed reveals that turbine blades experience significant thermal gradients, leading to elevated thermal stresses, particularly near the leading edge and blade tip areas. Structural analyses typically concentrated on von Mises stress, deformation patterns, and temperature distribution.

Material comparison studies revealed that titanium alloys and nickel-based superalloys provide superior performance under high-temperature conditions. Titanium alloys demonstrated lower deformation and improved thermal resistance compared to aluminium and magnesium alloys.

Thermal barrier coatings and internal cooling mechanisms were also found to improve blade life significantly. Conjugate heat transfer analysis showed that advanced cooling passages reduce temperature concentration and minimize thermal failure.

### Fatigue and Vibration Behaviour

Fatigue failure remains one of the most common causes of turbine blade damage. High cycle fatigue occurs because of cyclic loading, resonance and thermal stress fluctuations during turbine operation.

The reviewed studies highlighted that modal analysis is essential for determining blade natural frequencies and avoiding resonance conditions. Campbell diagrams were frequently used to identify critical operating frequencies.

Thermo-mechanical fatigue studies demonstrated that temperature variation significantly affects crack propagation and structural degradation. Finite element methods were widely used to predict fatigue life and identify high-risk regions.

Researchers also investigated vibration reduction using lattice structures and optimized internal geometries. Results indicated that lattice-based blades can improve vibration resistance while simultaneously reducing blade weight.

### Topology Optimization and Lattice Structures

Topology optimization has become increasingly important due to the development of additive manufacturing technologies. Traditional solid blade structures are gradually being replaced by lightweight optimized geometries with improved strength-to-weight ratio.

The reviewed literature discussed SIMP and SERA optimization techniques for reducing material volume while maintaining structural efficiency. Optimized turbine blades exhibited hollow and thin-walled structures with strategically distributed reinforcement regions.

Lattice structures such as gyroid, X-cell and octet truss geometries were also investigated. These structures reduced blade weight significantly while improving stiffness and vibration characteristics. Additive manufacturing techniques enabled the fabrication of these complex internal structures.

Researchers concluded that topology optimization combined with additive manufacturing provides a promising pathway toward lightweight and highly efficient turbine blades.

### Fluid Structure Interaction and Cooling Analysis

Fluid Structure Interaction combines aerodynamic loading with structural response prediction. FSI methods improve the realism of turbine blade simulations by accounting for blade deformation caused by airflow and pressure loading.

Internal cooling analysis also emerged as a major research focus. Advanced cooling channels and topology optimized internal passages were investigated to improve heat dissipation. Conjugate heat transfer methods helped evaluate the interaction between fluid flow and thermal conduction inside turbine blades.

Studies revealed that optimized cooling designs improve temperature uniformity and reduce thermal stresses. These methods are especially important for modern high-pressure turbine stages operating at extremely high temperatures.

### Artificial Intelligence and Defect Detection

Artificial intelligence and deep learning have recently become important tools in turbine blade inspection and maintenance. Traditional inspection methods depend heavily on experienced operators and are often time-consuming.

Deep learning approaches using convolutional neural networks and computer vision methods demonstrated high accuracy in detecting blade cracks, surface defects and anomalies. AI-based defect detection systems can automate inspection procedures and improve reliability.

Researchers highlighted that integrating AI with real-time monitoring systems can enable predictive maintenance of aero-engine components. Future systems may combine CFD, sensor data and machine learning algorithms to predict blade failure before catastrophic damage occurs.

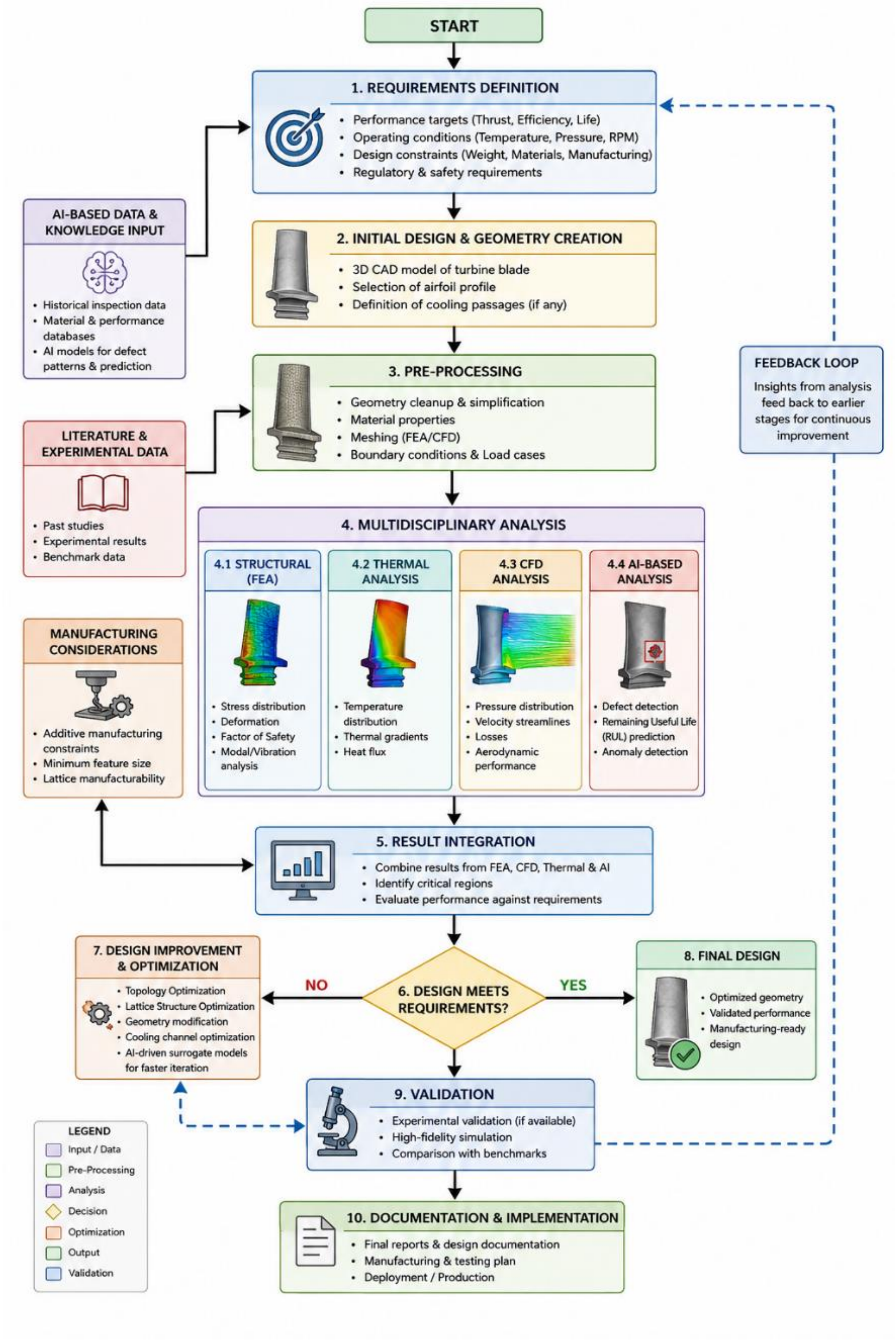

Fig. 2 Process flow chart for analysis

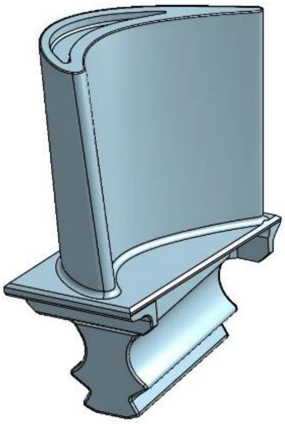

Fig. 1 A High pressure turbine blade with blade root

## IV. RESEARCH GAP AND FUTURE SCOPE

Although considerable advancements have been made in turbine blade research, several challenges still remain unresolved. Many CFD studies rely on simplified turbulence models that may not fully capture real operating conditions. Similarly, thermal fatigue prediction still requires more accurate coupling between thermal, structural and material degradation models.

Future research should focus on fully integrated multidisciplinary optimization frameworks combining CFD, FEA, topology optimization and machine learning. Additive manufacturing methods require further development to improve material consistency and manufacturability of lattice structures.

AI-assisted blade monitoring systems also require large high-quality datasets for training reliable models. Future work may involve digital twins, real-time health monitoring and autonomous optimization systems for turbine engines.

## V. CONCLUSION

This recent review paper examined recent developments in aero-engine turbine blade research with emphasis on finite element modelling, topology optimization, lattice structures and AI-based defect detection. The reviewed studies demonstrate that computational techniques have significantly improved turbine blade design efficiency and reliability.

CFD and FEA continue to dominate aerodynamic and structural analysis, while topology optimization and additive manufacturing are transforming lightweight blade development. Advanced cooling methods and thermal barrier coatings improve blade life under high-temperature operation. In addition, artificial intelligence has introduced new possibilities for automated defect detection and predictive maintenance.

The overall literature suggests that future turbine blade systems will depend on multidisciplinary integration involving computational simulation, intelligent optimization and advanced manufacturing. These developments have the potential to improve engine efficiency, reduce fuel consumption and increase operational safety in aerospace applications.

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