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Effect of Natural Frequency and Stress on Gas Turbine Solid and Lattice Structured Blades

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Gas turbine blades are critical components in aviation and power generation industries, requiring high mechanical strength, durability, and resistance to thermal and vibrational stresses. This study investigates the mechanical performance of gas turbine blades under different configurations, including uncoated, nano coated, and lattice-reinforced structures (Octet, Diamond, and Hybrid). Finite element analysis (FEA) was performed to evaluate maximum deformation, stress distribution, natural frequencies, and weight characteristics. This study provides insights into optimizing gas turbine blade design for improved efficiency and longevity.

1. Introduction

Gas turbine blades operate under extreme conditions of high temperature, centrifugal force, and vibrational stress. The efficiency and reliability of these blades directly impact the overall performance of the turbine system. Traditional blade materials, while strong, are susceptible to high thermal and mechanical stress, leading to deformation and fatigue over time. Protective coatings and advanced structural modifications, such as lattice reinforcements, have been explored to enhance their durability and performance.

Coating technologies improve thermal resistance and mechanical stiffness, reducing deformation and increasing vibrational stability. However, they often add extra weight to the blade, which may impact turbine efficiency. On the other hand, lattice structures present a novel approach by reducing weight while maintaining mechanical integrity. Understanding the trade-offs between these modifications is essential for optimizing turbine blade design.

This study aims to compare the mechanical performance of uncoated, coated, and lattice-reinforced turbine blades through finite element analysis (FEA). The findings will help in selecting an optimal blade design that balances strength, vibrational resistance, and weight reduction.

2. Literature Review

Haresh Pal Singh(2020) study analyzes gas turbine blade materials under extreme conditions of vibration, pressure, and temperature. Four materials—Titanium alloy, Nimonic 80A, INCONEL 617, and Rhenium—are evaluated using static structural, thermal, and modal analysis in ANSYS 2019. A 3D CAD model is developed in SolidWorks 2018 to determine stress, deformation, and natural frequencies, helping identify the most suitable material for turbine blade manufacturing.

Sajjad Hussain(2022) study explores the use of octet truss lattice structures in gas turbine blades to reduce weight and enhance vibration characteristics. A solid blade model based on the NACA 23012 airfoil was used as a reference, and three octet truss lattice-based blades were designed and 3D-printed with varying strut thicknesses. Vibration analysis showed a weight reduction, higher natural frequencies, stress reduction, and lower deformation. These findings confirm the potential of lattice-based blades for improving turbine efficiency and durability.

Ebrahim Ahamad(2021) study explores designing lightweight turbine blades using Topology Optimization (TO) and Additive Manufacturing (AM). A graded lattice structure replaces the internal solid volume to enhance endurance against thermal stresses. Lattice Structure Topology Optimization (LSTO) optimizes density distribution within the blade, using triply periodic minimal surfaces (TPMS) for improved mechanical performance. Finite element analysis validates the design, showing enhanced efficiency with weight reduction, lower stress, and reduced deformation compared to the initial design.

Prabhunandan (2016) study analyzes steam turbine blades using ANSYS, focusing on life cycle assessment to ensure over 20 years of operation with minimal failures. Blades and rotors face cyclic stresses due to high-frequency loads, necessitating titanium alloy for durability. The study examines various loads, stress distributions, and fatigue effects caused by steam speed variations, aiding in blade design and fatigue life prediction.

kokong(2021) study analyzes the natural frequency of the last-stage LP steam turbine blade at Tanjung Awar Awar, Indonesia, using ANSYS 2019 R2. Finite element analysis on single and five-blade systems shows natural frequencies between 2563–2915 rpm, confirming that under-frequency settings do not coincide with blade resonance, preventing lacing wire damage.

Kalapala prasad(2017) study reveals that Gas turbines generate mechanical power, but high-speed operation can cause blade instability and resonance, leading to failure. This study performs modal analysis using ANSYS V-14 to determine the natural frequency and plots a Campbell diagram to identify resonance speeds.

Wensheng Zhao(2017) study investigates the failure of a low-pressure steam turbine blade in a PWR nuclear plant through theoretical and experimental analysis. Using a 3D finite element model, natural frequencies and resonance conditions are identified via a Campbell diagram. Vibration tests confirm that the 2nd natural frequency aligns with the 9th rotor speed harmonic, causing fretting wear and fatigue failure. Stress analysis and fretting fatigue experiments reveal that high-cycle fatigue (HCF) combined with fretting wear significantly reduces blade life.

Sabaa Sattar (2023) study addresses hot corrosion issues in steam turbines at Al-Mussaib thermal power station by coating turbine blade samples with Ni-5%SiO2-TiO2 using electro-deposition. Coating thickness, surface roughness, hardness, and wear resistance were analyzed. Results show increased TiO2 content (5, 10, 15 g/l) enhances coating thickness, hardness, and wear resistance, with the 10 g/l TiO2 coating achieving the highest wear reduction.

Pradip Gedam(2017) study evaluates the effect of thermal barrier coatings (TBCs) on gas turbine blades made of Inconel-713 to reduce thermal stresses and deformation. Coatings of YSZ, Al_2O_3, and LHA (0.5 mm thickness) are analyzed using FEM. Results show that coated blades experience lower deformation and von-Mises stresses compared to non-coated blades, enhancing durability under high-temperature conditions.

Biao Li (2017)This study optimizes thermal barrier coating (TBC) thickness on gas turbine blades to balance thermal insulation, durability, and cost. Using 3D finite element models and a weighted-sum approach, a multi-region coating distribution is designed for improved performance while considering manufacturing accuracy and efficiency

Abbas Khammas Hussein(2020) study optimizes the pack cementation process for hot-corroded Ni-based superalloy K417G using grey relational analysis. Key parameters, including activator, master alloy, and Y_2O_3 content, were analyzed using ANOVA to determine their influence on corrosion resistance. The optimal process settings were identified, confirming that Y_2O_3 is the most significant factor in improving coating quality.

Jasem Alqallaf(2020) review examines solid particle erosion (SPE) effects on gas turbine components, particularly in harsh environments like deserts. It discusses ductile and brittle erosion mechanisms, key influencing parameters, and theoretical models. Additionally, it explores erosion-resistant coatings for surface protection and highlights gaps in research and future directions for improving turbine durability.

Matthew A. Meier (2020)study reveles that an additive-manufactured (AM) vaned diffuser was designed for a centrifugal compressor research facility to reduce lead time and enhance instrumentation capabilities. High-temperature stereolithography (SL) resin was selected for its precision and cost-effectiveness compared to metal. Mechanical testing verified its suitability for high-temperature environments. The diffuser was fabricated in seven radially symmetric sections for assembly, with precision measurements confirming accurate flow path dimensions.

3. Research Gap

Despite numerous studies on gas turbine blade performance, several gaps remain unaddressed:

1. Limited Studies on Nano-Coating Effects on Natural Frequency: While previous research has focused on the mechanical and thermal benefits of nano-coatings, limited studies have investigated their influence on the natural frequency and vibrational behavior of gas turbine blades.

2. Lack of Comprehensive Stress Analysis in Coated Blades: Most existing research emphasizes coating durability and thermal resistance but lacks detailed stress distribution analysis in nano-coated turbine blades under operational conditions.

3. Finite Element Analysis (FEA) for Comparative Studies: Few studies have employed FEA to compare the structural response of coated versus uncoated blades, particularly in terms of natural frequency shifts and stress variations.

4. Limited comparative studies exist on the combined effects of coating and hybrid lattice structures on turbine blade performance.

5. Most studies focus on either improving stiffness (coatings) or reducing weight (lattice structures), but not on achieving an optimal balance between the two.

Addressing these gaps, this research evaluates multiple blade configurations to identify the best compromise between structural strength and weight efficiency.

4. Methodology

To assess the mechanical performance of different gas turbine blade configurations, a finite element analysis (FEA) approach was adopted. The methodology includes the following steps:

1. Blade Model Selection: Five configurations were analyzed—Uncoated Blade, Coated Blade, and Lattice-reinforced Blades (Octet, Diamond, and Hybrid).

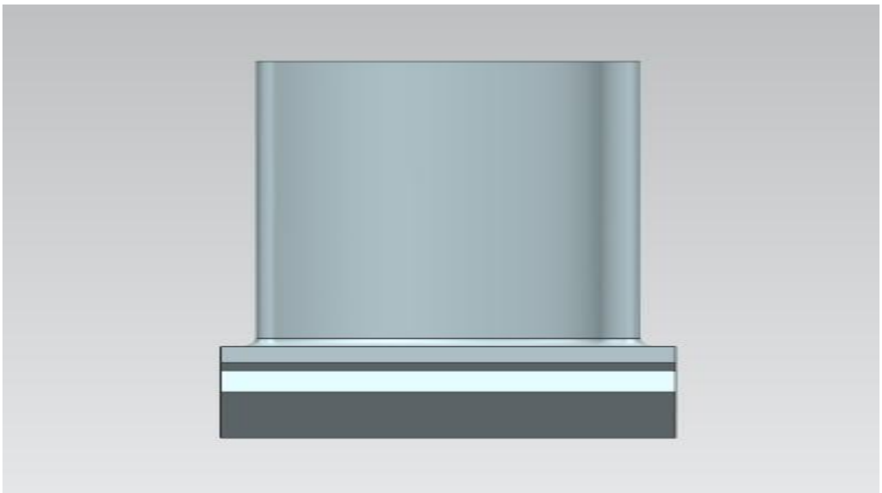


Fig1: Blade model view 1

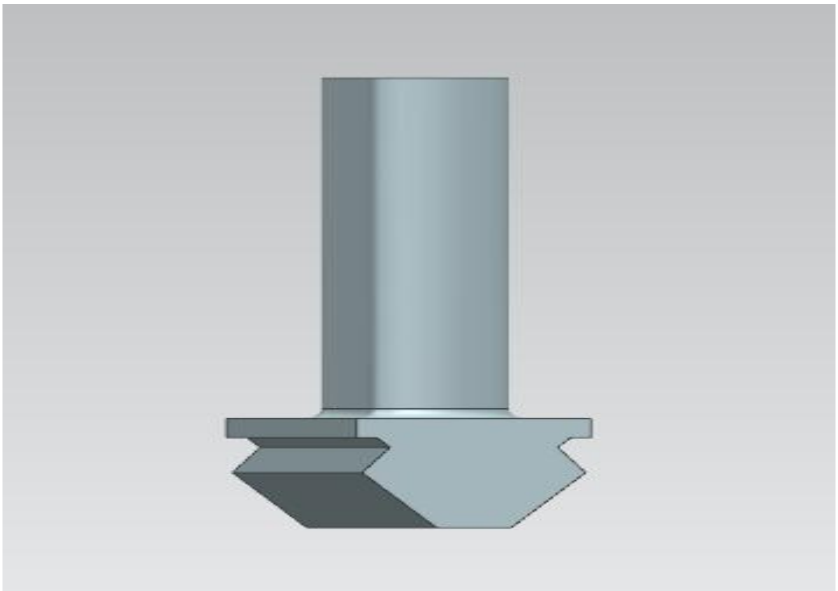


Fig2: Blade model view 2

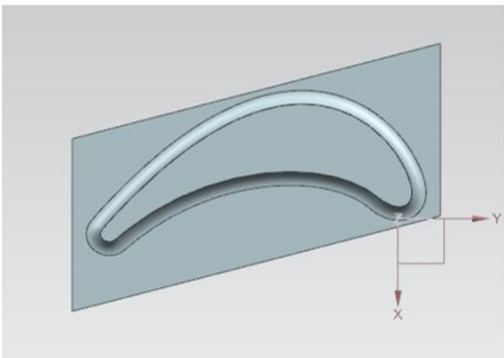


Fig3: Blade without coating

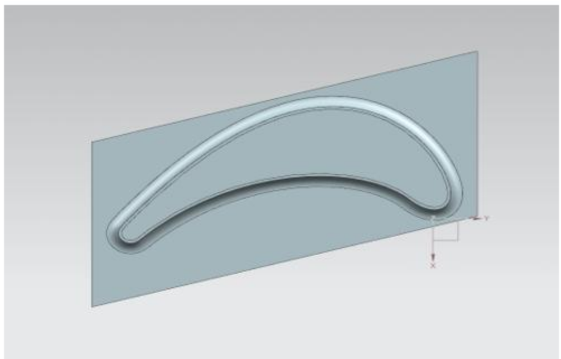


Fig4: Blade with coating

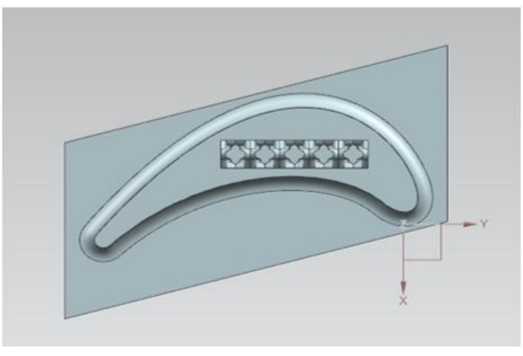


Fig5: Blade octet

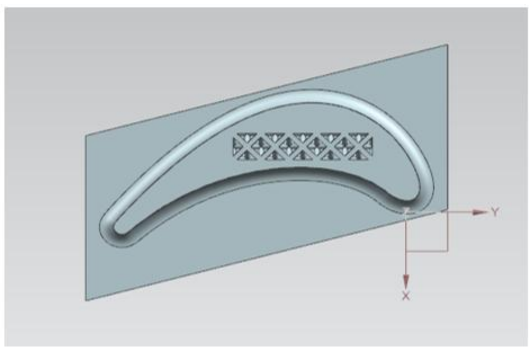


Fig6: Blade Diamond

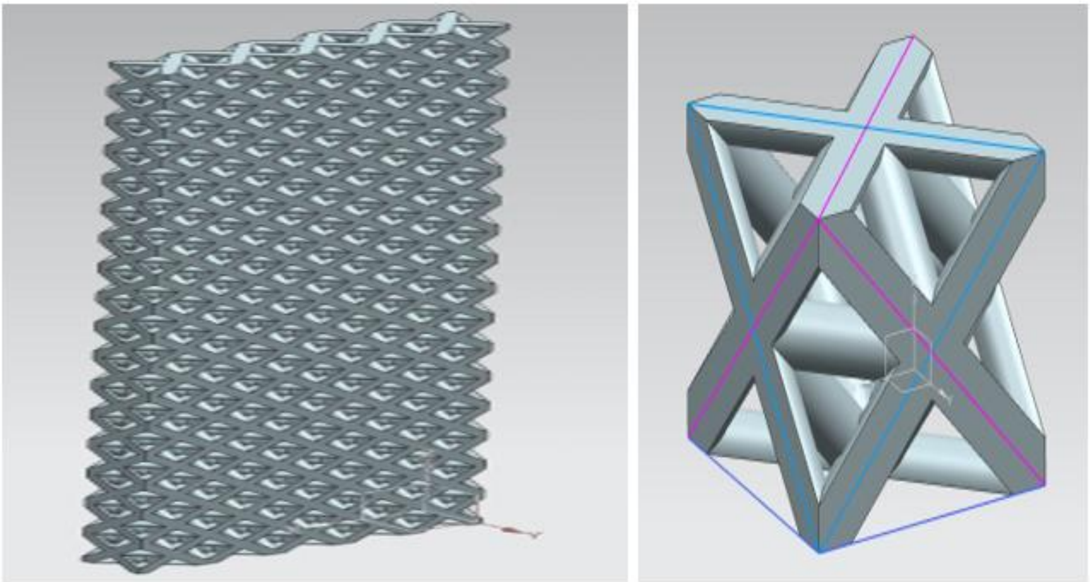


Fig7: Blade Octet lattice

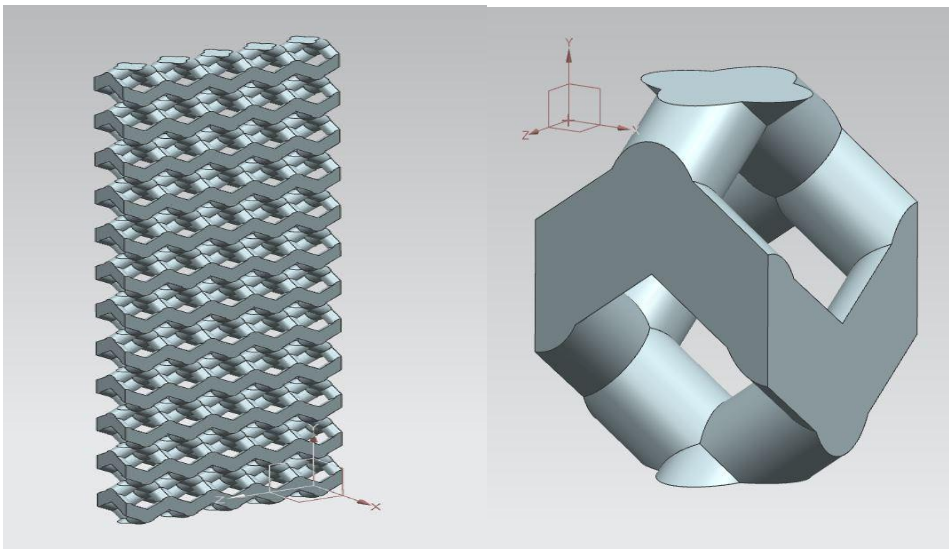


Fig8: Blade Diamond lattice

2. Material Properties Assignment: Standard materials for turbine blades were used, incorporating mechanical properties suitable for high-temperature applications.

Blade material - Inconel 718

Parameter	Values
Density [Kg/m^3]	8220
Young's Modulus [GPa]	165

Poisson's ratio	0.3
Yield Strength [GPa]	0.648
Coefficient of Thermal Expansion [1/K]	1.436e-5

Coating material - TiN

Parameter	Values
Density [Kg/m^3]	5300
Young's Modulus [GPa]	500
Poisson's ratio	0.24
Yield Strength [GPa]	0.8
Ultimate Tensile Strength [GPa]	1.1
Coefficient of Thermal Expansion [1/K]	9.4e-6

3. Meshing and Boundary Conditions: A fine mesh was applied to ensure accuracy, and boundary conditions were defined to simulate real-world operating conditions.

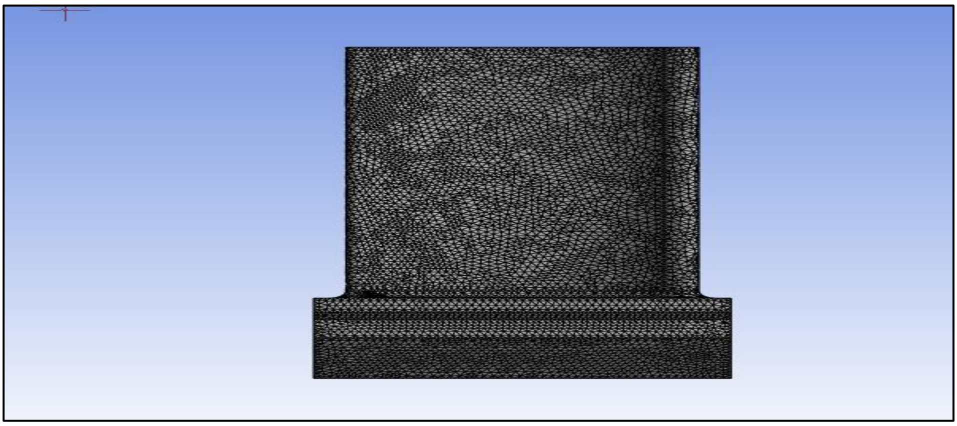


Fig 9: Blade Meshing view 1

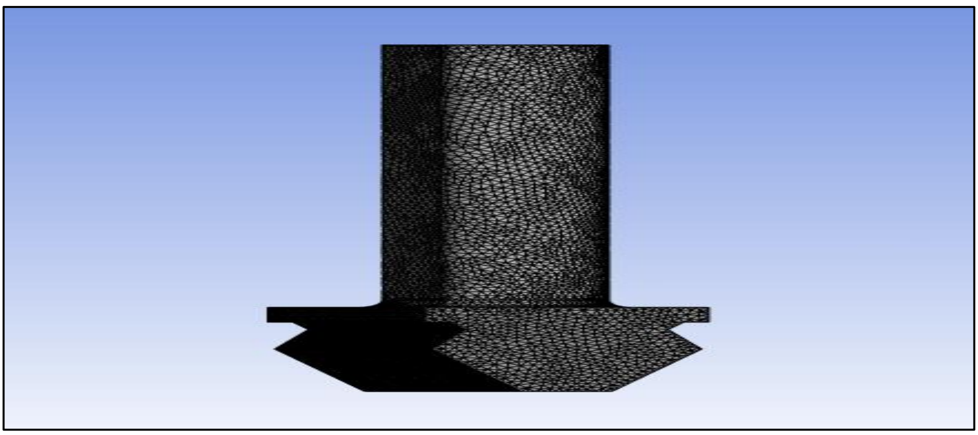


Fig 10: Blade Meshing view 2

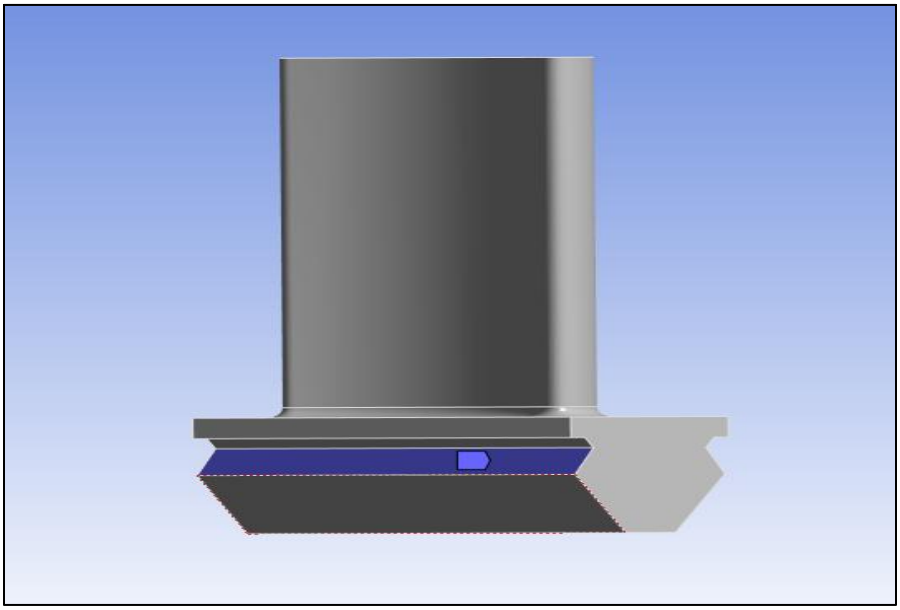


Fig 11: Base is fixed and rotated at 8000 RPM

4. Simulation Process: FEA was conducted to evaluate deformation, stress distribution, natural frequencies, and weight characteristics.

5. Comparison and Analysis: The results were compared to identify the most effective configuration based on strength, vibration resistance, and weight efficiency.

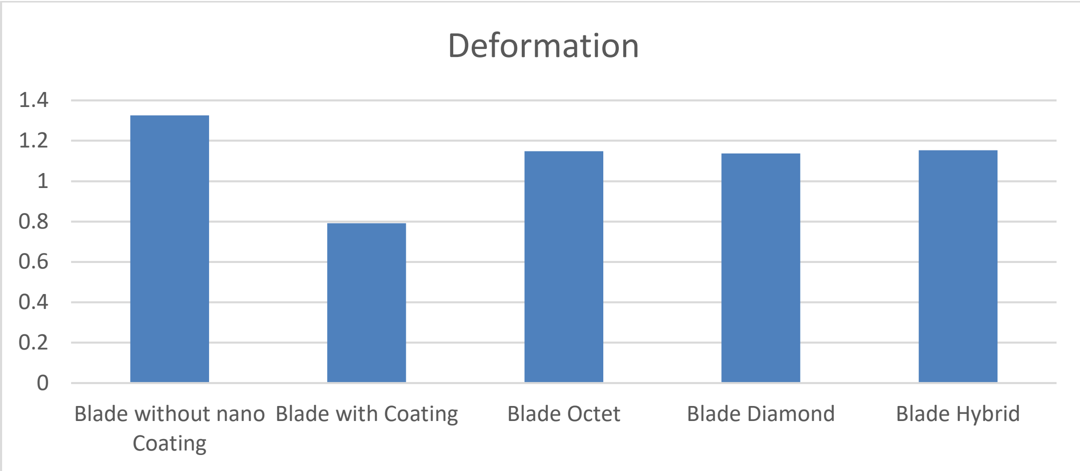
The findings from this analysis will provide valuable insights into optimizing gas turbine blade designs for enhanced performance and longevity.

5. Results and Discussion

The analysis of gas turbine blades under different configurations—uncoated, coated, and lattice-reinforced structures (Octet, Diamond, and Hybrid)—reveals significant variations in mechanical performance. The following key observations were made:

Maximum Deformation: The highest deformation was observed in the uncoated blade (1.326 mm), while the coated blade exhibited the least deformation (0.792 mm). Lattice-reinforced structures showed moderate deformations, with the Diamond configuration having the least (1.137 mm) among them.

Solid blade without nano coating	Solid blade with coating	Blade octet	Blade diamond	Hybrid Blade
1.326 mm	0.792 mm	1.149 mm	1.137 mm	1.153 mm



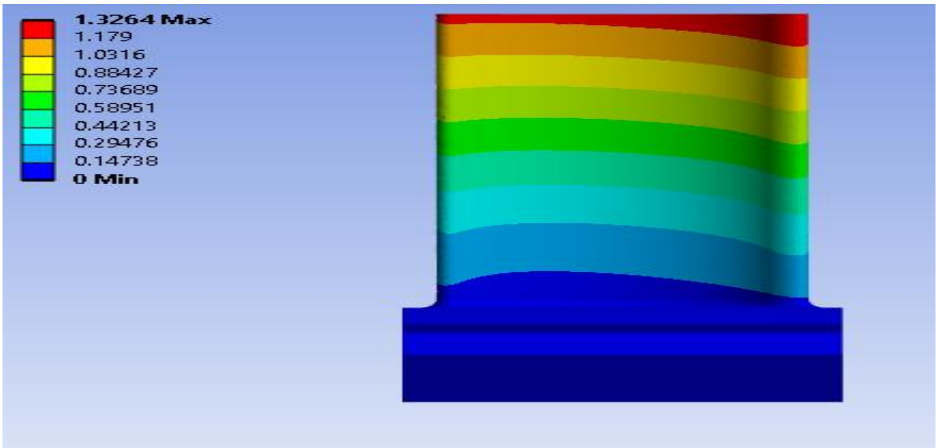


Figure 12: Deformation solid blade without nano coating

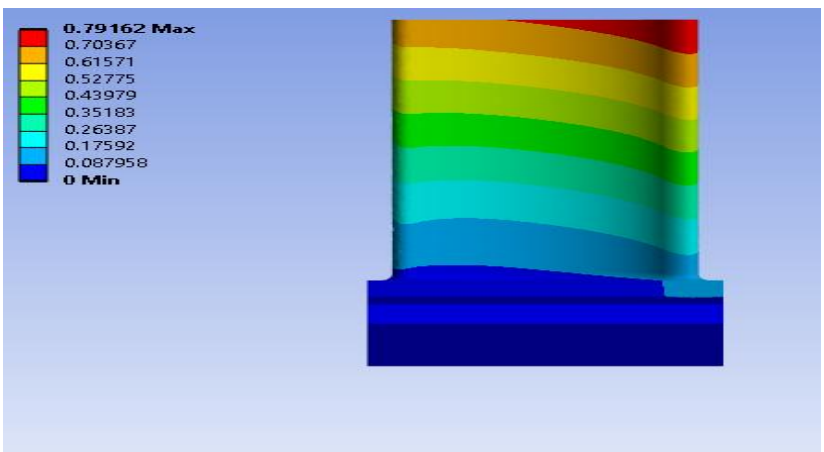


Figure 13: Deformation blade with nano coating

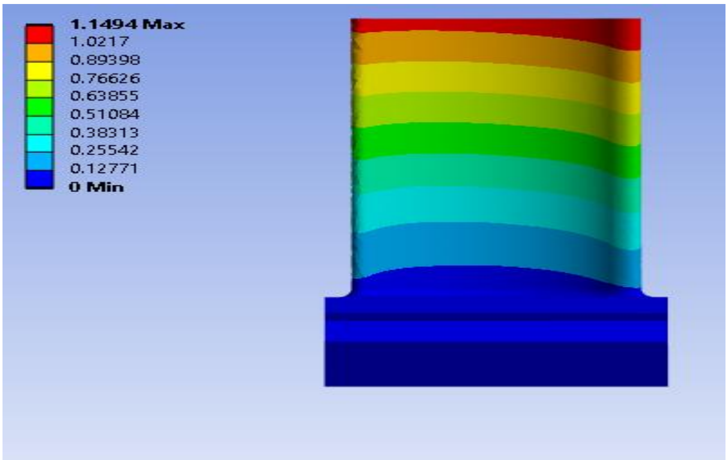


Figure 14: Deformation blade Octet

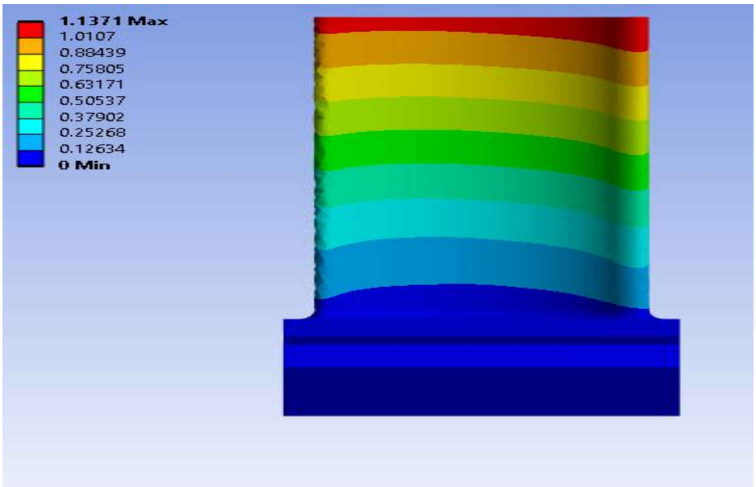


Figure 15: Deformation blade Diamond

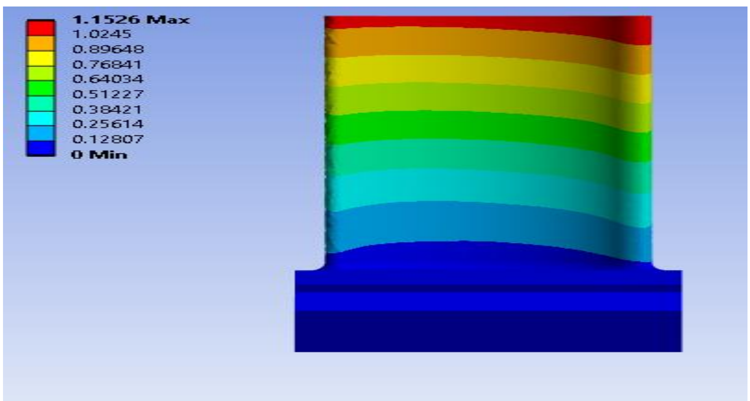
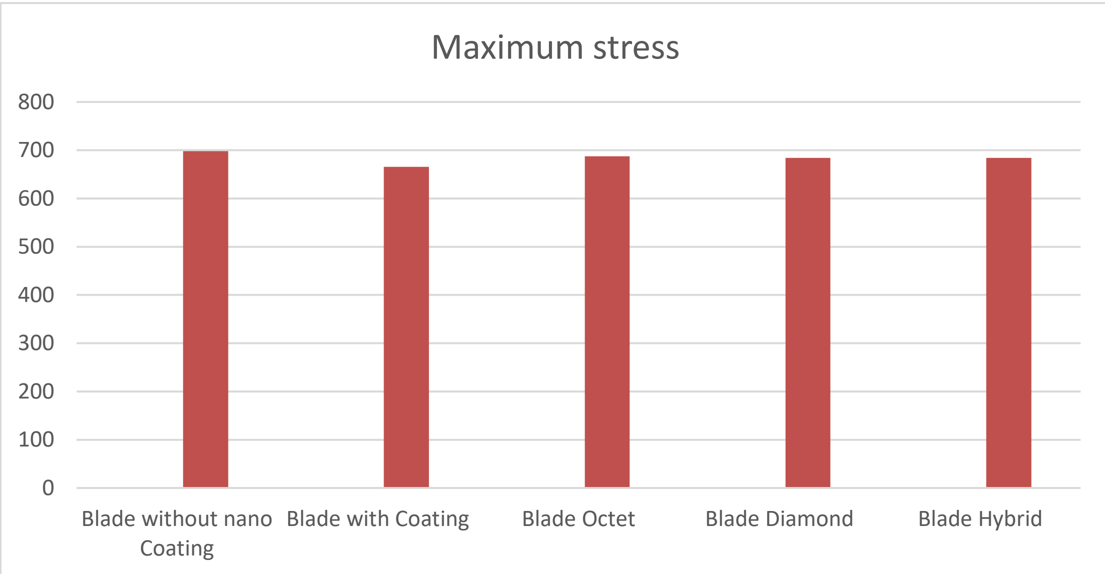


Figure 16: Deformation blade Hybrid

- Maximum Stress: The uncoated blade exhibited the highest stress (697.93 MPa), whereas the coated blade had the lowest (665.67 MPa). Lattice-reinforced blades demonstrated slightly lower stresses, with values ranging between 683.92 MPa (Hybrid) and 687.39 MPa (Octet).

Solid blade without nano coating	Solid blade with coating	Blade octet	Blade diamond	Hybrid Blade
697.93 MPa	665.67 MPa	687.39 MPa	684.11 MPa	683.92 MPa



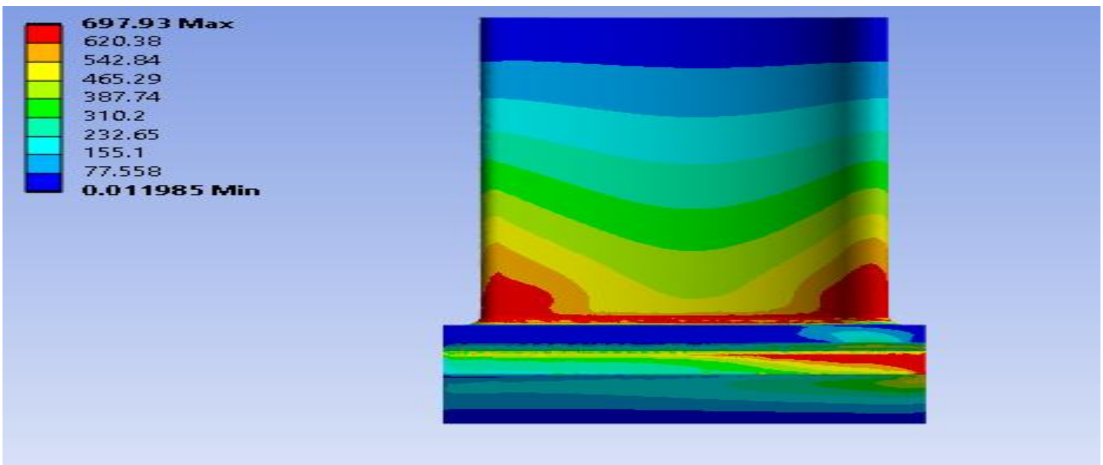


Figure 17: Maximum stress solid blade without nano coating

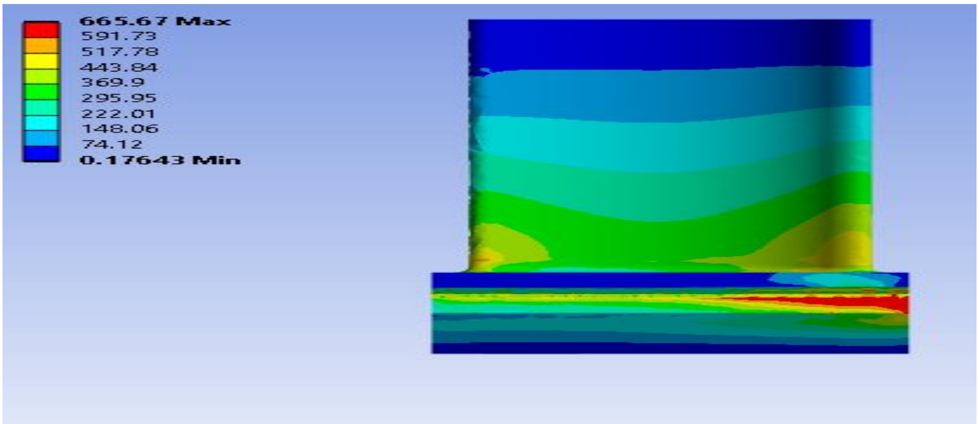


Figure 18: Maximum stress blade with nano coating

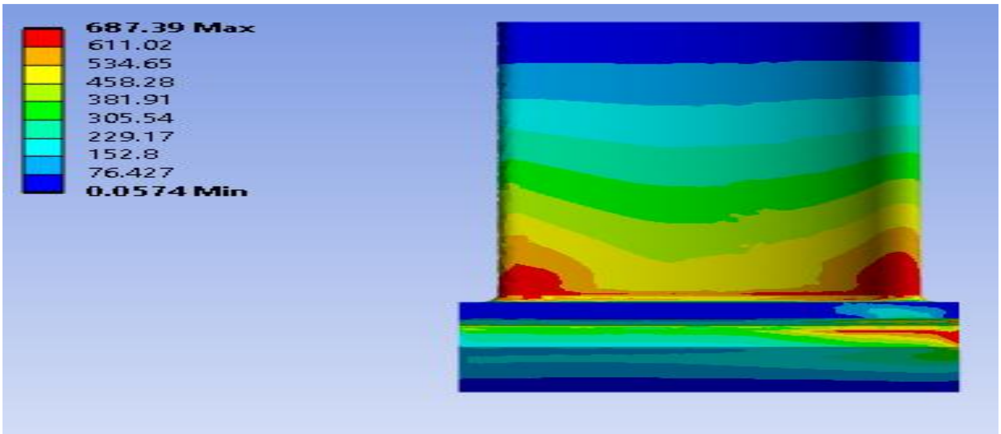


Figure 19: Maximum stress blade Octet

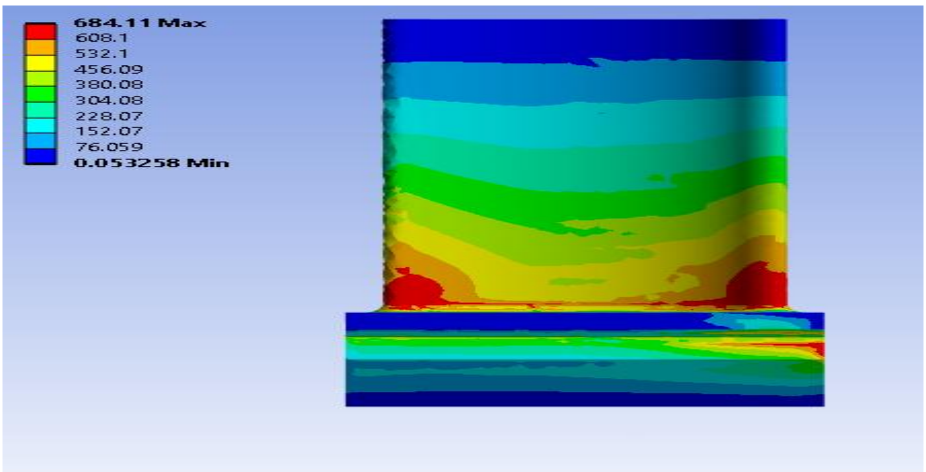


Figure 20: Maximum stress blade Diamond

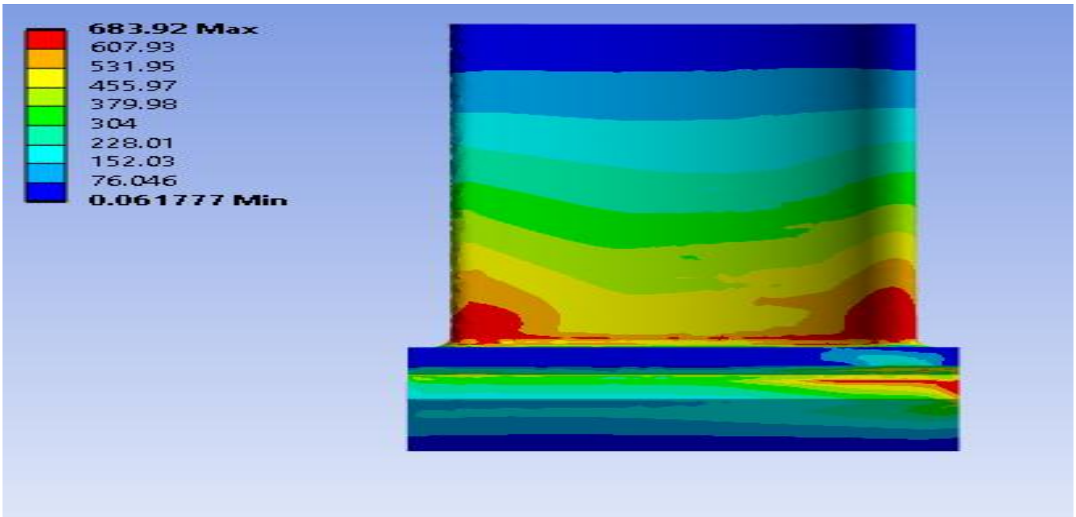
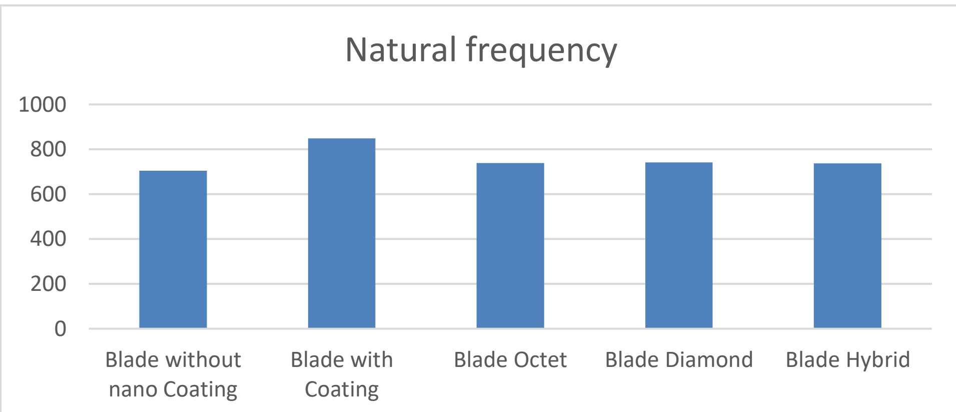


Figure 21: Maximum stress blade Hybrid

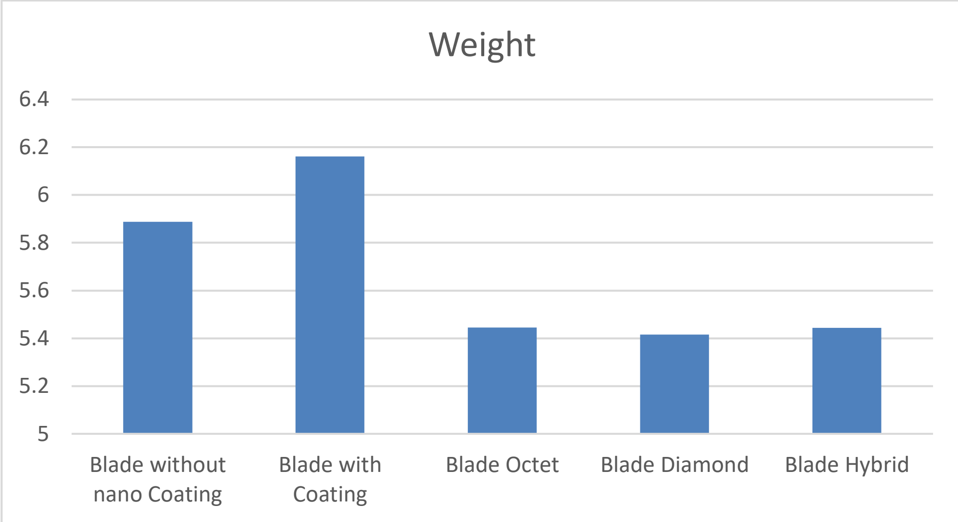
- Natural Frequencies: The coated blade significantly improved the fundamental frequency (848.43 Hz) compared to the uncoated blade (705.01 Hz). The lattice-reinforced blades exhibited frequencies in the range of 737.84 Hz to 741.57 Hz for Mode 1. Higher modes followed a similar trend, with the coated blade demonstrating superior stiffness.

Solid blade without nano coating	Solid blade with coating	Blade octet	Blade diamond	Hybrid Blade
705.01 Hz	848.43 Hz	738.43 Hz	741.57 Hz	737.84 Hz



- Weight: The coated blade was the heaviest (6.162 kg), while lattice-based structures were lighter, with Diamond having the least weight (5.4157 kg).

Solid blade without nano coating	Solid blade with coating	Blade octet	Blade diamond	Hybrid Blade
5.88 kg	6.16208 kg	5.4448 kg	5.4157 kg	5.4441 kg



- Lattice Density Ratio: Among the lattice structures, Octet had the highest density ratio (0.36), while Diamond had the lowest (0.32), indicating a reduction in weight without compromising stiffness.

The results indicate that coating significantly improves the mechanical properties of the blade, reducing deformation and increasing natural frequencies. However, this comes at the cost of increased weight. Lattice structures, on the other hand, offer a balance between weight reduction and mechanical performance.

- Impact of Coating: The reduction in deformation and stress in the coated blade highlights the effectiveness of coatings in improving stiffness. The enhancement in natural frequencies indicates improved dynamic stability, making the coated blade more resistant to vibrations.

- Performance of Lattice Structures: The introduction of lattice structures reduces weight while maintaining acceptable mechanical properties. Among the three configurations, the Diamond structure exhibited the least deformation and weight, making it an optimal choice for weight-sensitive applications.

- Trade-offs: While the coated blade offers superior strength and vibrational resistance, its increased weight may impact efficiency. Lattice structures provide a viable alternative, reducing weight while maintaining comparable mechanical integrity.

6. Conclusion

The study demonstrates that the application of coatings significantly enhances the strength and vibrational performance of gas turbine blades. However, lattice structures provide a lightweight alternative with reasonable structural performance. Among the lattice configurations, the Diamond structure exhibits the best balance between mechanical strength and weight reduction. Future work could explore hybrid approaches that optimize both weight and structural integrity by integrating coatings with lattice structures.

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