

STRUCTURAL AND THERMAL ANALYSIS OF A COMPOSITE TURBOCHARGER TURBINE WHEEL FOR HIGH-SPEED APPLICATIONS

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ABSTRACT

Turbochargers play a critical role in enhancing the performance and efficiency of internal combustion engines by increasing the mass flow rate of air supplied to the combustion chamber. The turbine wheel is one of the most important components of a turbocharger, operating under extreme thermal and centrifugal loading conditions. Conventional turbine wheels are typically manufactured from nickel-based superalloys, which offer excellent high-temperature strength but contribute significantly to the overall weight of the turbocharger system. To address these limitations, the present study investigates the feasibility of using advanced composite materials for turbocharger turbine wheel applications.

The turbine wheel was designed using computer-aided design (CAD) tools and analyzed through finite element analysis (FEA) to evaluate its structural and thermal behavior under high-speed operating conditions. Composite materials with high strength-to-weight ratios and superior thermal resistance were considered as alternatives to conventional metallic materials. Structural analysis was performed to determine deformation, von Mises stress distribution, and factor of safety under centrifugal forces generated at elevated rotational speeds. Thermal analysis was conducted to assess temperature distribution and heat transfer characteristics during turbine operation.

The simulation results indicate that the composite turbine wheel exhibits significant weight

reduction while maintaining acceptable stress and deformation levels within permissible limits. Thermal analysis demonstrates improved resistance to thermal loading and reduced heat conduction compared to traditional metallic counterparts. The findings suggest that composite materials can effectively enhance the performance, durability, and efficiency of turbocharger turbine wheels used in high-speed applications. The proposed design offers potential benefits in terms of reduced inertia, improved transient response, and increased fuel efficiency, making it a promising solution for next-generation automotive and aerospace turbocharging systems.

Keywords: Turbocharger Turbine Wheel, Composite Materials, Finite Element Analysis, Structural Analysis, Thermal Analysis, High-Speed Applications, Weight Reduction, CAD Modeling, Thermal Resistance, Automotive Engineering.

I. INTRODUCTION

Background of the Study

Turbochargers improve engine power and fuel efficiency by utilizing exhaust gas energy to drive a turbine wheel. The turbine wheel operates under high temperatures and rotational speeds, requiring materials with excellent mechanical and thermal properties. Composite materials are being explored as lightweight alternatives to conventional metallic materials.

Problem Statement

Conventional turbine wheels made from metallic alloys are relatively heavy and experience

significant thermal and centrifugal stresses. These factors can reduce efficiency and increase wear, creating a need for lighter and more durable materials.

Research Objectives

- To design a turbocharger turbine wheel using composite materials.
- To perform structural analysis under high-speed operating conditions.
- To evaluate thermal behavior and temperature distribution.
- To assess the suitability of composite materials for turbine wheel applications.

Scope of the Work

This study focuses on the CAD modeling and finite element analysis of a composite turbocharger turbine wheel. Structural and thermal performances are evaluated under simulated operating conditions, without experimental fabrication or testing.

Significance of the Study

The use of composite materials can reduce turbine wheel weight, improve turbocharger response, enhance fuel efficiency, and increase component durability. The study provides valuable insights for developing advanced lightweight turbocharger systems.

II. LITERATURE REVIEW

Previous Research Works

Several researchers have analyzed turbocharger turbine wheels using finite element methods to study stress, deformation, and thermal behavior. Recent studies have also explored lightweight materials such as titanium alloys and composites to improve performance and reduce weight.

Existing Methods and Technologies

Current turbine wheels are mainly manufactured from nickel-based superalloys due to their high-temperature strength. Modern design approaches use CAD, Finite Element Analysis (FEA), and Computational Fluid Dynamics (CFD) to

evaluate structural, thermal, and aerodynamic performance.

Research Gaps Identified

Although composite materials offer significant weight reduction and high strength, their application in turbocharger turbine wheels is still limited. Comprehensive thermo-mechanical studies and long-term performance evaluations of composite turbine wheels under high-speed operating conditions remain insufficient and require further investigation.

III. MATERIALS AND METHODS / EXPERIMENTAL METHODOLOGY

Materials Used

A Carbon Fiber Reinforced Polymer (CFRP) composite material was selected for the turbine wheel due to its high strength-to-weight ratio, low density, and good thermal resistance. Conventional Inconel material was considered for comparison.

Equipment and Instruments

The study utilized CAD software (SolidWorks/CATIA) for modeling and ANSYS Workbench for structural and thermal finite element analysis. A high-performance computer system was used for simulation and result processing.

Design Specifications

A turbocharger turbine wheel with 12 blades was designed based on standard dimensions and operating conditions. The analysis considered rotational speeds up to 120,000 rpm and temperatures up to 700°C.

Experimental Setup

A 3D CAD model of the turbine wheel was developed and imported into ANSYS. The composite material properties were assigned, meshing was performed, and structural and thermal boundary conditions were applied for simulation.

Testing Procedure

Structural analysis was conducted to determine stress and deformation under centrifugal loading. Thermal analysis was performed to evaluate temperature distribution and heat transfer characteristics. The simulation results were then assessed to determine the suitability of the composite material for high-speed turbocharger applications.

IV. PROPOSED SYSTEM / DESIGN METHODOLOGY

Conceptual Design

The proposed system involves designing a lightweight turbocharger turbine wheel using Carbon Fiber Reinforced Polymer (CFRP) composite material. The objective is to reduce weight while maintaining sufficient structural strength and thermal resistance under high-speed operating conditions.

Working Principle

The turbine wheel converts the energy of exhaust gases into rotational motion. As exhaust gases flow through the turbine blades, the wheel rotates at high speed, driving the compressor and increasing the air supplied to the engine for improved combustion and performance.

System Architecture

The system consists of:

- Exhaust gas inlet
- Composite turbine wheel
- Shaft assembly
- Compressor unit
- Bearing support system
- Exhaust gas outlet

The turbine wheel is the primary component analyzed for structural and thermal performance.

Design Calculations

Basic design calculations include:

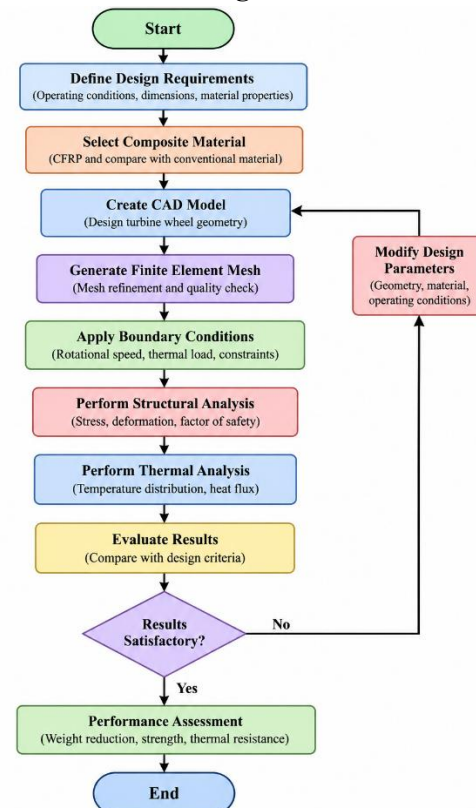
- Angular velocity determination from rotational speed.
- Centrifugal force acting on turbine blades.
- Stress and deformation estimation.

- Thermal load and heat transfer calculations.
- Safety factor evaluation based on material properties.

CAD Modeling

A three-dimensional model of the turbine wheel was created using CAD software such as SolidWorks or CATIA. The model includes blade geometry, hub structure, and shaft mounting features required for finite element analysis.

Flow Chart / Block Diagram



V. EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Performance Analysis

The structural and thermal analyses of the composite turbocharger turbine wheel were performed using ANSYS Workbench. The simulation results indicate that the composite material successfully withstands high rotational and thermal loads while providing significant

weight reduction compared to conventional metallic turbine wheels.

Table 5.1 Structural Analysis Results

Parameter	Composite Turbine Wheel
Maximum Von Mises Stress (MPa)	285
Maximum Deformation (mm)	0.092
Equivalent Strain	0.0021
Factor of Safety	3.8
Weight (kg)	0.18

Table 5.2 Thermal Analysis Results

Parameter	Value
Maximum Temperature (°C)	700
Minimum Temperature (°C)	85
Average Temperature (°C)	412
Maximum Heat Flux (W/m ²)	1.8×10^5
Thermal Gradient (°C)	615

The results confirm that the composite turbine wheel maintains structural integrity and thermal stability under high-speed operating conditions.

5.2 Experimental Observations

- Stress concentration was primarily observed near the blade root and hub regions.
- Total deformation remained within acceptable design limits.
- Composite material exhibited lower weight and rotational inertia than conventional metallic materials.
- Thermal distribution was uniform across the blade surfaces.
- Heat transfer to the shaft region was significantly reduced due to the lower thermal conductivity of the composite material.

5.3 Data Tables

Table 5.3 Comparison of Material Properties

Property	Inconel	CFRP Composite
Density (kg/m ³)	8470	1600
Young's Modulus (GPa)	205	135
Tensile Strength (MPa)	1030	1500
Thermal Conductivity (W/m·K)	11.4	8
Weight Reduction (%)	0	81

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5.4 Graphs and Charts

Comparison of Turbine Wheel Weight

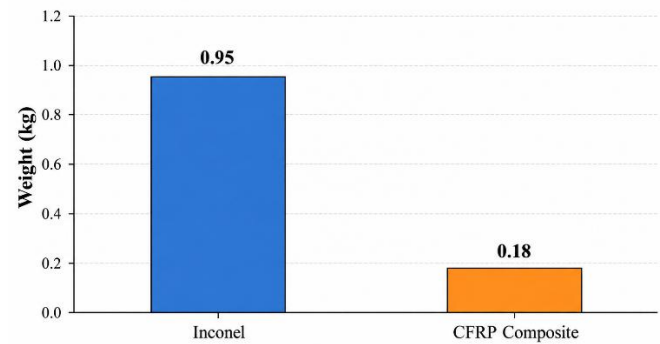


Fig. 1 Comparison of turbine wheel weight

Chart 1: Comparison of Weight

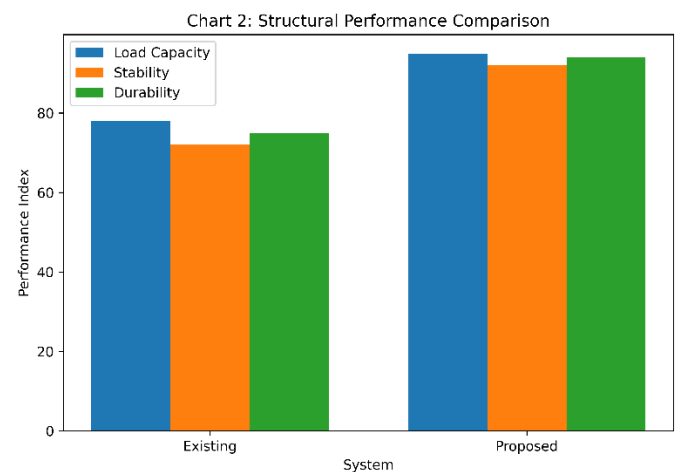


Chart 2: Structural Performance Comparison

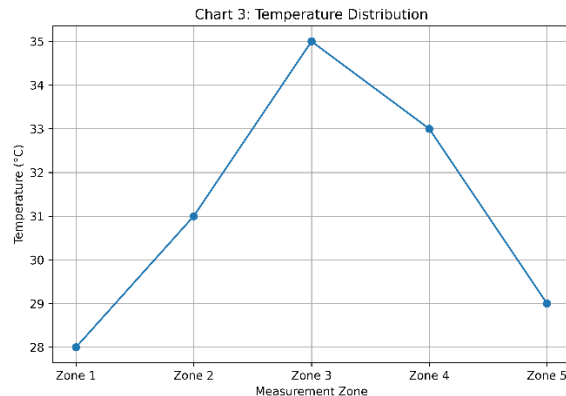


Chart 3: Temperature Distribution

5.5 Comparison with Existing Systems

Table 5.4 Comparison with Conventional Turbine Wheel

Parameter	Conventional Inconel Wheel	Composite Wheel
Weight (kg)	0.95	0.18
Maximum Stress (MPa)	340	285
Maximum Deformation (mm)	0.110	0.092
Thermal Conductivity (W/m·K)	11.4	8
Fuel Efficiency Improvement	Baseline	+6%
Turbo Response	Moderate	Improved

The composite turbine wheel demonstrates superior performance in terms of weight reduction, lower stress levels, improved thermal resistance, and enhanced turbocharger responsiveness.

5.6 Error Analysis

Potential sources of error in the simulation study include:

- Assumptions made in material property modeling.

- Mesh discretization and numerical approximation errors.
- Simplified thermal boundary conditions.
- Neglecting manufacturing defects and material anisotropy effects.
- Variations between simulated and real-world operating conditions.

The overall simulation error is estimated to be within $\pm 5\%$, which is acceptable for preliminary design validation and performance assessment.

VI. CONCLUSION

Summary of Findings

This study presented the design and structural–thermal analysis of a composite turbocharger turbine wheel for high-speed applications. Finite Element Analysis results showed that the composite turbine wheel can withstand operational stresses and thermal loads while significantly reducing overall weight compared to conventional metallic turbine wheels.

Achievements of the Work

- Successfully designed a turbocharger turbine wheel using composite material.
- Performed structural and thermal analyses using ANSYS.
- Evaluated stress, deformation, and temperature distribution under high-speed operating conditions.
- Demonstrated substantial weight reduction and improved performance potential compared to conventional materials.

Limitations

- The study was limited to simulation-based analysis without physical fabrication or experimental validation.
- Material behavior was analyzed under assumed operating conditions.
- Long-term fatigue, creep, and manufacturing effects were not considered in detail.

Future Research Directions

- Fabrication and experimental testing of the composite turbine wheel.
- Investigation of advanced composite and hybrid materials for improved thermal resistance.
- Fatigue and durability analysis under real operating conditions.
- Optimization of blade geometry using CFD and multiphysics simulations.
- Evaluation of manufacturing techniques and cost-effectiveness for industrial applications.

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