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FAILURE ANALYSIS OF TURBINE BLADES: THERMAL, MECHANICAL, AND MATERIAL PERSPECTIVES

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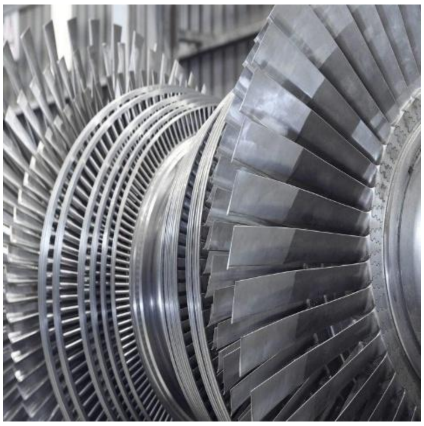
Abstract

Turbine blades operate under extreme thermal and mechanical loading conditions, making them highly susceptible to various failure mechanisms. Failures in turbine blades can lead to severe performance degradation, costly downtime, and catastrophic system breakdowns. This study presents a comprehensive failure analysis of turbine blades from thermal, mechanical, and material perspectives using numerical and analytical approaches. Finite element–based thermal, static structural, modal, and harmonic response analyses are carried out to evaluate temperature distribution, stress concentration, deformation behaviour, and vibration characteristics of a turbine blade. The results indicate that high cycle fatigue driven by vibrational stresses, combined with thermal gradients and material degradation, is a dominant failure mechanism. The study highlights critical regions prone to crack initiation and provides insight into improving turbine blade reliability through optimized design and material selection.

Keywords: Turbine blade failure, High cycle fatigue, Thermal stress, Finite element analysis, Vibration, Structural integrity

1. Introduction

Turbine blades are critical components in gas turbines, steam turbines, and aero-engines, where they are responsible for converting thermal energy into mechanical work. During operation, turbine blades are subjected to extreme environments involving high temperatures, centrifugal forces, cyclic loading, and aggressive chemical conditions. These demanding conditions make turbine blades vulnerable to various failure mechanisms, which can significantly affect the efficiency, safety, and lifespan of turbine systems.

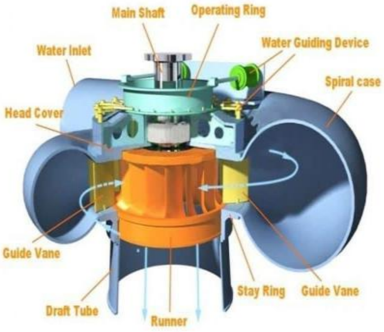


In this study, a numerical approach is adopted to analyze turbine blade failure mechanisms using thermal, mechanical, and dynamic analyses implemented in **ANSYS**. The objective is identify critical stress regions, dominant vibration modes, and failure-prone locations, thereby providing design insight for improving blade durability and operational reliability.

FRANCIS TURBINE:
The Francis turbine is a type of water turbine that was developed by James B. Francis in Lowell, Massachusetts. It is an inward –flow reaction turbine that combines radial and axial flow concepts.

PELTON WHEEL:
A Pelton wheel is an impulse-type water turbine invented by Lester Allan Pelton in the 1870s. The Pelton wheel extracts energy from the impulse of moving water, as opposed to water's dead weight like the traditional overshot water wheel.

TYPES OF MATERIALS:



Francis Turbine

- Metal
- Polymer
- Ceramic
- Composite material

ALUMINIUM: Aluminium is a chemical element with the symbol Al and atomic number 13. It is a silvery-white, soft, non-magnetic and ductile metal in the boron group.
STEEL 4340:

Alloy Steel 4340, also referred to as AISI 4340, is a nickel, chromium, and molybdenum alloy steel. This heat treatable alloy is known for its toughness and high-strength in a heat-treated condition.

JHONSON COOK MATERIAL:

The Johnson-Cook plasticity model:

- conjunction in is a particular type of Mises plasticity model with analytical forms of the hardening law and rate dependence;

- is suitable for high-strain-rate deformation of many materials, including most metals;

- is typically used in adiabatic transient dynamic simulations;

- can be used with the Johnson-Cook dynamic failure model in Abaqus/Explicit;

Johnson-Cook hardening

Johnson-Cook hardening is a particular type of isotropic hardening where the static yield stress, σ0, is assumed to be of the form

σ0=[A+B⊠(ε¯p⊠l)n]⊠(1-θ^m),

where ε¯p⊠l is the equivalent plastic strain and A, B, n and m are material parameters measured at or below the transition temperature, θ transition. θ^ is the non dimensional temperature defined as

θ^≡{0for θ<θtransition(θ-θtransition)/(θmelt- θtransition)for θtransition≤θ≤θmelt1for θ>θmelt,

Johnson-Cook strain rate dependence assumes that σ¯=σ0⊠(ε¯p⊠l,θ)⊠R⊠(ε¯˙p⊠l)

and

ε¯˙p⊠l=ε˙0⊠exp⊠[1C⊠(R-1)] for σ¯≥σ0, where

σ¯

is the yield stress at nonzero strain rate; ε¯˙p⊠l

is the equivalent plastic strain rate; ε˙0 and C

are material parameters measured at or below the transition temperature, θ transition;

σ0⊠(ε¯p⊠l,θ)

is the static yield stress; and R⊠(ε¯˙p⊠l)

is the ratio of the yield stress at nonzero strain rate to the static yield stress (so that R⊠(ε˙0)=1.0).

The yield stress is, therefore, expressed as σ¯=[A+B⊠(ε¯p⊠l)n]⊠[1+C⊠ ln⊠(ε¯˙p⊠lε˙0)]⊠(1-θ^m).

You provide the values of C and ε˙0 when you define Johnson-Cook rate dependence. The use of Johnson-Cook hardening does not necessarily require the use of Johnson-Cook strain rate dependence.

Input File Usage

Use both of the following options:

PLASTIC, HARDENING=JOHNSON COOK RATE DEPENDENT, TYPE=JOHNSON COOK

Abaqus/Explicit provides a dynamic failure model specifically for the Johnson-Cook plasticity model, which is suitable only for high-strain-rate deformation of metals. This model is referred to as the “Johnson-Cook dynamic failure model.” Abaqus/Explicit also offers a more general implementation of the Johnson-Cook failure model as part of the family of damage initiation criteria, which is the recommended technique for modeling progressive damage and failure of materials (see About damage and failure for ductile metals). The Johnson-Cook dynamic failure model is based on the value of the equivalent plastic strain at element integration points; failure is assumed to occur when the damage parameter exceeds 1. The damage parameter, ω, is defined as

ω=∑(Δ⊠ε¯p⊠lε¯fp⊠l),

where Δ⊠ε¯p⊠l is an increment of the equivalent plastic strain, ε¯fp⊠l is the strain at failure, and the summation is performed over all increments in the analysis. The strain at failure, ε¯fp⊠l, is assumed to be dependent on a non dimensional plastic strain rate, ε¯˙p⊠l/ε˙0; a dimensionless pressure-deviatoric stress ratio, p/q (where p is the pressure stress and q is the Mises stress); and the non dimensional temperature, θ^, defined earlier in the Johnson-Cook hardening model. The dependencies are assumed to be separable and are of the form

ε¯fp⊠l=[d1+d2⊠exp⊠(d3⊠pq)]⊠[1+d4⊠ln⊠(ε¯˙p⊠lε˙0)]⊠(1+d5⊠θ^),

3. IMPACT OF TURBINE:

FAILURE OF TURBINE:A common failure mode for turbine machine is high cycle of fatigue of compressor and turbine blades due to high dynamic stress caused by blade vibration and resonance within the operating range of machinery. Studies and investigations on failure of turbine blades are continuing since last five decades.

2. Literature Review

Extensive research has been conducted on turbine blade failure due to its importance in power generation and aerospace industries. Early studies identified thermal fatigue and creep as primary failure mechanisms in high-temperature turbine environments. Prolonged exposure to elevated temperatures was shown to cause microstructural degradation, leading to reduced material strength and eventual crack initiation.

High cycle fatigue (HCF) has been recognized as one of the most critical failure modes in turbine blades. Vibratory stresses induced by aerodynamic excitation, blade–row interaction, and resonance conditions can lead to crack initiation even when stress amplitudes are relatively low. Several experimental investigations have demonstrated that resonance between excitation frequencies and blade natural frequencies significantly accelerates fatigue damage.

With the advancement of numerical methods, researchers have increasingly relied on finite element–based modal and harmonic analyses to predict vibration characteristics and fatigue life of turbine blades. Studies incorporating coupled thermal–structural analysis revealed that thermal stresses can significantly alter natural frequencies and mode shapes, increasing the likelihood of resonance. Recent research emphasizes integrated thermo-mechanical analysis to accurately predict real operating conditions and failure behavior.

3. Failure Mechanisms of Turbine Blades

3.1 Thermal Failure

Thermal failure in turbine blades primarily arises from steep temperature gradients and cyclic thermal loading. Rapid startup and shutdown cycles induce thermal fatigue due to repeated expansion and contraction. Localized hot spots, often caused by non-uniform cooling or coating degradation, act as stress concentrators and promote crack initiation.

3.2 Mechanical Failure

Mechanical failure is mainly driven by centrifugal forces generated during high-speed rotation. These forces induce large tensile stresses along the blade span, particularly near the blade root. When combined with thermal stresses, the resulting stress state may exceed the material's yield or fatigue limits.

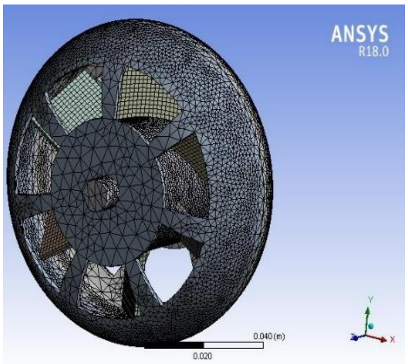
3.3 Material Degradation

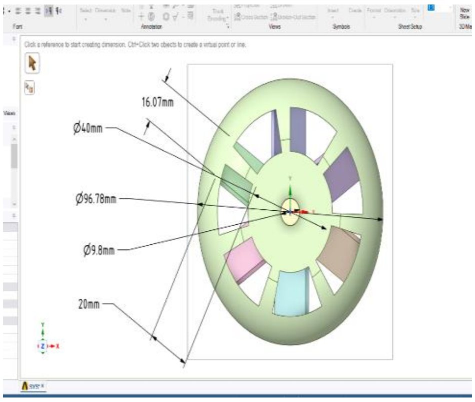
Material-related failures include creep, oxidation, and corrosion. At elevated temperatures, creep deformation accumulates over time, leading to permanent elongation and eventual rupture. Oxidation and hot corrosion weaken protective coatings and expose the base material, accelerating crack growth.

4. Numerical Methodology

4.1 Geometry and Material Properties

A three-dimensional turbine blade model is developed based on standard industrial blade geometry. The blade material is assumed to be a nickel-based superalloy, commonly used in high-temperature turbine applications, with temperature-dependent material properties.

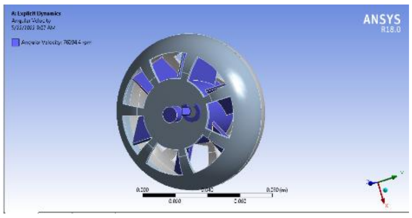




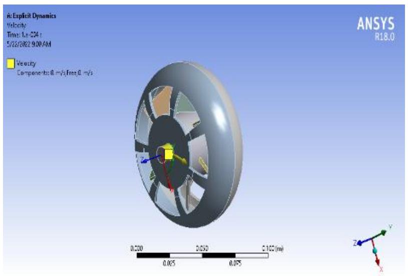
INTRODUCTION TO FEM

The finite element method (FEM) is the most widely used method for solving problems of engineering and mathematical models. Typical problem areas of interest include the traditional fields of structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential.

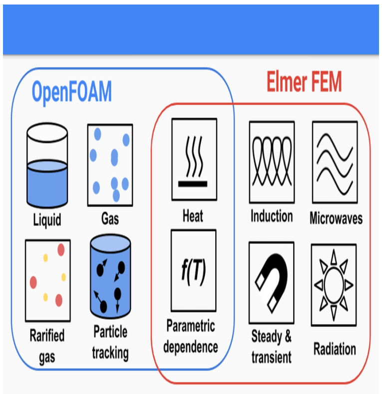
MESH: ANGULAR VELOCITY:

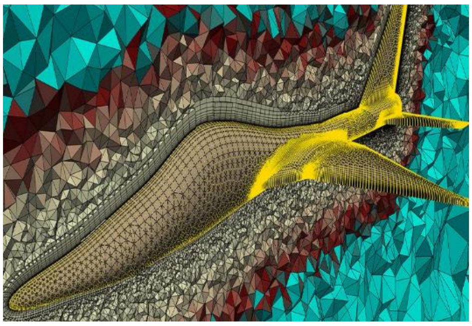


VELOCITY:



INTRODUCTION TO FVM:



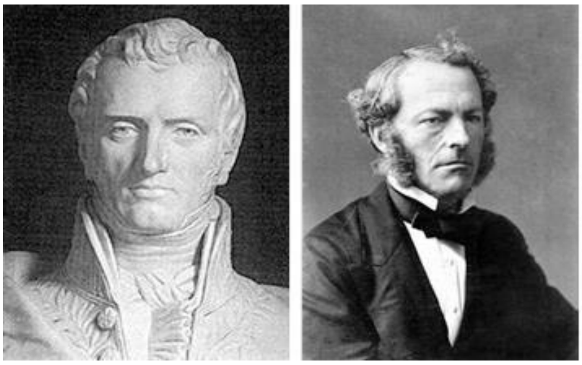


The finite volume method (FVM) is a method for representing and evaluating partial differential equations in the form of algebraic equations [LeVeque, 2002; Toro, 1999]. In the finite volume method, volume integrals in a partial differential equation that contain a divergence term are converted to surface integrals, using the divergence theorem

CFD:

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows

History of Computational Fluid DynamicsFrom antiquity to present, humankind has been eager to discover phenomena based on fluid flow. So, how old is CFD? Experimental studies in the field of computational fluid dynamics have one big disadvantage: if they need to be accurate, they consume a significant amount of time and money.The bigger picture: The central mathematical description for all theoretical fluid dynamics models is given by the Navier-Stokes equations, which describe the motion of viscous fluid domains.



Governing Equations

The main structure of thermo-fluids examinations is directed by governing equations that are based on the conservation INLET: law of fluid's physical properties. The basic equations are the three physics laws of conservation10,1110,11:

1. Conservation of Mass: Continuity Equation

2. Conservation of Momentum: Momentum Equation of Newton's Second Law

3. Conservation of Energy: First Law of Thermodynamics or Energy Equation

These principles state that mass, momentum and energy are stable constants within a closed system. Basically: What comes in, must also go out somewhere else.

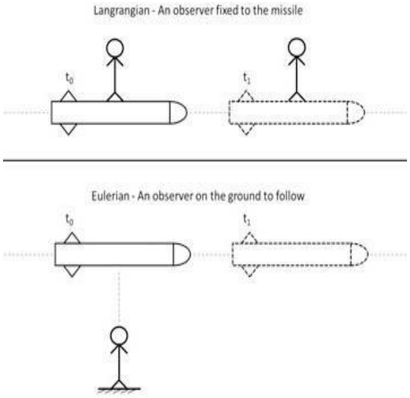
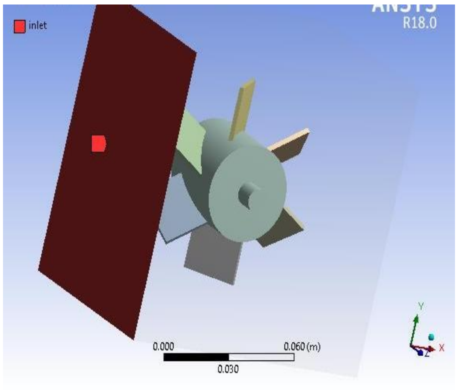
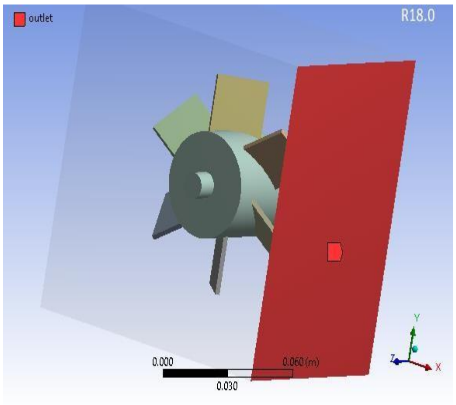


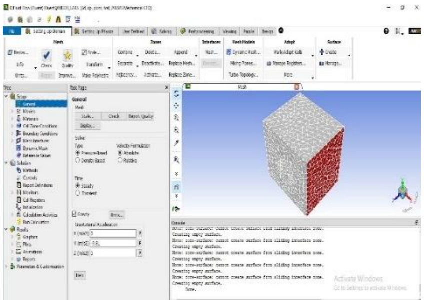
Figure 3: Observation of fluid motion with the methods of Lagrange and Euler

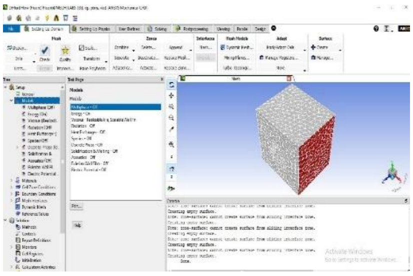


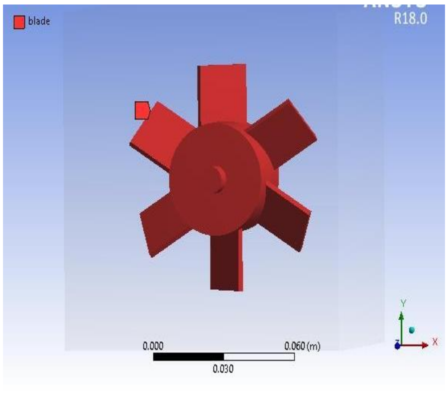
OUTLET:



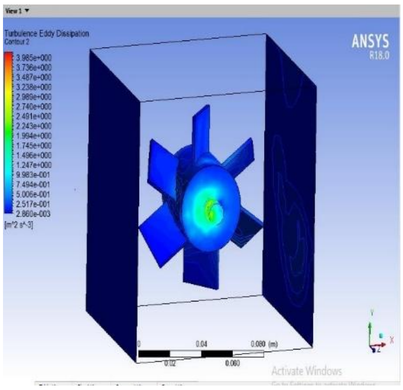
BLADE:



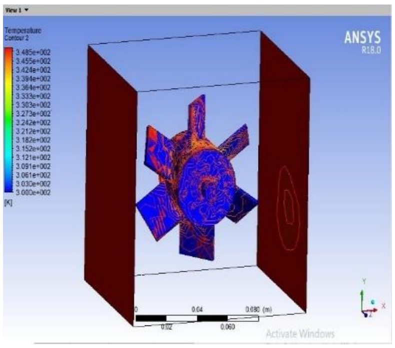




GENERAL:



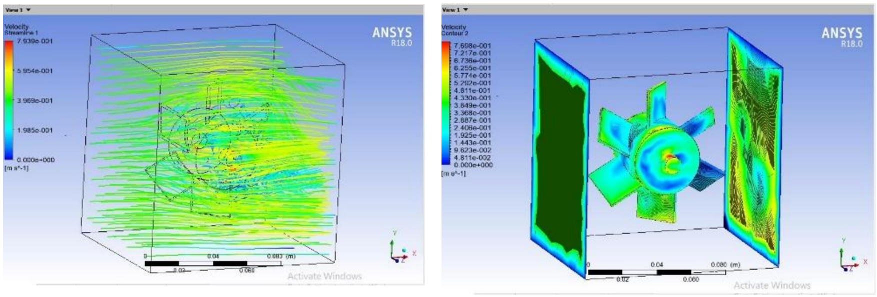
MODELS:
TEMPERATURE:



TURBOLANCE EDDY DISSIPATION:

TURBOLANCE KINETIC ENERGY:

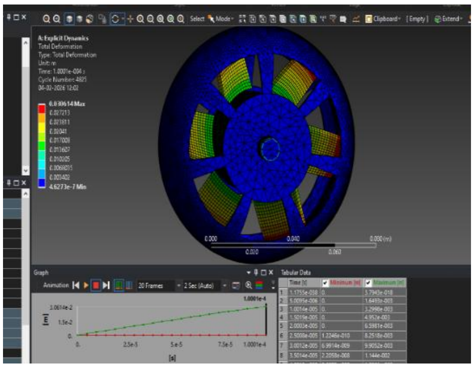
VELOCITY CONTOUR:



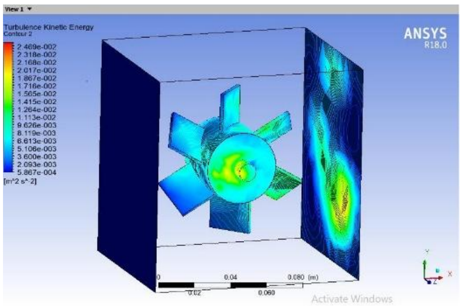
EXPLICIT DYNAMICS:With the implementation of an explicit solver in ANSYS Workbench there is another advanced analysis type available in this versatile user interface. The phrase “Explicit” refers to a type of time integration used to perform dynamic simulations.

Prerequisites: ANSYS Mechanical, Non-Linear Structural Analysis with ANSYS Mechanical

TOTAL DEFORMATION:


A: Explicit Dynamics
Total Deformation
Type: Total Deformation
Unit: m
Time: 1.0001e-004 s
Cycle Number: 4825
04-02-2026 12:02

TOTAL DEFORMATION



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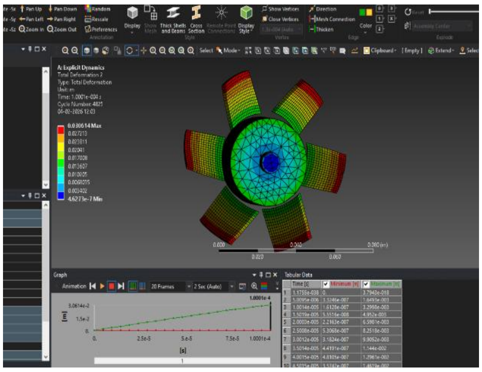
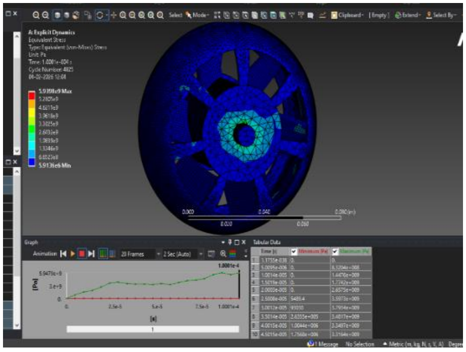
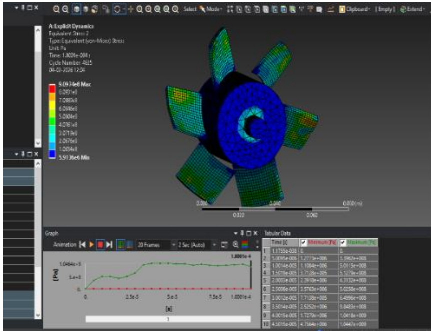

A: Explicit Dynamics
Total Deformation 2
Type: Total Deformation
Unit: m
Time: 1.0001e-004 s
Cycle Number: 4825
04-02-2026 12:03

EQUIVALENT STRESS:

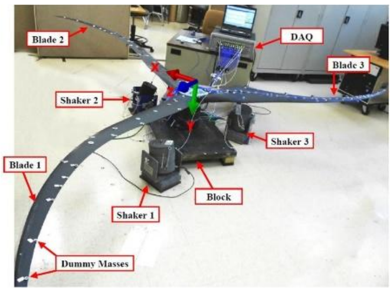

A: Explicit Dynamics
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1.0001e-004 s
Cycle Number: 4825
04-02-2026 12:04

EQUIVALENT STREES 2:

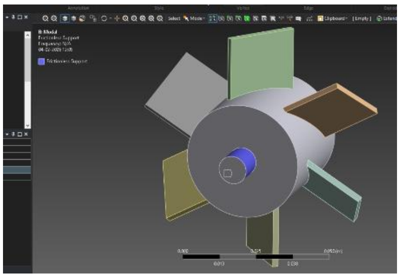

A: Explicit Dynamics
Equivalent Stress 2
Type: Equivalent (von-Mises) Stress
Unit: Pa
Cycle Number: 4825

MODEL ANALYSIS:

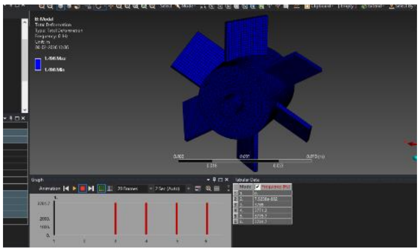
Modal analysis is the study of the dynamic properties of systems in the frequency domain. Examples would include measuring the vibration of a car's body when it is attached to a shaker, or the noise pattern in a room when excited by a loudspeaker.



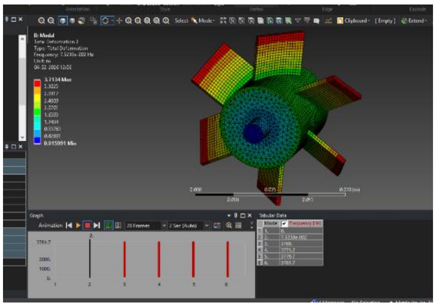
FRICTIONLESS SUPPORT:



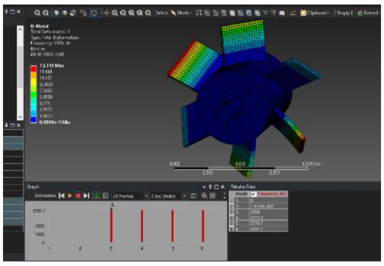
Total Deformation:



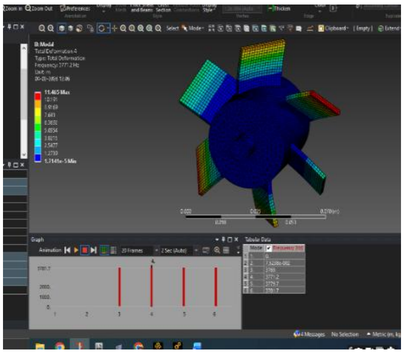
Total Deformation 2:



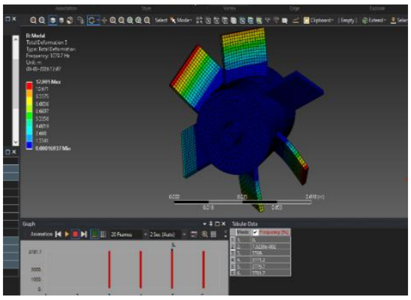
Total Deformation 3:



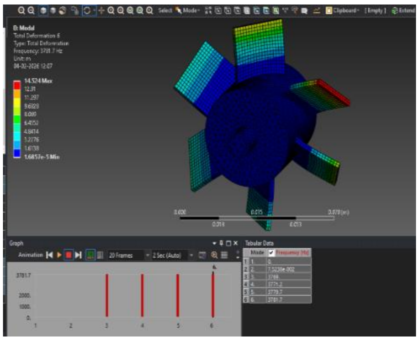
Total Deformation4:



Total Deformation 5:

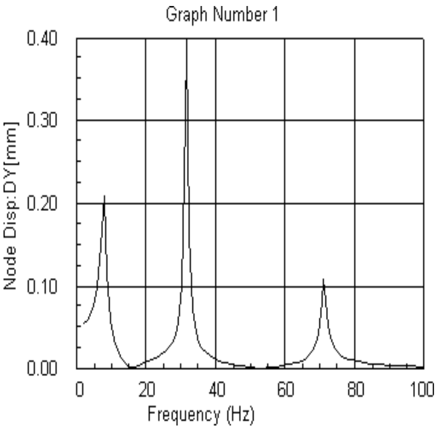


Total Deformation 6:

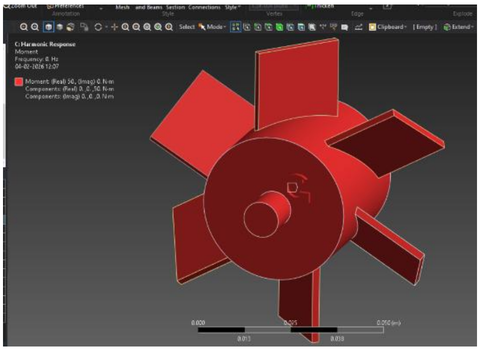


Base Excitation

The structure is excited harmonically at the fixed degrees of freedom. The excitation is defined by a direction vector of displacement, velocity or acceleration. This type of loading is particularly useful for modeling shaker table tests, as the base nodes are often the locations where nodal degrees of freedom are fixed.



Moment:



2 Thermal Analysis

Thermal analysis is conducted to determine temperature distribution along the blade under steady operating conditions. Convective heat transfer is applied on the blade surface, while internal cooling passages are modeled using effective heat transfer coefficients.

4.3 Structural and Dynamic Analysis

The temperature field obtained from thermal analysis is imported into structural analysis to compute thermal stresses and deformation. Modal analysis is performed to determine the blade's natural frequencies and mode shapes. Harmonic response analysis is then carried out to evaluate vibration amplitude under periodic excitation and to assess high cycle fatigue risk.

5. Results and Discussion

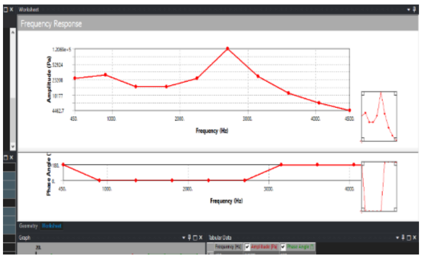
5.1 Temperature Distribution

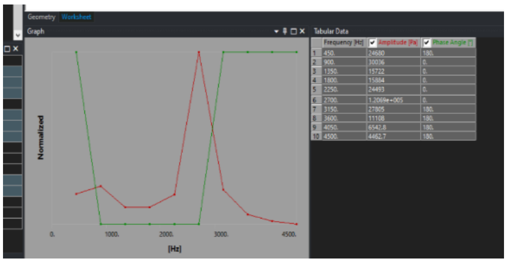
The thermal analysis shows a non-uniform temperature distribution along the blade span, with maximum temperatures occurring near the leading edge and blade tip. These regions experience the highest thermal gradients, making them susceptible to thermal fatigue.

5.2 Stress and Deformation

Structural results indicate that maximum von Mises stresses occur at the blade root and near cooling hole locations. The combined effect of centrifugal and thermal loads significantly increases stress levels, highlighting potential crack initiation zones.

Frequency response steel





	Frequency [Hz]	☑ Amplitude [Pa]	☑ Phase Angle [°]
1	450.	24680	180.
2	900.	30036	0.
3	1350.	15722	0.
4	1800.	15884	0.
5	2250.	24493	0.
6	2700.	1.2069e+005	0.
7	3150.	27805	180.
8	3600.	11108	180.
9	4050.	6542.8	180.
10	4500.	4462.7	180.

Phase changes

5.3 Modal and Harmonic Response

Modal analysis reveals several closely spaced natural frequencies within the operating excitation range. Harmonic response results show amplified vibration amplitudes near resonance conditions, confirming high cycle fatigue as a dominant failure mechanism.

6. Conclusion

This study presents a comprehensive numerical investigation of turbine blade failure mechanisms from thermal, mechanical, and material perspectives. The results demonstrate that turbine blade failure is governed by a complex interaction between thermal gradients, centrifugal loading, vibrational stresses, and material degradation. High cycle fatigue, driven by resonance and dynamic excitation, is identified as the most critical failure mode under normal operating conditions.

The integrated thermal–structural–dynamic approach adopted in this work provides an effective framework for early-stage failure prediction and design optimization. The findings emphasize the importance of accurate thermal management, vibration control, and material selection in enhancing turbine blade reliability and service life.

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