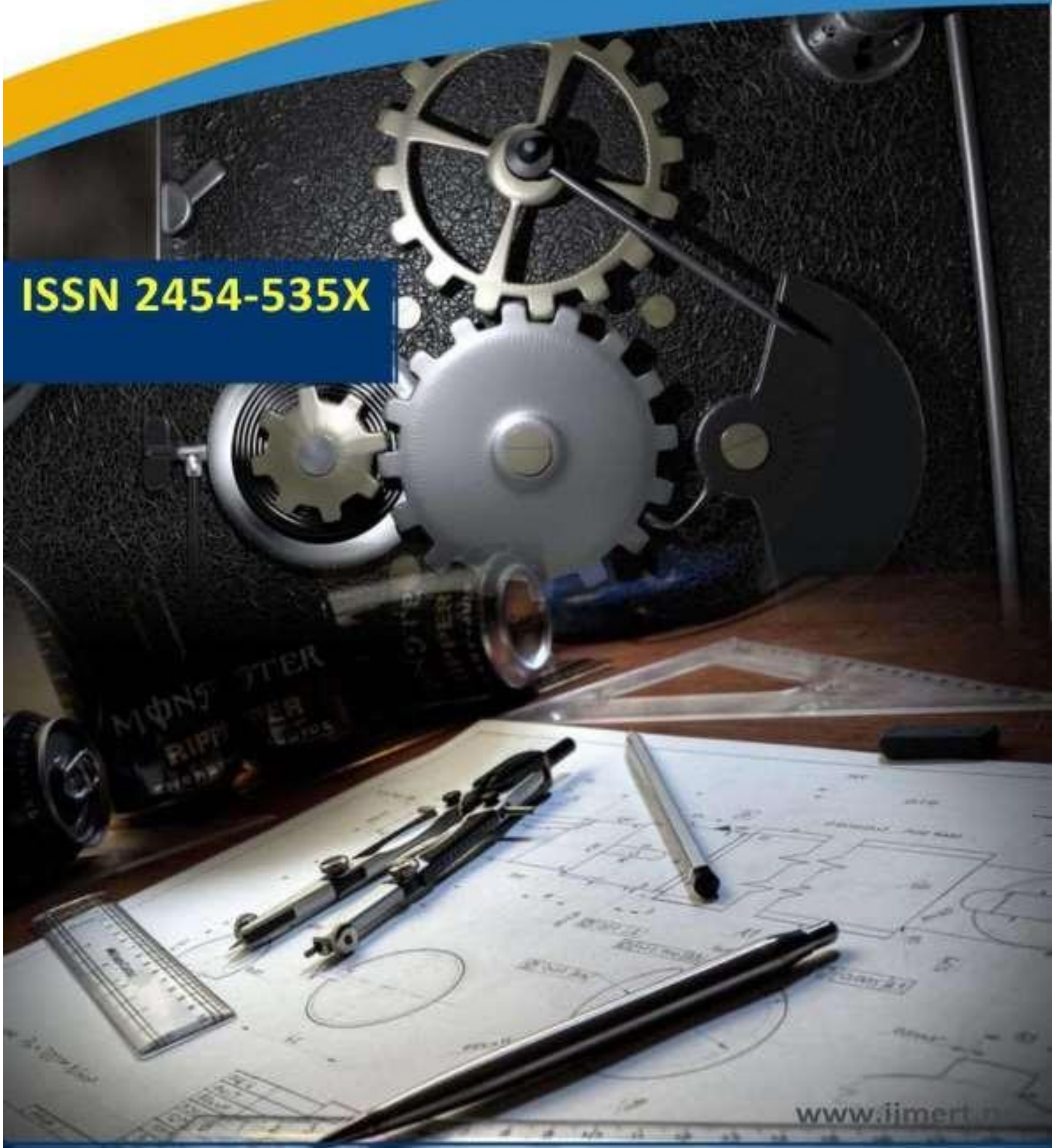
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STATIC STRUCTURAL AND MODAL ANALYSIS OF A MULTISTAGE AXIAL COMPRESSOR USING MULTISTAGE CYCLIC SYMMETRY

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Abstract

Multistage cyclic symmetry analysis provides an efficient framework for evaluating complex turbomachinery assemblies composed of multiple cyclically symmetric subsystems with different sector counts. This study presents the static structural, modal, and prestressed modal analysis of a four-stage axial compressor model consisting of three blade rows and a supporting rim.

Each stage is modeled as an independent cyclic subsystem and connected using multistage interstage coupling. The structure is subjected to rotational speed, stage-wise pressure loading, and thermal gradients to simulate realistic operating conditions.

Static results show stress concentration at blade roots and interstage interfaces, while modal analysis reveals harmonic-index-dependent vibration behavior. Prestressed modal analysis demonstrates centrifugal stiffening effects and frequency shifts under operational loads.

1. Introduction

Axial compressors are critical components in gas turbines and aero-engines. They operate under:

- High rotational speeds
- Aerodynamic pressure loads
- Thermal gradients
- Complex multistage coupling

These conditions induce combined centrifugal, thermal, and bending stresses that directly influence fatigue life and vibration behavior.

Modeling full 360° compressor assemblies using conventional FEA is computationally expensive. Cyclic symmetry allows modeling of a single representative sector instead of the full geometry. However, traditional cyclic symmetry assumes identical sector counts across the entire structure.

Real compressors consist of multiple stages with different blade counts. This requires **multistage cyclic symmetry**, which enables coupling of cyclic subsystems with different periodicities.

This study demonstrates a complete workflow for multistage cyclic symmetry analysis using:

- Static structural analysis
- Modal analysis
- Prestressed modal analysis

2. Literature Review

2.1 Cyclic Symmetry in Rotating Machinery

Cyclic symmetry reduces computational effort by exploiting circumferential periodicity. Mode shapes are described using **harmonic indices (HI)** or **nodal diameters (ND)**.

For HI > 0:

- Traveling wave modes occur
- Frequencies appear in pairs

2.2 Limitations of Classical Cyclic Symmetry

Single-stage cyclic symmetry cannot model:

- Different blade counts across stages
- Interstage stiffness coupling
- Multi-row vibration interaction

2.3 Multistage Cyclic Symmetry

Multistage cyclic symmetry:

- Allows different sector counts per stage
- Enforces compatibility at interstage boundaries
- Maps harmonic behavior across subsystems

It accurately captures:

- Interstage mode coupling
- Traveling wave propagation
- Prestress-induced stiffness changes

2.4 Importance of Prestress

Centrifugal forces cause:

- Tensile stress
- Centrifugal stiffening
- Increased natural frequencies

Thermal stresses modify stiffness and must be included for realistic modal prediction.

3. Material Modeling

All components are modeled as:

- Homogeneous

- Isotropic
- Linearly elastic

Assumptions:

- Hooke’s law applies
- No plasticity
- No creep
- No temperature-dependent properties

Thermal strain:

$$\varepsilon_{th} = \alpha \Delta T$$

Von Mises stress is used to evaluate equivalent stress distribution.

3.1 Material Modeling Assumptions

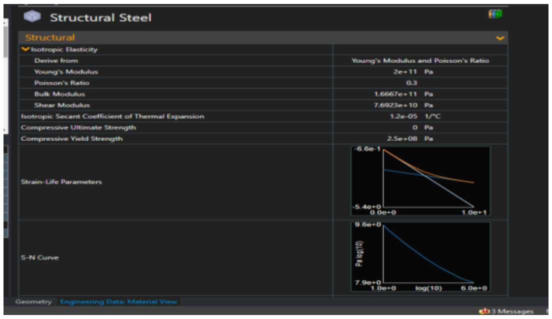
All compressor components, including the blade rows and the supporting rim, are modeled as **homogeneous, isotropic, and linearly elastic solids**. This assumption is widely adopted in preliminary design and vibrational studies of turbomachinery, where the objective is to evaluate global deformation patterns, stress distribution, and modal characteristics rather than localized material nonlinearities.

The linear elastic assumption implies:

- Stress is proportional to strain (Hooke’s law).
- Material behavior is independent of loading history.
- Superposition of loads is valid.
- No plastic deformation, creep, or damage evolution is considered.

Such assumptions are appropriate for:

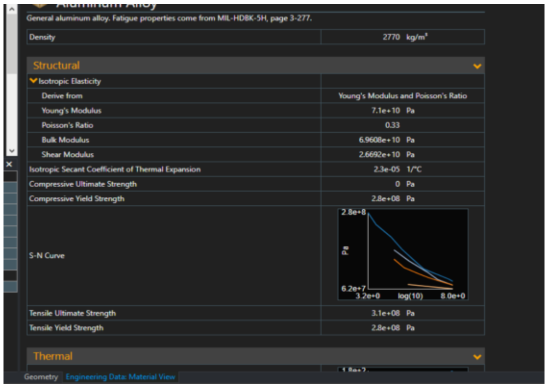
- Modal and prestressed modal analyses.
- Operating conditions within elastic limits.
- Comparative studies focusing on structural response trends.



Structural Steel

Structural

Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2e+11 Pa
Poisson's Ratio	0.3
Bulk Modulus	1.6667e+11 Pa
Shear Modulus	7.6923e+10 Pa
Isotropic Secant Coefficient of Thermal Expansion	1.2e-05 1/°C
Compressive Ultimate Strength	0 Pa
Compressive Yield Strength	2.5e+08 Pa
Strain-Life Parameters	
S-N Curve	



Aluminum Alloy

General aluminum alloy. Fatigue properties come from MIL-HDBK-5H, page 3-277.

Density	2770 kg/m³

Structural

Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	7.1e+10 Pa
Poisson's Ratio	0.33
Bulk Modulus	6.9608e+10 Pa
Shear Modulus	2.6692e+10 Pa
Isotropic Secant Coefficient of Thermal Expansion	2.3e-05 1/°C
Compressive Ultimate Strength	0 Pa
Compressive Yield Strength	2.8e+08 Pa
S-N Curve	
Tensile Ultimate Strength	3.1e+08 Pa
Tensile Yield Strength	2.8e+08 Pa

Thermal

Aluminum Alloy

4. Geometry and Model Description

4.1.1 General Configuration of the Compressor Model

The axial compressor considered in this study consists of **three blade rows mounted on a common supporting rim**, forming a simplified but representative multistage compressor assembly. For the purpose of structural and vibrational analysis, the geometry is idealized as **four axially aligned cyclic stages**, where each stage represents a cyclically repeating structural subsystem.

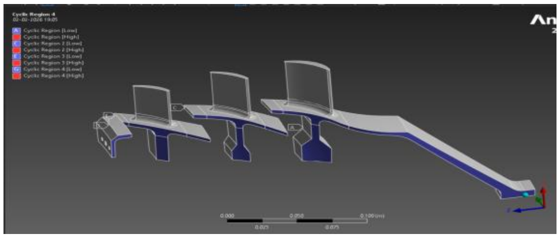
The four stages include:

- **Stage 1:** First blade row
- **Stage 2:** Second blade row
- **Stage 3:** Third blade row
- **Stage 4:** Outer rim (supporting structure)

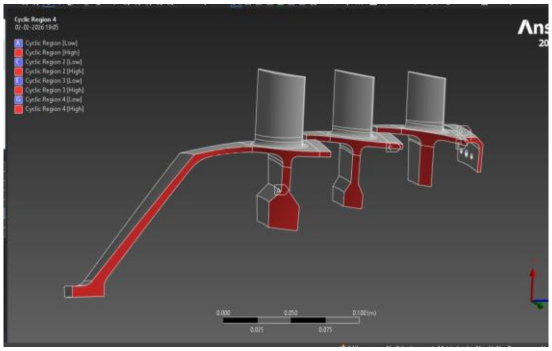
Each blade row is modeled as a solid three-dimensional body attached to the rim, reflecting the load path typically observed in real compressor assemblies, where centrifugal and aerodynamic loads from the blades are transferred to the disk or rim.

4.1.2 Cyclic Sector Modeling

Instead of modeling the full 360° compressor geometry, each stage is represented by **a single circumferential sector**, exploiting the periodic nature of turbomachinery structures. The sector angle for each stage is determined by the total number of identical repeating segments (sector count) in that stage.



Cyclic Region 1



Cyclic Region 2

The sector counts for the four stages are summarized in **Table 1**.

The compressor consists of four cyclic stages:

Stage	**Component**	**Sector Count**
1	Blade Row 1	43
2	Blade Row 2	48
3	Blade Row 3	54
4	Supporting Rim	30

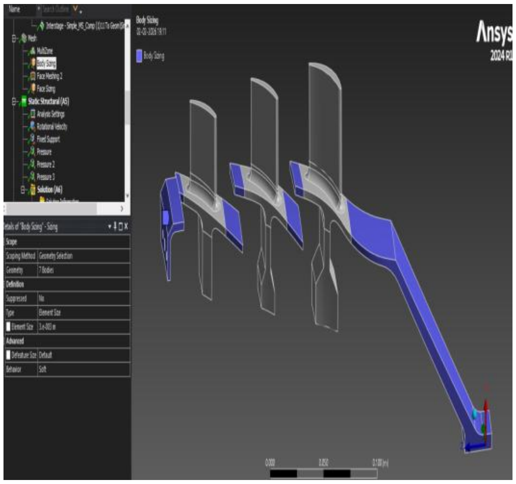
Each stage is modeled using one representative sector.

Compressor Configuration

Three blade rows are axially aligned and mounted on a supporting rim. Interstage boundaries connect adjacent stages and allow load transfer.

5. Meshing Methods

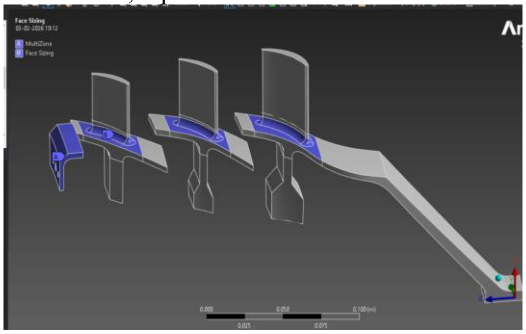
Finite element mesh quality plays a decisive role in the accuracy, convergence, and numerical stability of multistage cyclic symmetry analyses. In axial compressor models, meshing is particularly challenging due to complex blade geometries, high stress gradients near blade roots, and the presence of multiple cyclic and interstage interfaces. This chapter describes the meshing strategy adopted for the multistage compressor model and discusses the theoretical considerations underlying mesh selection for cyclic and multistage coupling.



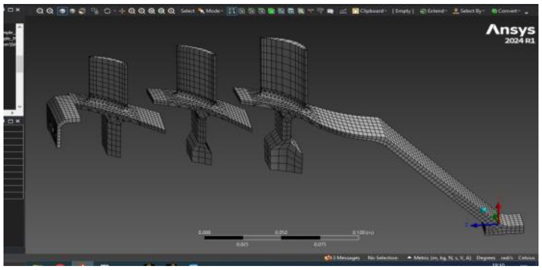
Details of "Body Sizing" - Sizing

Scope	
Scoping Method	Geometry Selection
Geometry	7 Bodies
Definition	
Suppressed	No
Type	Element Size
Element Size	1.e-003 m
Advanced	
Defeature Size	Default
Behavior	Soft

Body sizing



Face Sizing



Mesh

5. Multistage Cyclic Symmetry Methodology

5.1 Stage Definition

Each stage:

- Has independent cyclic region
- Uses cylindrical coordinate system
- Has defined harmonic indices

5.2 Interstage Objects

Interstage boundaries enforce:

- Displacement compatibility
- Force equilibrium
- Harmonic mapping

5.3 Meshing Strategy

- Quadratic solid elements

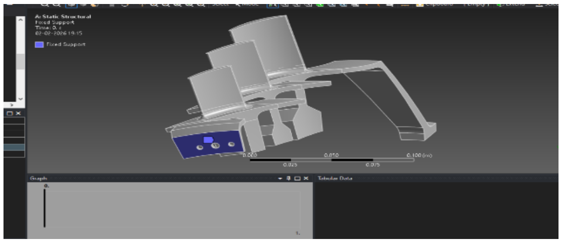
- Similar mesh size at interstage boundaries
- Local refinement at blade roots
- Matching cyclic boundaries preferred

6. Boundary Conditions and Loading

Boundary conditions and loading definitions play a critical role in determining the accuracy and physical realism of structural and dynamic simulations of axial compressors.

6.1 Support Condition

Fixed support applied to outer rim face.



Fixed Support

6.2 Rotational Loading

Angular velocity:

$$\omega = 1000 \text{ rad/s}$$

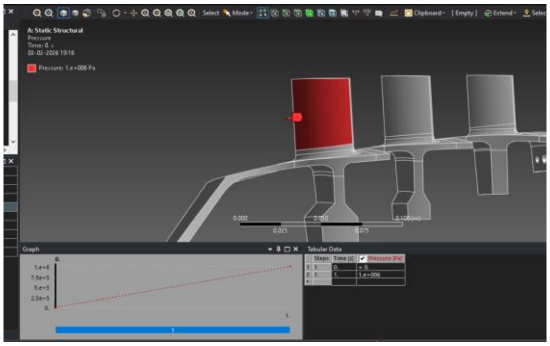
Centrifugal body force:

$$F = \rho\omega^2 r$$

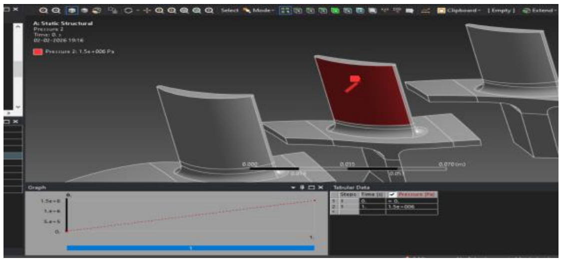
6.3 Pressure Loading

Stage	Pressure
Stage 1	1 MPa
Stage 2	1.5 MPa
Stage 3	2 MPa

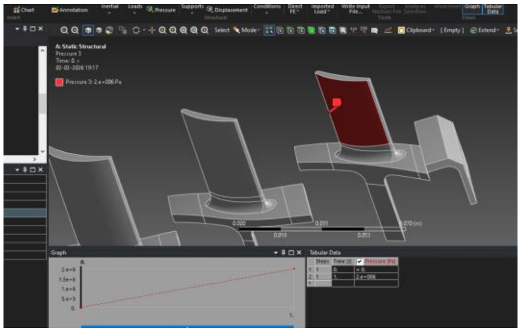
These pressures are applied as **surface loads** normal to the blade faces and are assumed to be uniformly distributed over the loaded areas.



Pressure 1



Pressure 2



Pressure 3

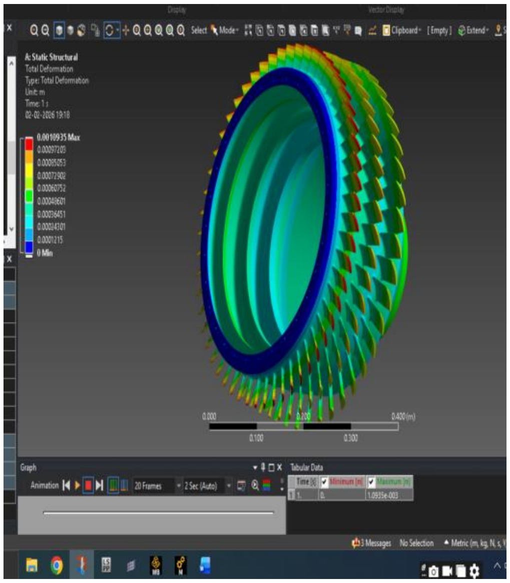
6.4 Thermal Loading

Stage	**Temperature**
Stage 1	200°C
Stage 2	250°C
Stage 3	300°C
Rim	350°C

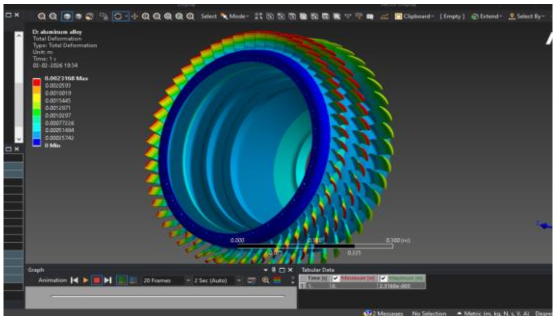
All loads are axisymmetric (HI = 0).

7. Static Structural Results

7.1 Total Deformation



Deformation



Deformation aluminum

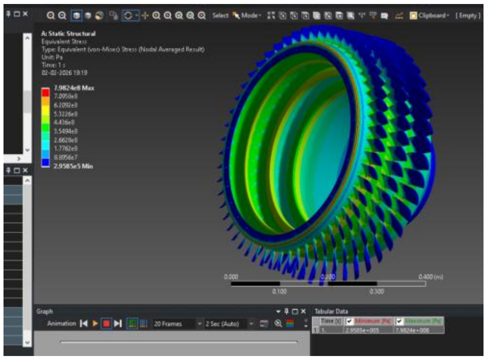
Observations:

- Maximum deformation at blade tips
- Radial displacement dominant
- Continuous deformation across stages

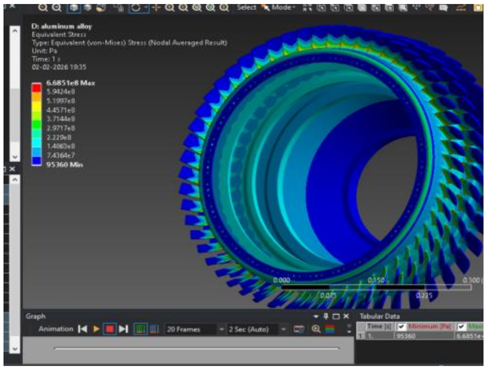
7.2 Equivalent Stress Distribution

The von Mises equivalent stress results provide insight into the internal stress state of the compressor under static loading. The stress contours reveal that:

- **Peak von Mises stresses reach values on the order of 3004 MPa** in the tutorial results.
- High stress concentrations are observed primarily in:
  - Blade root regions
  - Blade–rim junctions
  - Interstage interfaces



Equivalent Stress



Equivalent stress aluminum

These regions experience combined effects of centrifugal tension, bending due to pressure loading, and constrained thermal expansion.

Key findings:

- Peak stress ≈ 3004 MPa
- Highest stress at blade roots
- Stress concentration at interstage boundaries

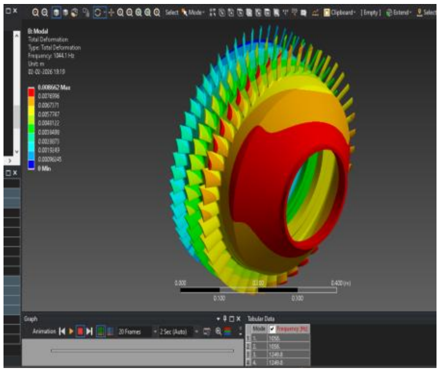
8. Modal Analysis (Unstressed)

8.1 HI = 0 (Axisymmetric)

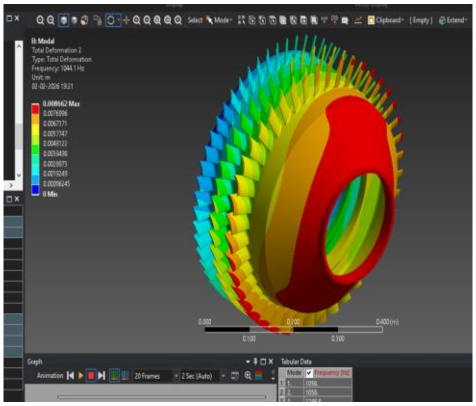
First natural frequency ≈ 1006 Hz

Characteristics:

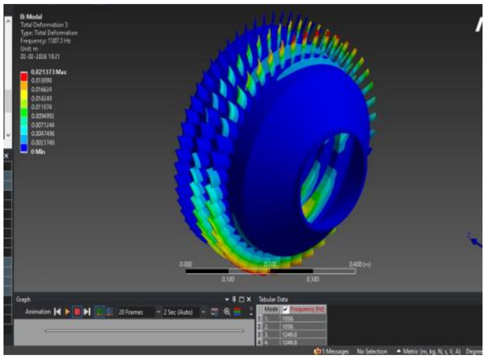
- No nodal diameters
- Global bending behavior



Deformation 1



Deformation 2



Deformation 3

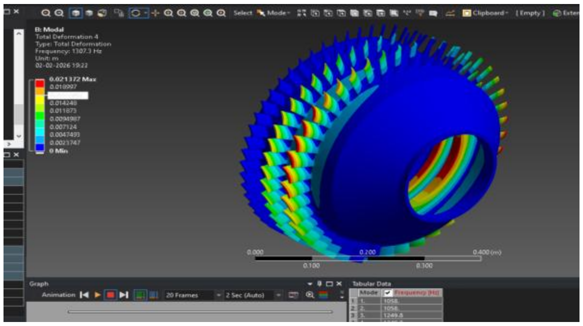
8.2 HI = 1 and HI = 2

When harmonic indices **HI = 1** and **HI = 2** are assigned consistently across all stages, additional families of natural frequencies are obtained.

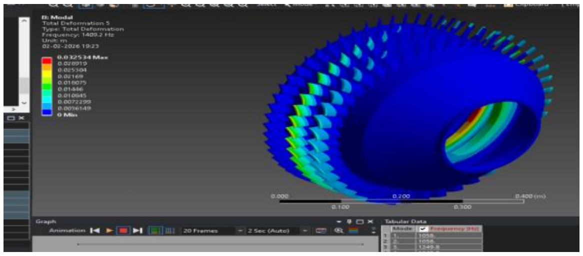
For HI > 0:

- Paired frequencies
- Traveling wave modes

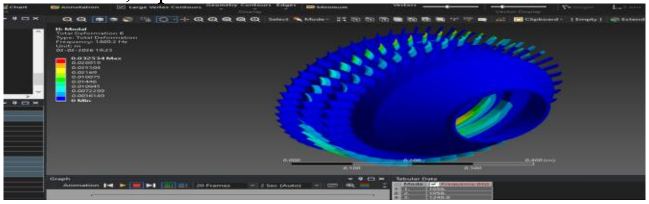
Forward and backward wave pairs An example from the tutorial shows HI = 1 mode shapes at frequencies near **1249.5 Hz**, labeled as **Mode 3 and Mode 4**, clearly demonstrating the paired traveling wave nature.



Deformation 4



Deformation 5



Deformation 6

9. Prestressed Modal Analysis

Including prestress shifts natural frequencies.

Example:

Case	**First Frequency**
Unstressed	1006 Hz
Prestressed	1054 Hz

Effects Observed:

- Centrifugal stiffening increases frequencies
- Thermal stress modifies stiffness
- Mode topology unchanged

10. Material Comparison

Material	**Max Deformation (m)**	**Equivalent Stress (Pa)**
Structural Steel	0.0007	5.0E8
Aluminum Alloy	0.0018	5.4E8

Aluminum shows:

- Higher deformation
- Similar stress magnitude

- Lower stiffness response

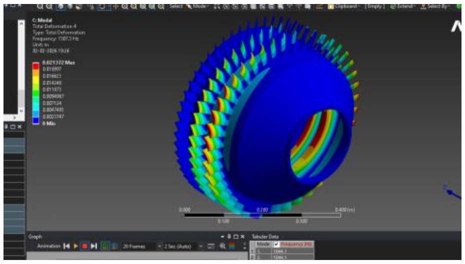
11. Discussion

The study demonstrates:

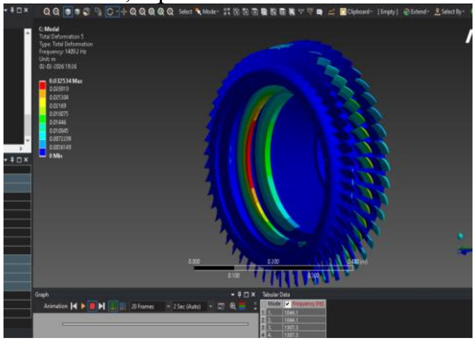
- Accurate interstage load transfer
- Correct harmonic behavior
- Proper frequency pairing for HI > 0
- Realistic centrifugal stiffening

Multistage cyclic symmetry:

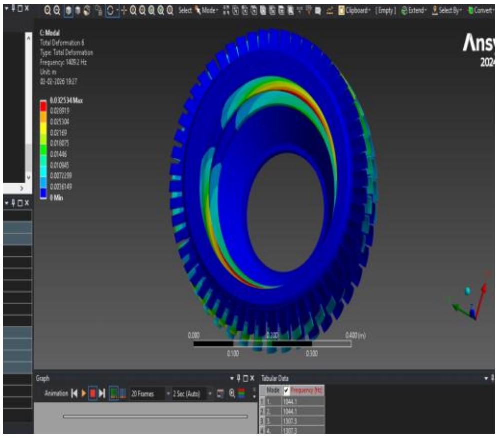
- Reduces computational cost drastically
- Preserves physical accuracy
- Handles mismatched sector counts
- The close agreement between expected theoretical behavior and computed results validates the modeling strategy and solver implementation.



Deformation 4

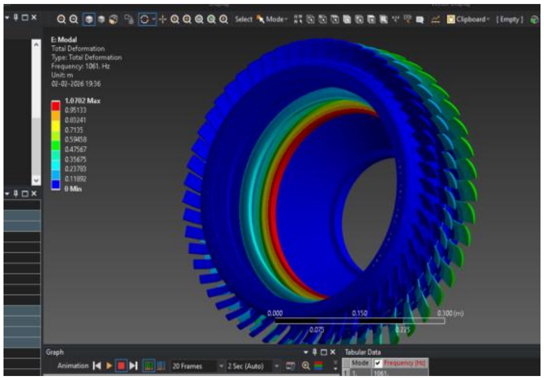


Deformation 5

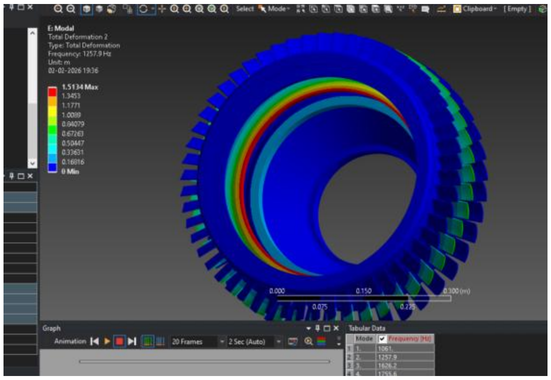


Deformation 6

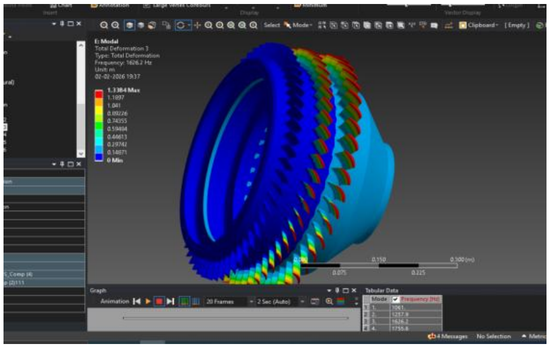
Aluminum Mode shapes



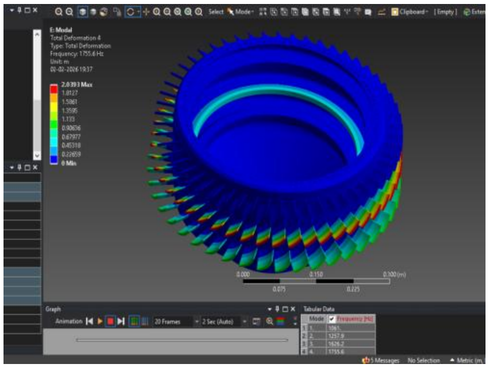
Deformation 1



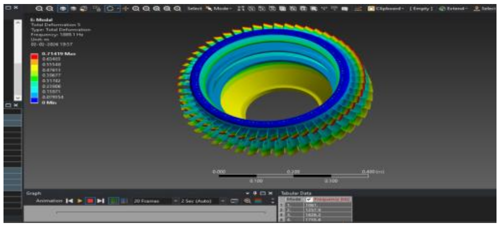
Deformation 2



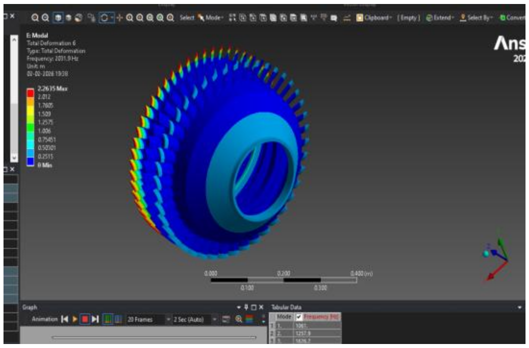
Deformation 3



Deformation 4



Deformation 5



Deformation 6

12. Conclusion

This study successfully demonstrates static, modal, and prestressed modal analysis of a multistage axial compressor using multistage cyclic symmetry.

Key conclusions:

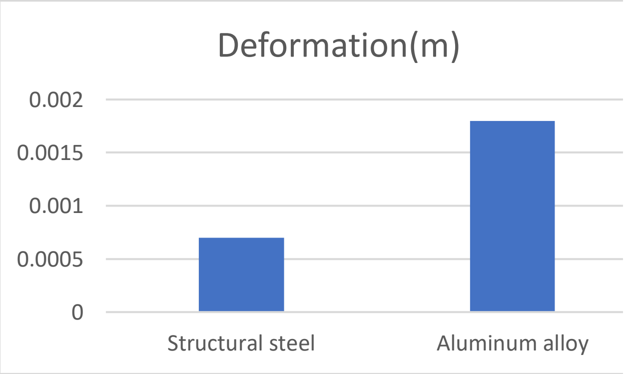
1. Maximum deformation occurs at blade tips.
2. Highest stresses occur at blade roots and interstage regions.
3. Harmonic indices govern circumferential vibration patterns.
4. HI > 0 modes occur in frequency pairs.
5. Prestress increases natural frequencies due to centrifugal stiffening.
6. Multistage cyclic symmetry effectively models different sector counts.

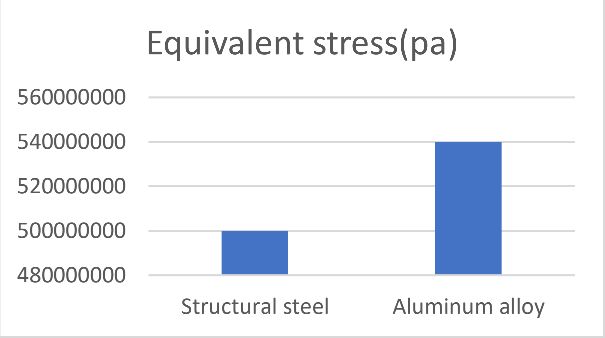
The methodology provides an efficient and accurate framework for turbomachinery structural and vibration analysis.

S.No	Material	Deformation (m)	Equivalent stress(pa)
1	Structural steel	0.0007	500000000
2	Aluminum alloy	0.0018	540000000

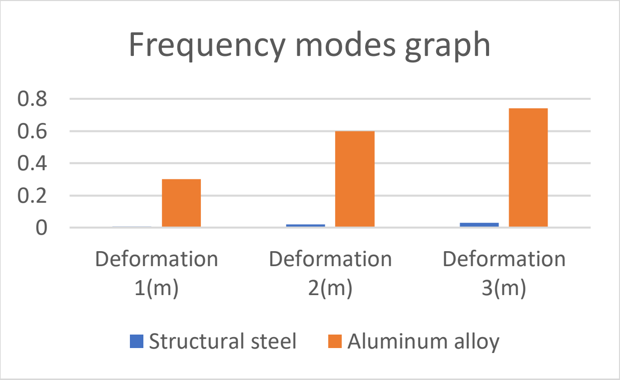
Frequency Tabular data

Material	Deformation 1(m)	Deformation 2(m)	Deformation 3(m)
Structural steel	0.008	0.02	0.03
Aluminum alloy	0.3	0.6	0.74





Frequency graph



9. References

Ansys, Inc.“*Chapter 14: Static and Modal Analysis of a Compressor Model with 4 Axial Stages,*” in **ANSYS Mechanical Tutorials 2025 R2.**This tutorial provides practical step-by-step instructions for setting up and solving multistage cyclic symmetry problems in Ansys Mechanical and was used as the primary workflow reference in this study. It includes definitions of cyclic regions, stage and interstage objects, load application, and example result interpretation.

Ansys, Inc.*Multistage Cyclic Symmetry Analysis Guide,* Release 2025 R2. This guide serves as the main methodological and theoretical reference for multistage cyclic symmetry modeling with details on cyclic symmetry formulation, interstage coupling, harmonic indices, limitations, and best practices for setup and interpretation.

Ansys, Inc.*Mechanical User's Guide*, sections on **Cyclic Symmetry** and **Multistage Cyclic Symmetry Analysis**, Release 2025 R2.These sections explain the general theory and practical application of cyclic symmetry features in Ansys Mechanical, including boundary condition enforcement, cyclic region definitions, supported analysis types, and post-processing of cyclic results.

Scholarly and Technical References

Bonnet, E., & Sas, P.*Reduced models of multi-stage cyclic structures using cyclic symmetry reduction and component mode synthesis,* Journal of Sound and Vibration, Vol. 333, Issue 21, pp. 5443–5463 (2014).This paper develops reduced finite element models for multi-stage cyclic structures using cyclic symmetry reduction combined with component mode synthesis. It provides a rigorous mathematical basis for multi-stage modeling and traveling wave representations, extending classical cyclic analysis techniques to more complex assemblies.

Dong, B.*Modal Analysis of General Cyclically Symmetric Systems with Applications to Multi-Stage Structures*, PhD Thesis, Virginia Tech (2019).This dissertation investigates modal properties of general cyclically symmetric systems, including multi-stage assemblies such as planetary gears and coupled blades, and discusses efficient numerical strategies to compute natural frequencies and mode shapes in the presence of cyclic symmetry.

Kim, C. B., Ahn, Y. C., Kim, B. Y., Cho, C. D., & Beom, H. G.*Finite Element Analysis of Blower Impeller Using Cyclic Symmetry,* Key Engineering Materials, Vols. 353–358, pp. 1082–1085 (2007). This study applies cyclic symmetry in finite element analysis of impeller structures to evaluate static and dynamic behavior efficiently using reduced sector models. While not a multistage case, it provides insight into cyclic modeling techniques, harmonic displacement representation, and validation of reduced models against full models.

Tabriz, M. S. E.*Finite Element Analysis of Compressor Wheel Geometry (PhD Thesis)*, University of Huddersfield (2025).This research explores the application of cyclic symmetry in finite element modeling of compressor wheels, emphasizing model reduction benefits, cyclic boundary enforcement, and comparative studies between reduced and full-geometry analysis.

Additional Technical and Engineering Sources

NASA/TM-20250005209.
Cyclic Symmetry Modeling and Vibration Response Prediction for Fan-Rotor Assemblies.
This NASA technical memorandum discusses the implementation of cyclic symmetry for aerodynamic and structural vibration analysis in turbomachinery, illustrating how a single sector model can

represent the full assembly with accurate stress and modal predictions.

Applied Mechanics and Materials – Thermal Buckling of Cyclic Structures. A study on thermal buckling behavior of cyclic symmetry structures using finite element methods. Although focused on thermal buckling rather than compressor dynamics, this work underscores the fundamentals of cyclic finite element analysis and its sensitivity to thermal effects.

NAFEMS Technical Resource.*Combined 3D Cyclic Symmetry and 2D Axisymmetric Simulation for Turbine Engine Systems* (Siemens Digital Industries Software presentation).
This technical resource discusses hybrid modeling techniques combining cyclic symmetry with axisymmetric representations for rotating systems and highlights their advantages and limitations for predicting static and modal responses.