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Modal Analysis of Rotor Disc

Rajkumar Bhagat[1], Geetesh Rajurkar[2], Piyush Shingankar[3], Nikita Surwase[4], Shrushti Wakchaure[5], Siddharth Shimilkar[6]
[1, 2, 3, 4, 5]*Mechanical Engineering, Vishwakarma Institute of Technology, Pune, India*
[6]*Dept of E&T Engineering, Vishwakarma Institute of Technology, Pune, India*

Abstract: Rotor discs are critical elements in rotating machinery, directly influencing both operational performance and structural reliability. During service, these components are subjected to dynamic loads, centrifugal forces, and gyroscopic effects, which make them highly prone to vibrations. If left unaddressed, such vibrations can lead to fatigue failure, increased noise levels, reduced efficiency, and even catastrophic breakdowns. Modal analysis serves as an essential tool in understanding the vibrational behaviour of rotor discs by determining their natural frequencies and associated mode shapes. By identifying these parameters, engineers can effectively design systems to avoid resonance conditions, thereby enhancing durability and ensuring safe operation.

The present study aims to perform a comprehensive modal analysis of a rotor disc using simulation techniques to evaluate its dynamic response under rotating conditions. The inner edge of the disc is constrained to replicate realistic boundary conditions, and the impact of rotational speed is considered. The analysis focuses on calculating natural frequencies, studying mode shapes, and observing the total and directional deformations corresponding to various modes. Based on the findings, strategies are proposed to optimize the rotor design for improved vibration resistance and overall performance. This work highlights the importance of modal analysis in predictive maintenance, fault diagnosis, and the development of more robust rotating machinery systems.

I. INTRODUCTION

Rotating machinery forms the foundation of a wide range of industrial and mechanical systems, with rotor discs being pivotal components in ensuring their reliable operation. These discs are extensively used in turbines, compressors, generators, and other high-speed machinery, where they are subjected to complex loading conditions such as centrifugal forces from rotation, thermal stresses from temperature variations, and dynamic loads arising from manufacturing imperfections or material inconsistencies. These operational stresses make rotor discs highly susceptible to vibrations, which, if uncontrolled, can lead to increased noise, excessive wear of mechanical components, loss of efficiency, and even catastrophic failures through fatigue or resonance effects. Therefore, understanding and controlling the dynamic behaviour of rotor discs is a crucial aspect of their design and maintenance.

One of the most powerful techniques employed to investigate the vibrational characteristics of rotor discs is **modal analysis**. Modal analysis enables the identification of natural frequencies, mode shapes, and critical deformation patterns, providing engineers with insights to avoid resonance and enhance structural integrity. Modern simulation tools like ANSYS Workbench have significantly advanced the ability to conduct detailed and realistic modal analyses by accurately modelling complex geometries and applying practical boundary conditions. In this study, a comprehensive modal analysis of a rotor disc is performed using ANSYS, where the inner edge is fixed to replicate realistic mounting conditions, and rotational motion is introduced to assess the dynamic response.

II. OBJECTIVE

The primary objective of this study is to investigate the vibrational behavior of a rotor disc used in rotating machinery through finite element-based modal analysis. The goal is to enhance the understanding of the disc's dynamic response under operational conditions and to contribute to the development of safer, more stable, and efficient mechanical systems. To achieve this, the specific objectives are outlined as follows:

1) Modelling of the Rotor Disc: Develop an accurate three-dimensional representation of the rotor disc geometry using CAD tools, ensuring that the model is suitable for finite element-based modal analysis within a simulation environment.
2) Modal Analysis of the Rotor Disc: Perform a detailed modal analysis using ANSYS Workbench to determine the natural frequencies and corresponding mode shapes of the rotor disc, thereby identifying its critical vibrational characteristics.
3) Evaluation of Deformations: Analyze the total and directional deformations associated with different vibration modes to better understand the structural behavior and identify regions susceptible to high dynamic stresses.

III. METHODOLOGY

The methodology adopted for this study involves a systematic approach to modelling, simulating, and analysing the rotor disc to determine its vibrational characteristics. The process is divided into several stages as outlined below:

Fig.1 Rotor Disc

A. Modelling of the Rotor Disc

The rotor disc is modelled either using ANSYS Design Modeler or imported from an external CAD software such as SolidWorks or Autodesk Inventor. Key dimensions, including the outer and inner diameters, thickness, and any specific geometric features such as holes or fillets, are defined based on design requirements or real-world component specifications. To simplify the analysis, the model is assumed to be symmetric, homogeneous, and isotropic unless more complex real-world features need to be incorporated.

B. Material Assignment

A suitable material is selected based on the intended application, typically structural steel or an aluminum alloy. Material properties, including Young's modulus, density, and Poisson's ratio, are assigned either from the ANSYS Engineering Data Library or manually entered if a custom material is being used.

C. Meshing the Model

An appropriate finite element mesh is generated using tetrahedral or hexahedral elements. Mesh refinement is applied, particularly near critical areas such as the inner edge and regions with geometric discontinuities, to enhance the accuracy of the simulation. Mesh quality is assessed by evaluating parameters such as aspect ratio and skewness, and a mesh convergence study may be conducted to ensure consistency and reliability of the results.

D. Defining Boundary Conditions

Boundary conditions are applied to simulate realistic operational constraints. The inner edge (central bore) of the disc is fixed to represent the disc being mounted on a shaft or hub. Additionally, a rotational velocity of 100 RPM is applied to study the effects of gyroscopic forces and centrifugal stresses on the vibrational behaviour and mode shapes of the rotor disc.

E. Performing Modal Analysis

Modal analysis is performed in ANSYS Workbench to extract the natural frequencies and corresponding mode shapes of the rotor disc. The analysis focuses on determining the first six to ten modes to obtain a comprehensive understanding of the disc's vibrational characteristics. Solver settings are kept at default or adjusted as necessary depending on model complexity.

F. Post-Processing and Results Interpretation

The simulation results are carefully examined to extract natural frequencies and visualize the corresponding mode shapes. These results help in identifying resonance-prone modes and critical vibrational behaviours. Total deformation and directional deformations (along X, Y, and Z axes) are analysed to locate areas of maximum.

G. Conclusion and Design Insights

Based on the results, conclusions are drawn regarding the safe operating frequency range for the rotor disc. Design recommendations are made to avoid resonance and improve the mechanical stability and performance of the rotor disc. The insights derived from this study aim to support the development of more efficient, durable, and reliable rotating machinery systems.

IV. CALCULATIONS

Here we are calculating the basic properties of the rotor disc on which the shape of the rotor disc depends. Lets get the practical outcomes from the calculations:

A. Basic Properties

- Disc Area(A): Area of angular disc -

$$A = \pi(\frac{D_o^2}{4} - \frac{D_i^2}{4})$$
$$A = \pi(\frac{(0.240)^2}{4} - \frac{(0.140)^2}{4})$$
$$A = \pi(\frac{0.056}{4} - \frac{0.0196}{4})$$
$$A = \pi(0.0144 - 0.0049)$$
$$A = \pi(0.0095)$$
$$A \approx 0.0298\, m^2$$

- Volume(v):

$$V = A \times t$$
$$V = 0.0298 \times 0.030$$
$$V = 0.000894 m^3$$

- Mass(m):

$$m = \rho \times V$$
$$m = 8000 \times 0.000894$$
$$m \approx 7.153\, kg$$

B. Calculate Flexural Rigidity (D) Flexural rigidity for plates-

$$D = \frac{E \times t^3}{12(1 - v^2)}$$
$$substituting\ D = \frac{193 \times 10^9 \times (0.030)^3}{12(1 - 0.29^2)}$$
$$0.030^3 = 2.7 \times 10^{-5}$$
$$D = \frac{193 \times 10^9 \times 2.7 \times 10^{-5}}{12(1 - 0.0841)}$$
$$D = \frac{5.211 \times 10^6}{12 \times 0.9159}$$
$$D = \frac{5.211 \times 10^6}{10.9908}$$
$$D \approx 474{,}168\, Nm$$

C. Natural Frequency Formula (Fundamental Mode)

For an angular disc (fixed at inner ,free at outer), appropriate first natural frequency using simplified formula:

$$f = \frac{K}{2\pi}\sqrt{\frac{D}{\rho t r_m^4}}$$

Where,

- K = empirical constant (approx.. 10.21 for fundamental mode, angular plate, fixed inner edge, free outer edge – from vibration theory table).
- r_m = mean radius = $\frac{D_o+D_i}{4}$

First calculate r_m,

$$r_m = \frac{0.204+0.140}{4}$$
$$r_m = 0.095\,m$$

Now plug into frequency formula:

First calculate r_m^4,

$$r_m^4 = (0.095)^4 = 8.514\times 10^{-6} m^4$$

Then:

$$f = \frac{10.21}{2\pi}\sqrt{\frac{474168}{8000 \times 0.030 \times 8.145 \times 10^{-6}}}$$

Simplify denominator:

$$\sqrt{242{,}485{,}960} \approx 15{,}571$$

Finally:

$$f = \frac{10.21}{6.283} \times 15{,}571$$
$$f = 1.625 \times 15{,}571$$
$$f \approx 25{,}320\, H_z$$

V. RESULTS

1) Mode 1: Directional Deformation Visualized the first mode shape indicating primary deformation areas.
2) Mode 2: Identified secondary vibrational characteristics.
3) Mode 3: Observed complex deformation patterns under higher mode excitation.

([Figures should be inserted here: Fig. 1: Mode 1, Fig. 2: Mode 2, Fig. 3: Mode 3])

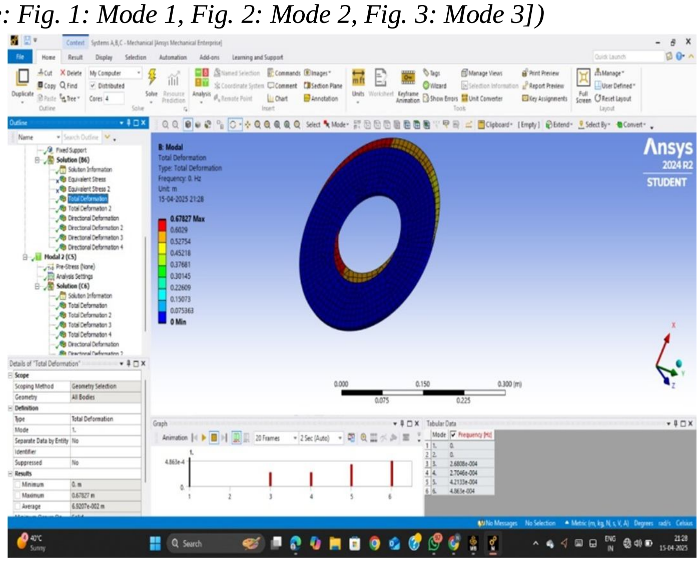

Fig. 2 Mode 1 directional deformation

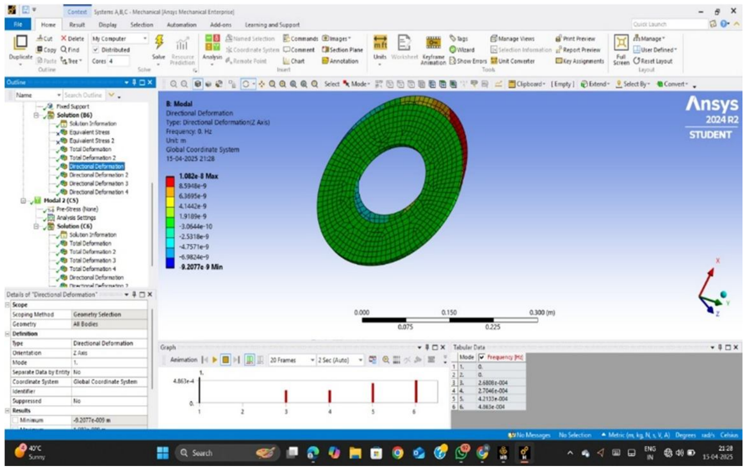

Fig. 3. Mode 2

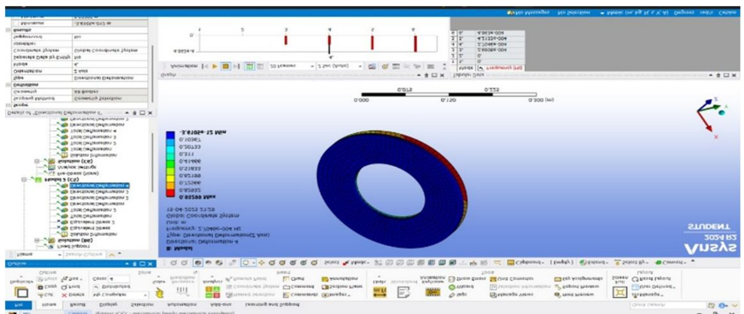

Fig.4. Mode 3 Deformation

VI. CONCLUSION

A modal analysis of the rotor disc was successfully conducted using ANSYS Workbench. The disc, with its inner edge fixed and subjected to a rotational speed of 1000 RPM, exhibited distinct natural frequencies and corresponding mode shapes. Understanding these vibrational patterns is crucial for preventing resonance and ensuring the mechanical stability of the system. The analysis highlighted how rotational effects such as gyroscopic forces can slightly shift the natural frequencies, underlining the importance of considering operational speeds during the design phase. Total and directional deformation patterns identified critical zones that may require structural reinforcement for improved durability and lifespan. The comparison between stationary and rotating conditions emphasized that neglecting rotational effects could lead to inaccurate predictions of dynamic behavior and potential design failures. Overall, this study reinforces the necessity of conducting early-stage modal analysis to ensure the safe and efficient operation of rotor discs in high-speed machinery. In future work, the investigation can be extended to include the effects of damping, thermal stresses, and harmonic response analysis to provide an even more comprehensive understanding of rotor behavior under real-world conditions. Based on the results, conclusions are drawn regarding the safe operating frequency range for the rotor disc. Design recommendations are made to avoid resonance and improve the mechanical stability and performance of the rotor disc

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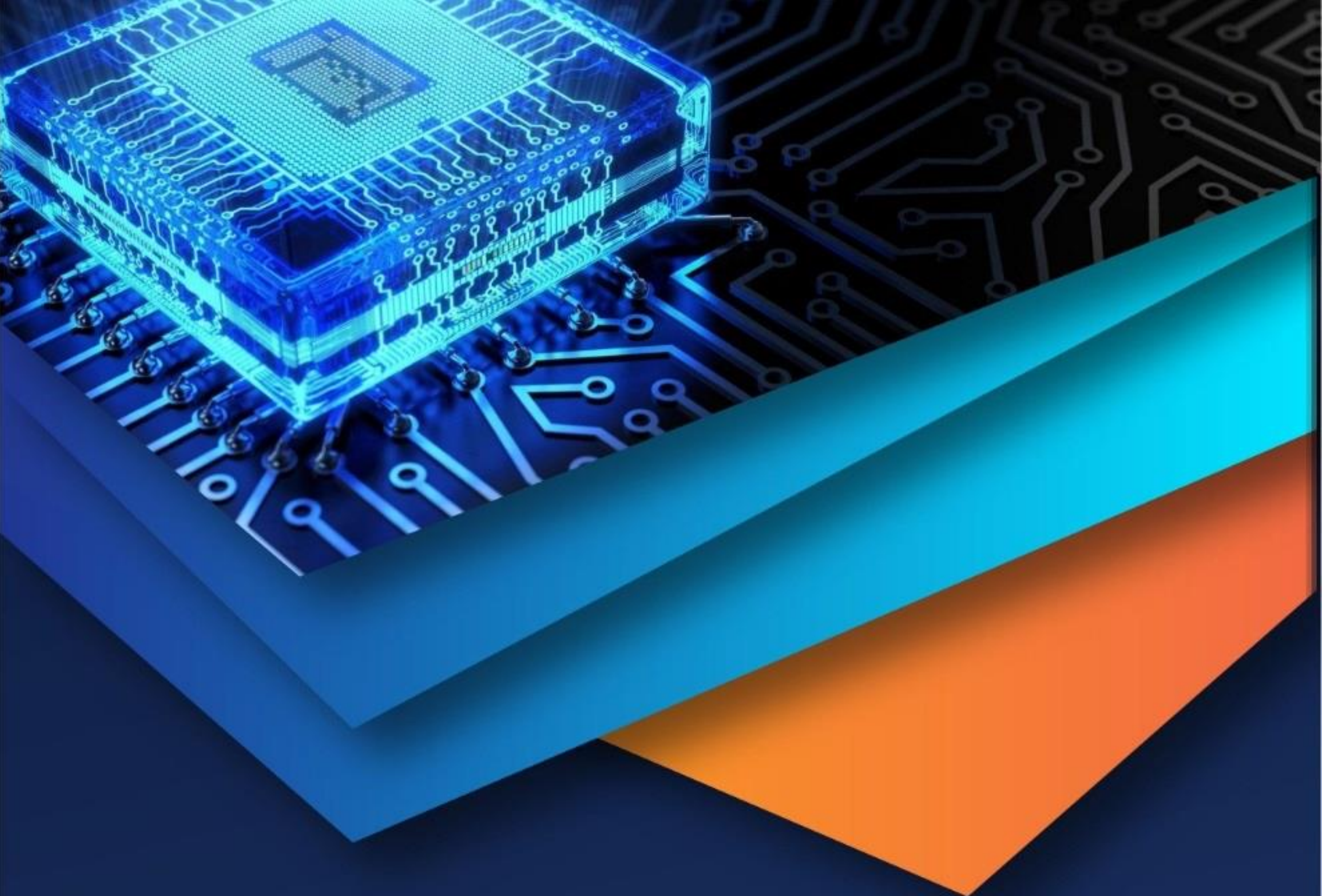

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