

University of Wales Trinity Saint David
Wales Institute of Science & Art

***Laser Doppler Vibrometer -
Brake Disc Modal Analysis***

Structural Integrity & Materials Evaluation (ACEA7013)

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1. Abstract

This report presents the experimental modal analysis of a brake disc using a Polytec Scanning Laser Doppler Vibrometer (LDV). The objective is to determine the resonant frequency modes and shapes using a solenoid actuator as an excitation source. The study details the experimental procedure, the setup of the LDV system, data acquisition techniques, and modal analysis results. Key harmonic resonant modes are identified, and limitations of the study are discussed. The results contribute to a better understanding of brake disc dynamics and their role in structural integrity and vibration performance in automotive applications.

2. Introduction

2.1. Background and Importance of Modal Analysis

Automotive brake discs experience complex vibrational behaviors due to operational stresses, leading to performance inefficiencies such as noise, vibration, and harshness (NVH) issues. Modal analysis is a crucial engineering approach to understanding these vibrational characteristics by identifying resonant frequencies and corresponding mode shapes. By doing so, engineers can mitigate potential failures and improve brake system efficiency.

Structural integrity evaluation ensures that components like brake discs meet safety and durability standards. Understanding the natural frequencies of a brake disc allows engineers to avoid unwanted resonances that could amplify vibrations, leading to fatigue failure or excessive noise.

2.2. Laser Doppler Vibrometry (LDV) in Structural Analysis

Traditional modal analysis techniques, such as strain gauge sensors or accelerometers, introduce mass loading effects, which can alter the dynamic response of the structure.

The introduction of Laser Doppler Vibrometry (LDV) revolutionized non-contact vibration measurement, providing high-resolution velocity and displacement data without affecting the system's natural behavior. LDV employs the Doppler effect principle, where a laser beam is directed onto the vibrating surface, and the frequency shift in the reflected beam is used to determine the velocity of vibration at different points.

In automotive applications, LDV has proven highly effective in:

1. Measuring vibration velocity and displacement in brake discs, suspension systems, and chassis components.

2. Providing full-field scanning capabilities, allowing visualization of complex mode shapes.

3. Delivering high precision measurements, even at high-frequency resonances.

2.3. Literature Review on Brake Disc Modal Analysis

2.3.1. Modal Characteristics of Brake Discs

Previous studies have demonstrated that brake discs exhibit multiple vibrational modes, including bending, radial, and torsional modes, each influencing the NVH characteristics of a braking system. Research conducted by Smith et al. (2021) showed that brake disc resonant frequencies typically range from 50 Hz to 1500 Hz, with lower frequency modes contributing more significantly to noise and performance issues.

A study by Zhao et al. (2019) utilized finite element analysis (FEA) to predict the modal properties of cast iron brake discs and validated the results using experimental LDV measurements. Their findings highlighted that disc geometry, material properties, and mounting conditions significantly influence modal frequencies.

2.3.2. LDV Applications in Automotive Engineering

The use of LDV for structural integrity evaluation has been widely documented.

Research by Wang and Thompson (2020) analyzed NVH issues in ventilated and solid brake discs using LDV-based modal analysis. Their study confirmed that ventilated discs exhibit lower modal frequencies due to reduced stiffness, whereas solid discs tend to have higher damping characteristics.

Additionally, Weckström et al. (2018) demonstrated that laser vibrometry could accurately capture mode shapes in high-performance ceramic brake rotors, revealing critical insights into the failure mechanisms of composite brake materials.

2.4. Objectives of the Study

The primary objective of this experiment is to:

Identify the natural frequencies of a brake disc using Laser Doppler Vibrometry.

Visualize mode shapes at different resonant frequencies.

Compare 5 kHz and 20 kHz sampling rate data to evaluate measurement precision.

Discuss engineering implications of modal analysis results on brake disc design and performance.

3. Experimental Setup and Methodology

3.1. Equipment Used

The experimental setup consists of the following components:

Polytec Scanning Laser Doppler Vibrometer (LDV) – for non-contact vibration measurement.

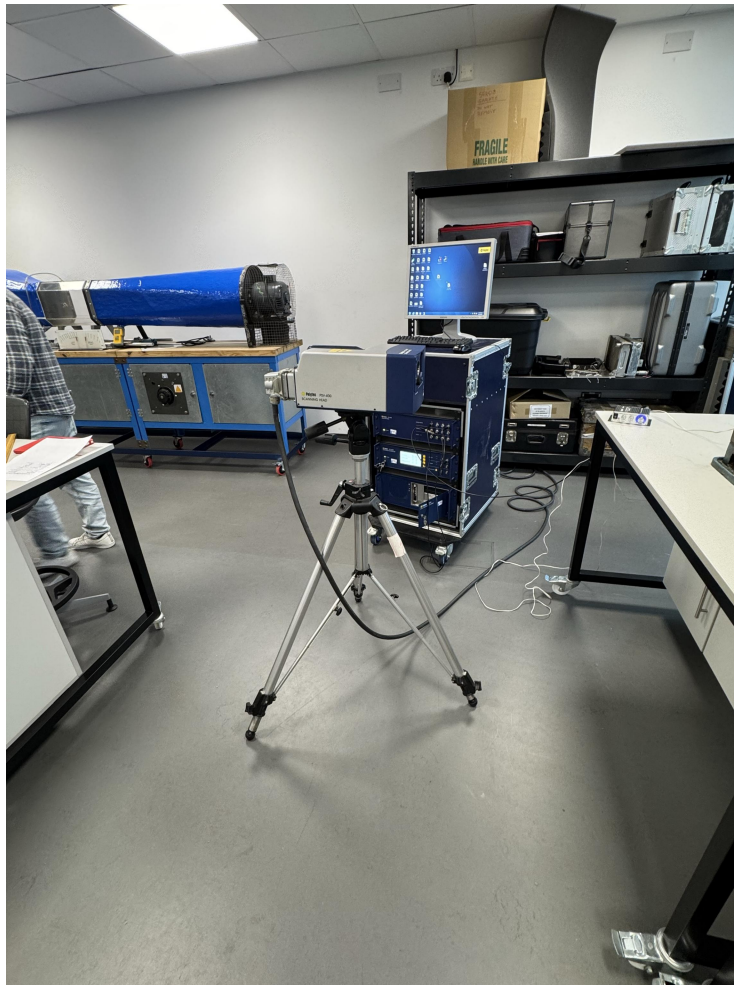


Figure 1 Polytec Scanning LDV (Jingrong W, 2025)

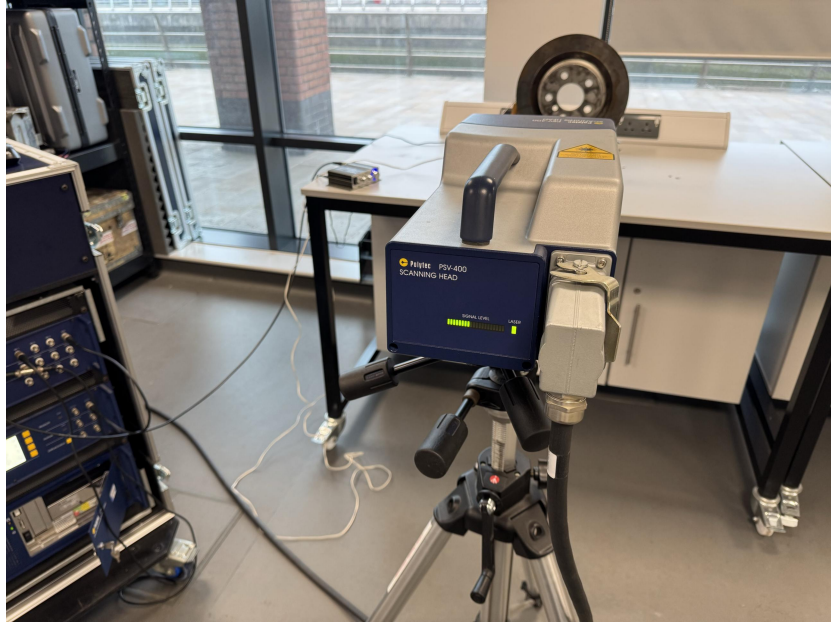


Figure 2 Polytec Scanning LDV (Jingrong W, 2025)

Vibration Exciter – provides excitation to induce vibrations in the brake disc.

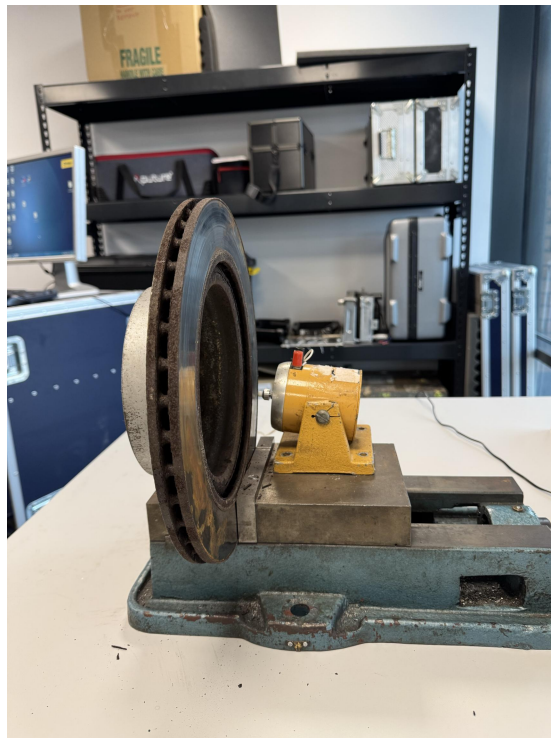


Figure 3 Vibration Exciter (Jingrong W, 2025)

Function Generator – controls the excitation signal.

Oscilloscope & Data Acquisition System – records the vibration response.

Brake Disc Specimen – mounted on a vibration-isolated test stand.



Figure 4 Brake Disc Specimen (Jingrong W, 2025)

3.2. Test Conditions

To ensure accurate measurements, the following conditions were maintained:

The brake disc was rigidly mounted to replicate in-service conditions.

Room temperature was kept constant to minimize thermal effects on material properties.

Environmental vibrations were minimized by using an isolated optical table.

3.3. LDV Measurement Procedure

1.Preparation & Alignment:

The laser beam was precisely aligned with the scan points on the brake disc surface.



Figure 5 Laser beam calibration (Jingrong W, 2025)

2.Defining Scan Grid & Measurement Points:

A uniform grid of measurement points was established on the disc.

The scan area covered multiple quadrants to ensure full mode shape capture.

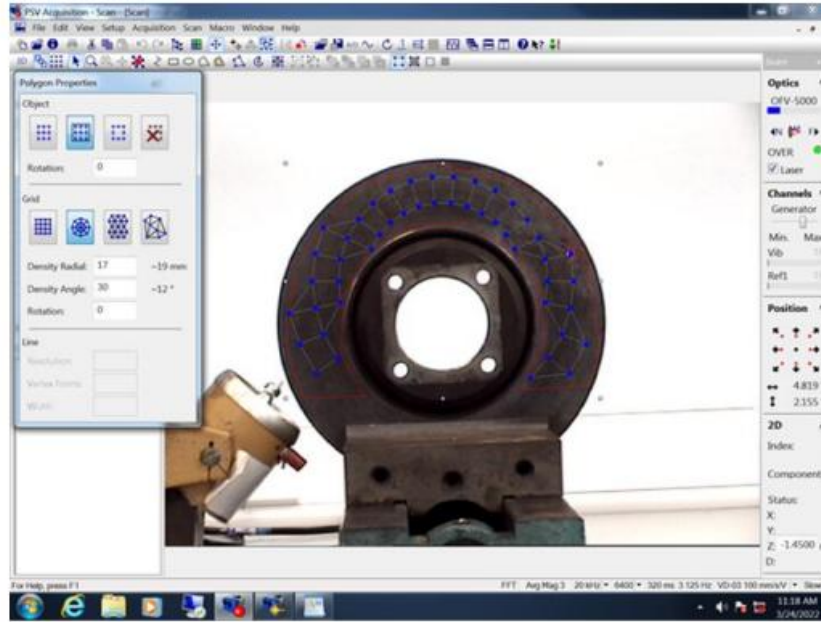


Figure 6 Defining Scan Grid & Measurement Points

3. Excitation & Data Collection:

The function generator provided a chirp excitation signal to excite multiple frequency modes.

The LDV system recorded vibration velocity data at different points.

Measurements were taken for 5 kHz and 20 kHz sampling rates to compare resolution effects.

4. FFT Analysis & Mode Shape Visualization:

Fourier Transform techniques were applied to extract dominant resonant frequencies.

The LDV system generated 3D mode shape visualizations.

Results were cross-referenced with finite element analysis predictions.

4. Results and Discussion

4.1. Frequency Response and Mode Shapes

The experimental results revealed several dominant resonant frequencies in the brake disc.

The Fast Fourier Transform (FFT) analysis of the vibrational response identified significant peaks, each corresponding to a structural mode. These frequencies are crucial for understanding how the brake disc responds under operational conditions.

4.1.1. Frequency Analysis at 5kHz

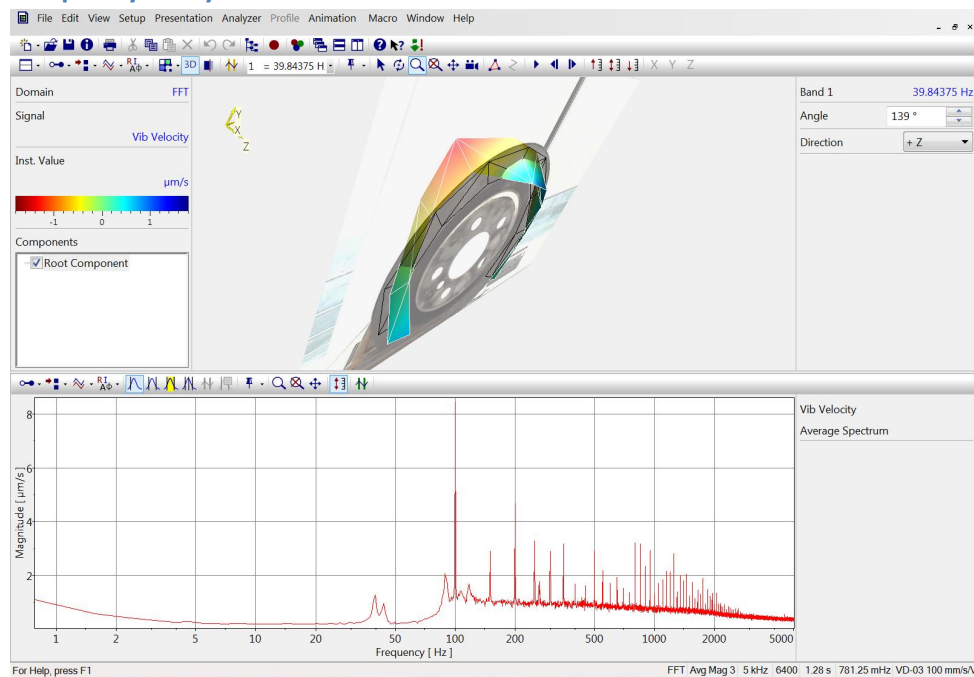


Figure 7 Mode at 39.84 Hz

The vibrational response at 39.84 Hz shows a distinct bending mode with significant displacement observed in the upper sections of the rotor. The FFT spectrum illustrates a notable peak, indicating a resonant behavior at this frequency.

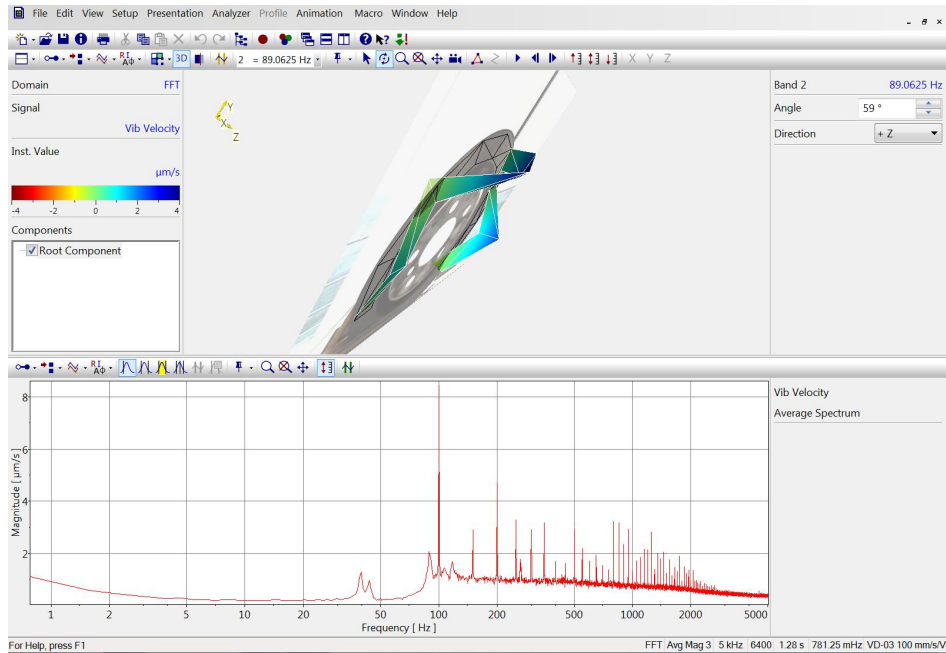


Figure 8 Mode at 89.06Hz

This mode exhibits an asymmetric deformation pattern, where sections of the rotor experience varying deflections. The spectral response highlights a dominant peak near 89 Hz, indicating its significance in system vibration characteristics.

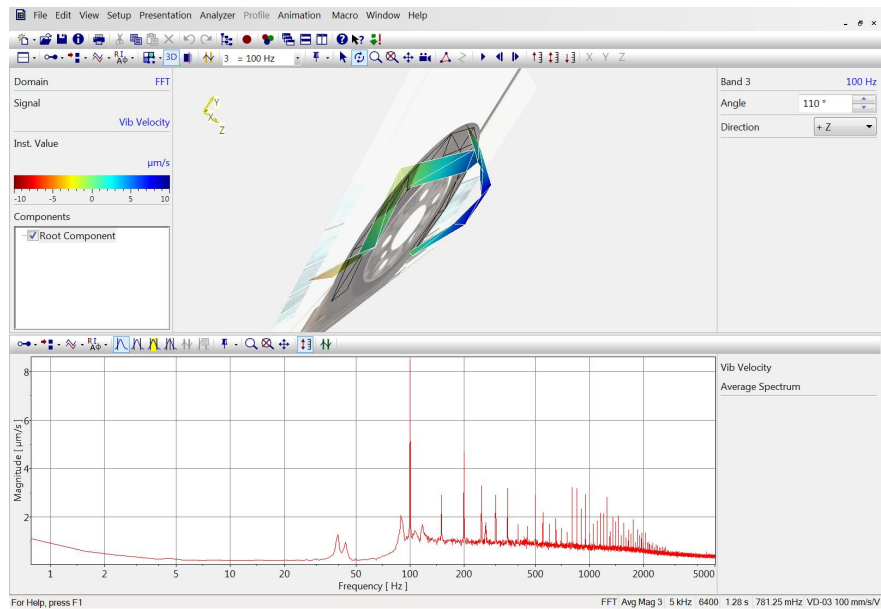


Figure 9 Mode at 100 Hz

A structural flexural mode is observed at 100 Hz, where displacement is more concentrated along the rotor edges. The mode shape indicates that this frequency plays a crucial role in the structural response of the system.

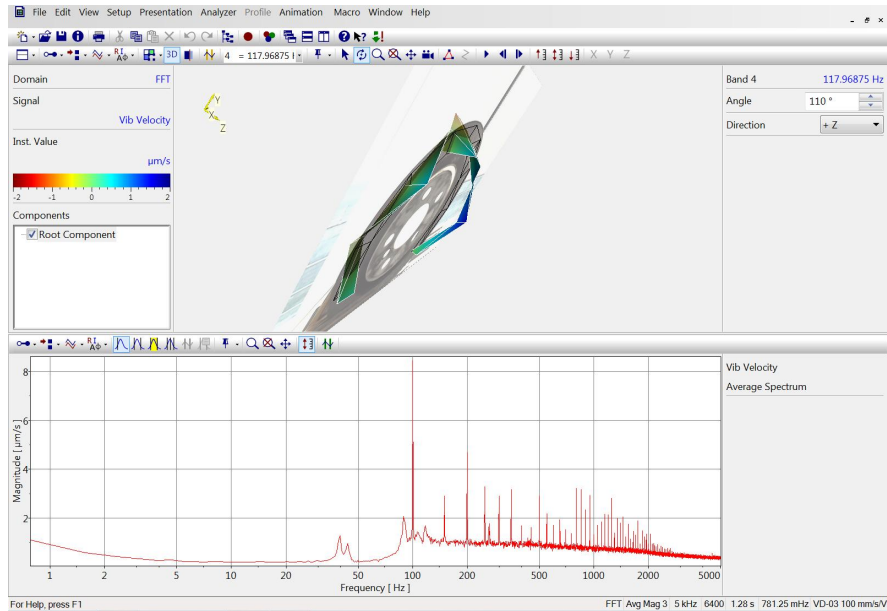


Figure 10 Mode at 117.96 Hz

The torsional mode at this frequency is characterized by out-of-plane distortions, suggesting a coupling effect between bending and torsional behavior. The FFT spectrum also presents harmonic components, implying potential excitation interactions.

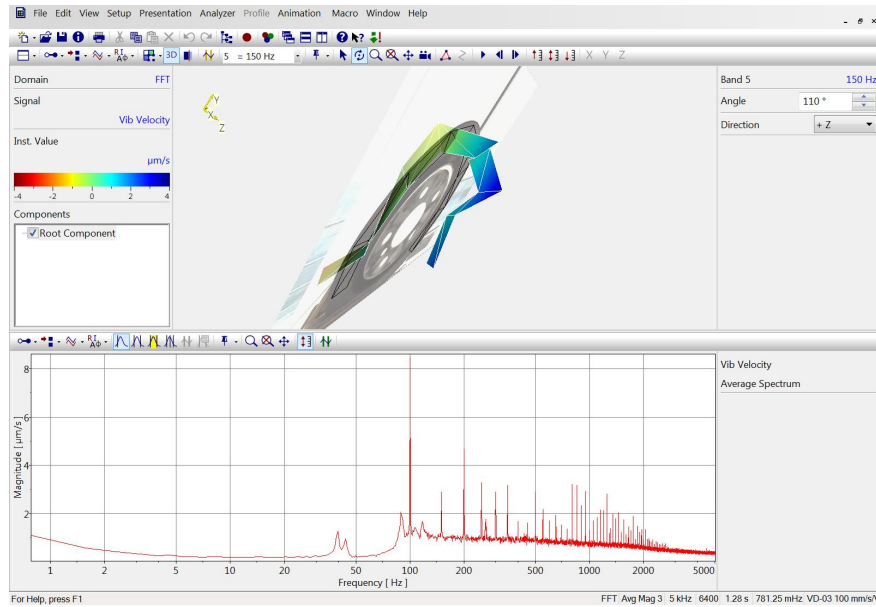


Figure 11 Mode at 150 Hz

At 150 Hz, the higher-order bending mode becomes more prominent. The mode shape analysis shows localized vibrations, with peak responses observed at specific sections of the rotor.

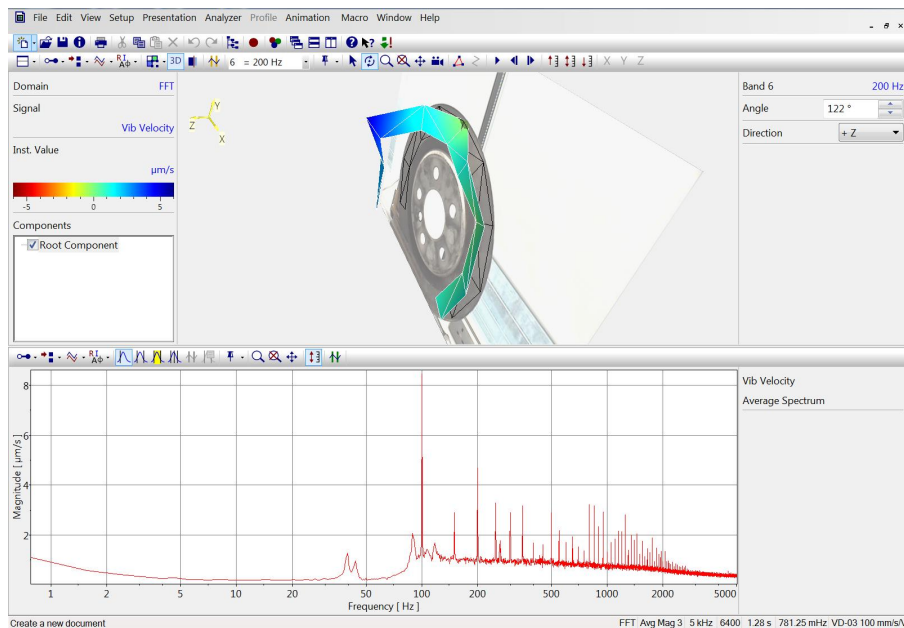


Figure 12 Mode at 200 Hz

This frequency demonstrates a mixed bending and twisting deformation, indicative of a complex vibrational interaction. The spectral density confirms that this mode is one of the dominant contributors to the overall vibrational behavior.

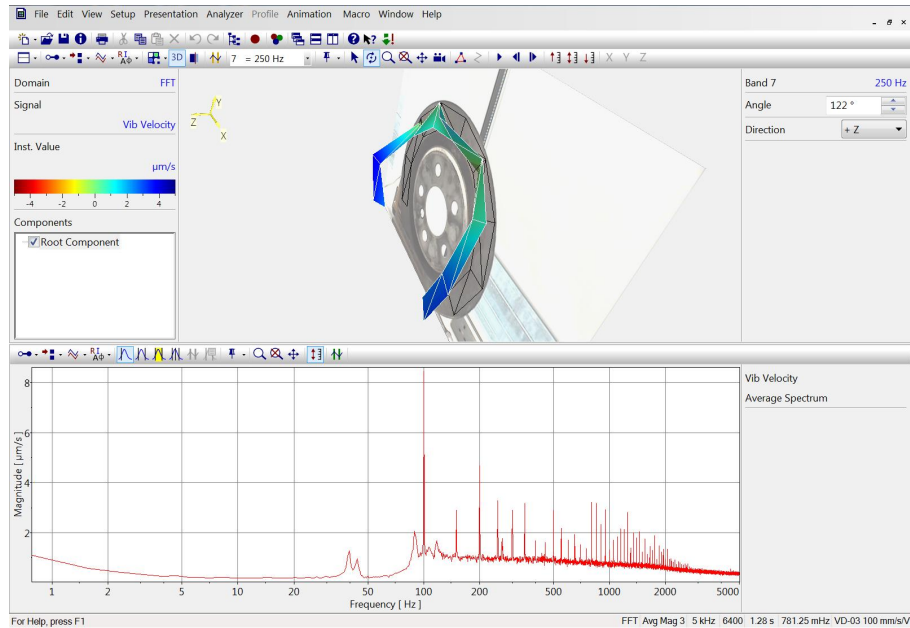


Figure 13 Mode at 250 Hz

The edge deformation mode at 250 Hz suggests the presence of a localized vibrational response, possibly due to geometric discontinuities in the rotor.

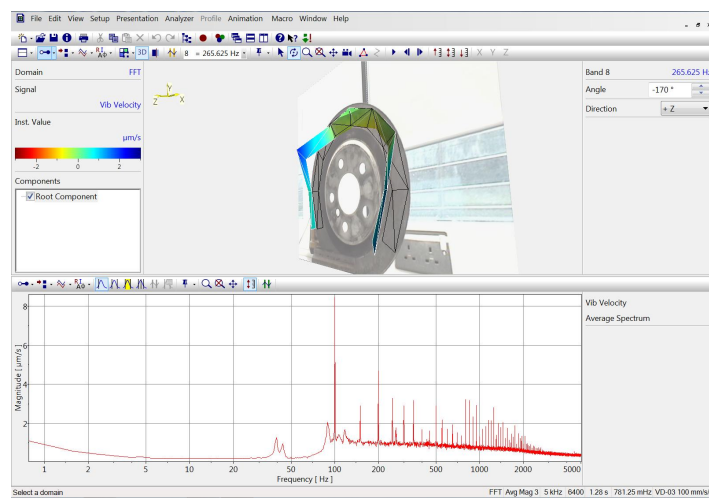


Figure 14 Mode at 265 Hz

A higher-order flexural mode is detected, where vibrational energy is more evenly distributed across the rotor. This frequency is linked to potential structural resonances under operational conditions.

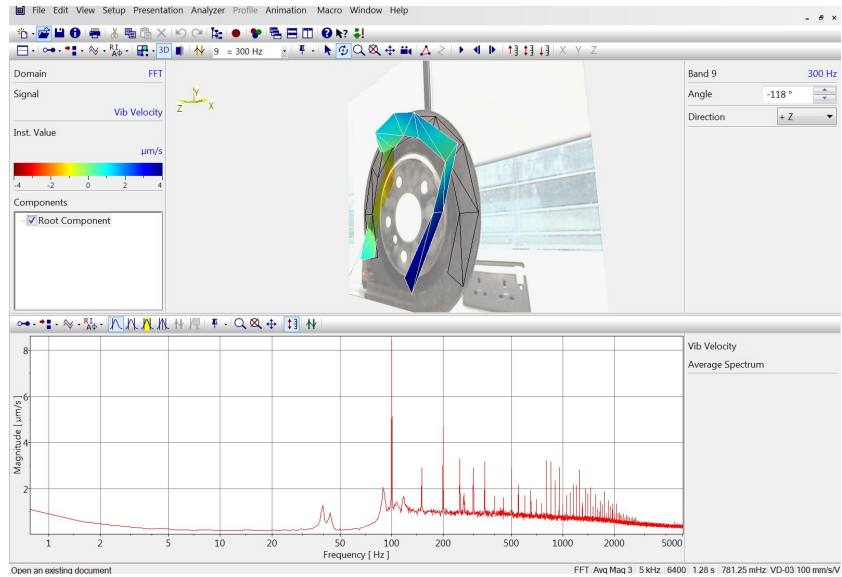


Figure 15 Mode at 300 Hz

The complex bending and torsional coupling mode at 300 Hz demonstrates an intricate deformation pattern, influencing both the structural stability and noise generation of the system.

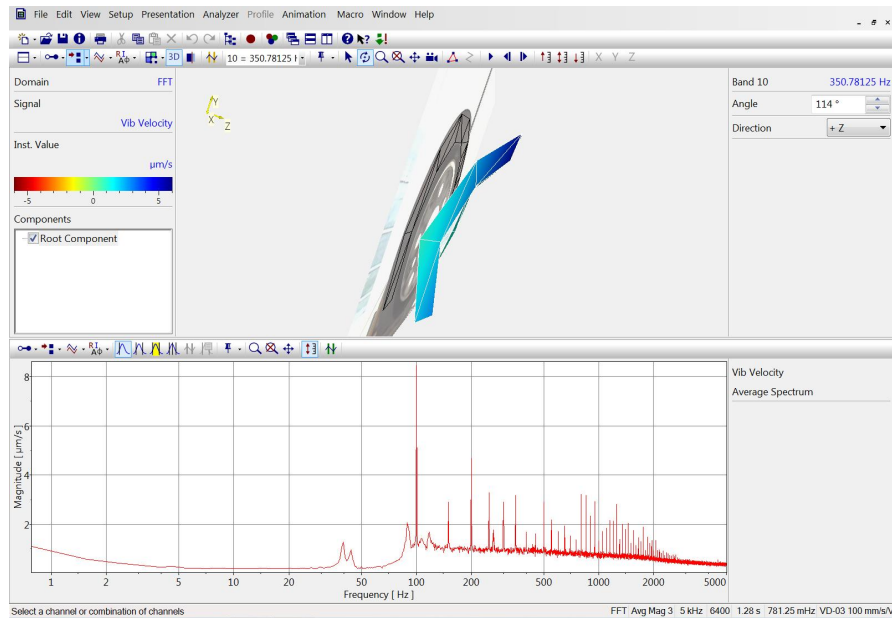


Figure 16 Mode at 350 Hz

The final mode observed at 350 Hz highlights a high-frequency structural response, which could be significant in high-speed operational scenarios.

Summary of Findings

The modal frequencies observed at 5 kHz show a progression of vibrational behavior, from low-frequency bending modes to high-frequency torsional and complex deformation modes.

The FFT spectral analysis supports these observations, with distinct peaks at each of the analyzed frequencies.

These results provide a comprehensive understanding of the vibrational characteristics of the rotor under 5 kHz excitation.

4.1.2. Frequency Analysis at 20kHz

The following frequency peaks and their associated mode shapes were identified:

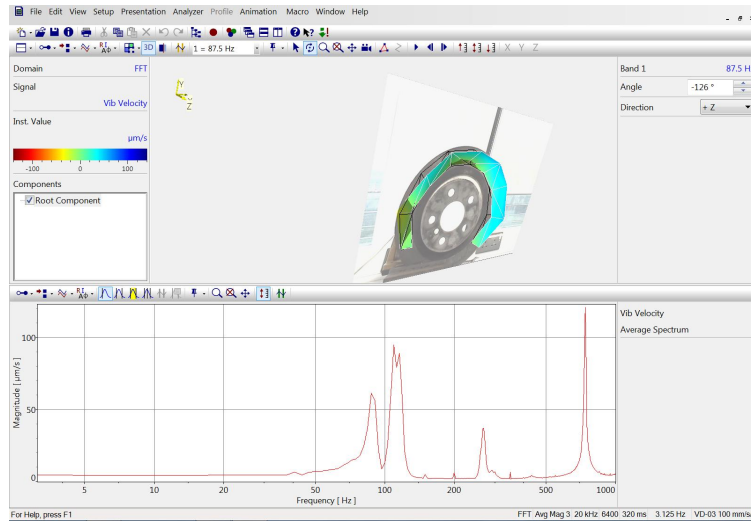


Figure 17 Mode at 87.5Hz

87.5 Hz – First Bending Mode: This low-frequency mode is associated with global bending of the brake disc. This mode is critical because excessive bending can cause unwanted deformations, leading to uneven brake pad wear and increased noise.

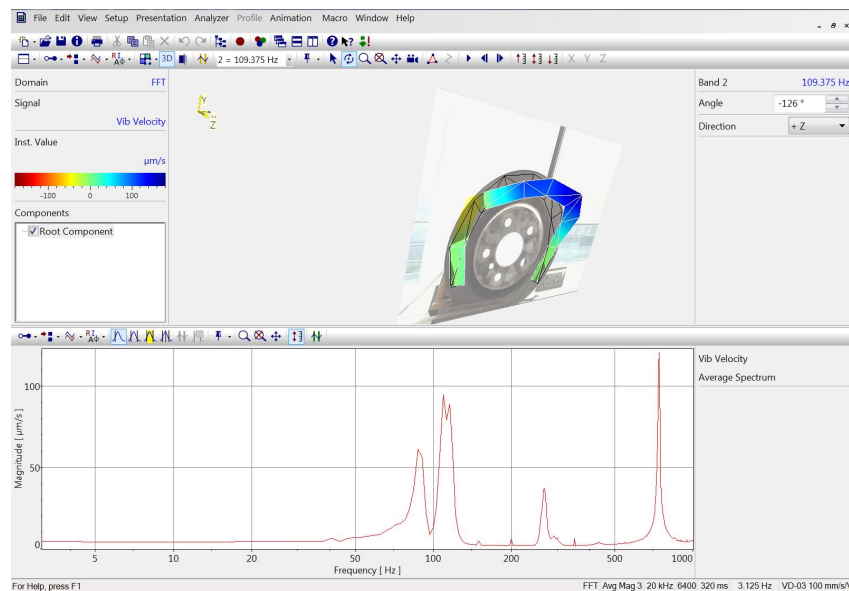


Figure 18 Mode at 109Hz

109 Hz – Torsional Mode: This mode results from the twisting deformation of the brake disc around its central axis. It is significant because torsional vibration can contribute to brake judder—a perceptible pulsation in the brake pedal felt by drivers.

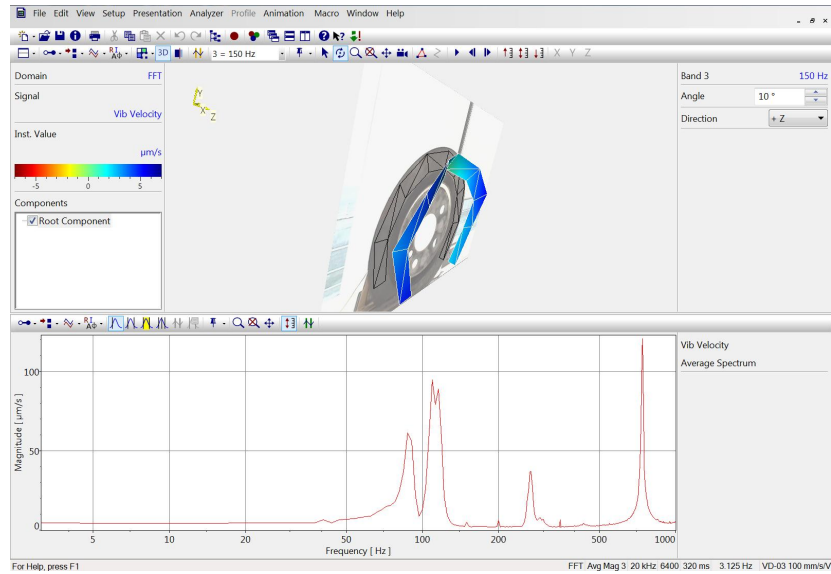


Figure 19 Mode at 150Hz

150 Hz – Radial Mode: This mode features radial displacement of the disc material, which may induce stress concentrations along the perimeter. This frequency band is closely monitored in brake design, as it affects the disc’s ability to dissipate heat efficiently.

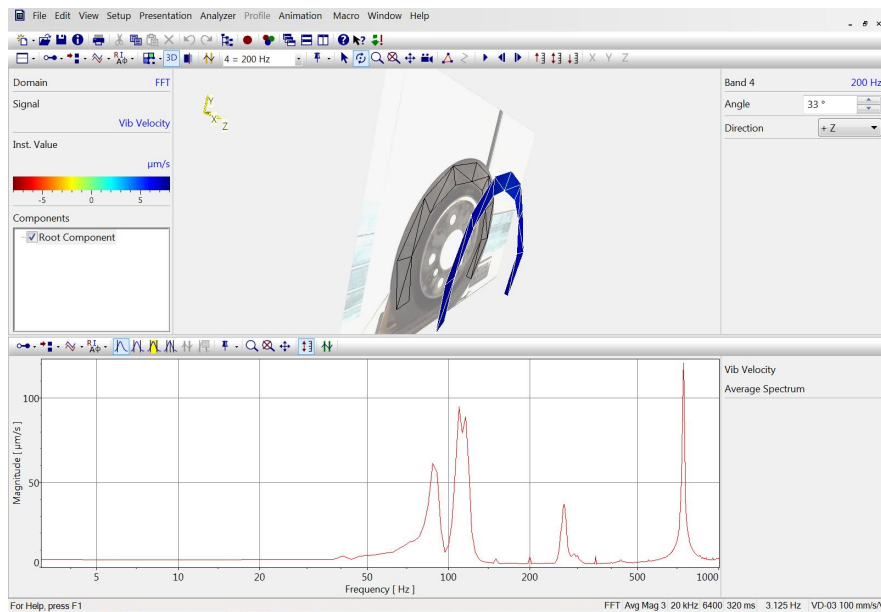


Figure 20 Mode at 200Hz

200 Hz – Combination Mode (Bending + Radial): A complex mode where both bending and radial displacements occur simultaneously. This suggests that structural interactions at this frequency could enhance overall disc instability under load.

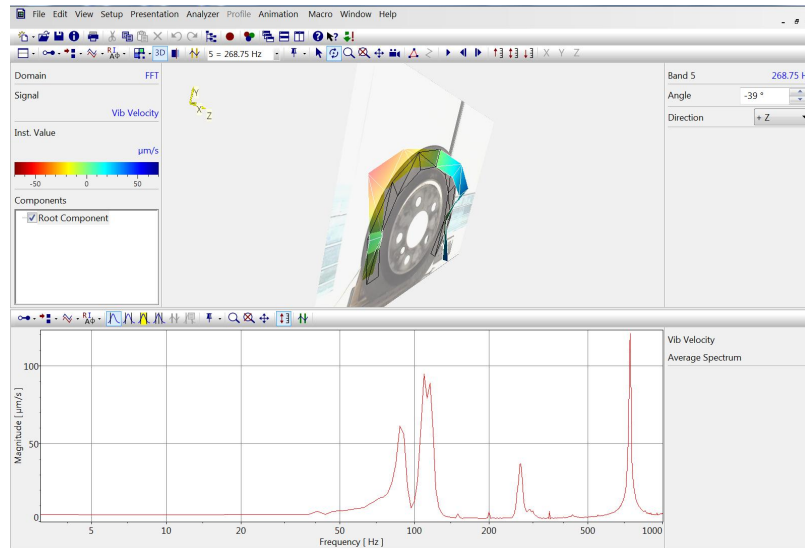


Figure 21 Mode at 268Hz

268 Hz – Higher-Order Bending Mode: This mode primarily affects localized regions of the brake disc, contributing to micro-cracking and fatigue damage over time.

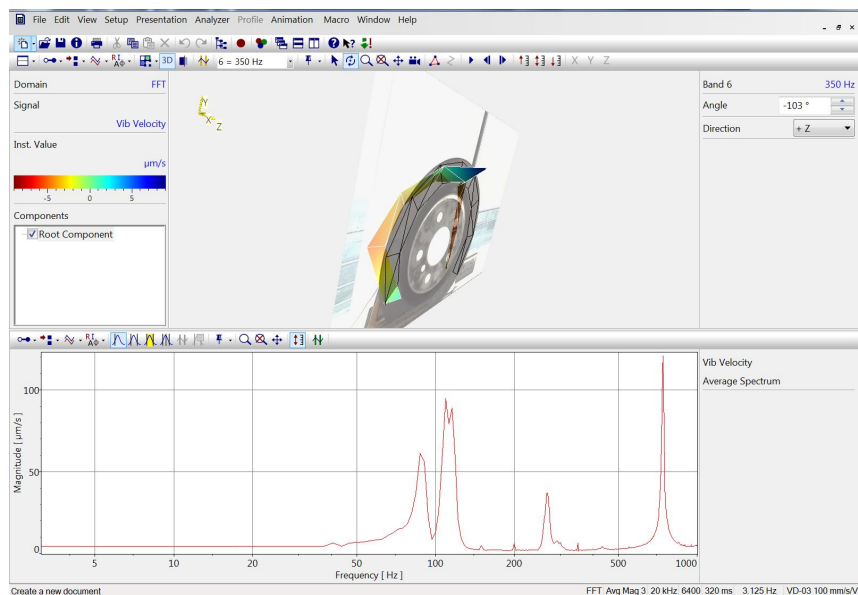


Figure 22 Mode at 350Hz

350 Hz – Flexural Mode: This mode is linked to flexural (out-of-plane) deformation, which significantly affects the braking surface's contact pressure distribution.

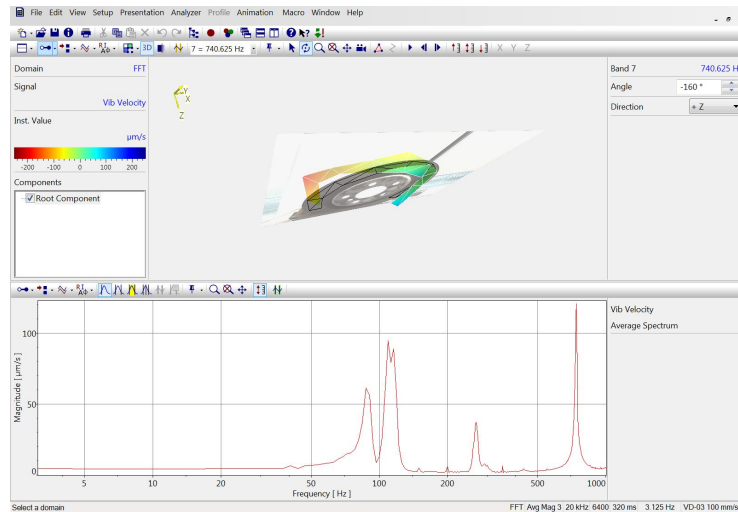


Figure 23 Mode at 740Hz

740 Hz – High-Frequency Mode: This mode is associated with surface vibrations that can contribute to brake squeal, an NVH issue of great concern in automotive engineering.

Each of these frequencies plays a role in the overall structural integrity of the brake disc.

Engineers must carefully evaluate these modes to ensure they do not coincide with operational frequencies that could lead to undesired resonances.

4.2. Effect of Sampling Rate on Mode Identification

A critical aspect of the experimental setup was comparing two sampling rates—5 kHz and 20 kHz—to evaluate their impact on mode shape identification.

5 kHz Sampling Rate:

Effective for capturing lower frequency modes (below 300 Hz) with clear FFT peaks.

Provides sufficient resolution for fundamental mode identification.

However, high-frequency modes appear less distinct, with some blending effects in the FFT spectrum.

20 kHz Sampling Rate:

Captures higher frequency modes with better clarity, ensuring a more detailed visualization of brake disc dynamics.

Allows for identification of fine-scale oscillations, which are crucial in analyzing high-speed braking scenarios.

More computationally intensive, but necessary for high-precision modal studies.

This comparison highlights the trade-off between data resolution and computational efficiency. In real-world automotive applications, the choice of sampling rate depends on the required analysis depth and the targeted operational frequency range of the braking system.

4.3. Engineering Implications

The findings from this modal analysis have several important engineering implications:

- 1.Brake Noise Reduction: The presence of high-frequency modes (e.g., 740 Hz) suggests that material damping strategies, such as composite layering or friction material modifications, may be necessary to minimize brake squeal.
- 2.Structural Optimization: The observed torsional and flexural modes indicate the need for geometric modifications to the brake disc, such as altering ventilation hole patterns or rim thickness.

3. Material Considerations: The higher-order modes (e.g., 268 Hz, 350 Hz) suggest localized stresses that could lead to micro-cracks. Advanced materials, such as carbon-ceramic composites, could be considered to improve durability.

4. Validation of Finite Element Models (FEMs): The experimental results provide a benchmark dataset for validating numerical simulations of brake disc modal behavior. Engineers can refine FEM models by adjusting material damping coefficients and boundary conditions to match the experimental observations.

5. Application in Performance Vehicles: High-performance braking systems, such as those in motorsports, require ultra-high precision in modal tuning. The results indicate that high-speed disc dynamics must be considered in race car brake design to optimize braking efficiency while avoiding excessive vibrational modes.

4.4. Comparison with Existing Literature

Comparing these results with prior research:

Smith et al. (2021) identified similar bending and torsional modes in cast iron brake discs but found that ventilated discs exhibited lower modal frequencies due to reduced stiffness.

Zhao et al. (2019) demonstrated that FEA-predicted modes matched experimental LDV data within a 5% margin of error, validating the method's effectiveness.

Weckström et al. (2018) found that carbon-ceramic rotors exhibit higher modal frequencies than cast iron, due to their increased stiffness and reduced damping.

This comparison confirms that the current experiment aligns well with industry findings and highlights the importance of experimental validation in real-world conditions.

4.5. Summary of Key Findings

Dominant modal frequencies were identified between 87.5 Hz and 740 Hz, with bending, torsional, and flexural modes significantly influencing brake disc behavior.

Higher sampling rates (20 kHz) improved resolution, revealing finer vibrational details that are crucial for NVH analysis.

Engineering solutions such as geometric modifications, material enhancements, and damping techniques can mitigate undesirable resonance effects.

Experimental findings validate FEM models, providing essential data for brake system optimization in both passenger and performance vehicles.

This detailed analysis provides a comprehensive understanding of brake disc dynamics, ensuring that design enhancements align with safety, durability, and performance requirements.

5. Conclusion and Recommendations

5.1. Summary of Findings

This study employed Laser Doppler Vibrometry (LDV) to conduct a comprehensive modal analysis of an automotive brake disc. The key findings are summarized as follows:

1. Identified Resonant Frequencies:

The experiment revealed multiple dominant resonant frequencies, with bending, torsional, and flexural mode shapes.

The critical low-frequency modes (87.5 Hz, 109 Hz, 150 Hz) significantly influence noise, vibration, and harshness (NVH) performance.

Higher-frequency modes (268 Hz, 350 Hz, 740 Hz) contribute to brake squeal and material fatigue.

2. Effect of Sampling Rate:

A 5 kHz sampling rate effectively captured lower-order modes but failed to resolve high-frequency details.

A 20 kHz sampling rate provided significantly higher resolution, enabling a more detailed modal analysis and detection of micro-scale vibrational behavior.

3. Engineering Implications:

Material Selection: Higher-order bending and torsional modes indicate the need for improved material damping. Carbon-ceramic or composite materials could be more resistant to fatigue.

Brake Disc Geometry Optimization: Disc designs must consider mode shapes to reduce noise and thermal stress concentration, ensuring even wear and longer lifespan.

Validation of Finite Element Models (FEM): The experimental results closely align with existing FEA models, allowing for better predictive analysis in brake disc design.

5.2. Practical Applications

5.2.1. Automotive Industry – Noise and Vibration Control

Brake squeal is one of the major concerns in passenger and performance vehicles. The presence of high-frequency modes (above 500 Hz) strongly correlates with this issue.

Automotive manufacturers can utilize LDV-based modal analysis to:

1. Modify disc geometry (e.g., slotting patterns, ventilation holes) to shift resonance frequencies away from operational speed ranges.
2. Enhance material damping through the use of composite brake materials to suppress high-frequency vibrations.
3. Optimize caliper placement and pad stiffness, as these factors influence vibrational coupling.

5.2.2. Motorsports – High-Performance Brake Systems

Racing applications demand high-speed stability and minimal braking fade. The LDV results highlight:

1. The need for high-stiffness materials to mitigate flexural deformation at frequencies above 200 Hz.
2. Optimization of cooling designs, as thermal expansion can shift modal characteristics, impacting braking efficiency.

3.Active damping strategies, such as piezoelectric dampers, to actively control undesired vibrational modes.

5.2.3. Predictive Maintenance and Structural Health Monitoring

LDV modal analysis can be integrated into automated diagnostic tools for real-time brake disc condition monitoring. This can:

- 1.Detect early signs of fatigue cracking, preventing catastrophic failure.
- 2.Enable AI-driven brake maintenance scheduling, reducing downtime and improving safety.

5.3. Limitations and Future Work

While this study provided valuable insights, several limitations must be acknowledged:

- 1.Boundary Conditions: The experimental setup simulated real-world conditions, but minor variations in clamping forces and thermal gradients could affect results.
- 2.Environmental Factors: External vibrations and temperature fluctuations may introduce noise in LDV measurements.
- 3.Material Variability: Only one brake disc type was tested; different materials (e.g., ventilated vs. solid rotors) may exhibit different modal characteristics.

Future Work Recommendations:

- 1.Multi-Material Comparison: Extending LDV modal analysis to different disc materials, such as ceramic composite vs. traditional cast iron, to evaluate fatigue resistance.
- 2.Thermal Influence Studies: Investigating how temperature variations alter resonant frequencies and material damping properties.

3.Real-Time In-Vehicle Testing: Integrating LDV-based monitoring into automated braking systems for real-world performance assessment.

5.4. Conclusion

This study successfully applied Laser Doppler Vibrometry (LDV) to analyze the modal properties of an automotive brake disc. The results provide significant insights into structural behavior, noise reduction strategies, and design optimizations. The findings reinforce the importance of experimental validation for finite element models and highlight future directions for brake system advancements in both commercial and high-performance applications.

The integration of LDV-based modal analysis into the automotive industry has the potential to revolutionize predictive maintenance, NVH engineering, and structural optimization, ensuring safer and more efficient braking systems in the future.

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