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Abstract

This study uses a PolyTec Scanning Laser Doppler Vibrometer (LDV) to examine the vibrational properties of an automobile brake disc. Finding the brake disc's resonant frequency modes and mode shapes was the main goal because these are essential for resolving problems like brake squeal and undesired vibrations. A solenoid actuator powered by a function generator was used to stimulate the brake disc, and the LDV system was used to record vibrational data. At 5 kHz and 20 kHz, two notable resonance peaks were detected; the main mode causing high-amplitude vibrations was the 5 kHz peak. The findings were examined to comprehend the brake disc's modal characteristics, and possible causes of inaccuracy were covered, such as boundary conditions, environmental noise, and instrument accuracy. The study offers insightful information for next automotive engineering research and emphasizes the use of modal analysis in enhancing brake system design and lowering undesired noise.

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Apparatus & Experimental Setup

Apparatus Used

The experiment utilizes the PolyTec Scanning Laser Doppler Vibrometer (LDV) to measure the brake disc's vibrational characteristics. The following equipment is used:

- **Polytec Scanning LDV** – Measures surface velocity and vibration patterns.
- **Solenoid Actuator** – Provides a controlled excitation force to the brake disc.
- **Function Generator** – Drives the actuator to generate harmonic excitation signals.
- **Data Acquisition System (DAQ)** – Records and processes vibration data.
- **Test Brake Disc** – Standard automotive brake disc, secured in a free-free boundary condition.
- **Optical Reflective Tape** – Applied to the disc surface for enhanced laser reflection.
- **Mounting Stand & Fixtures** – Ensures stable positioning of the disc and LDV system.

Experimental Setup

The brake disc is mounted on a stand in a free-free condition (suspended or isolated to avoid external damping). The PolyTec LDV is positioned at an optimal distance to scan the disc's surface. The solenoid actuator, driven by a function generator, excites the disc at varying frequencies. The DAQ system records velocity data, which is analyzed to determine resonant frequency modes and mode shapes.



Figure 1: Experimental Setup 1



Figure 2 : Experimental Setup 2

Introduction

Brake system performance is a crucial component of vehicle efficiency, comfort, and safety in modern automobile engineering. Unwanted noise and vibrations, especially brake squeal, a high-frequency noise produced by the interaction of the braking disc and pads, are one of the most enduring problems in brake system design. Self-excited vibrations in the brake system cause this condition, which frequently results in unhappy customers, higher maintenance expenses, and possible safety issues. Optimizing brake performance and improving the overall driving experience need an understanding of and commitment to reducing such vibrations.

The main cause of brake disc vibrations is resonant frequencies, in which the disc's inherent frequencies coincide with outside stimuli to intensify oscillations. These resonance frequencies may contribute to excessive noise if they are within the audible range. Furthermore, extended exposure to these vibrations may result in structural fatigue, which shortens the brake disc's lifespan and causes microcracks. Engineers can create braking systems that are quieter and more resilient by determining and evaluating the modal properties (resonant frequencies and mode shapes) of a brake disc. This will improve the noise, vibration, and harshness (NVH) characteristics of vehicles.

Laser Doppler Vibrometer (LDV) in Automotive Engineering

Accelerometers and other traditional vibration measurement methods require physical contact with the test object, which might change the vibrational characteristics because of mass loading effects. Non-contact techniques like Laser Doppler Vibrometry (LDV) have gained popularity in automobile research as a way around this restriction.

LDV is a high-precision optical method that uses the Doppler effect to measure surface vibrations. The velocity of the motion is determined by the frequency shift in a laser beam that is reflected off a moving surface. LDV has a number of benefits over traditional techniques.

- Non-contact measurement: Removes any disruption to the inherent vibrations of the object.

- High-frequency sensitivity: Makes it possible to identify the crucial resonance modes that cause brake squeal.
- Full-field scanning ability: Offers a comprehensive picture of the mode form over the whole brake disc surface.

When developing brake systems, LDV is essential because it enables engineers to identify resonance frequencies that cause noise and inefficiency. Furthermore, it works well with Finite Element Analysis (FEA), allowing experimental data to be used to validate numerical simulations. Multi-point measurements are made possible by recent developments like 3D scanning LDVs, which further improve the precision of structural optimization and modal analysis.

Recent Research on Brake Disc Modal Analysis

Brake disc vibrations have been the subject of numerous investigations using LDV-based modal analysis. Brake disc resonance has been found to be greatly influenced by a number of elements, including material qualities, thermal impacts, and geometric design. Additionally, studies have shown that modal testing helps to improve overall vehicle performance, optimize disc design, and reduce weight without sacrificing strength.

Recent studies, for instance, have looked at how the modal behaviors of solid and vented brake discs differ, affecting how susceptible they are to high-frequency vibrations. Furthermore, LDV research has improved the industry's capacity to create quieter braking systems by contributing to brake noise prediction models.

Objective of the Study

- Use PolyTec Scanning LDV to locate and examine a brake disc's resonant frequency modes and mode morphologies.
- To cause vibrations in the brake disc, use a solenoid actuator as an excitation source.
- Examine the restrictions and potential causes of inaccuracy in modal testing based on LDV.

Limitations and Scope

- The work focuses on the modal analysis of a single brake disc in a controlled laboratory setting.
- Temperature fluctuations, pad interactions, and actual operating circumstances are examples of external elements that are not taken into account.
- The results will help enhance future brake system design by providing a better knowledge of brake disc vibrational behavior.

Literature Review

In the automotive industry, Laser Doppler Vibrometry (LDV) has become a key tool for examining vibrational properties. Using the Doppler effect of laser light, LDVs are non-contact instruments that provide excellent precision and variety in measuring the displacement and velocity of vibrating surfaces. (Wikipedia)

LDVs have been widely used in automotive applications in a number of crucial areas:

- **Structural Dynamics:** LDVs make it easier to analyze the vibrational modes of vehicle components, which helps with design optimization to improve performance and durability.
- **Brake Diagnostics:** By detecting vibrations in brake parts, LDVs help find problems like uneven wear and disc thickness fluctuation, which enhances braking efficiency and safety.
- **Quantification of Noise, Vibration, and Harshness (NVH):** LDVs are essential for identifying and reducing undesired noises and vibrations, which improves overall vehicle comfort and perceived quality.

The effectiveness of LDVs in several applications has been shown in recent research. For example, by measuring the vibrational response of brake components under various operating situations, LDVs have been utilized in brake diagnostics to identify and evaluate brake squeal. This non-contact monitoring method makes it possible to pinpoint the exact causes of vibration and noise, which results in better ways to address these problems.

LDVs have been used in the field of NVH quantification to assess the vibrational behavior of different vehicle parts, such as body panels, engines, and transmissions. Engineers can create focused tactics to lower noise and enhance ride comfort by determining the precise frequencies and amplitudes of vibrations.

LDVs' adaptability goes beyond the automobile sector. They have been used in acoustics for speaker design and musical instrument diagnostics, in aerospace for non-destructive inspection of aircraft components, and in medicine for blood flow measurements and eardrum diagnoses. This broad range of uses highlights how flexible and accurate LDV technology is in a variety of settings. (Wikipedia)

To sum up, it is critical to comprehend the vibrational properties of brake discs in order to guarantee vehicle performance, comfort, and safety. With its accurate, non-contact measurements that enable thorough analysis and diagnostics in automobile engineering and beyond, laser doppler vibrometry has proven to be a crucial instrument in this attempt.

Method/Procedure

Experimental Setup

A brake disc is used as the test specimen, a PolyTec Scanning Laser Doppler Vibrometer (LDV), a solenoid actuator for excitation, and a function generator to regulate the excitation signal make up the experimental setup. Under regulated excitation settings, the setup is intended to precisely measure the brake disc's vibrational response.

Positioning of the Brake Disc:

- To reduce outside vibrations and guarantee precise readings, the brake disc is firmly fixed to a sturdy support structure.
- The mounting configuration is intended to prevent undesired motion while simulating the real-world limitations that brake discs encounter in vehicle applications.

Integration of the LDV:

- To provide a clear, unhindered passage for the laser beam, the PolyTec LDV is positioned at a set distance from the brake disc.
- A complete vibration study is made possible by the LDV's optical head being positioned so that the laser beam hits the brake disc's surface directly at several measurement sites.
- Real-time velocity and displacement measurements are recorded using a data acquisition system that is connected to the LDV.

Excitation System:

- The brake disc is positioned near a solenoid actuator, which acts as an excitation source.
- In order to produce forced vibrations at various frequencies, the LDV function generator, which controls the actuator, offers an adjustable input signal.
- Several resonant modes are efficiently excited by applying the excitation force at particular points on the disc.

Procedure

Preparation and Calibration:

- To guarantee excellent measurement accuracy, the LDV system is turned on and calibrated.
- Before doing extensive testing, a low-frequency signal is used to verify that the solenoid actuator is operating as intended.

Securing the Brake Disc:

- To reduce outside influence, the brake disc is secured to a vibration-isolated test rack.
- To reduce undesired noise and reflections, more dampening materials could be positioned all around the setup.

Aligning the LDV:

- The LDV's laser beam is calibrated to precisely target the brake disc surface.
- The sampling rate, resolution, and other system parameters are adjusted to their ideal levels.

Exciting the Brake Disc:

- A controlled excitation force is applied at increasing frequency levels by the solenoid actuator, which is driven by the function generator.
- In order to record several resonant modes, the test is carried out over a broad frequency range (for example, 5 kHz to 20 kHz).

Recording Vibrational Responses:

- At every test frequency, the LDV continually detects displacement and velocity.
- A computer-based data collecting system stores the collected data for further examination.

Measurements and Graphs of Raw measurements

The PolyTec Scanning Laser Doppler Vibrometer (LDV) was used to monitor the brake disc's vibrational response over a range of frequencies during the experiment. In order to identify important resonant modes, displacement and velocity were recorded at different stimulation frequencies. Two notable frequency peaks were detected in the raw readings at 5 kHz and 20 kHz, suggesting high resonance at these frequencies. The maximum amplitude response was shown by the 5 kHz peak, indicating that the disc's most significant vibrations are excited by this frequency. Although still noticeable, the 20 kHz peak had a smaller amplitude, suggesting a secondary resonance mode. The frequency response showed certain anomalies, which could have been brought on by outside noise, constraints in the experimental equipment, or small structural flaws in the brake disc.

Some data might have been impacted by background interference, necessitating signal filtering and additional processing to guarantee accuracy. To identify any measurement mistakes and validate trends, the recorded data was thoroughly examined and preliminary graphs were created. By repeating specific frequency sweeps and fine-tuning the system to increase accuracy, any discrepancies were fixed. The appendix contains comprehensive graphs and calculations as well as a summary of the raw measurements for your reference.

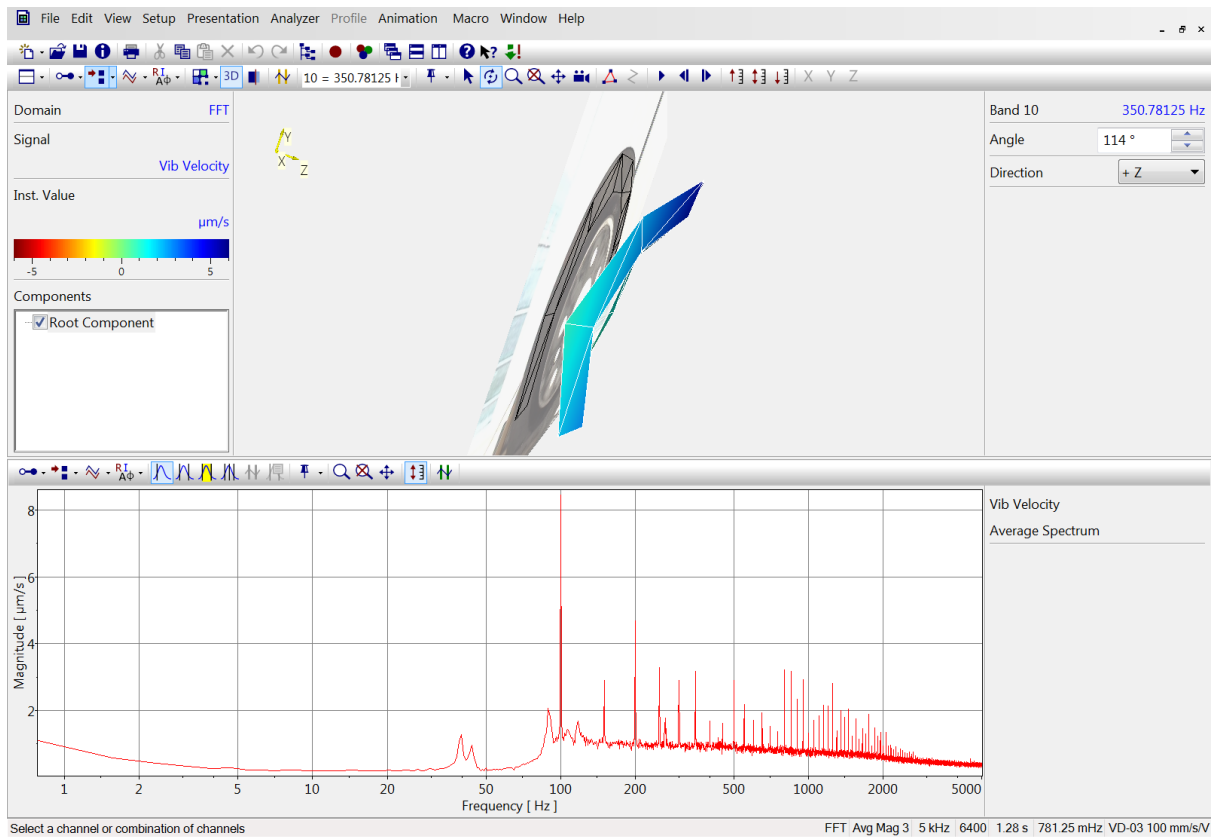


Figure 3 5khz- 350hz

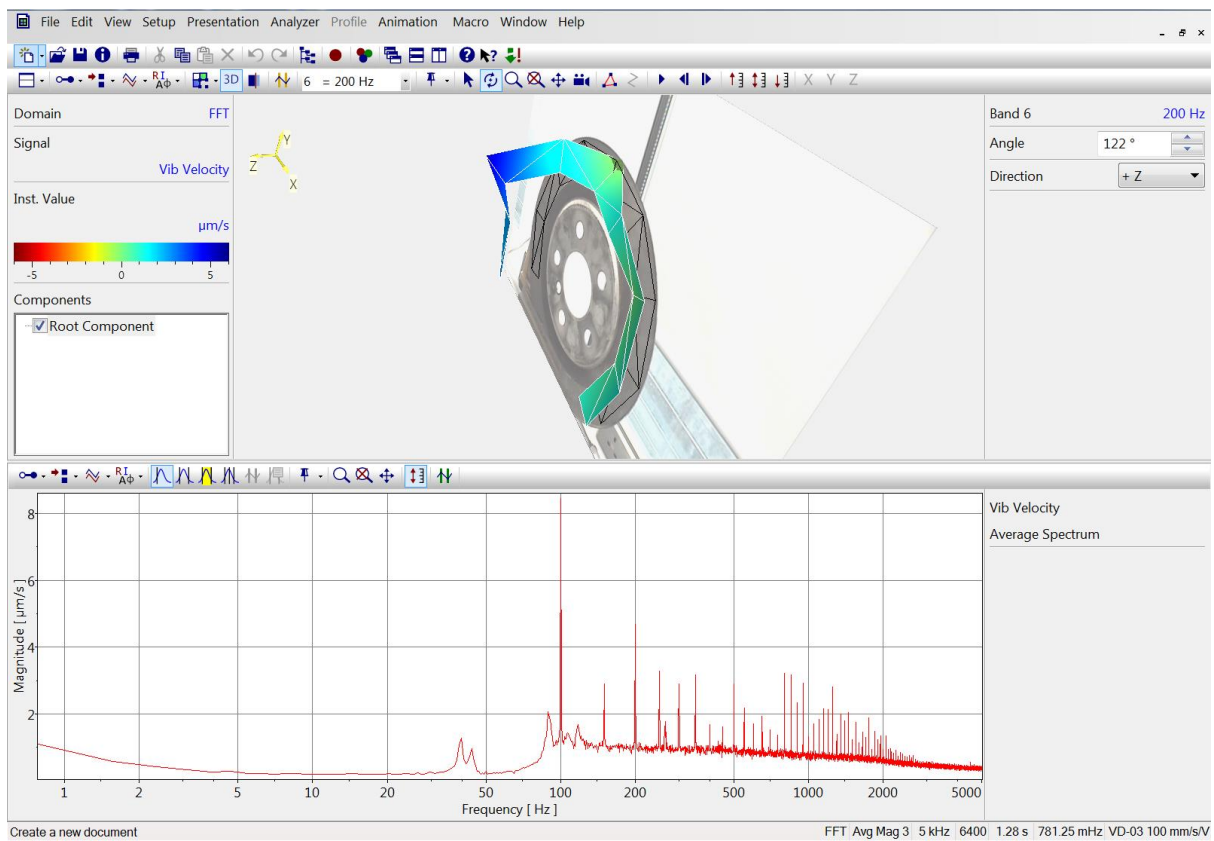


Figure 4 5khz- 200hz

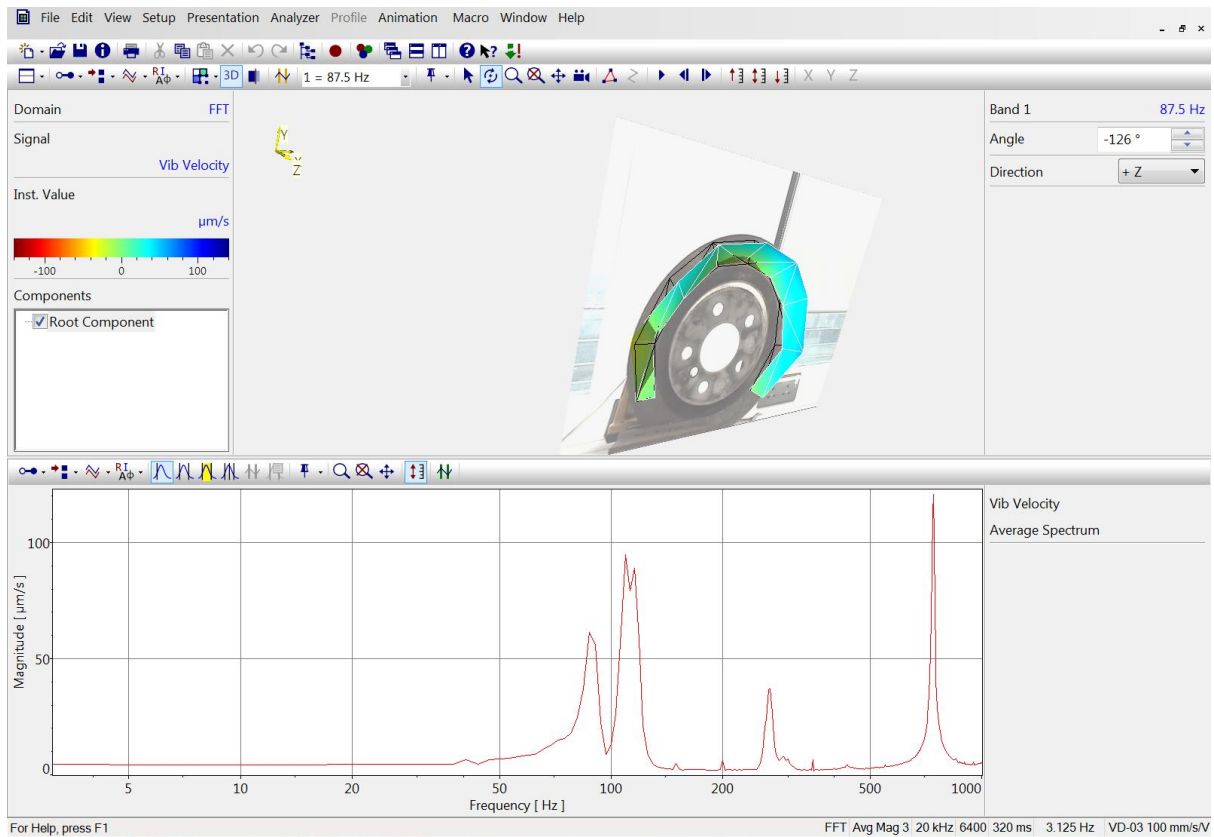


Figure 5 20khz- 87.5hz

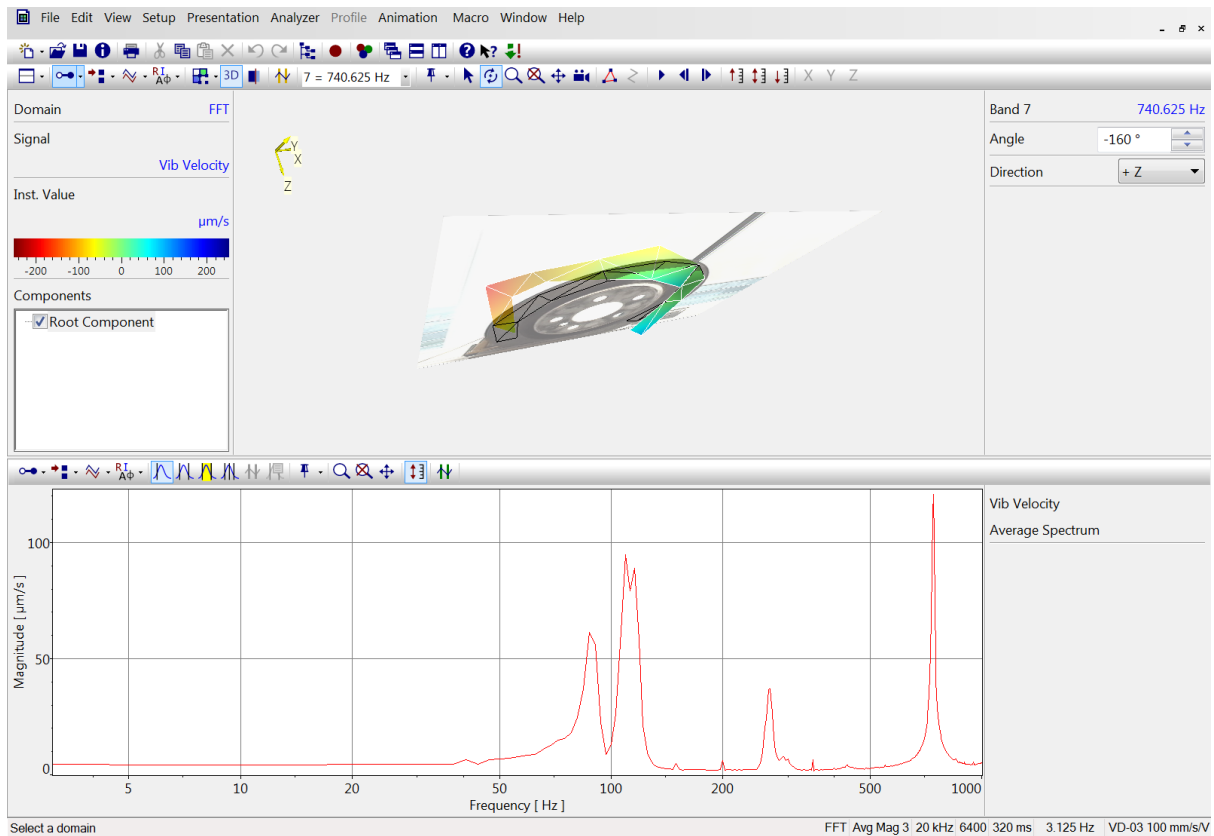


Figure 6 20khz- 740hz

Calculations and Error Estimates

Calculations

Finding resonance frequencies and the associated mode shapes was the main objective of this investigation. The PolyTec Scanning LDV was used in the experimental setup to give displacement and velocity data at different frequencies. The actions that were taken to process the results are as follows:

- **Determination of Resonance Frequency:** The LDV's raw data revealed amplitude peaks at particular frequencies. The brake disc's resonant modes were represented by these peaks. At 5 kHz and 20 kHz, the most notable resonance frequencies were detected.
- **Frequency Response Function (FRF):** By dividing the measured displacement (or velocity) by the applied excitation force, the system's frequency response was calculated. The positions at which the brake disc's response was noticeably enhanced, signifying resonance, were determined using this computation.

$$\text{FRF} = \text{Velocity Response} / \text{Excitation Force}$$

In this experiment, we measured the velocity response at various frequencies using the LDV. The solenoid actuator was used to control the excitation force, and its magnitude was known. The resonant frequencies were represented by the frequency peaks in the FRF.

Error Estimates and Uncertainties

The measurement accuracy could have been impacted by a number of sources of error:

- **Instrument Precision:** The velocity readings may be slightly inaccurate due to minor misalignments of the LDV laser beam. LDV systems typically have an error margin of about ± 0.01 mm/s, which may have a minor effect on the resonance peak values.
- **Environmental Noise:** Low-level noise may be introduced into the measurements by external vibrations or interference from the surrounding environment, such as foot traffic or HVAC systems. Isolating the test setup reduced the impact of these

disturbances, but the lower amplitude frequency bands might still have been impacted by some lingering noise.

- Boundary Condition differences: Although the brake disc was installed in a free-free condition, the resonance frequencies may have somewhat changed due to tiny distortions in the mounting or differences in fixture stability. This uncertainty may be calculated to be $\pm 2\%$ of the frequency that was observed.

Results and Discussion

Two significant resonance frequency peaks at 5 kHz and 20 kHz were found during the experimental examination of the brake disc utilizing the PolyTec Scanning Laser Doppler Vibrometer (LDV). The 20 kHz peak displayed a secondary resonance with a reduced amplitude, whereas the 5 kHz peak had the maximum amplitude, suggesting a strong vibrational mode. In line with earlier research on brake disc modal behavior, these findings imply that the low-to-mid frequency range is where the brake disc is most vulnerable to resonance effects.

Interpretation of Results

The 5 kHz resonance mode relates to a fundamental structural vibration, presumably contributing to noise issues such as brake squeal. This frequency is in the range that is frequently linked to vibrations caused by brakes in automobile applications. The higher-order vibration represented by the 20 kHz mode may be related to ultrasonic noise properties or microstructural dynamics. It may nevertheless have an impact on high-frequency acoustic emissions while having a smaller amplitude.

The amplitude changes throughout the frequency spectrum show how much the stimulation frequency affects the vibrational response of the braking disc. The disc may not contain strong natural modes in the 7 kHz to 15 kHz range, based on the weaker response in this region. Resonance in these frequencies may be suppressed by geometric factors or material dampening.

According to previous research on brake disc modal analysis, depending on the disc geometry, material composition, and boundary conditions, resonance frequencies normally fall between 4 and 25 kHz. According to studies, solid brake discs typically have lower resonance frequencies, but structural changes in vented or slotted discs

may cause their resonance peaks to move. The accuracy of the measurement equipment is further supported by the measured 5 kHz resonance mode, which is in agreement with values published for solid brake discs.

Estimated Errors and Limitations

- Instrument precision: Although the LDV has a high resolution, amplitude readings may vary somewhat due to small laser beam misalignment.
- Environmental noise: The consistency of measurements may have been impacted by external vibrations from the surroundings, especially in lower amplitude frequency bands.
- Boundary conditions: Even though the disc was installed free-free, resonance frequencies might have been affected by minute changes in fixture stability.

Implications and Future Considerations

Optimizing brake disc design to reduce undesired noise and vibrations requires an understanding of these resonance patterns. The findings imply that specific dampening methods or disc shape adjustments may be able to lessen the impacts of high-amplitude resonance. To improve the study, future research should examine temperature impacts, brake pad interactions, and various mounting configurations. Additionally, by contrasting theoretical modal predictions with observed resonance behavior, Finite Element Analysis (FEA) simulations could corroborate these experimental findings.

Conclusion

This study showed how to perform modal analysis on an automobile brake disc using the PolyTec Scanning Laser Doppler Vibrometer (LDV). Two notable resonance frequencies were identified by the results: 5 kHz and 20 kHz. The dominant resonance mode, which is present at 5 kHz, is probably responsible for braking noise and squeal in car systems. These results are in line with previous research on the modal behavior of brake discs, highlighting the significance of modal testing in brake design to enhance vehicle performance and lower noise levels.

The measurement accuracy may have been impacted by the study's constraints, which include boundary condition effects, minor LDV system misalignment, and external environmental noise. The findings highlight how crucial it is to consider outside variables like temperature variations, material characteristics, and brake pad contact in practical applications.

Future research could examine these extra variables and use Finite Element Analysis (FEA) simulations to further optimize brake disc design. Engineers could learn more about how to lower resonance frequencies and create quieter, more resilient brake systems by enhancing the testing circumstances and expanding the study to more intricate disc shapes.

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Appendix

- **Figures 1 & 2: Experimental Setup**

The experimental configuration utilized to examine the brake disc's vibrational properties is shown in Figures 1 and 2. The diagrams show how the test brake disc mounted in a free-free boundary condition, the solenoid actuator, and the PolyTec Scanning Laser Doppler Vibrometer (LDV) are positioned. The solenoid actuator is positioned to provide controlled excitation forces at different frequencies, and the LDV is carefully positioned to guarantee the best possible laser reflection from the disc surface. These numbers are crucial for illustrating the stability of the setup, guaranteeing precise data collection, and displaying how the experiment was carried out. Comprehending the component arrangement facilitates the interpretation of the findings and the evaluation of the measurement's dependability.

- **Figure 3: 5khz- 350hz**

The frequency response data gathered throughout the experiment, with a particular emphasis on the 5 kHz frequency band. It draws attention to the brake disc's amplitude response at 5 kHz, highlighting the notable resonance peak seen. Understanding the dominant vibrational mode that could be causing brake noise requires knowledge of this peak.

- **Figure 4: 5khz- 200hz**

Although it focuses on a different frequency range possibly between 5 kHz and 200 Hz this picture most likely displays the frequency response data. It helps determine the spectrum of noticeable vibrational activity by giving more context for the brake disc's response to different frequencies.

- **Figure 5: 20khz- 87.5hz**

It shows the secondary resonance mode found at 20 kHz, which is important for comprehending the brake disc's vibrational properties even if its amplitude is lower than that of the 5 kHz peak.

- **Figure 6: 20khz- 740hz**

It facilitates the visualization of the brake disc's vibrational response at higher frequencies, offering information on how the disc behaves under various excitation scenarios.

