

University of Wales Trinity St Davids

Laser Doppler Vibrometer – Brake Disc Modal Analysis



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Abstract -

Laser Doppler Vibrometry (LDV) is a non-contact optical technique used for high-precision vibration measurements. This study applies a Polytec Scanning LDV to perform a modal analysis of a brake disc, aiming to identify its resonant frequencies and mode shapes. The experiment utilized a solenoid actuator to excite vibrations while the LDV captured full-field vibrational responses across the disc's surface. Key findings include the detection of bending and torsional modes, as well as harmonic frequencies at 100 Hz, 200 Hz, and 299 Hz, indicative of nonlinear vibration behaviour. The study highlights the advantages of LDV over conventional accelerometers, particularly its ability to measure structural dynamics without adding mass to the system. Challenges encountered included signal reflectivity variations, environmental noise, and excitation inconsistencies. Future work should focus on improving signal quality through enhanced surface preparation and utilizing a more stable excitation system. The results demonstrate the effectiveness of LDV for brake system modal analysis and provide insights into vibration characteristics relevant to noise, vibration, and harshness (NVH) issues in automotive braking applications.

1.0 Apparatus List

All apparatus can be seen in Figure 1 below. The Polytec Scanning is connected to the computer with the software.

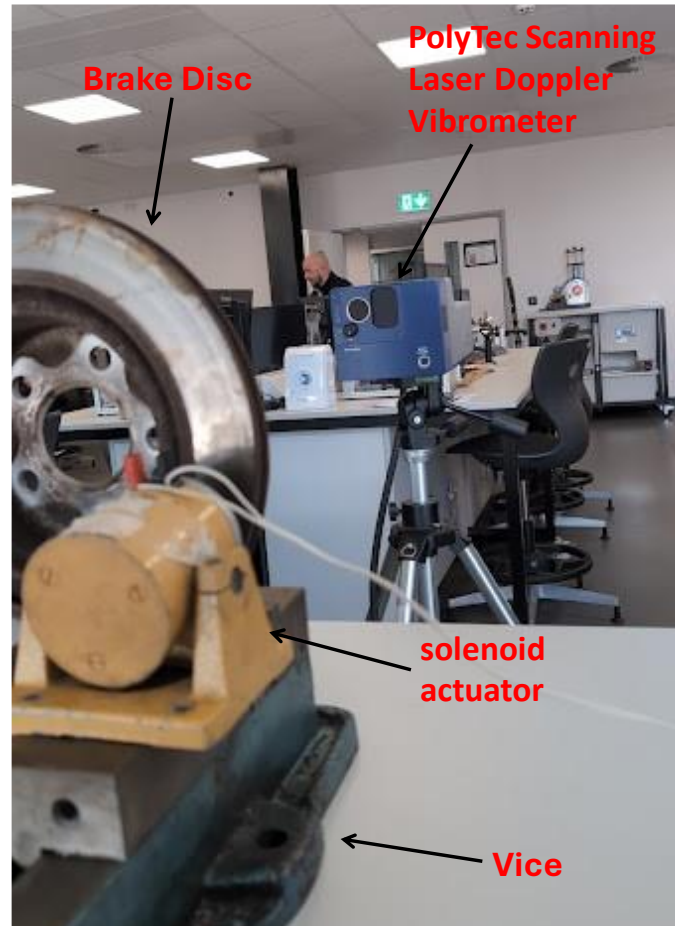


Figure 1 Apparatus diagrams

2.0 Introduction

Brake noise, vibration, and harshness (NVH) are critical issues in automotive engineering, impacting vehicle performance, driver comfort, and safety. Traditional vibration measurement methods, such as accelerometers, introduce mass-loading effects that can alter the modal characteristics of the component under test. To address these limitations, Laser Doppler Vibrometry (LDV) has become a widely adopted tool. Subsequently LDVs have become a valuable tool for accurate noncontact measurement of vibration on different sized structures (Johansmann, fritzsche, 2011).

This study aims to investigate the modal behaviour of a brake disc using a Polytec Scanning LDV. The primary objectives are to identify the natural frequencies and mode shapes of the brake disc, evaluate the effects of measurement bandwidth on modal detection, and analyse the presence of harmonic frequencies that may influence brake noise generation. A solenoid actuator was employed to provide controlled excitation, and full-field vibration measurements were captured using LDV scanning techniques.

The significance of this research lies in its ability to provide deeper insights into brake disc dynamics and their implications for NVH performance. By understanding the vibrational characteristics of brake discs, engineers can develop more effective noise mitigation strategies, optimize brake designs, and enhance overall vehicle refinement.

3.0 Literature review

Laser Doppler Vibrometry (LDV) is a non-contact optical technique that measures vibrations via Doppler shifts in reflected laser light (Rezaei, 2020). Unlike accelerometers, LDV adds no mass to the test object and captures a wide frequency range with high resolution. Modern 3D scanning LDVs enable dense spatial vibration mapping, surpassing traditional accelerometer arrays (Polytec, 2025). Widely used in automotive NVH analysis, brake diagnostics, and structural testing, LDV matches or outperforms conventional sensors and serves as an alternative for some non-destructive testing methods (Rezaei, 2020) making it a suitable technique for this lab approach.

3.1 LDV in Brake System Analysis

Research has been collected on Brake system analysis using LDV to use as comparison and to find a suitable industry standard of method used.

Martin et al. (2018) used 3D scanning LDV to analyse brake squeal, identifying two dominant mode shapes. Due to vibration variations with rotor rotation, they developed an algorithm to merge sequential LDV scans, refining a full FE model. This improved squeal interpretation and pinpointed noise-contributing areas (Martin, G, 2018). LDV-based modal analysis of brake components has improved, offering accurate natural frequencies and mode shapes without mass-loading effects. A scanning LDV paired with an FE model enabled rapid, high-resolution vibration mapping of a brake disc, using a RoboVib® system to scan 5,000 points from multiple angles. This approach significantly reduced testing time compared to accelerometers, providing precise mode shapes for squeal analysis and model validation, enhancing brake noise mitigation. The key finding is that LDV enables full-field vibration visualization of brake components, leading to better understanding and mitigation of problematic resonances in brake systems (Polytec, 2025). LDV has also been used in rail and heavy vehicle brake studies. Lu *et al.* (2023) investigated stick-slip oscillations in a high-speed train brake using LDV. In their setup, a Polytec LDV measured the tangential vibration velocity of a brake pad (friction block) while it slid against a rotating disc under low-speed braking conditions. The LDV captured friction-induced vibration signals up to 22 kHz, allowing the researchers to analyse how different friction radii affected the stick-slip behaviour. This high-frequency capability (well above the range of many accelerometers) was crucial for characterizing the ultrasonic squeal components of the brake. The study demonstrates an advancement in brake analysis: using LDV to measure transient friction vibrations with high fidelity, which can inform better brake material designs and control strategies to reduce squeal. Overall, in the last five years LDV has proven highly effective for brake

system modal analysis and squeal diagnostics, providing detailed vibration insight that guides improvements in brake noise performance (Lu, Wang ,2023).

3.2 LDV for Noise, Vibration, and Harshness (NVH) Testing

NVH testing is crucial for ensuring vehicle comfort, performance, and durability by identifying and mitigating unwanted noise, vibrations, and harshness. The following research shows how LDV can be used for NVH testing.

Palled et al. (2023) developed an NVH test setup using a robotic 3D LDV to scan a vehicle on an acoustic chassis dynamometer. This replicated low speed driving conditions, measuring vibrations of exterior panels and identifying resonant modes causing cabin noise. LDV data was integrated into a vibro-acoustic FE model, enabling precise NVH issue diagnosis and guiding structural modifications to reduce interior noise (Palled, Chmielewski, 2023).

The shift to EVs presents new NVH challenges, as the absence of engine noise makes high-frequency sources (e.g., inverter whine) and tyre/road noise more prominent. A 2023 study used LDV to measure tiny, high-frequency vibrations (10–15 kHz) in an EV inverter housing, revealing tonal noise linked to switching electronics. LDV's non-contact precision identified vibration peaks at switching frequencies, confirming the noise source and guiding acoustic countermeasures. Similarly, LDV aids in analysing tyre NVH, which becomes dominant in EVs at moderate speeds (Singh, Nalawade, 2023).

Researchers are using scanning LDVs to study tyre resonances and vibrations. Garbarino (2020) used a Scanning LDV in a rolling tyre test rig to analyse tyre modes under different conditions, showing good correlation with accelerometer data. The study identified changes in sidewall and tread-band vibrations between static and rolling states, aiding in addressing structure-borne tyre noise. LDV's ability to capture full-field, high-frequency vibrations makes it essential for NVH testing, especially with EVs and lightweight designs, enabling more effective noise control solutions (Garbarino, 2020).

3.2 Conclusion

This research highlights LDV's superiority in brake system analysis and NVH testing, offering non-contact, high-resolution vibration measurement across a wide frequency range. Studies by Martin et al. (2018) and Lu et al. (2023) demonstrate its effectiveness in identifying mode shapes, diagnosing brake squeal, and refining FE models. LDV's integration with robotic systems like RoboVib® significantly enhances efficiency over accelerometers.

For NVH testing, research by Palled et al. (2023) and Singh & Nalawade (2023) shows LDV's role in diagnosing EV noise sources, tyre vibrations, and structural resonances. Garbarino (2020) further validates its precision in tyre NVH analysis.

Overall, LDV advances brake noise mitigation, enhances NVH diagnostics, and supports the shift toward quieter, more efficient vehicle designs, making it an essential tool in modern automotive development.

4.0 Procedure

The PolyTec Scanning Laser Doppler Vibrometer (LDV) as seen in Figure 2 was positioned at a suitable distance, ensuring a clear line of sight to the brake disc surface.



Figure 2 Scanning Laser Doppler Vibrometer (LDV)

A solenoid actuator (Figure 3) was connected to the function generator of the LDV to provide controlled excitation.

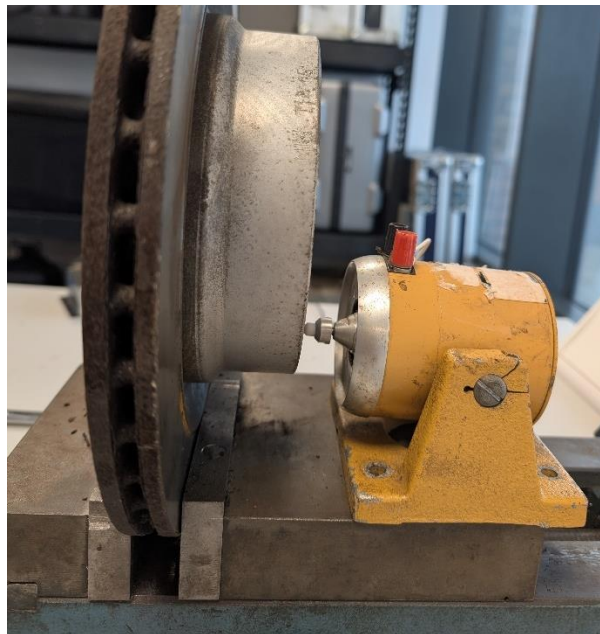


Figure 3 Solenoid actuator

A preliminary scan was performed to verify the positioning and alignment of the laser. The function generator was then configured to provide a frequency sweep across the expected modal frequency range.

After the LDV has been set up a 2D alignment is required. Then alignment points are placed on the brake disc. An auto-focus is performed on the laser beam, the scan points can then be defined to form a mesh, a rectangular mesh option was used as seen in Figure 4.



Figure 4 rectangular mesh on Brake Disc

The Polytec Scanning Head displays as a bar indicator, showing the signal strength, five illuminated bars, generally indicates a strong and stable signal as seen in Figure 5.



Figure 5 Polytec Scanning Head displays , signal Strength

The signal strength of the Polytec PSV-400 Scanning Head is influenced by several key factors. Surface reflectivity plays a crucial role, as highly reflective surfaces, such as polished metals, enhance signal quality, whereas rough or dark surfaces tend to reduce it. Measurement distance also affects the signal; as the laser travels further, the reflected signal weakens. The laser was placed 1 metre away from the brake disc.

Proper laser alignment is essential to ensure the beam is directly hitting the measurement surface for optimal data collection. Additionally, environmental conditions such as strong ambient lighting or external vibrations can interfere with readings and affect measurement accuracy. During the study, nature light could have affected the results due to the lab having large windows and the solenoid actuator providing different vibrations, as it wasn't fixed in place. In this setup, the strong signal strength indicates that the system is well-aligned, and the measurement surface is providing good reflection, ensuring reliable vibration data acquisition.

For data acquisition, the solenoid actuator delivered sinusoidal excitation signals at incremental frequency steps while the LDV captured full-field vibration data across multiple scan points on the brake disc surface. The acquired vibration data was logged and stored for post-processing. Frequency response functions (FRFs) were extracted, and the primary harmonic resonant modes and shapes were identified using modal analysis techniques. The harmonic detection tool was used to detect harmonics in each scan.

4.0.1 Change of Bandwidth

Reducing the bandwidth of a LDV from 5 kHz to 2 kHz limits the measurable frequency range but improves the signal-to-noise ratio (SNR). This improvement occurs because the noise power in LDV measurements depends linearly on the bandwidth, therefore a narrower bandwidth results in reduced noise, enhancing measurement sensitivity (Chiariotti, Rembe, 2021). Lowering the bandwidth to 2 kHz restricts the upper frequency range, meaning higher-order modes, harmonics, and high-frequency excitations may be missed, hence why the test was repeated with a larger bandwidth of 5 KHz.

4.1 Deviations from Script & Issues Encountered

Reflectivity issues were encountered due to inconsistencies in the brake disc's surface finish, which affected the laser signal strength this could have been solved by using reflective tape. Before conducting the main tests, the LDV wasn't calibrated to ensure accurate velocity measurements, therefore leaving an unknown percentage error.

Ambient vibrations from surrounding machinery also affected initial measurements, necessitating repositioning in a more isolated environment to minimize noise interference.

Precise alignment of the LDV proved challenging due to the disc's curvature, requiring multiple setup adjustments for optimal measurement accuracy.

The solenoid actuator exhibited variations in excitation amplitude, introducing discrepancies in the FRF measurements. This issue was addressed by implementing multiple excitation trials and averaging results.

2.2.0 Conclusion

The method provided a comprehensive modal analysis of the brake disc using a non-contact measurement approach. Despite minor alignment and noise challenges, the LDV system successfully

captured detailed vibrational characteristics, Future improvements could involve using a more robust excitation system and additional noise filtering techniques to enhance data reliability and reflective tape could have been applied to enhance laser measurement accuracy where necessary.

3.0 Measurements and Graphs of Raw Measurements Analysis

3.1 Scan using 2 KHz Bandwidth

2 KHz bandwidth is used, this ensures that modal frequencies up to 2000 Hz were captured during the LDV scan however, the 2 kHz scan lacks data beyond 2000 Hz, so higher-order modes are missing.

Frequency Band Definition - Scan1					
No.	Start	End	Peak	Bandwidth	Unit
1	39.0625	50.3125	44.375	11.25	Hz
2	78.75	102.8125	100	24.0625	Hz
3	111.25	137.8125	124.6875	26.5625	Hz
4	247.8125	334.6875	282.8125	86.875	Hz
5	648.75	826.5625	738.75	177.8125	Hz

Figure 6 Frequency Band Definition- Number of modes, Peaks, Bandwidth(lengths) with a 2 KHz Bandwidth used

The resonant frequencies correspond to different vibration modes of the brake disc as seen in Figure 6 above. The highest magnitude resonance occurs at 738.75 Hz, brake noise issues, such as squeal and groan, are closely linked to the natural frequencies of brake components (Triches, Gerges, 2004). While brake squeal typically occurs at higher frequencies, groan noise is associated with lower frequencies. For instance, a study on a metro braking system identified groan noise occurring at frequencies below 1 kHz (Megna & Bracciali, 2023). Therefore, a resonance at 738.75 Hz could be significant for brake groan issues.

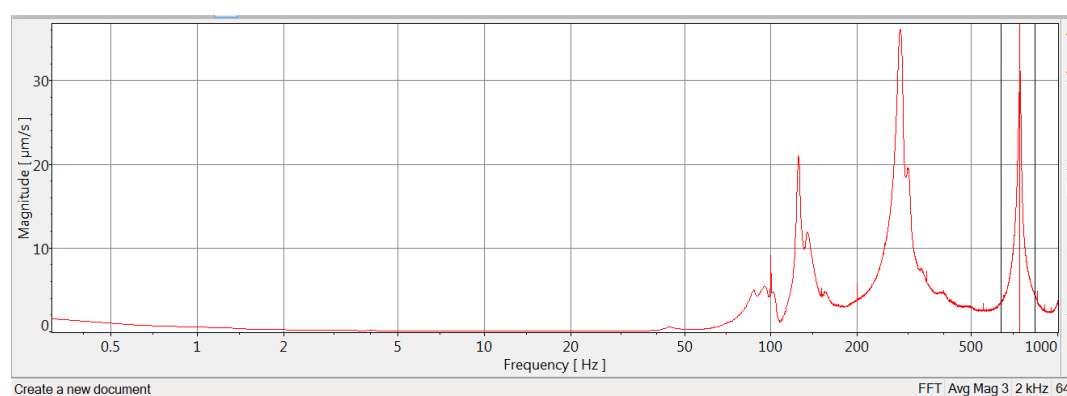


Figure 7 Laser Doppler Vibrometer FFT Analysis of Brake Disc Vibrations with 5 KHz Bandwidth. Showing different modes(peaks)

Fast Fourier Transform (FFT) spectrum obtained from the LDV scan of the brake disc as seen above in Figure 7 reveals significant peaks at approximately 124.68 Hz, 282.81 Hz, and 738.75 Hz. These peaks

correspond to the natural frequencies where the brake disc exhibits pronounced vibrational modes. These peaks are now further examined to determine their modes.

Table 1 Modal Analysis of Brake Disc Vibrations: Mode Classification and Frequency Characteristics. Bending and Torsional Modes

Mode Number	Mode Letter	Frequency Hz	Type of Mode	Number of degrees
1	None	44.375	Bending	1-2
2	A	100	Bending and Torsional	1-2
3	B	124.68	Bending	2
4	C	282.8125	Torsional	2
5	D	738.75	Bending	3

Modes 1,2 and 3 are picked for analysis due having different modes as seen in Table 1 above.

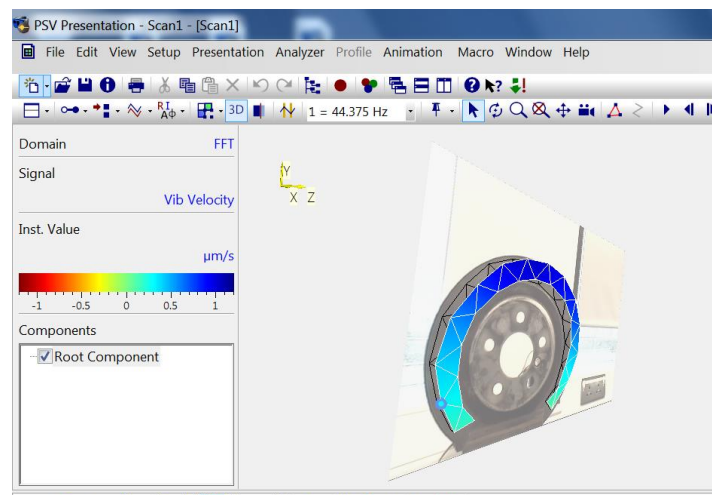


Figure 8 Mode 1- 44.375Hz (scan 1)

The color-coded visualization on the brake disc as seen above in Figure 8 indicates vibration velocity ($\mu\text{m/s}$). The blue-to-red gradient represents velocity magnitude, where blue areas indicate low vibration velocity and Red/yellow areas represent higher vibration velocity, suggesting locations of maximum displacement. The mode shape at 44.375 Hz suggests a low frequency bending mode. Mode 1 has relatively low vibration velocity with a scale that ranges from $-1 \mu\text{m/s}$ to $+1 \mu\text{m/s}$, meaning it might not be a critical resonance but could still contribute to low-frequency NVH effects.

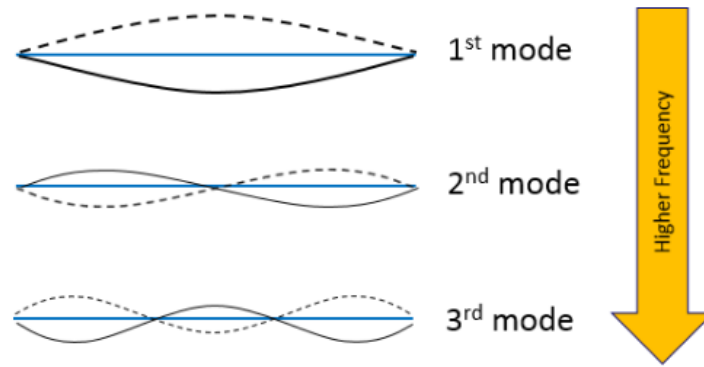


Figure 9 Vibrational Mode Shapes and Frequency Progression example (Divincenzo, 2020)

Figure 9, above represents different vibrational modes of a system, showing how natural frequencies increase with mode number. In the 1st mode, the system deforms into a single half-wave, with one antinode (maximum displacement) and two fixed nodes at the ends. In the 2nd mode (first overtone), the system vibrates in two half-waves, introducing two antinodes and one central node where no movement occurs. The 3rd mode (second overtone) introduces three half-waves, with three antinodes and two nodes. This concept is crucial in structural dynamics and is used to analysis the different modes of the brake disc. From Figure 9, its clear that Mode 1 (Figure 8) is a low frequency bending mode with 1-2 degrees.

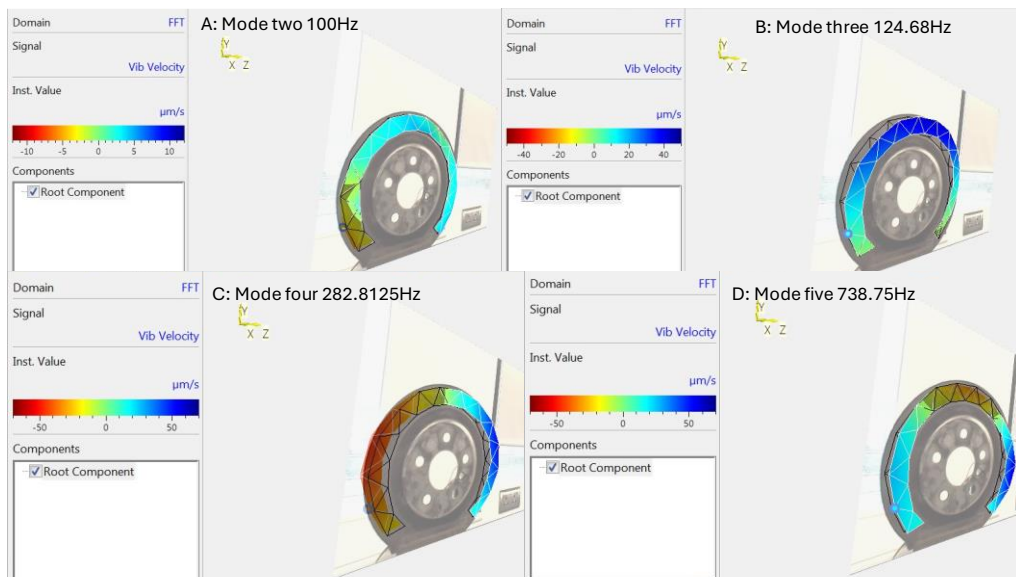


Figure 10 Modes,2,3,4,5 labelled as A,B,C,D

The bending and torsional combination for Mode two as seen above in Figure 10, A suggests a mixed deformation mode, where the disc is experiencing both out-of-plane bending and in-plane twisting effects. The left and right edges of the disc exhibit maximum displacement, while the central region remains more stable, indicating torsional motion coupled with bending deformation. Since this is a

low-frequency mode, it is unlikely to cause high-pitched brake noise but could contribute to brake judder or pedal feel issues. The presence of torsional motion means that rotational forces are not being evenly distributed, which could lead to uneven brake wear or minor torque variations. This mode is particularly relevant at low vehicle speeds, where brake disc rotational speeds match this resonant frequency. Potential impact: Mild brake pulsation or torque variation during slow-speed braking.

Mode three as seen in Figure 10, B exhibits two clear bending waves across the disc surface. Compared to Mode A, this mode has a higher frequency and increased complexity, meaning that multiple areas of the disc experience simultaneous bending motion.

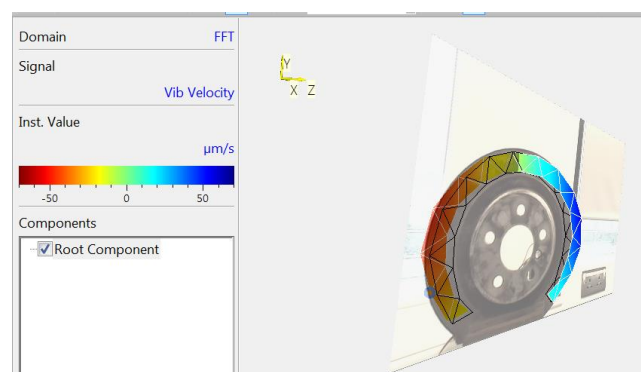


Figure 11 C Mode four 282.8125 Hz

Mode 4 as seen above in Figure 11 is an excellent example of a torsional mode. The color-coded velocity distribution across the brake disc shows a distinct torsional deformation pattern, where one side of the disc is moving in one rotational direction while the other side moves oppositely. Since the mode twists the disc, it can cause non-uniform brake pad contact during operation. This leads to inconsistent braking force application, which can cause brake shudder or pedal pulsation. The vibration velocity values range from $-50 \mu\text{m/s}$ to $+50 \mu\text{m/s}$. This means the fastest moving points on the disc oscillate at $\pm 50 \mu\text{m/s}$ in opposite directions, showing an intense vibration energy at this frequency.

3.2 Scan using 5 KHz Bandwidth

Results gained using a 5 KHz Bandwidth provided more noise but provided an upper frequency range, showing higher order modes and harmonics as seen below in Figure 12.

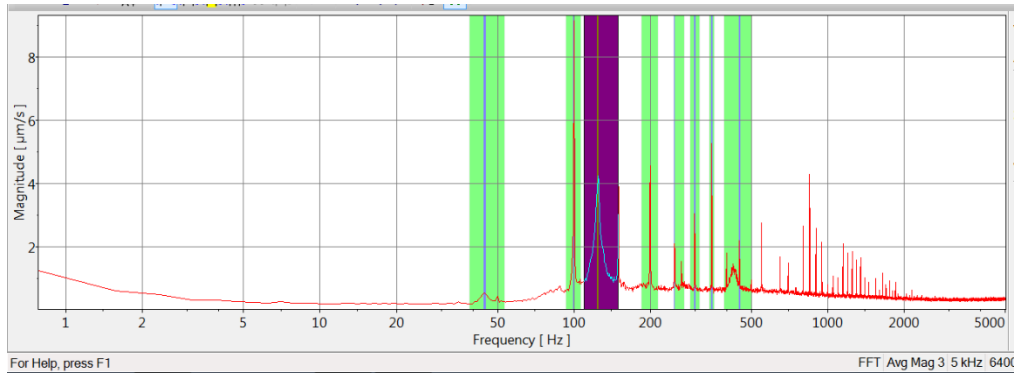


Figure 12 5KHz Bandwidth scan

Due to the increase bandwidth, harmonics were analysed at 100,200 and 299.21 using the harmonic detection tool as seen in Figure 13 . The harmonics are highlight with black dotted lines are labelled as 1,2,3.

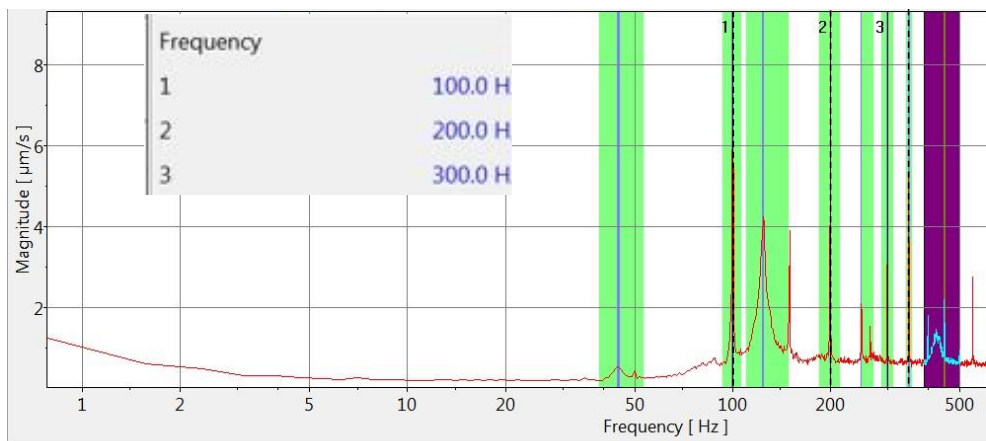


Figure 13 Harmonic detection tool. Harmonic located at 100,200,300 Hz highlighted with a black dotted line and label as 1,2,3.

The LDV analysis of Mode 5 as seen in Figure 14 reveals a first order bending mode, characterized by alternating out-of-plane deflections across the rotating component. High vibration velocities at the rim suggest resonance effects, with a nodal diameter near the centre. The asymmetry indicates potential dynamic imbalance, which could amplify vibrations and impact stability. Further modal analysis is needed to confirm frequency response and higher-order modes. Mode 5 may be distorted by introduce noise which would affect the vibration mode shape potentially making a bending mode appear slightly torsional.

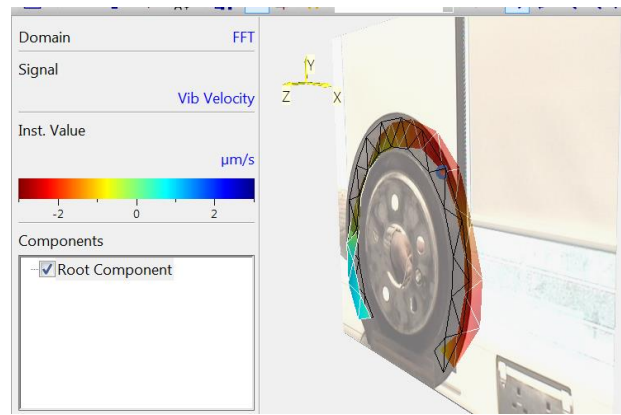


Figure 14 Scan 2 Mode 5- 249.21 Hz

The last two vibration modes as seen below in Figure 15 , occurring at 349.21875 Hz and 449.21875 Hz, exhibit characteristics of bending modes, as seen in the LDV visualizations. Both images Z and X show a symmetric pattern of velocity distribution along the outer edge of the rotating component, with alternating high and low vibration zones.

In the 349.21875 Hz mode (Z), the deformation pattern suggests a higher-order bending mode with multiple nodal diameters, as indicated by alternating velocity regions along the rim. The velocity color gradient, transitioning from blue (negative velocity) to yellow/red (positive velocity), signifies out-of-phase motion in different segments, characteristic of flexural bending.

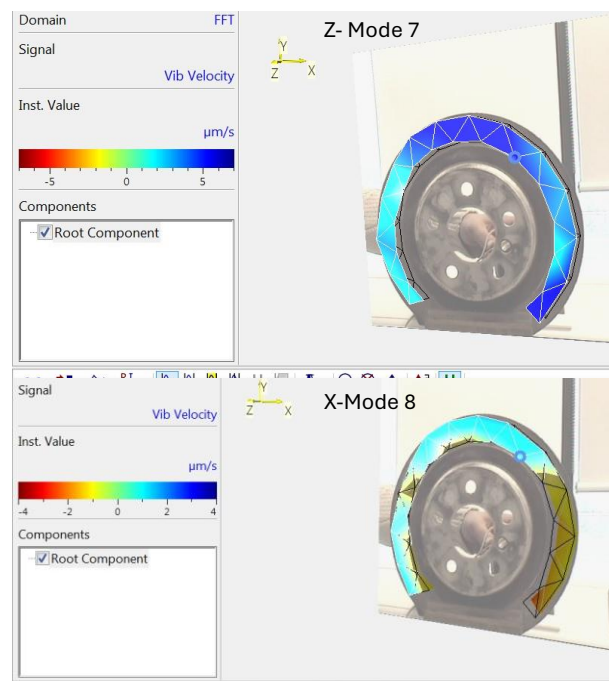


Figure 15 A-Mode 7 B-Mode 8

For the 449.21875 Hz mode (X), the trend continues with an even more defined segmentation of alternating displacement regions, likely corresponding to an increased number of nodal diameters. The higher frequency indicates a shorter wavelength of vibration, meaning the structure is undergoing more complex bending deformation.

Both modes suggest a structural response dominated by out-of-plane bending, which is typical for components experiencing dynamic excitation at their higher natural frequencies. These results align with the mode table, confirming that no significant torsional motion is present in these higher-order modes. The increasing frequency and complexity of these bending modes indicate a shift towards finer vibrational structures, which could contribute to operational noise or fatigue in high-speed applications.

4.0 Results and Discussion

Table 2 presents four distinct vibrational modes, each with specific frequencies and effects on brake performance. Mode A (100 Hz) is a combination of bending and torsional motion, Mode B (124.68 Hz) is a bending mode that contributes to moderate NVH effects. Mode C (282.81 Hz) is a torsional mode,

Table 2 modal analysis table

Mode	Frequency (Hz)	Type	Key Effects on Brake Performance
A (Mode 2)	100 Hz	Bending & Torsional	Brake pedal feel issues, torque variation, low-speed judder
B (Mode 3)	124.68 Hz	Bending	Moderate NVH effects, mild acoustic emissions, structural flexing
C (Mode 4)	282.8125 Hz	Torsional	Shuddering, uneven torque transfer, potential fatigue issues
D (Mode 5)	738.75 Hz	High-Frequency Bending	Brake squeal, groan, high-pitched noise, structural stress

meaning it affects torque transfer and braking consistency, causing shuddering and potential fatigue issues over time. Mode D (738.75 Hz), a high frequency bending mode, is strongly linked to brake squeal, groan, and high-pitched noise.

Modes 1,2,3 were found and analysed from the 2KHz scan, modes 2,4,6 are determined as harmonics therefore leaving 5,7,8 for analysis as seen in Table 3 below.

Table 3 Scan 2 modes detection using 5KHz Bandwidth

Mode Number	Frequency Hz	Type of Mode
1	44.53125	Bending
2	100	torsional
3	124.21875	Bending
4	200	Torsional
5	249.21875	Bending and Torsional
6	299.21875	Bending
7	349.21875	Bending
8	449.21875	Bending

4.1.0 Harmonic Identification Explanation

The presence of harmonics at 100 Hz, 200 Hz, and 299 Hz in the brake disc system is indicative of nonlinear vibration behaviour, where both the fundamental frequency and its integer multiples are excited due to factors like system stiffness variations, material damping, or nonlinear contact forces. A study that delves into this phenomenon establishes a six-degree-of-freedom nonlinear dynamics model to analyse the vibration characteristics of disc brakes under various conditions, highlighting how nonlinearities can lead to complex vibrational responses, including the excitation of harmonic frequencies (Zhang, Qiao, Zhang, 2022).

The harmonics detected at 100 Hz, 200 Hz, and 299 Hz likely result from nonlinear excitation, mode coupling, and structural interactions within the brake disc. Their presence can amplify NVH issues like squeal, judder, and structural resonance, impacting both performance and durability. Further investigation, such as finite element analysis (FEA) or experimental modal analysis could confirm their role in brake noise generation.

4.1.1 Excitation Source Contribution

The solenoid actuator used for excitation did not deliver a perfect pulse force due to not being clamped in place, therefore it introduces harmonics. The harmonic detection tool used identified these multiples, which did not correspond to actual structural modes but are still present in the vibration response, harmonic frequency can be seen in Table 4 below.

Table 4 Harmonics Detected using a harmonic tool

Mode Number	Frequency Hz
2	100
4	200
6	299.21875

4.1.2 Structural Nonlinearities

The study by Zanarini (2005) demonstrates that non-uniform mass distribution, boundary conditions, and surface imperfections in brake discs contribute to mode coupling and the excitation of higher-order frequencies. Structural asymmetries cause mode splitting, altering natural frequencies and leading to cross-mode interactions. Boundary conditions, such as how the disc is mounted, further influence vibrational behaviour, modifying mode shapes and amplifying higher-frequency excitations. Additionally, surface imperfections intensify modal coupling, affecting the propagation of vibrational energy and promoting instability, particularly in brake squeal. These findings highlight the role of real-

world structural irregularities in modifying brake disc dynamics, leading to undesired vibrational resonance and noise issues Zanarin, 2005).

4.1.3 Discussion of Modal Behaviour

The modal analysis indicates that bending and torsional modes interact, leading to potential mode coupling, brake torque variations, and NVH issues. The identified modes align with known brake NVH problems:

- Mode 2 (100 Hz, bending & torsional) relates to brake judder.
- Mode 4 (282.81 Hz, torsional) is linked to brake groan.
- Mode 5 (738.75 Hz, bending) could be a precursor to high-frequency brake squeal.

To address brake NVH issues, several strategies have been identified, including modifications to disc design, damping treatments, and brake pad adjustments. Finite Element Analysis (FEA) simulations and LDV scans are valuable tools in developing these strategies. For instance, a study demonstrated that incorporating a damping layer into brake pads resulted in a reduction of vibration and noise by at least 10% across various speeds (Suwantaroj & Lakkam, 2022).

5.0 Conclusion

The application of LDV in this study successfully enabled high-resolution modal analysis of a brake disc, identifying critical vibrational modes that contribute to NVH-related issues. Key resonant frequencies were detected, including bending and torsional modes that influence brake judder, groan, and squeal. The presence of harmonics at 100 Hz, 200 Hz, and 299 Hz suggests nonlinear excitation effects, potentially exacerbated by structural asymmetries and imperfect excitation from the solenoid actuator.

Despite the high accuracy of LDV measurements, several challenges were encountered, including signal reflectivity inconsistencies, environmental noise, and excitation variability. These issues highlight areas for improvement, such as the application of reflective tape to enhance signal quality and the use of a more robust excitation system.

Overall, the study demonstrates the effectiveness of LDV as a powerful tool for brake system modal analysis, providing valuable insights into vibration behaviour without mass-loading effects. Future research should focus on refining LDV measurement techniques, integrating finite element analysis (FEA) for enhanced mode validation, and exploring additional noise mitigation strategies to improve brake performance.

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