

Laser Doppler Vibrometer – Brake Disc Modal Analysis

Iatrakis Ilias (2011922)

Motorcycle Engineering, University of Wales Trinity Saint David, Swansea, SA1 8EW

Abstract - *Laser Doppler Vibrometry (LDV) is a non-contact, optical measurement technique widely used in automotive engineering for vibration analysis. This paper presents a methodology for measuring the vibration modes of a car brake disc using a LDV system. The LDV system operates based on the Doppler shift principle, enabling precise determination of vibrational characteristics without physical contact, thereby avoiding mass loading and intrusive effects. Vibration analysis in automotive components is crucial for noise and comfort considerations, driving the need for advanced measurement techniques like LDV.*

The study outlines the experimental setup using a Polytec PSV-400 LDV system and a solenoid actuator to tap the brake disc for excitations. A detailed methodology is provided, covering sample setup, system connection, acquisition settings, 2D alignment, scan point definition, scanning procedure, and analysis. Results from vibration measurements conducted at different mesh densities and scanning frequencies are presented and, highlighting the identified vibration modes and their frequencies. Limitations, including measurement inaccuracies and mounting method constraints, are acknowledged

1. INTRODUCTION

Laser Doppler Vibrometry (LDV) is a non-contact, optical measurement technique used to measure the velocity and displacement of vibrating structures. The Polytec Scanning LDV system operates based on the Doppler shift principle, where a laser beam is directed at the surface of the object under study [1]. The vibration of the surface causes frequency shifts in the reflected laser light, which are then measured by the LDV system [2]. This allows for the precise determination of the vibrational characteristics of the object without any physical contact, avoiding mass loading and other intrusive effects associated with traditional contact sensors [3]. The following paper shows a methodology in order to measure vibration modes of excitations carried out on a car brake disc. The following paper presents the method of using a Laser Doppler Vibrometer system, to monitor and determine the resonant frequency modes and shapes of a brake disc.

1.1 Vibration Analysis in Automotive

The study of vibrations in automotive components is an important aspect in the automotive world. As one of the three main parts of NVH (Noise, vibrations and harshness), it's an important aspect to consider during development for structural and comfort considerations. The noise and feeling emitted by vibrations is a critical point in this. Outside of manufacturers pushing for more silent and comfortable cars, standard rules on noise reduction put a pressure on designers [3].

The Laser Doppler Vibrometry [4], and in particular the Tracking Laser Doppler Vibrometer [5–7], is a technique that also allows measurements in operative conditions. In 2002, Bosch & polytec carried out measurements first carried out simultaneous measurements of in-plane and out-of-plane vibrations utilizing a single point 3D LDV. Scanning was achieved by mechanically traversing the LDV sensor head across the surface, To gain a deeper insight into the squeal generation. The scanning method was thus the same as used by the author.

Using the new measurement process, the Bosch researchers were able to clearly characterize the interactions between brake pads and brake disc without any ambiguity. The investigation showed that, under certain conditions, cross coupling between in-plane and out-of-plane natural vibrations causes the squealing noise as explained in reference [8]. The data shown in this article was measured on a non-rotating brake disc excited by an automatic impact hammer with force reference transducer. The force was applied in a different direction, and the disc was also mounted as it would in a car.

Vibration analysis can also be used for monitoring machine and structure conditions, for certain machines such as big milling machines/ ISO standards apply with maximum recommended vibration frequencies, from testing and manufacturers, vibration frequency values can also be used to analyse the condition of parts, machines as they wear and tolerances start getting less tight etc.

PolyTec [9] shows significant use of the LDV in automotive industries, showing highly versatile use;

Body Lightweighting: LDV assists in evaluating the impact of lightweighting efforts on NVH performance, facilitating the rapid development of new vehicles by validating CAE simulations.

Body-in-White (BiW): It aids in verifying the safety and structural integrity of lightweight materials used in the BiW through analytical planning and experimental validation.

Damping Material Placement: LDV's high spatial detail enables precise localization of vibration modes, enhancing sound package design by transforming trial-and-error processes into defined design strategies.

Trimmed Body: LDV provides direct measurement input for acoustic simulation and troubleshooting, especially in lightweight structures where material removal affects transfer paths and noise levels.

Buzz, Squeak & Rattle (BSR): LDV's 3D scanning capability helps locate sources of BSR events, crucial for addressing lightweight components' high-frequency interactions and in-plane motion.

Heating, Ventilation & Air Conditioning (HVAC): LDV assists in identifying noise sources and optimizing HVAC system components to minimize cabin noise, enhancing passenger comfort.

Brake Modeling & Validation: It aids in validating component models through Experimental Modal Analysis (EMA), ensuring accurate CAE predictions and effective countermeasure design.

Testing on the Assembly Level: LDV facilitates validation of assembly-level modal damping, ensuring accuracy by integrating measured data directly into finite element models.

Brake Dyno Testing: LDV provides high-density modal data for fine-tuning brake designs, enabling comparison between operational and modal data to minimize dynamic instabilities.

Axle and Steering Components: LDV aids in validating lightweight axle and steering components, identifying modes contributing to wear and unwanted noises.

Dampers: LDV ensures the precision of shock absorber manufacturing processes, guaranteeing optimal vehicle performance and safety.

Aero-Acoustics: LDV measures wind-induced vibrations to identify panel contributions to acoustic noise, aiding in vehicle aero-acoustic optimization.

Engine Acoustics: LDV measures deflection shapes of critical engine components, aiding in resonance analysis and sound radiation assessment for both combustion and electric propulsion systems.

Gearboxes/Differential: LDV assists in detecting high-frequency excitations and torsional oscillations in gear meshing, crucial for gearbox and drivetrain optimization.

In summary, LDV offers invaluable insights across various automotive engineering domains, from lightweighting and structural validation to noise reduction and drivetrain optimization. Its non-contact measurement capabilities and high spatial resolution make it an indispensable tool for enhancing vehicle performance, safety, and comfort.

2 Apparatus

The following part shows the apparatus used throughout the measurement of the following paper, the apparatus was made available for use by the University of Wales Trinity Saint David.

Figure 1 shows the used material sample. A used brake disc from a car has been used to perform the measurements on.



Figure 1: Brake disc and Solenoid used for Measurement. (Iatrakis, 2024)

A PolyTec PSV-400 Laser Doppler Vibrometer system has been used. The measurements have been executed at room temperature in a controlled science lab. Following list gives a summary of the PSV-400 system's components.

Figure 2 shows the system's analysis components with the wiring junction box, Vibrometer Controller and Data Management System (DMS or computer).

Figure 2 displays the PSV 400 scanning head.



Figure 2: PSV 400 Data Management system & Scanning head (NetScope Solutions)

A Solenoid (figure 1) was used to ‘tap’ the brake disc and generate excitations.

An amplifier (figure 3) was used in junction with the PolyTec DMS to control the frequency and Force magnitude of the ‘taps’ on the brake disc.



Figure 3: Stereo Amplifier (Iatrakis, 2024)

3. Methodology

The following part describes the procedure followed by the author for using UWTSD’s PolyTec PSV-400 Laser Doppler Vibrometer system for an experimental modal analysis. The measurements have been performed on a used car brake disc. The ‘PolyTec PSV 9.3 Acquisition’ Software is used to perform and analyse the measurements.

3.1 Sample Setup

The used sample/ brake disc has been clamped in a vice on part of its friction surface (figure 1). The solenoid actuator has been attached to the vice, “tapping” on the mounting surface of the brake disc. The distance between the amplifier solenoid and the brake disc is set that when an excitation is generated, a ‘ringing’ sound is generated by the brake disc.

The excitation is generated in-plane. Schell. ET al. [8] have conducted measurements using out-of-plane excitations.

This setup is not mounted as a brake disc is intended to be mounted on a vehicle. Due to material, mounting method limitations, and the goal of the conducted measurement being for education on the LDV system, this is accepted as a limitation by the author. For realistic measurement results, a setup as close to intended use on a vehicle as possible is recommended [10].

3.2 Connecting & Positioning scanning system

The first step is connecting the scanning system to the data management system, thus the Scanning head, amplifier, and solenoid actuator. It’s important to mention that the latch on the scanning head in front of the laser is to be kept shut when not performing measurements and moving the scanning head, to avoid any direct eye contact with the laser and causing eye damage.

The scanning head has been positioned parallel to the measurement object, at a 1m distance. The PolyTec PSV-400’s working distance is >0.4m [11].

3.3 Acquisition Settings

The ‘acquisition settings’ menu, in the “PSV 9.3 Acquisition” software is used to set the system, measurement parameters and modes for the following measurement. Most settings have been kept as default for the basic modal analysis performed in this paper. The scanning bandwidths have been switched between 10KHz and 20KHz for the measurements.

3.4 2D Alignment

The used LDV system incorporates a 3D geometry measurement system [8], which allows the coordinate system of the scanning head to be matched to the surface which is scanned, by using at least 3 points on the surface for the system to use and calculate the orientation of the surface. A wider spread, or higher amount of points, offers higher accuracy in the coordinate system acquisition. The LDV’s incorporated video camera, shows a clear image of the aim of the LDV and helps with clearly defining scanning points.

During the 2D alignment, it’s also important to focus the laser beam, which is done through an auto-focus function in the PSV 9.3 software. The distance between the scanning head and the scanned surface is also to be defined.

This alignment is done through the ‘2D-Alignment’ function in the ‘Setup’ menu.

The vector components v_x , v_y and v_z of the vibration are automatically defined in the object coordinate system. consequently, there is no need to measure the Euler angles, unlike with accelerometers [8].

3.5 Defining Scan Points

After configuring the acquisition settings and aligning the coordinate system. The scanning points for the measurement can be defined. The PSV 9.3 software offers predefined 'grids' of points that you can use, the size of the grid, grid configuration and amount of points can be set (figure 4). Due to the limited shapes of the grid available and the specific shape of the brake disc, the author has manually defined the points.

As the main goal of the experiment was to get familiar with the LDV procedure rather than results. Three grids have been defined with a lower and higher amount of scanning points compared to each other, in order to familiarise with the impact of grid density on results (figure 5).



Figure 4: Predefined Scanning Grids (Charlton, 2024)

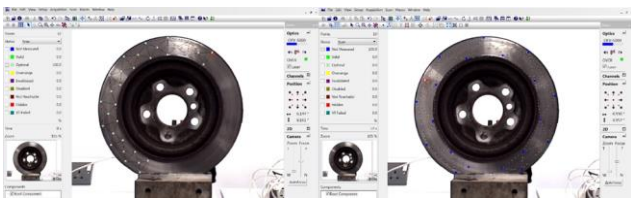


Figure 5: Fine Half Mesh (Left) – Low Full Mesh (Right) (Iatrakis, 2024)

3.6 Scanning

The scanning procedure is how the actual 'measurement' is conducted. Multiple scanning options are available (Figure 6). Single shot and Continuous modes perform analysis on the current selected laser position. The 'Scan' function has been used for the measurements in this experiment. The scan function scans all the previously defined scan points while using the solenoid actuator to excite the brake disc.

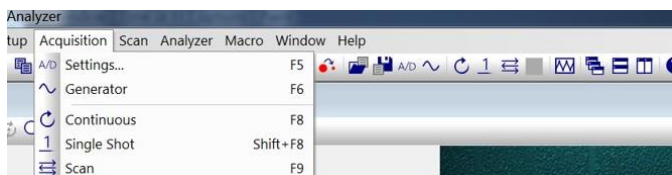


Figure 6: Scanning Mode Options (Charlton, 2024)

During the scan, the points that have been scanned will be coloured, the colour indicates the quality of the scan at that point. Figure 5 shows the colour indication on the left, as visible, all scan points for the low mesh scan were optimal after the scan.

The scan will be complete once data has been collected for all the defined scan points. When the scan is completed successfully, it can be saved for further analysis.

3.7 Analysis

The following part shortly describes the analysis functions in the polyTec PSV 9.3 software, the actual results of the measurements conducted in this experiment will be discussed further on. The PSV Analysis application is used to analyse a scan file saved after conducting the previous steps.

When opening an analysis file, the default window will display a mode shape based on the entire measured bandwidth. Through the 'Setup' menu, frequency bands can be specified. Using the 'Select Bands' option, areas of interest, usually peaks in the frequency domain [12] can be specified (figure 7). After having selected the areas of interest, the software will recalculate the frequency bands and these can then be viewed separately for analysis of the resulting vibration modes. Detailed information of the selected Frequency bands can be seen in the table on the right. (Figure 7)

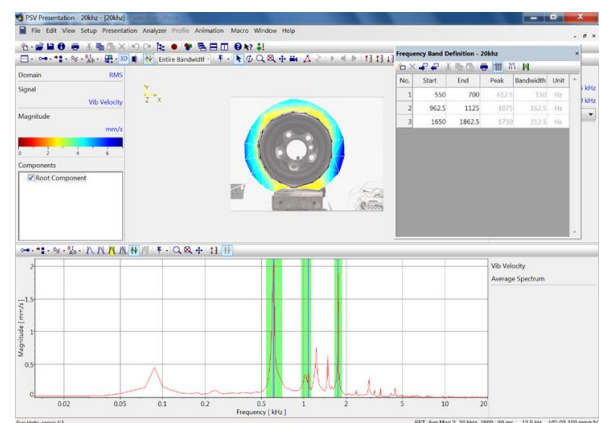


Figure 7: Full Bandwidth scan + areas of interest highlighted. (Iatrakis, 2024)

4. Discussion

In the following section, select results from vibration measurements conducted by the author, using Laser Doppler Vibrometry (LDV) will be presented. Since the primary focus of this paper lies on the methodology, a detailed technical analysis of these results will not be provided, they will be shown to demonstrate a fundamental grasp of measurement processing techniques.

As outlined in the methodology section, measurements were carried out using the prescribed procedure. The presented results will show three meshes scanned at both 10 kHz and 20 kHz scanning frequencies. The primary identified vibration modes will be highlighted.

The two meshes specified in the methodology are used, as 'fine' and 'low' meshes. A third 'normal' mesh is displayed in the results, the frontal view of this mesh has been lost before data was collected from the PolyTec DMS.

The 'low' mesh consists of 19 scanning points across the complete visible brake disc surface. (figure 8)

The 'normal' mesh consists of 36 scanning points across the complete visible brake disc surface. (figure 9)

The 'fine' mesh consists of 32 scanning points across half the brake disc surface. (figure 10)

4.1 Mesh Comparison 10kHz

The following part shows a comparison between the different mesh densities scanned at 10Khz. A major limitation for mesh comparison here is that the 'fine' mesh only consists of half the brake disc. The half disc and full disc scan's surface difference do allow for comparison between different coverages of the object and it's results.

A higher density mesh or higher amount of scan points usually leads to a higher accuracy up to a certain point, ideally, a mesh independence study should be performed [13]. The chosen mesh is accepted as a limitation by the author.

The scans with the different mesh sizes shows vibration modes or 'peaks' occurring at the same frequencies between each scan. The differences are mainly recognised in magnitude differences at the peaks. The half surface, high mesh shows a significant difference in peak magnitude compared to the magnitude difference between full surface scans.

This shows that the same vibration mode frequencies can be recognised between the three scans and depending on the goal of the measurement, Expected accuracy, and time

available, an adequate mesh density and scanning surface can be selected.

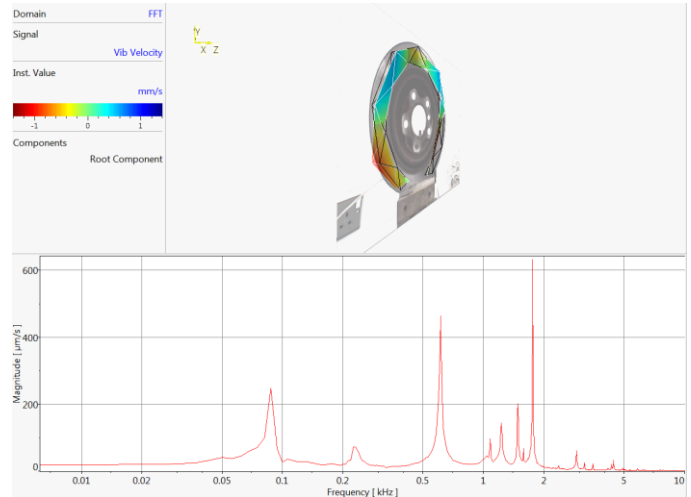


Figure 8: 10kHz 'Low' Mesh Density Scan (Iatrakis, 2024)

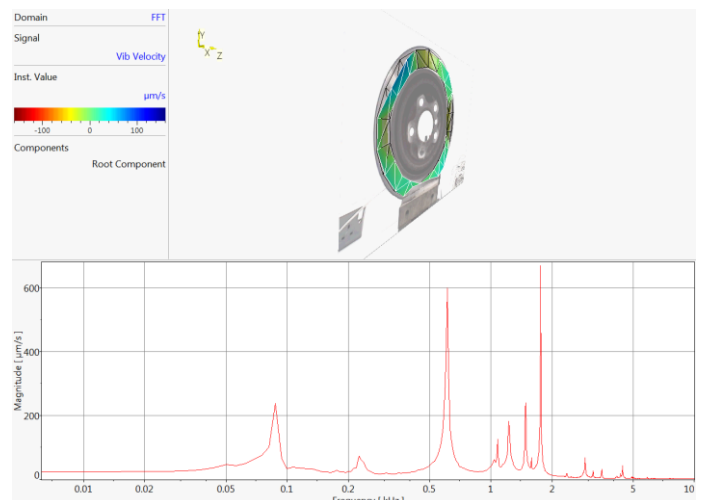


Figure 9: 10kHz 'Normal' Mesh Density Scan (Iatrakis, 2024)

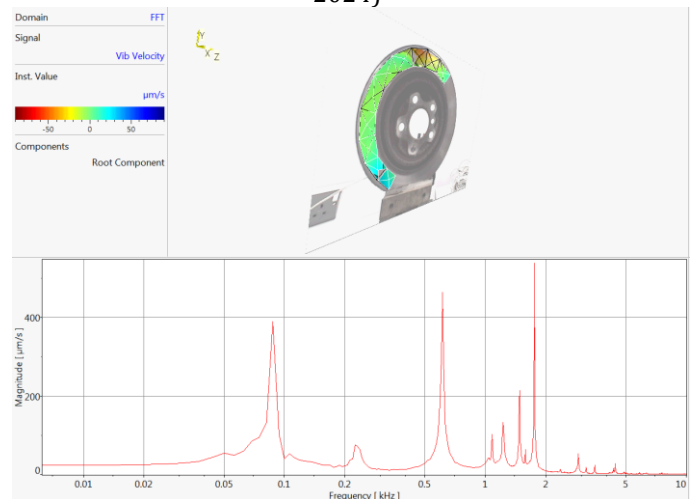


Figure 10: 10kHz 'Fine' Mesh Density Scan (Iatrakis, 2024)

4.2 Bandwidth Comparison

In a similar trend as with the 10KHz scans, the vibration modes or peaks, occur at the same frequency between the half surface scan (figure 12) and the full surface scan (figure 11), with magnitude differences.

At frequencies higher than 10Khz, the 20Khz scan hasn't picked up any vibration modes. Thus showing no need for a 20khz scan if any more scans were to be conducted.

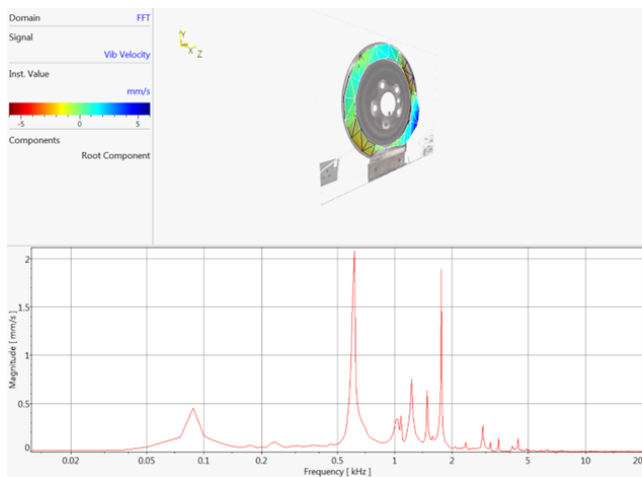


Figure 11: 20kHz 'Normal' Mesh Density Scan (Iatrakis, 2024)

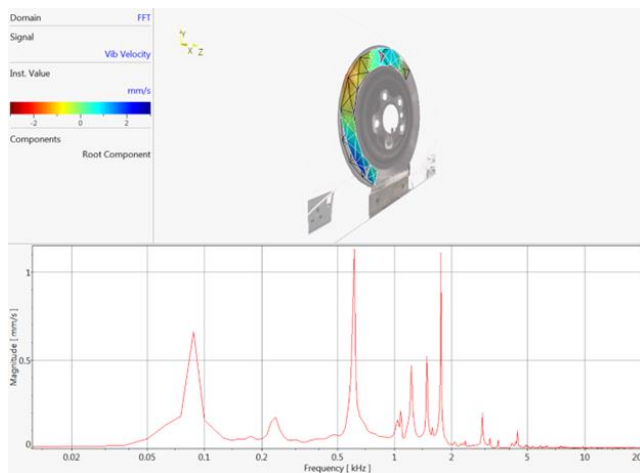


Figure 12: 20kHz 'Fine' Mesh Density Scan (Iatrakis, 2024)

4.3 Vibration Modes

The following part shows the brake disc's main vibration modes and shapes along with a brief discussion. The scans using the 'Normal' Mesh covering the complete brake disc have been used for the modal analysis. The scan bandwidth used is 10Khz.

11 Bending modes were identified and selected using the frequency bands for further inspection. Table 1 mentions the frequencies of the bending modes.

Table 1: Bending Mode Frequencies (Iatrakis, 2024)

<i>Bending mode</i>	<i>Frequency (KHz)</i>
1	0.088
2	0.225
3	0.613
4	1.081
5	1.225
6	1.481
7	1.756
8	2.350
9	2.900
10	3.175
11	4.431

Triches M. Et Al. [14] mentions Brake squeal is distinct between low frequency and high frequency. Their distinction lies in the mode shapes involved in their coupling mechanism. Low frequency squeal results from coupling between out-of-plane rotor modes and bending modes of the brake pad, whereas high frequency squeal arises from coupling between in-plane rotor modes. High frequency squeal typically occurs in the 8-16 kHz range, while low frequency squeal occurs between 1-7 kHz. Since the human ear is most sensitive to frequencies between 1-4 kHz, low frequency squeal is often considered the most bothersome.

The highlighted bending modes from the conducted measurements only represent out-of-plane bending, as they fall below 7KHz, which agrees with source [14].

Figure 13 shows the inspected Bending modes

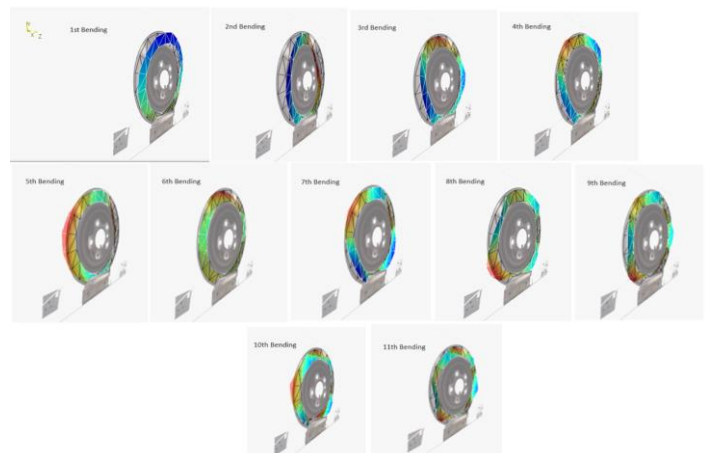


Figure 13: Scanned Bending Modes (Iatrakis, 2024)

4.4 Limitations

The study's limitations include the potential for measurement inaccuracies due to external vibrations, the assumption of linear material properties, and the spatial resolution limits of the LDV system. The impact force of the solenoid tap, while controlled, may introduce variability due to mechanical wear and inconsistencies in the actuator's performance over time. Also think about the mounting method of the solenoid, not all the taps might have been quite as consistent. The hardness of the taps have also been determined by sound, by making sure there is a "ring to the metal when it taps, thus when measurements might be done on other days, you most likely will not get the taps to the same strength as before. The mounting method of the brake disc, as it has been clamped on the actual surface of the braking area, Figure 14 shows a proposed more realistic mounting method. Due to the big difference in mounting method, the results will not be representative of what you'd expect in real life. Thus it's also important to mention that this paper is more so to show the understanding of the process and processing the results instead of collecting data from the measurement.

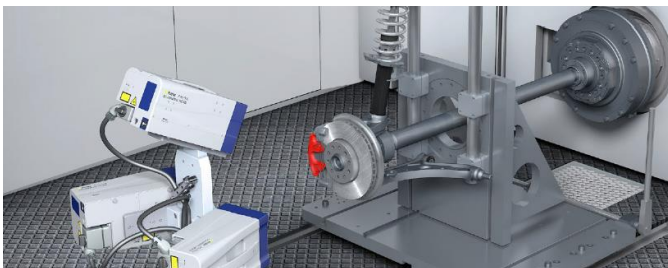


Figure 14: Ideal Brake LDV test rig (PolyTec, 2024)

5. CONCLUSIONS

In conclusion, this study illustrates the utility of Laser Doppler Vibrometry (LDV) in automotive vibration analysis, particularly in characterizing the vibrational behaviour of car brake discs. By employing a PolyTec PSV-400 LDV system and a solenoid actuator, the methodology presented enables precise measurement of vibration modes without physical contact, offering insights into structural dynamics critical for noise and comfort considerations in vehicle design.

The results demonstrate the effectiveness of LDV in identifying vibration modes at different mesh densities and scanning frequencies, providing valuable data for understanding the behaviour of brake discs under excitation. Despite limitations such as potential measurement inaccuracies and mounting method constraints, the study showcases the fundamental understanding of LDV processes and the capability to process results effectively.

REFERENCES

- [1] PolyTec GMBH, "Laser Doppler Vibrometry." Accessed: Mar. 18, 2024. [Online]. Available: <https://www.polytec.com/uk/vibrometry/technology/laser-doppler-vibrometry>
- [2] Manfred Schreiner, Matija Strlic, and Renzo Salimbeni, Handbook of the use of Lasers in Conservation and Conservation Science. COST Office, 2008.
- [3] P. Castellini, "Vibration measurements by tracking laser doppler vibrometer on automotive components," IOS Press, 2002.
- [4] D. Di Maio et al., "Continuous Scanning Laser Vibrometry: A raison d'être and applications to vibration measurements," Mechanical Systems and Signal Processing, vol. 156. Academic Press, Jul. 01, 2021. doi: 10.1016/j.ymssp.2020.107573.
- [5] P. Castellini and C. Santolini, "Vibration measurements on blades of a naval propeller rotating in water with tracking laser vibrometer," 1998.
- [6] P. Castellini, M. Martarelli, and E. P. Tomasini, "Laser Doppler Vibrometry: Development of advanced solutions answering to technology's needs," Mechanical Systems and Signal Processing, vol. 20, no. 6. pp. 1265–1285, Aug. 2006. doi: 10.1016/j.ymssp.2005.11.015.
- [7] L. F. Lyu and W. D. Zhu, "Full-field mode shape estimation of a rotating structure subject to random excitation using a tracking continuously scanning laser Doppler vibrometer via a two-dimensional scan scheme," Mech Syst Signal Process, vol. 169, Apr. 2022, doi: 10.1016/j.ymssp.2021.108532.
- [8] J. Schell, M. Johansmann, M. Schüssler, D. Oliver, and V. Palan, "Three Dimensional Vibration Testing in Automotive Applications Utilizing a New Non-Contact Scanning Method," 2024.
- [9] PolyTec GMBH, "Automotive optical measurements that drive progress," 2024.
- [10] P. GmbH, "Innovative Vibration Measurement Technology for Brake Development Measuring Techniques."
- [11] PolyTec GMBH, "PSV-400-3D Scanning Vibrometer." [Online]. Available: www.polytec.com

- [12] Jyoti Kumar Sinha, Vibration Analysis, Instruments, and Signal Processing. 2015.
- [13] I. Sadrehagighi, "Mesh Sensitivity & Mesh Independence Study," 2021.
- [14] M. Triches, S. N. Y. Gerges, and R. Jordan, "Reduction of Squeal Noise from Disc Brake Systems Using Constrained Layer Damping."