



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

MSc - Motorsport Engineering

Laser Doppler Vibrometer – Brake Disc Modal Analysis

Module Name	Structural Integrity & Materials Evaluation
Module Number	ACEA7013
Student Name	Sean Doyle
Student Number	2305948
Lecturer	Luca Pagano
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Laser Doppler Vibrometer – Determination of Resonant Frequencies

Date: 04/02/2025

Title: Determining the resonant frequency modes and shapes of an automotive brake disc using laser doppler vibrometer (LDV).

Abstract

This experiment utilized Laser Doppler Vibrometer (LDV) to identify the resonant frequency modes and shapes of an automotive brake disc. The report also outlines the fundamental principles of LDV and its applications within the automotive industry. The most common observed modes were first and third order bending, with occasional torsional resonant modes detected between 100 and 290 Hz. Harmonics at 100, 200, and 299 Hz were recorded during the second scan, which employed a higher testing bandwidth of 5 kHz compared to 2 kHz. The validity of these results is critically evaluated, with extensive discussion of potential error sources. Comparisons with published literature are presented to analyse experiment methodologies and propose improvements to enhance the reliability and accuracy of results.

Apparatus

- Polytec Laser Doppler Vibrometer scanning head and tripod.
- Brake disc test component.
- Vice.
- Solenoid actuator
- Computer with PSV (Acquisition and Presentation) software installed.

Introduction

This experiment utilizes laser doppler vibrometer (LDV) to investigate the natural resonant modes of a steel brake disc. A Polytec scanning head is used to examine the test piece, which is secured in a vice and excited with a solenoid actuator. The LDV system functions by detecting doppler shifts caused by surface vibrations. Two tests, conducted at different bandwidths, identify the resonant frequencies of the component. The resulting data, combined with supporting literature, assist in determining the resonant frequency modes and shapes. This experiment focuses on two categories of modes: bending and torsion, further divided into subcategories that define the order/mode of each shape (Pagano & Lake, 2017). This report outlines the experimental procedure for obtaining these results as well as a comprehensive data analysis to evaluate laboratory methodology and result accuracy, reliability and validity.

1 Literature Review

1.1 LDV Overview

The LDV scanning head functions on wave mechanics and doppler shift. The doppler effect is defined as the change in wave frequency for an observer, relative to wave source movement (Petrescu, 2012). When the source moves towards the observer a higher received frequency is experienced due to observer and source distance decreasing. On the other hand, when a source moves further from the observer this perceived frequency is lower due to reverse effects (figure 1).

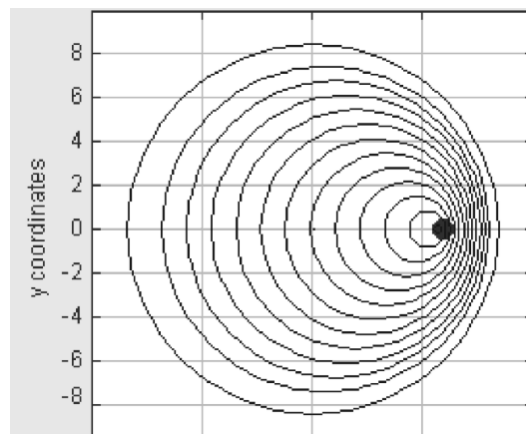


Figure 1: The Doppler Effect with the Source at Centre (Petrescu, 2012).

Figure 2 illustrates the pathing of laser beams as well as critical components within the scanning head. A reference beam is obtained from the initial beam to compare reference frequency to return frequency. Figure 3 provides an illustration of the full LDV experiment with a scanning head, test component and reflected wave. Excitation and surface vibration of the test specimen causes disturbances to reflected wave frequency (Palan, 2023), thus allowing for a comparison between the reference and return beam to calculate resonance modes.

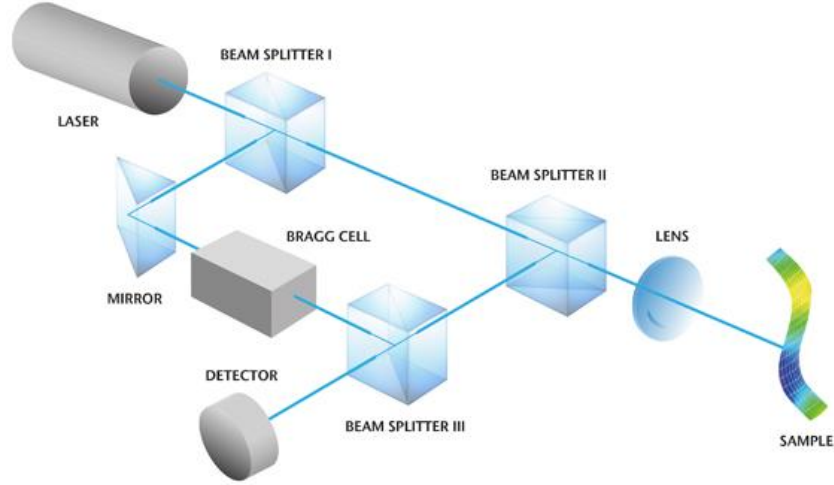


Figure 2: Schematic Working Diagram of Polytec LDV Scanning Head (Polytec, 2025).

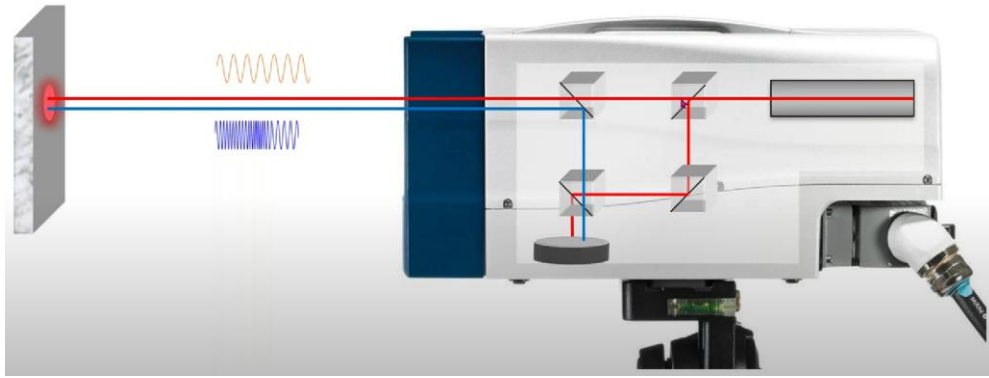


Figure 3: LDV Scanning Head Operating Principles (Palan, 2023).

This shift in frequency can be calculated with equation 1, where v is object velocity (m/s), λ is emitted wave wavelength (m), and Δf measured frequency shift (Hz) (Polytec, 2025).

$$f_D = 2 \times \frac{v}{\lambda} \quad (1)$$

1.2 Automotive Applications

LDV has a range of applications within the automotive industry, common applications include: brake discs, suspension and chassis components, powertrain vibration, drivetrain vibration and diagnostics (wear and imbalance detection), and much more (Polytec (3), 2025). The non-intrusive nature of LDV testing ensures components remain undamaged when results are retrieved. Applications are particularly useful in drivetrain systems when vibration analysis can be used to ensure vehicle ride comfort, as well as, the prevention of resonance in high load torsional components such as drive shafts and axles.

Additional applications for LDV include tyre testing machines to analyse the vibration of tyre sidewall and tread (Castellini, 2002). This assists in the manufacturers understanding of tyre performance. LDV setups can also be applied to timing belts for vibration testing analysis. LDV testing is also operated to analyse resonant frequencies, modes and shapes of engine covers to better understand their interaction with vibrations caused by the engine (Martarelli, et al., 2006).

Latest developments within automotive applications have seen scanning laser doppler vibrometer connected to robotic arms in tri-axial configurations for three-dimensional vibration surveys on structures (figure 4), such as a body-in-white (Rothberg, et al., 2017).

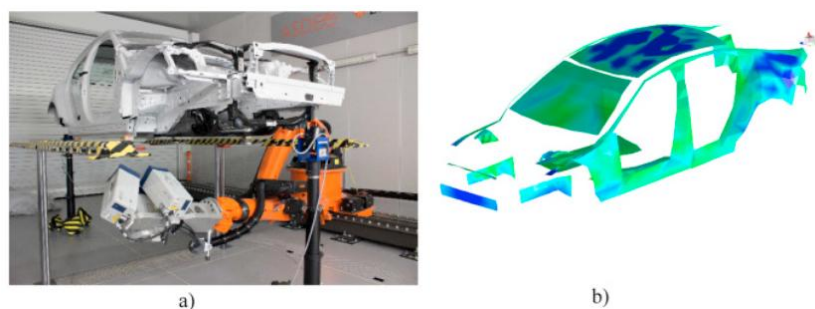


Figure 4: Example of SLDV Application in Automotive Body-in-White (a) Robotic Setup, (b) Typical Vehicle Mode Shape (Rothberg, et al., 2017).

1.3 Modal Types Investigations

Prior to analysing brake disc results, modes and shape types are investigated. According to Beebe and Moss (2019), mode order is determined by the arrangement of nodes and anti-nodes, with anti-nodes at maximum displacement and nodes at zero displacement (Hu, 2024). A positive correlation is often seen between increases in frequency generally resulting in a higher order, figure 5.

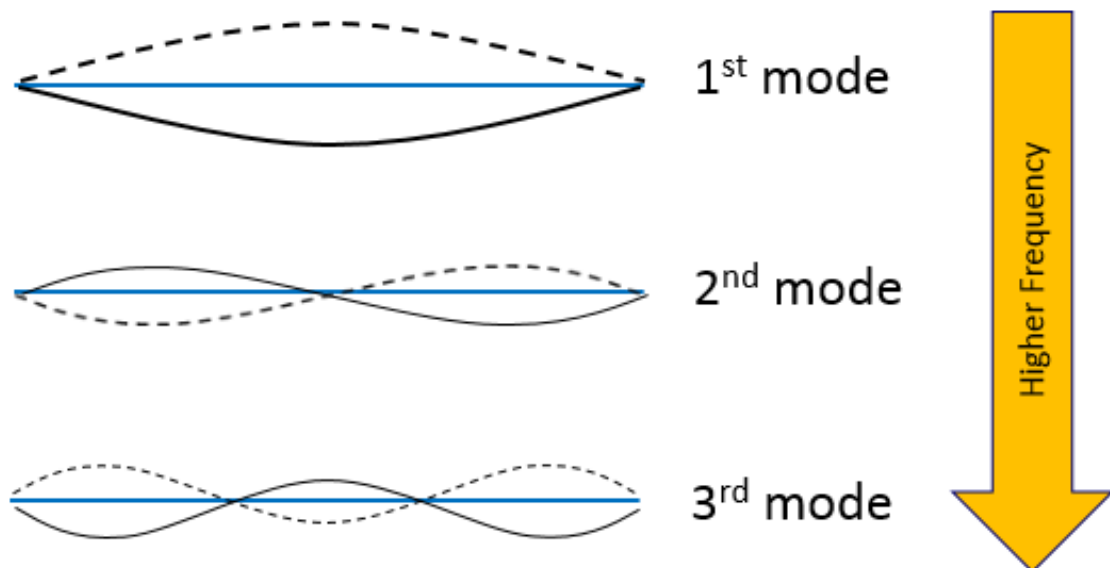


Figure 5: Visual Representation of Bending Orders where Higher Frequencies Tend to Increase Mode/Order (Beebe & Moss, 2019).

Published experimental results for a cantilever beam are researched and demonstrated in figure 6 to better understand different mode types and shapes in practical component applications. Whilst this is not a definitive list, it provides valuable insight into the main shape types: bending, torsional and traction (Azarniya & Rahimi, 2024). Under these main categories are multiple variants; for example, the bending mode has 1st, 2nd, 3rd and continued orders of modes. It is often the case that as frequency increases, modal shape complexity also increases (Beebe & Moss, 2019).

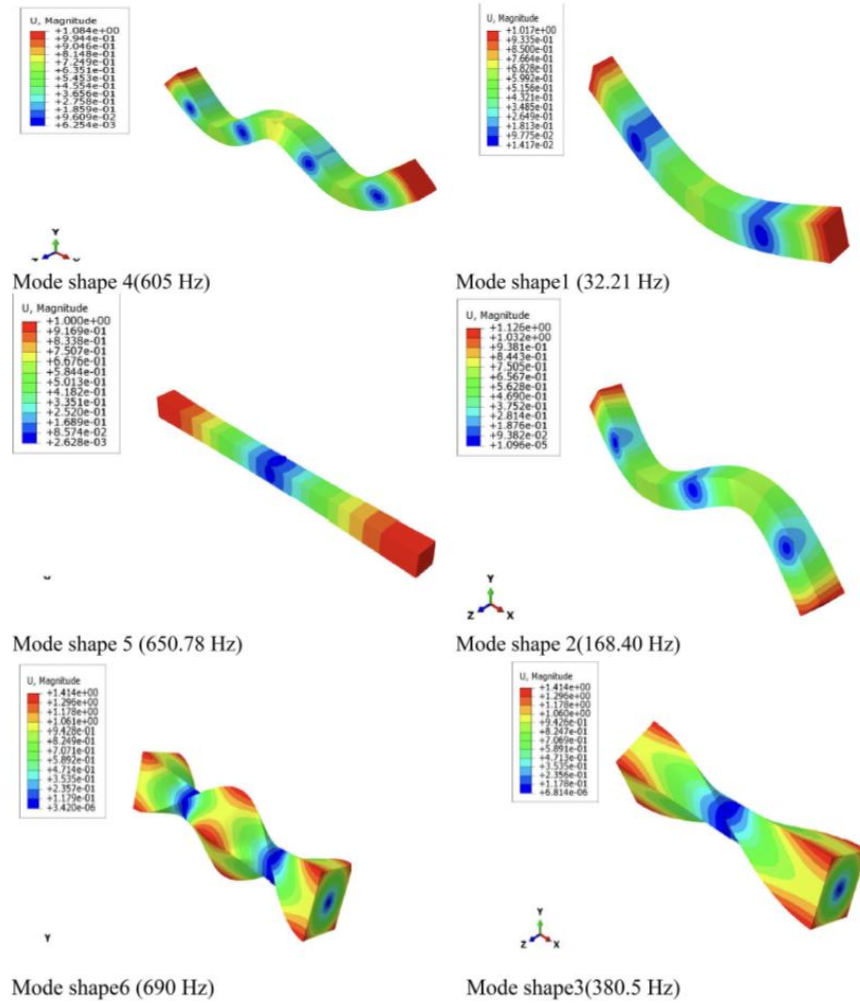


Figure 6: Natural Frequency of Homogenous Beam Example Modes and Shapes (1,2,4) Bending, (5) Traction and (3,6) Torsional (Azarniya & Rahimi, 2024).

2 Methodology

1. Test Piece Setup: Initial setup of the equipment requires securing the brake disc within the vice and locating the solenoid actuator against the component (figure 7), adjusting until a ‘ringing’ pitch is observed.

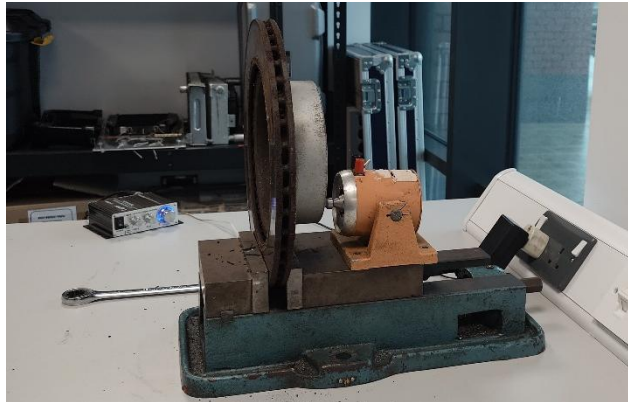


Figure 7: Securing of Test Piece and Solenoid Actuator.

2. Software Setup: Prior to any testing, software setup is required. Two different bandwidths were used within this experiment, 2 kHz and 5 kHz. A ‘Fast Fourier Transform’ (FFT) algorithm is used as the measurement system to convert the signal from time to frequency domains (Zhang, et al., 2019), whilst a velocity sensitivity of 100mm/s/V is used.

3. Equipment Alignment: Following software and test piece setup, a 2D alignment between the scanning head and test specimen is essential. This involves placing five calibration points across the brake disc surface to ensure optimal signal strength at a 1-metre distance. Safety precautions must be observed during laser operation. Operators should never look directly into the scanning head, and the shutter should remain closed whenever testing is halted.

4. Surface Scan Mesh: To study the response of the brake disc friction surface, a mesh (shown figure 8) was implemented to study multiple points across the surface. These points would then be analysed by the laser.

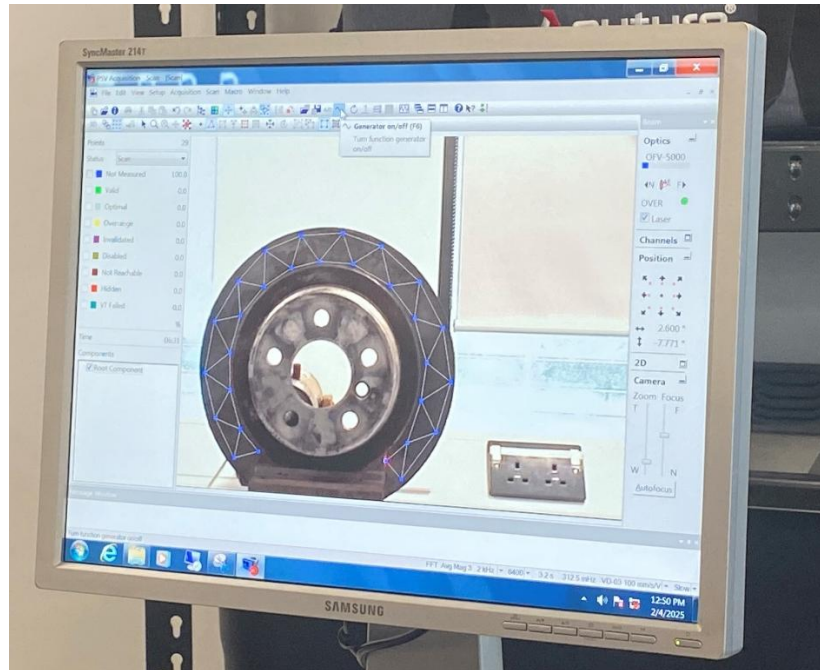


Figure 8: Surface Mesh for Brake Disc Study.

5. Data Collection: After all initial setup stages are completed, testing can begin (figure 9). Special attention was paid to ensure that the scanning head and component remained undisturbed throughout the whole testing procedure to prevent invalid results. Each node of the mesh is analysed by the equipment; depending on the signal strength and node result, a rating is given to each node, ensuring that result quality was high, any node below ‘good’ classification was retested. Data was collected and recorded for each peak across the frequency range, taking screen grabs for modal and resonant frequency analysis.

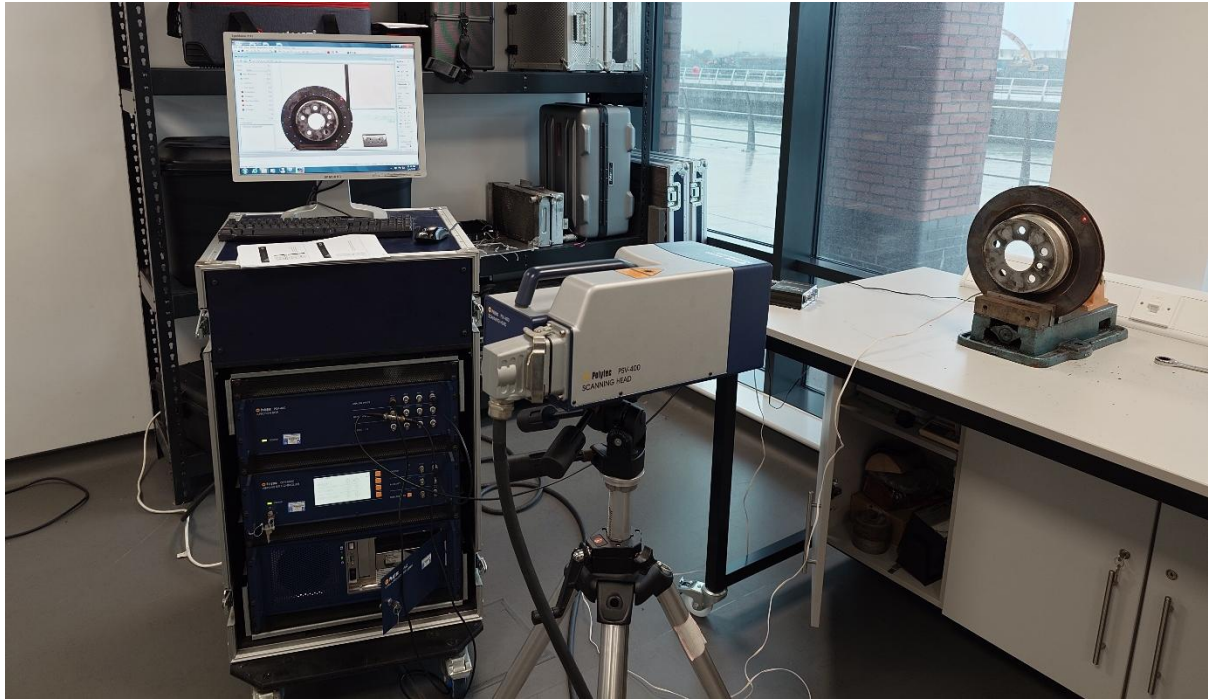


Figure 9: LDV Equipment Testing Brake Disc.

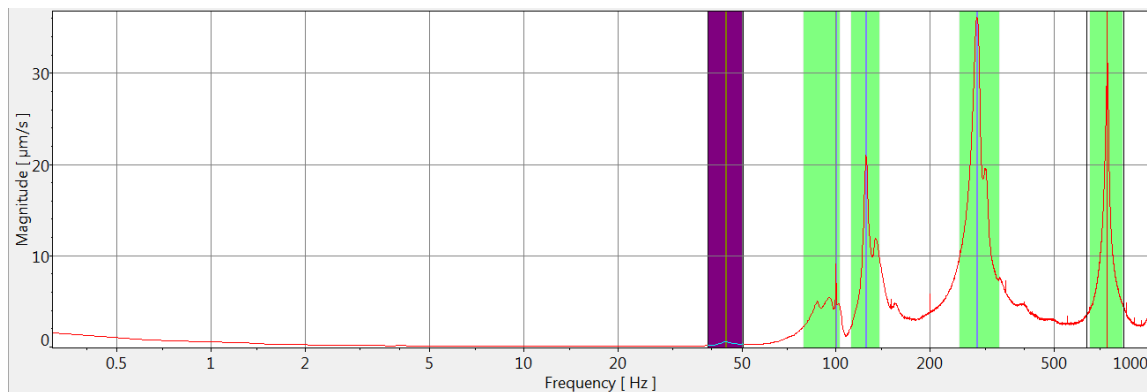
Challenges: During initial testing, it was established that positioning of the brake disc within the vice caused issues with the solenoid actuator striking the brake disc effectively. To overcome this problem, the disc was rotated 180 degrees where the centre hub was easier to strike. Significant amounts of noise and indistinct resonant frequencies were observed in the results. A common cause of this can be attributed to ‘speckle noise’ which can impact the signal to noise ratio, significantly more noticeable during higher bandwidth testing (Lv, et al., 2019). Limited options are available to overcome this, suggestions however, include: multi-path interferometer to prevent reduction in signal quality (Polytec, 2025), surface preparation to increase reflectivity of component (less of an issue on the brake disc), further optimization of scanning head 2D alignment and finally, careful data filtering techniques.

3 Raw Measurements and Graphs

Two scans of the component were completed, the first consisted of a bandwidth of 2 kHz with a range of 0-1 kHz, whilst the second utilised a 5 kHz bandwidth and 0-5 kHz range. The following sections detail the raw measurements and graphs for each scan where noise, accuracy and precision can be assessed.

3.1 Scan 1 Results

The results for scan 1 are shown in graph 1, revealing a total of five peaks at the highlighted frequency bandwidths. The large magnitudes demonstrate high amounts of surface vibration velocities giving indications to the resonant frequencies. The cause of this is a close match between the brake discs natural frequency, and the excitation frequency (Kurvinen, et al., 2020). The initial analysis indicates minimal noise and well-defined peaks for identification of resonant frequencies (as listed in table 1). Initial modal interpretations are made when accessing resultant animations within presentation software, these are detailed in table 1.

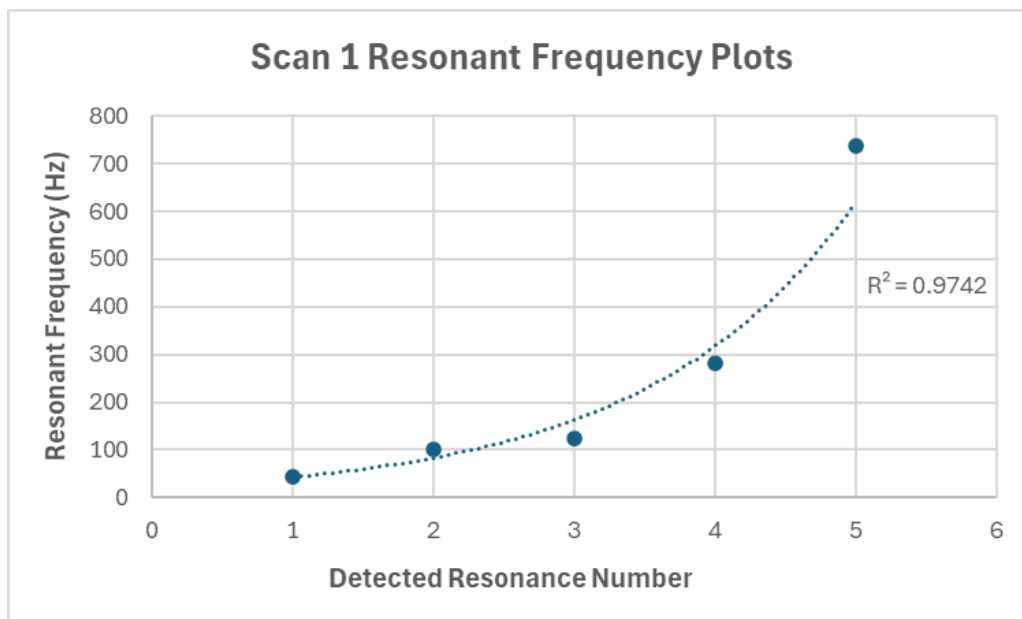


Graph 1: Scan 1 Resonant Frequencies in Frequency Against Magnitude Plot.

Table 1: Scan 1 LDV Resonant Frequencies and Bandwidth Values for a Range of 1 kHz and bandwidth of 2 kHz.

Scan 1			
Mode	Frequency (Hz)	Bandwidth (Hz)	Mode Type
1	44.375	11.25	Bending
2	100	24.0625	Bending & Torsional
3	124.6875	26.6525	Bending
4	282.8125	86.875	Torsional
5	738.75	117.8125	Bending

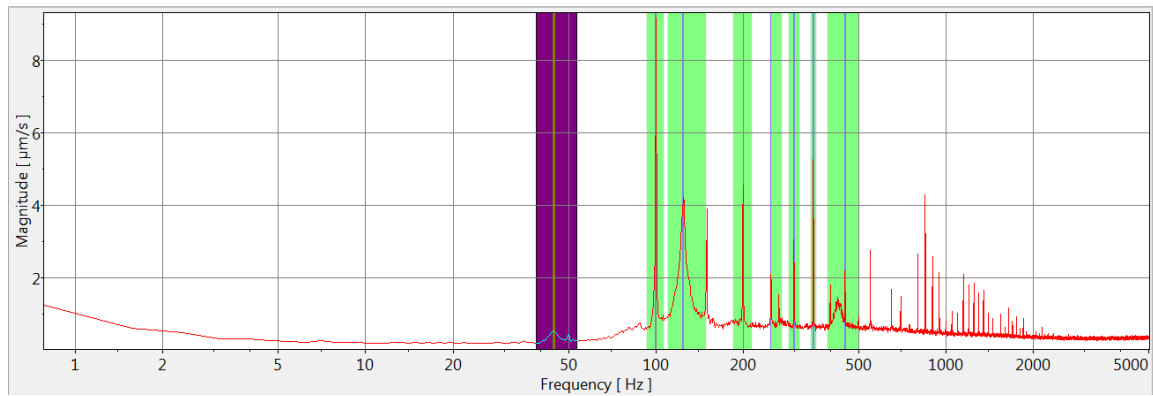
Prior to analysis, peak resonant frequencies from table 1 were plotted in graph 2 for accuracy and validity analysis. The results are seen to best match an exponential trendline with an R^2 value of 0.9742, however, some deviations are noticeable at resonance numbers 3 and 5 in particular. It also gives insight into differences in frequency between each detected peak (detected resonance number). Differences in frequency between 1-2 and 2-3 are approximately 56 and 24 respectively but a significant difference of 158 and 456 between 3-4 and 4-5 could potentially indicate some modes may have been missed between these frequencies.



Graph 2: Scan 1 Raw Resonant Frequency Measurements Against Resonance Detected Number.

3.2 Scan 2 Results

Scan 2 consisted of 5 kHz bandwidth over a range of 5 kHz as demonstrated in graph 3. A significantly larger signal to noise ratio caused difficulties distinguishing the true resonant frequencies from noise. Similar to scan 1, initial interpretation of resonant modes was completed during inspections of result animations. These modes, frequencies and bandwidths are detailed in table 2.

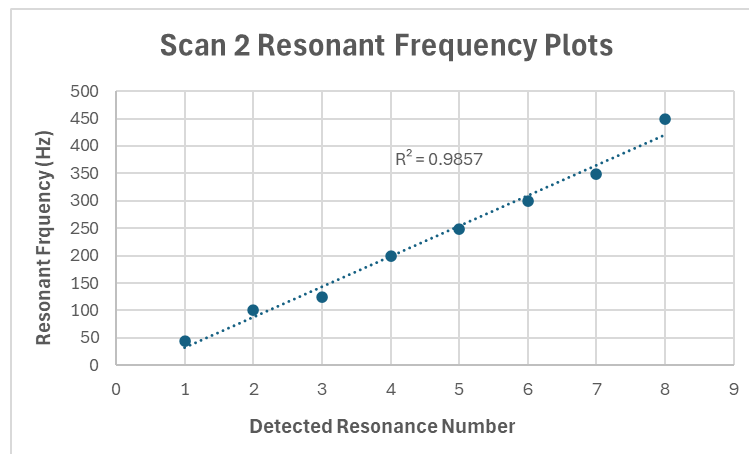


Graph 3: Scan 2 Resonant Frequencies in Frequency Against Magnitude Plot.

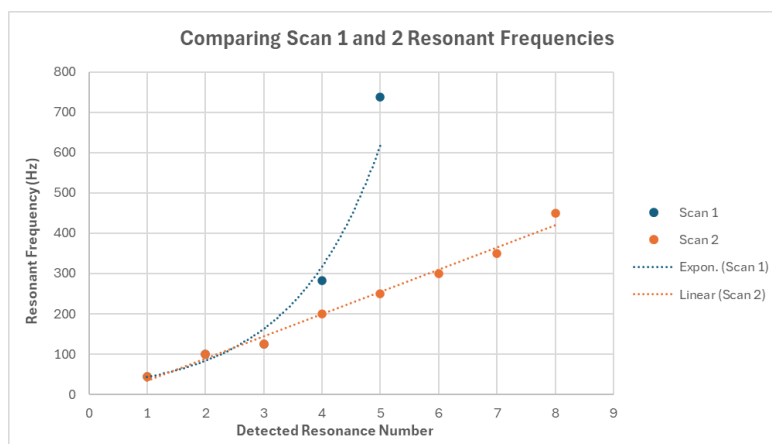
Table 2: Scan 2 LDV Resonant Frequencies and Bandwidth Values for a Range of 5 kHz and bandwidth of 5 kHz.

Scan 2			
Mode	Frequency (Hz)	Bandwidth (Hz)	Mode Type
1	44.5313	14.0625	Bending
2	100.0000	13.2813	Torsional
3	124.2188	39.0625	Bending & Torsional
4	200.0000	30.4688	Torsional
5	249.2188	25.0000	Bending & Torsional
6	299.2188	25.0000	Bending
7	349.2188	15.6250	Bending
8	449.2188	110.9375	Bending

Applying a similar logic to scan 2, a resonant frequency against detected resonance number graph is created (graph 4). From this input data, a linear trendline is implemented as it has the best data fitment. The R^2 value of 0.9857 shows excellent correlation and trends within the data, also providing insight into harmonics at numbers 2, 4 and 6. Small deviations are seen from the trendline indicating the results are valid and for the most part reliable. Largely consistent frequency steps of approximately 50 Hz are seen between each case number, some instances experience lower jumps (2-3) whilst others see greater differences (3-4 and 7-8). Graph 5 compares the two different scans showing good precision for initial 3 resonant frequencies but deviations from this point onwards.



Graph 4: Scan 2 Raw Resonant Frequency Measurements Against Resonance Detected Number.



Graph 5: Comparing Scan 1 and 2 Resonant Frequencies.

4 Results and Discussion

From the collected data above, resonant modes and shapes can be analysed and determined. Investigation into harmonics can also be conducted.

4.1 Scan 1 Results:

The images in figures 10-12 demonstrate resonant frequency modes for the 2 kHz bandwidth of scan 1. The five images are captures from the analysis software for modal and shape analysis. Figure 10 (left) is a resonant frequency mode at 44.375 Hz which demonstrates a clear example of a 1st order bending mode where two nodes and a single anti-node are present (Beebe & Moss, 2019). The capture in figure 10 (right) is less distinct, but a torsional mode is the more prominent shape with the potential to have some bending element as well.

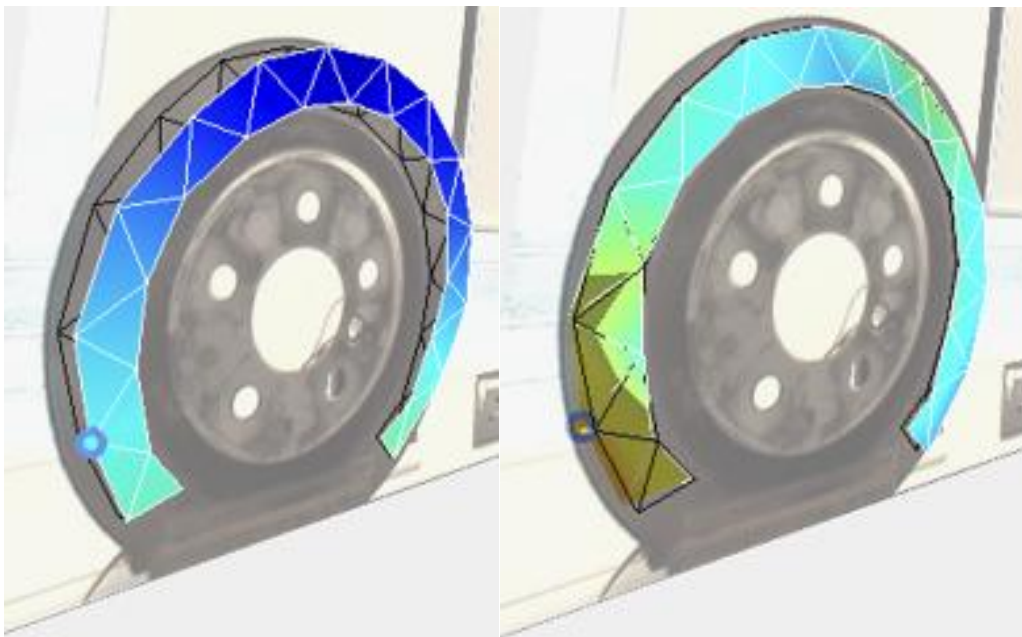


Figure 10: Scan 1 Resonant Modes and Shapes (Left) 1st Order Bending at 44.375 Hz, (Right) Torsional with Potential Bending at 100 Hz.

The results in figure 11 (left) demonstrate a first order bending mode at 124.6875 Hz where one large displacement is noticed at the anti-node. On the other hand, figure 11 (right) demonstrates an excellent example of a torsional shape at 282.8125 Hz (Azarniya & Rahimi, 2024). The mode and shape in figure 12 indicates another bending shape but represents a third order mode at 738.75 Hz. This aligns with statements made by Beebe and Moss (2019) regarding increases in frequency tend to see increases in mode order.

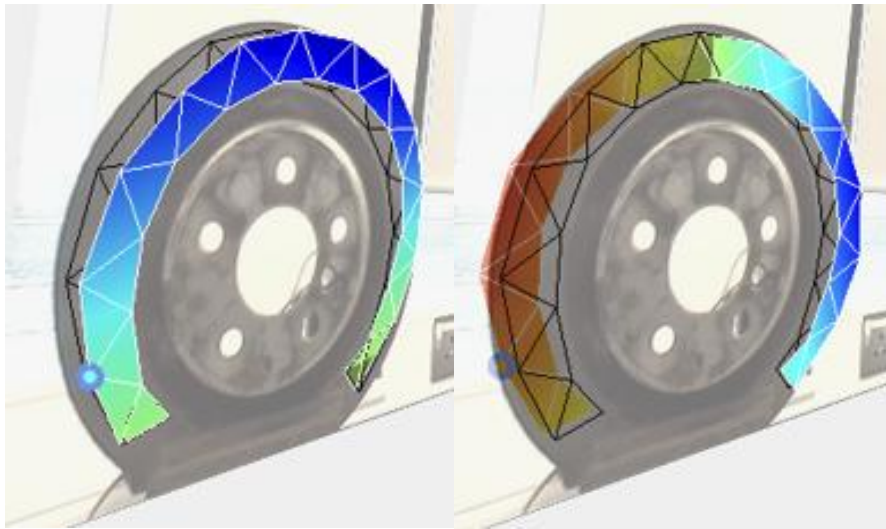


Figure 11: Scan 1 Resonant Modes and Shapes (Left) 1st Order Bending at 124.6875 Hz, (Right) Torsional at 282.8125 Hz.

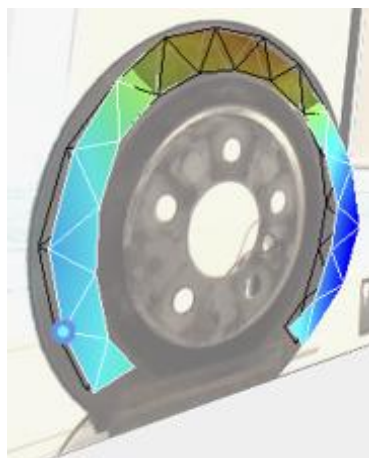


Figure 12: Scan 1 5th Resonant Mode and Shape, 3rd Order Bending at 738.75 Hz.

4.2 Scan 2 Results:

Figures 13-16 contain screen captures of results from the second scan which had a bandwidth of 5 kHz. For some of these results there is no initial distinct shape and/or mode that can be detected and therefore assumptions are made for mode and shape. When inspecting figure 13 (left) the shape is a clear bending and first order mode at 44.53125 Hz, whilst figure 13 (right) is less distinct but indicates a torsional element with a second order at 100 Hz.

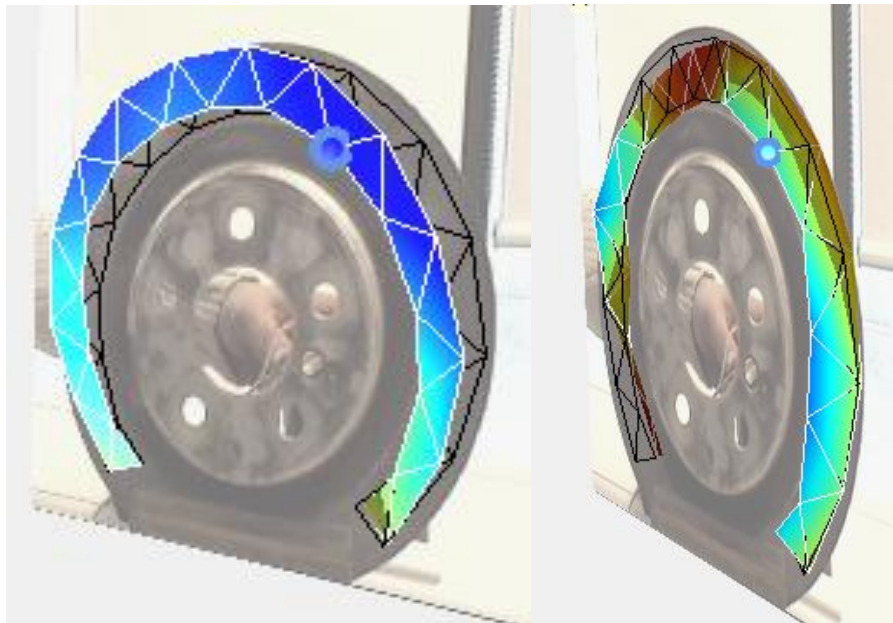


Figure 13: Scan 2 Resonant Modes and Shapes (Left) 1st Order Bending at 44.53125 Hz, (Right) 2nd Order Torsional at 100 Hz.

The results for 124.21875 Hz (figure 14 left) are indistinct, however, results do somewhat resemble a higher order bending mode and shape with a small argument to be made for torsional elements. Figure 14 (right) however, is a clear example of a first order torsional resonant mode; and at 200 Hz, is a second harmonic to figure 13 (right) at 100 Hz (Kroschel, 2020).

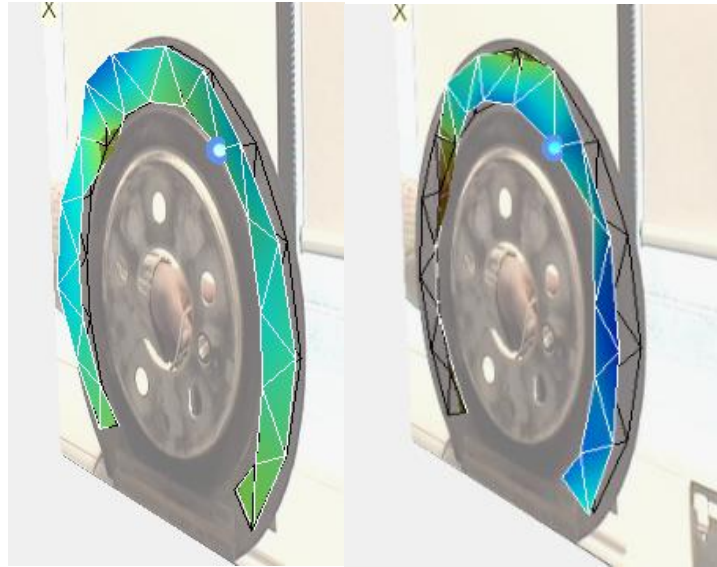


Figure 14: Scan 2 Resonant Modes and Shapes (Left) Indistinct but Could be Considered Bending and Torsional 124.21875 Hz, (Right) 1st Order Torsional at 200 Hz.

The fifth resonant frequency was detected at 249.21875 Hz (figure 15 left) and is considered a first order torsional mode with small traces of potential bending. The third and final detected harmonic was at 299.21875 Hz and resembled a first order bending mode (figure 15 right).

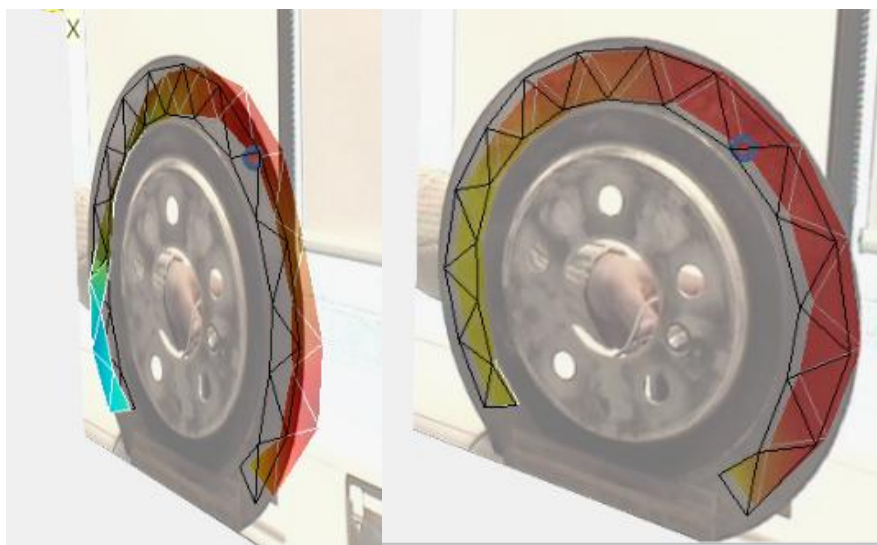


Figure 15: Scan 2 Resonant Modes and Shapes (Left) 1st Order Torsional with Slight Bending at 249.21875 Hz, (Right) 1st Order Bending at 299.21875 Hz.

Final resonant frequencies are presented in figure 16 for 349.21875 Hz and 449.21875 Hz respectively. With the resemblance in resonant frequencies for Figure 15 (left) and both images in figure 16, the possibility of a harmonic presence here is plausible as well. The only difference to this harmonic proposal is the variation in amplitudes; meaning magnitude does not decrease as harmonic number (frequency) increases (graph 3). The modal and shape analysis for figure 16 (left) is less prominent, however, a first order bending mode seems most plausible. As for figure 16 (right), bending characteristics most reflect a second (potentially third) mode. To determine harmonic frequencies within results, the following criteria was applied: best fitment of harmonic bandwidth tool within scanning presentation software (graph 6), accurate/consistent frequency intervals (100 Hz difference), progressively decreasing amplitudes, and correlation of data to examples presented by Kroschel (2020).

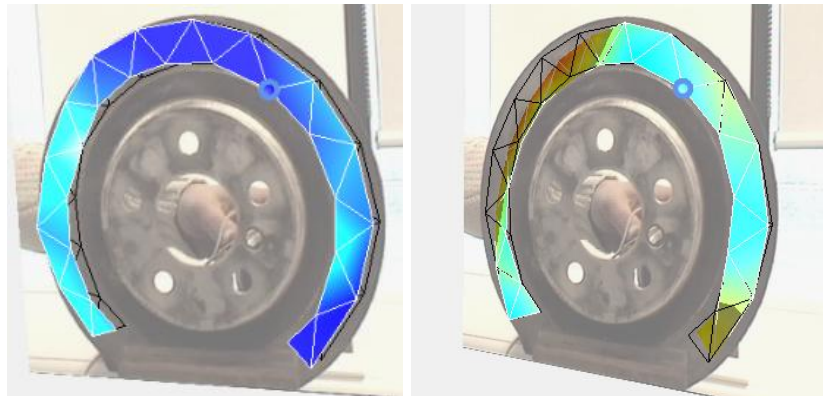
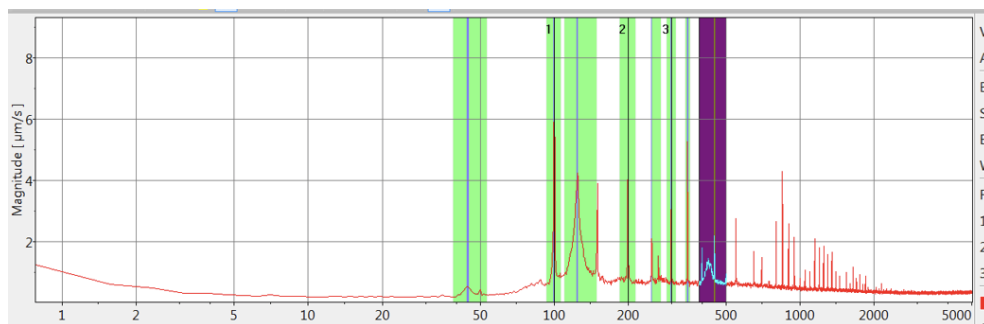


Figure 16: Scan 2 Resonant Modes and Shapes (Left) 1st Order Torsional with Slight Bending at 349.21875 Hz, (Right) 2nd Order Bending at 449.21875 Hz.



Graph 6: Scan 2 Harmonic Bandwidth Fitment to Resonant Frequencies.

4.3 Validation and Error Estimates

Prior to any initial testing, industry standard calibration methods should have been applied to ensure system accuracy. A suitable calibration method for this type of LDV is detailed in the International Organisation for Standardisation (ISO) 16063-41:2011 standard. This standard specifies procedures for primary and secondary calibrations for “rectilinear laser vibrometers in the frequency range typically between 0,4 Hz and 50 kHz” (ISO, 2011).

To assess the validity of this experiments results, a comparison is conducted against test results from Polytec (2025) in figure 17. The first critical observational difference is in component mesh/scan geometry. This report and experiment utilised a worktop vice to secure the component during testing, whereas the experiment in figure 17 uses an alternative approach due to the inclusion of the full surface. This therefore impacts the validity of this experiments results where for future testing, an alternative support mechanism such as weak springs or bungee cords could be utilised instead. It is also plausible that the LDV scanning head has not been properly calibrated as specified by retailing company guidelines that state calibration should be conducted every 2 years or after 2000 operational hours (Polytec, 2025).

This experiment is also prone to many types of errors, the main categories being systematic and random. As mentioned previously, calibration will contribute to the data’s true accuracy and result validity. Other systematic errors are caused by environmental changes such as temperature, dust and pressure and impact consistency in results (Martarelli, et al., 2006). The operator is always prone to introducing errors within an experiment, whether this is incorrect equipment setup, use, or data collection (Szczepinski & Kotulski, 2010). To reduce these effects/chances multiple operators control the equipment together and follow a pre-specified methodology for optimum results. The random errors aspect can be attributed to the brake disc where surface irregularities, texture and reflectiveness can impact signal strength and introduce

noise. Considering all of these potential errors and sources, best practices should see: conducting multiple tests to average results (assisting in anomaly identification), controlling of environmental factors such as temperature and pressure, equipment calibration and alignment to test piece, improved supporting mechanisms of brake disc (Pagano & Lake, 2017), mesh optimisation studies, comparison to a finite element analysis simulation, refinement of test piece surface area and implementation of an effective/reliable noise cleaning program (Polytec, 2025).

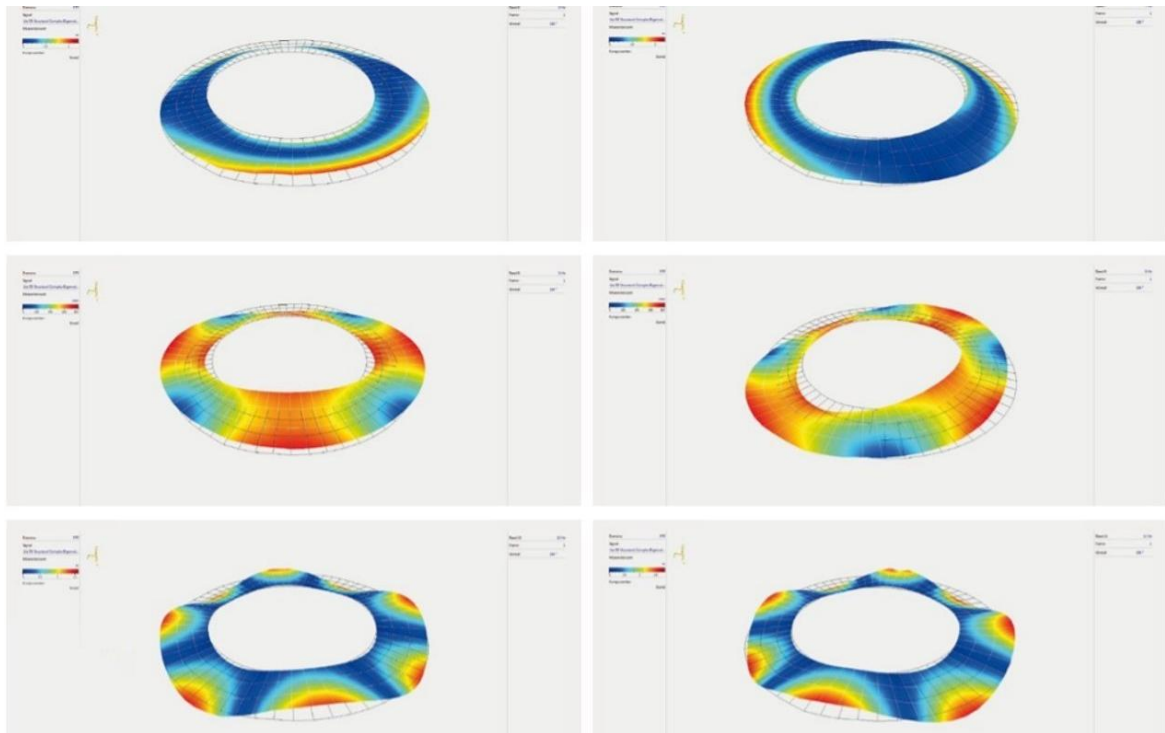


Figure 17: Brake Disc Modal Shapes Examples (Polytec (2), 2025).

Conclusion

In conclusion this experiment found multiple resonant frequencies for the brake disc, some being: 44.53, 100, 124.22, 200, 249.22, 299.22, 349.22 and 449.22 Hz. The most common modes and shapes identified for these resonant frequencies are first and third order bending, and first order torsional. The reliability and validity of this experiments results is questionable when considering: testing methodology (supporting mechanism), lack of industry standard calibration, operator errors and inexperience, and high signal to noise ratio in experimental results. Some similarities detected between scan 1 and 2 results demonstrate some validity in earlier resonant frequencies but further work including conduction of multiple test runs and FEA simulations would significantly improve the experiments reliability, accuracy and validity.

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