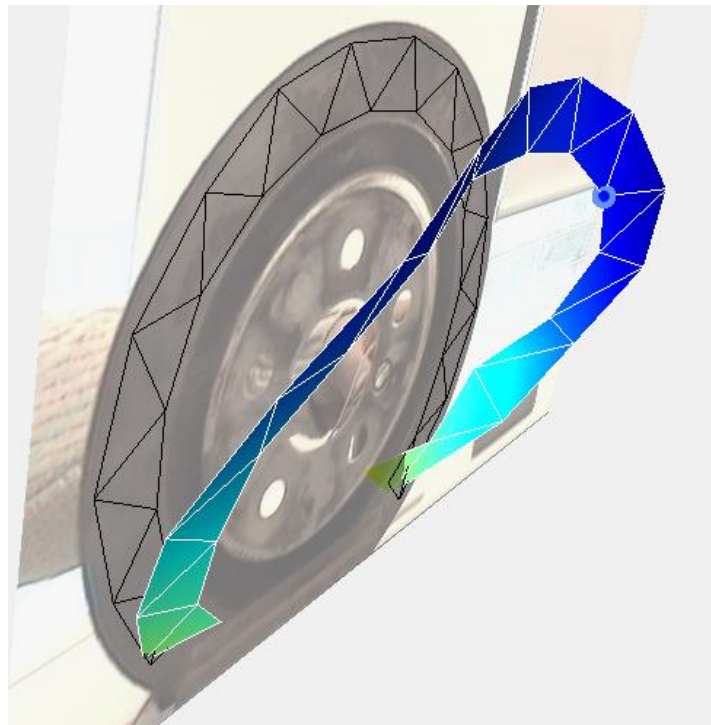


University of Wales Trinity Saint David
Wales Institute of Science & Art



Laser Doppler Vibrometer – Brake Disc Modal Analysis

Structural Integrity & Materials Evaluation ACEA7013



Diego Alexander Valencia Flores
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Abstract

This study investigates the modal response of a brake disc using Laser Doppler Vibrometry (LDV), capturing its bending and torsional vibrational modes. Two distinct frequency bandwidths, 2 kHz (SCAN 1) and 5 kHz (SCAN 2), were employed to compare the vibrational behavior of the brake disc across different excitation conditions. The results revealed five primary resonance modes in SCAN 1 and eight in SCAN 2, with SCAN 2 capturing higher-order modes and harmonic frequencies at 100 Hz, 200 Hz, and 300 Hz, which were not detected in SCAN 1.

The presence of harmonics in SCAN 2 suggests a structured frequency response pattern influenced by higher excitation bandwidths. However, variability in actuator positioning between the two scans introduces potential uncertainty in mode comparison. The findings emphasize the necessity of consistent excitation methods and expanded frequency range testing for a more comprehensive characterization of brake disc dynamics.

Contents

Abstract.....	2
1 Apparatus.....	6
2 Introduction.....	9
2.1 NDT Historical Context	9
2.2 Starting point of LDV research	11
2.3 Aims of this Research	13
3 Literature Review.....	15
4 Methodology/Procedure	17
3. Raw Measurements.....	19
3.1 Scan 1.....	19
3.2 Scan 2.....	21
4. Calculations and error estimates.....	24
5. Results and Discussion	25
5.1 Bending & Torsional Modes	25
5.1.1 SCAN 1	25
5.1.2 SCAN 2	28
5.2 Harmonic Frequencies	30
6. Limitations of the Study	32
7. Conclusion	33
8. Reference List.....	34
Figure 1 Data Acquisition Hardware	6
Figure 2 USB Security Key.....	7
Figure 3 Polytec Scanning Head PSV-400	7
Figure 4 Brake Disc	8
Figure 5 Amplifier Actuator which taps the brake disc (the specimen)	8
Figure 6 Ultrasonic - NDT - on pipes using an ultrasonic flaw detector (ETITB, 2024) ...	9
Figure 7 Ultrasonic Non-Destructive Testing - NDT - on Pipes using an ultrasonic flaw detector (sentin, 2020)	10

Figure 8 ILTS Fatigue Test - Destructive Testing (Applus+ BKW, Materials testing at a high level, n.d.)	10
Figure 10 Visual Representation LDV results in a Brake Disc using a frequency of 109 hz at a bandwidth of 5kHz	11
Figure 11 Basic measurement principle of vibrometry and setup of a Laser Doppler Vibrometer (www.polytec.com, n.d)	12
Figure 12 Polytec Scanning Head PSV-400 & Brake Disc	13
Figure 13 Tim-frequency analysis of signal recorded by the accelerometer located at mid-point during rail car passage (32 km/h equals to 20 mph): (a)1st Mode (b)2nd Mode (c)3rd Mode	15
Figure 14 Real (a) and imaginary (b) components of an ODS, measured by a demodulated uniform-rate continuous LDV area scan (Stanbridge, Martarelli and Ewins, 2003)	16
Figure 15 PVS Acquisition Software showing the 5 most important modes and their peaks	19
Figure 16 Peak frequencies detected in SCAN 1, mapping the relationship between the mode number and its corresponding resonant frequency.....	20
Figure 17 Frequency spectrum and band identification from SCAN 2 (5 kHz bandwidth)	21
Figure 18 Peak frequencies detected in SCAN 2, mapping the relationship between the mode number and its corresponding resonant frequency.....	22
Figure 19 Depiction of the frequency bandwidth used to analyze the brake disc behavior under vibration stress	25
Figure 20 5 Highest Peaks found in the first scan, showing different bending and torsional modes where a) Bending, b) Bending & Torsion, c) Bending, d) Torsion, e) Torsion	26
Figure 21 Illustrates the modes 1-8 (a to h), each corresponding to a unique frequency at which resonance occurs	28
Figure 22 Peak frequencies of SCAN 2 and their natural frequencies in the dark blue box.....	30
Table 1 Frequency Band Definition, the first highlighted five primary vibration modes, with peaks at 1) 44.38 Hz, 2) 100 Hz, 3) 124.69 Hz, 4) 282.81 Hz, and 5) 738.75 Hz ...	20
Table 2 Frequency band definitions at which peak frequencies were detected	22
Table 3 Showing which mode from 1-5 (a-e) is undergoing which type of stress of movement from SCAN 1	26

Table 4 Showing which mode from 1-8 (a-h) is undergoing which type of stress of movement from SCAN 2	29
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1 Apparatus

The following equipment and components were utilized for the modal analysis of the brake disc using Laser Doppler Vibrometry (LDV):

1. PSV Acquisition Software – The primary software responsible for interfacing the scanning head with the hardware system, enabling data acquisition and visualization on a connected display.
2. Data Acquisition Hardware – The central processing unit to which the scanning head is connected, facilitating communication between the software and the measurement system.



Figure 1 Data Acquisition Hardware

3. USB Security Key – A key device inserted into the hardware unit, granting access to the PSV Acquisition Software and enabling full functionality.



Figure 2 USB Security Key

4. PolyTec Scanning Head (PSV-400) – A high-precision Laser Doppler Vibrometer (LDV) scanning head, used for capturing the structural response of the brake disc by measuring displacement, velocity, and vibration modes.



Figure 3 Polytec Scanning Head PSV-400

5. Test Specimen (Brake Disc) – The brake disc under analysis, serving as the subject for modal characterization.



Figure 4 Brake Disc

6. Amplifier Actuator – A controlled excitation system that applies a precise frequency input to the brake disc, inducing vibration. The scanning head then records the resulting modal behavior.



Figure 5 Amplifier Actuator which taps the brake disc (the specimen)

7. Peripheral Equipment – Includes essential accessories such as cables, display screen, keyboard, and mouse, which facilitate system operation and data acquisition during testing.

2 Introduction

2.1 NDT Historical Context

Non-Destructive Testing (NDT) refers to the inspection of a structure using techniques that do not compromise its integrity or cause damage. It is sometimes distinguished from Non-Destructive Evaluation (NDE), which not only detects flaws but also assesses a structure's fitness for purpose there are different methods for specific capabilities such as ultrasonic (UT), laser-based UT, thermography, and X-ray Computed Tomography (XCT) (Howell, n.d.).



Figure 6 Ultrasonic - NDT - on pipes using an ultrasonic flaw detector (ETITB, 2024)

NDE, therefore, integrates NDT with an evaluation of the significance of identified defects. NDT techniques capable of evaluating mechanical, acoustic, chemical, electrical, magnetic, and physical properties of materials (Helal, Sofi and Mendis, 2015). However, in practical applications, the terms NDT and NDE are often used interchangeably (Cawley, 2001).

NDT is generally considered distinct from condition monitoring, where a machine's operational status is inferred through real-time measurements, and from process control, which involves using measurements of process parameters—such as temperature and pressure—as control inputs. NDT is commonly employed for the detection of discrete defects (Cawley, 2001).



Figure 7 Ultrasonic Non-Destructive Testing - NDT - on Pipes using an ultrasonic flaw detector (sentin, 2020)

On the other side of the spectrum of testing materials “Destructive Testing” investigates failure mechanisms to determine the mechanical properties of materials, such as yield strength, compressive strength, tensile strength, ductility, and fracture toughness. In contrast,

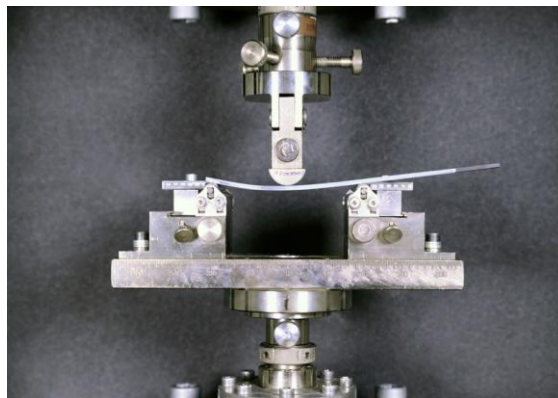


Figure 8 ILTS Fatigue Test - Destructive Testing (Applus+ BKW, Materials testing at a high level, n.d.)

2.2 Starting point of LDV research

As advancements in Non-Destructive Testing (NDT) continued, the Laser Doppler Vibrometer (LDV) emerged as a pivotal technology. According to a 1964 study by Yeh and Cummins at Columbia University (Rothberg et al., 2017), LDV was initially developed for fluid velocity measurements. Over time, its application expanded, particularly in non-contact measurements of lightweight structures. This potential was recognized early by loudspeaker designers, who leveraged LDV to refine sound quality and structural performance.

Further advancements in LDV technology have enabled the detection of bending modes in various components by utilizing an optical head for precise vibration measurement. The optimization of geometry and collection direction has been crucial in balancing sensitivity to in-plane vibrations while ensuring the efficient collection of light intensity. These refinements have solidified LDV as a powerful tool in structural analysis, vibration monitoring, and material characterization, making it a significant contributor to modern NDT methodologies (Rothberg et al., 2017).

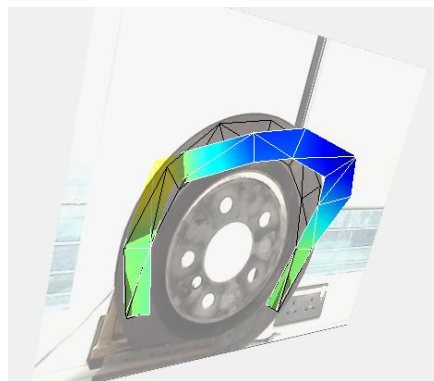


Figure 9 Visual Representation LDV results in a Brake Disc using a frequency of 109 hz at a bandwidth of 5kHz

Currently, Laser Doppler Vibrometry (LDV) is the most advanced method for achieving high-resolution displacement and velocity measurements, making it widely applicable across various fields of fundamental science. It offers femtometer-level amplitude resolution and maintains linearity, ensuring consistent amplitude measurements even at extremely high frequencies, with current capabilities exceeding 6 GHz (www.polytec.com, n.d.).

One of LDV's most significant advantages is its independence from measuring distance, allowing it to be utilized in both microscopic applications and large-scale measurements. Since light acts as a sensor, it does not physically interact with or alter the sample, making the method completely non-invasive. This characteristic enables precise measurements on extremely small and lightweight structures, making LDV an essential tool in precision engineering, material science, and high-frequency vibration analysis (www.polytec.com, n.d.).

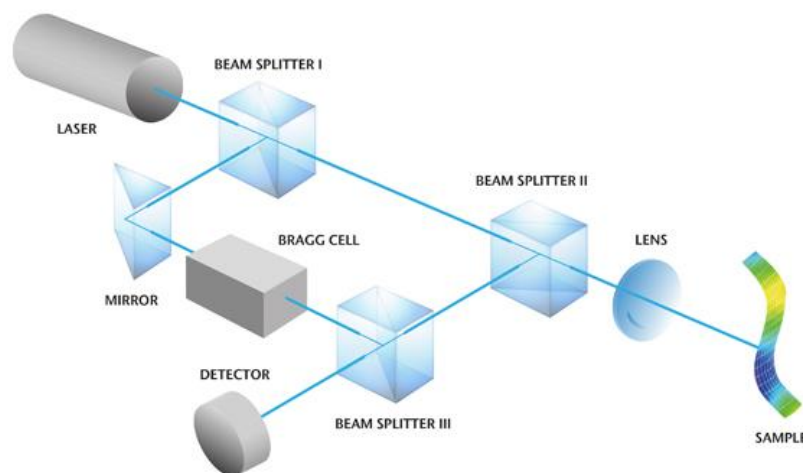


Figure 10 Basic measurement principle of vibrometry and setup of a Laser Doppler Vibrometer (www.polytec.com, n.d)

2.3 Aims of this Research

This study aims to conduct a modal analysis of a brake disc using Polytec Scanning Head PSV-400 (Figure 3) which uses Laser Doppler Vibrometry (LDV) to identify and characterize its bending and torsional modes. Additionally, it seeks to determine whether different degrees of bending, and torsional behavior exhibit similar characteristics across varying harmonic frequencies, irrespective of the bandwidth used during testing. The analysis will be performed using two distinct bandwidths: 2 kHz and 5 kHz.



Figure 11 Polytec Scanning Head PSV-400 & Brake Disc

The results, as illustrated in Figure 10, will be visually analyzed and compared across different mode shapes and frequencies within the same bandwidth. The primary objective of this research is to identify the specific frequencies at which bending and

torsional modes occur in the brake disc, providing valuable insights into its vibrational characteristics and structural response under dynamic excitation.

3 Literature Review

In recent years, extensive research has been conducted using Laser Doppler Vibrometry (LDV) as a primary method for measuring bending and torsional modes, as well as identifying harmonic frequencies in various structures. A study published in 2021 by K. Kaynardag et al. focused on the development of laser-based vibration measurement technology for detecting bending modes in railway tracks. The research proposed using LDV to capture vibrations induced by wheel-rail interaction forces from a moving rail vehicle (Kaynardag et al., 2020).

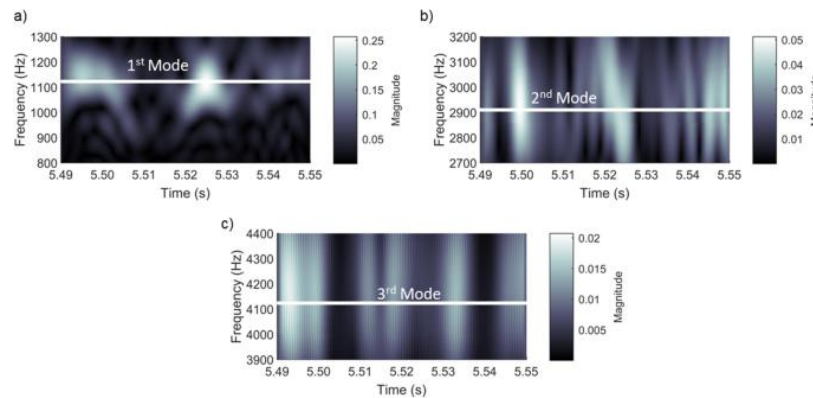


Figure 12 Tim-frequency analysis of signal recorded by the accelerometer located at mid-point during rail car passage (32 km/h equals to 20 mph): (a)1st Mode (b)2nd Mode (c)3rd Mode

The study involved two sets of tests. In the first, the rail car traversed an instrumented span to generate excitation, while in the second, a moving LDV system mounted on the rail car was used to identify the bending modes of the rail (Kaynardag et al., 2020). The results demonstrated a clear and interpretable dataset, offering insights that are somewhat comparable to the objectives of this research, particularly in terms of modal identification and vibration analysis using LDV.

For a deeper understanding of the subject, a study published in the early 2000s investigated the response mode shape of a vibrating surface subjected to sinusoidal excitation at a known frequency. This was achieved using a sinusoidal area-scan LDV over a rectangular surface, allowing for precise mode shape identification (Stanbridge, Martarelli and Ewins, 2003).

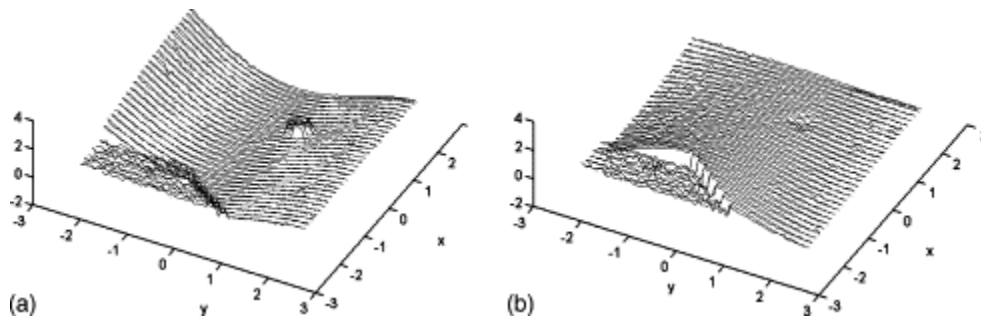


Figure 13 Real (a) and imaginary (b) components of an ODS, measured by a demodulated uniform-rate continuous LDV area scan (Stanbridge, Martarelli and Ewins, 2003)

As illustrated in Figure 14, the basic bending mode of the plate is influenced by the presence of a hole and the plate edges, disrupting the continuity of the mode shape. Consequently, the vibration pattern could not be accurately represented by a single polynomial expression, highlighting the complexity of real-world modal behavior and the advantages of LDV in capturing these intricate structural responses (Stanbridge, Martarelli and Ewins, 2003).

4 Methodology/Procedure

The following steps outline the procedure for conducting the modal analysis of a brake disc using Laser Doppler Vibrometry (LDV):

1. System Initialization

1. Power on the computer to access the PSV Acquisition Software
2. Turn on the solenoid actuator, which will apply controlled excitation to the brake disc
3. Ensure the laser protection is either opened or closed as required, depending on the safety guidelines

2. Software and LDV Configuration

1. Open the PSV Acquisition Software to establish communication with the PolyTec Scanning Head
2. Navigate to the camera section within the software to visualize the area under analysis.
 - a. Check lighting conditions, as improper illumination may affect measurement accuracy
3. Activate the auto-focus function to ensure precise laser targeting
4. Perform the alignment process to calibrate the scanning system with the test specimen

3. Plane Reference and Measurement Setup

1. Define the measurement grid by placing a minimum of 3 to 5 reference points on the brake disc.

- a. Increasing the number of points results in a denser mesh, improving accuracy but increasing analysis time

2. Create connecting lines between the reference points to form a triangular mesh, ensuring a structured scanning area

4. Excitation and Data Acquisition

1. Activate the amplifier actuator to introduce controlled vibrations into the brake disc
2. The PolyTec Scanning Head (LDV) captures the response, measuring velocity, displacement, and mode shapes
3. The acquired data is used to generate a 2D representation of the brake disc's vibrational behavior

5. Data Analysis

1. Analyze the resulting frequency response graphs, identifying key harmonic frequencies where vibrations are most pronounced
2. Examine the frequency peaks to determine the presence of bending and torsional modes at various degrees
3. Compare the findings across different bandwidths (2 kHz and 5 kHz) to assess variations in modal behavior

3. Raw Measurements

Knowing the procedure to follow for the experiment, the first scan results were obtained using a 2 kHz bandwidth and the second scan using 5 kHz. These scans identified multiple peak frequencies at different ranges, as shown in Table 1 and Table

3.1 Scan 1

The Laser Doppler Vibrometer (LDV) scan identified multiple resonant frequency modes of the brake disc, as shown in Figure 15. The lower graph presents the Vib Velocity spectrum, where distinct peaks indicate resonant frequencies, with the most dominant mode reaching approximately 30 $\mu\text{m/s}$ in magnitude. The upper table lists the corresponding frequency bands, detailing start and end frequencies, peak values, and bandwidths. The highlighted green regions mark detected vibrational modes, while the dark blue boxes enclose the peak frequencies.

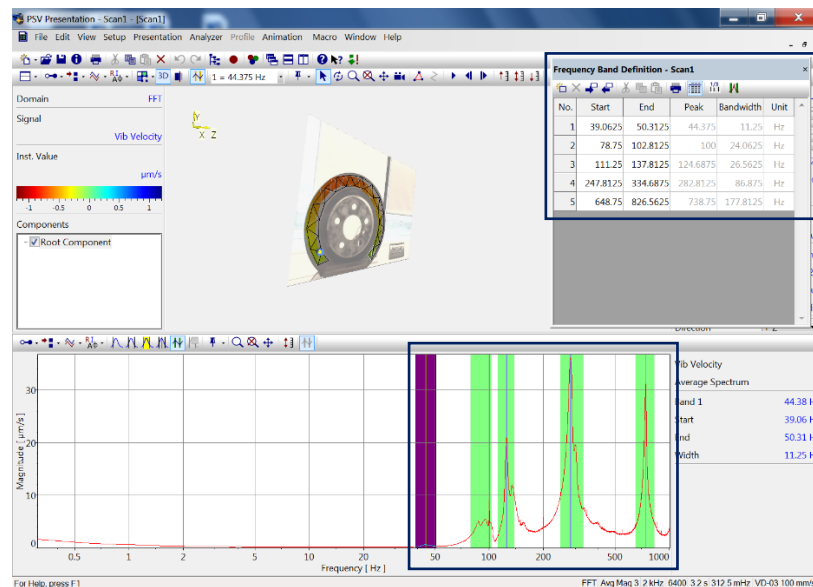


Figure 14 PVS Acquisition Software showing the 5 most important modes and their peaks

Table 1 presents the frequency band definition for SCAN 1 (2 kHz Bandwidth). It includes the start and end frequencies, peak frequencies, and bandwidths of the detected resonant modes.

Table 1 Frequency Band Definition, the first highlighted five primary vibration modes, with peaks at 1) 44.38 Hz, 2) 100 Hz, 3) 124.69 Hz, 4) 282.81 Hz, and 5) 738.75 Hz

Frequency Band Definition - SCAN 1 - 2kHz				
# - Mode	Start	End	Peak	Bandwidth Unit
1	39.06	50.31	44.375	11.25
2	78.75	102.81	100	24.06
3	111.25	137.81	124.688	26.56
4	247.81	334.68	282.813	86.87
5	648.75	826.56	738.75	177.81

Hz

The data points illustrate in Figure 16, how the frequency increases with each mode, showing a non-linear progression in which higher modes exhibit significantly larger frequency values.

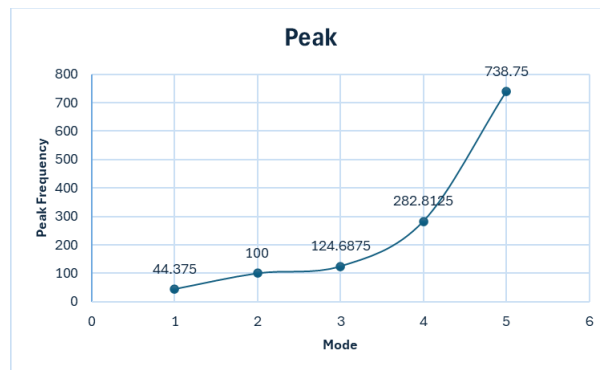


Figure 15 Peak frequencies detected in SCAN 1, mapping the relationship between the mode number and its corresponding resonant frequency

It is evident that the first three modes (44.38 Hz, 100 Hz, and 124.69 Hz) are relatively close in frequency, while Mode 4 (282.81 Hz) and Mode 5 (738.75 Hz) show a steeper increase. This suggests that as the vibration mode order increases, the system's stiffness and mass distribution effects influence the frequency response more significantly.

The lack of a harmonic pattern implies that the brake disc does not follow a simple multiple-frequency relationship, which can be attributed to its complex geometry, material properties, and boundary conditions.

3.2 Scan 2

The second scan (5 kHz bandwidth) further refined the frequency response, capturing additional resonant modes of the brake disc. Figure 17 illustrates the Velocity spectrum, where eight primary peaks were detected, marked by green and purple bands. Compared to SCAN 1, this scan provided a wider range, with an additional mode detected contributing to a more comprehensive modal analysis.

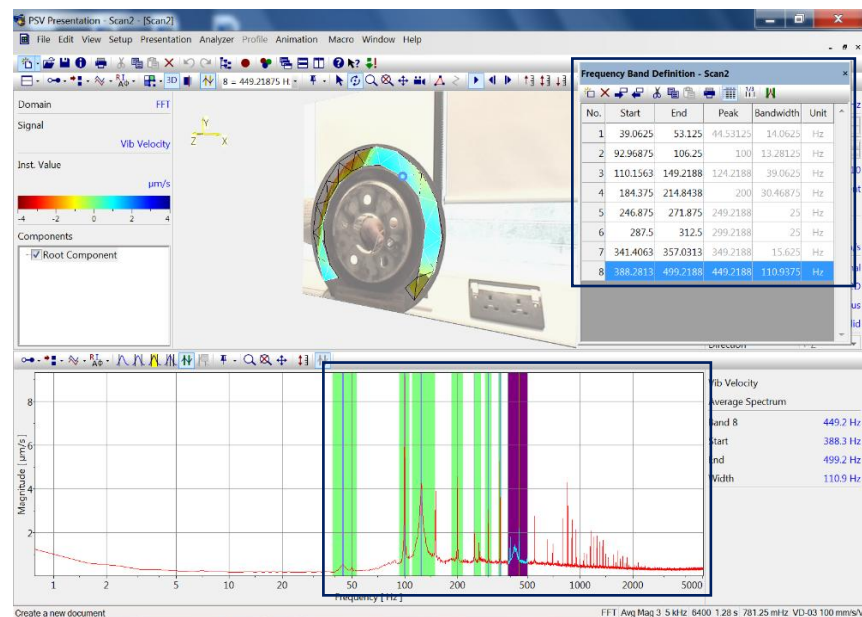


Figure 16 Frequency spectrum and band identification from SCAN 2 (5 kHz bandwidth)

Table 2 presents the frequency bands where peak resonances were detected during SCAN 2 (5 kHz bandwidth). It lists eight modes, specifying the start and end frequencies, peak frequency, and bandwidth for each.

Table 2 Frequency band definitions at which peak frequencies were detected

Frequency Band Definition at which peak frequencies showed - SCAN 2 - 5kHz				
#	Start	End	Peak	Bandwidth Unit
1	39.06	53.13	44.5313	14.0625
2	92.9688	106.25	100	13.2813
3	110.156	149.219	124.219	39.0625
4	184.375	214.844	200	30.4688
5	246.875	271.875	249.219	25
6	287.5	312.5	299.219	25
7	341.406	357.031	349.219	15.625
8	388.281	499.219	449.219	110.938

Hz

Compared to SCAN 1, this scan covers a wider range, capturing additional resonance modes beyond 300 Hz. Notably, Mode 8, with a peak at 449.2 Hz, exhibits the widest bandwidth (110.94 Hz), indicating a complex vibrational behavior in that region. The table helps to understand how the brake disc responds dynamically to excitation over an extended frequency spectrum.

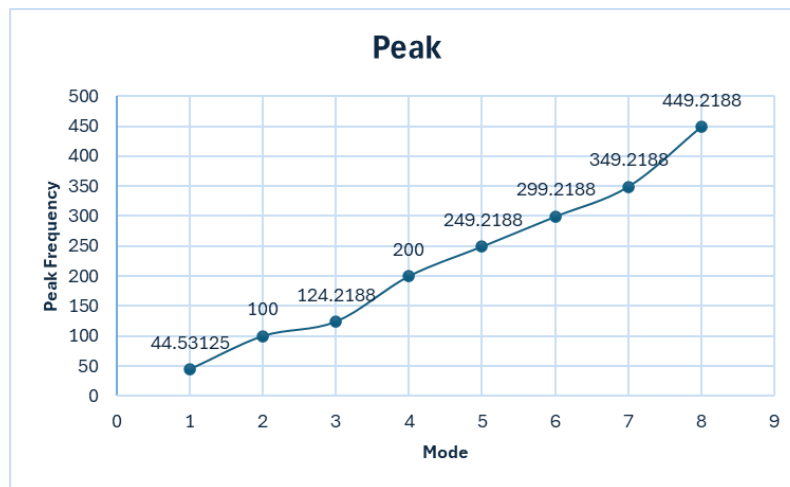


Figure 17 Peak frequencies detected in SCAN 2, mapping the relationship between the mode number and its corresponding resonant frequency

Unlike the previous scan, this version accurately reflects the incremental increase in peak frequencies, showing a more structured frequency progression.

The highest recorded peak frequency (449.22 Hz) at Mode 8 suggests a significant resonant response at this mode, with intermediate peaks at 100 Hz, 124.22 Hz, 200 Hz, 249.22 Hz, 299.22 Hz, and 349.22 Hz. This steady increase indicates a more systematic modal distribution, contrasting with the irregular jumps observed in SCAN 1.

The absence of drastic frequency jumps, as seen in SCAN 1, indicates that SCAN 2 provides a more refined modal analysis, capturing additional vibrational characteristics crucial for evaluating the brake disc's dynamic behavior and durability.

4. Calculations and error estimates

The primary calculations in this study involve identifying resonant frequencies, determining bending and torsional mode shapes, and evaluating harmonic frequency presence. To assess the structural response, the peak modes were classified based on bending or torsional deformation, correlating their amplitudes to the applied excitation force.

The harmonic analysis in SCAN 2 demonstrated a clear pattern at multiples of 100 Hz, while SCAN 1 lacked such harmonics, indicating a difference in the excitation response. This discrepancy is attributed to the variation in bandwidth selection, which altered the data resolution and modal detection capabilities.

5. Results and Discussion

In this experiment, two different frequency bandwidths were used for modal analysis: 2 kHz and 5 kHz. The first scan was conducted at 2 kHz, followed by a second scan at 5 kHz. The bending and torsional modes of the brake disc were identified and visualized using Laser Doppler Vibrometry (LDV).



Figure 18 Depiction of the frequency bandwidth used to analyze the brake disc behavior under vibration stress

The mode shapes were captured through graphical representations of the brake disc at various frequencies. The color gradient in these images serves as a critical indicator of modal behavior, helping to differentiate between bending and torsional modes as well as the degree of deformation, determined by the number of nodes present at each frequency.

5.1 Bending & Torsional Modes

The results from Scan 1 (2 kHz) and Scan 2 (5 kHz) are presented and compared to evaluate the modal response of the brake disc under different excitation conditions.

5.1.1 SCAN 1

Figure 20 presents the bending and torsional deformation modes identified in SCAN 1, focusing on the highest resonant peaks of the brake disc. These modes indicate how the disc deforms under vibrational excitation, with bending modes causing out-of-plane displacement and torsional modes involving rotational deformation around the

disc's axis. Understanding these deformation characteristics is essential for evaluating the brake disc's structural integrity, as different modes contribute to stress concentration and potential fatigue failure over time. The analysis of these modes helps in optimizing the disc's design and material selection to enhance durability and performance under real-world braking conditions.

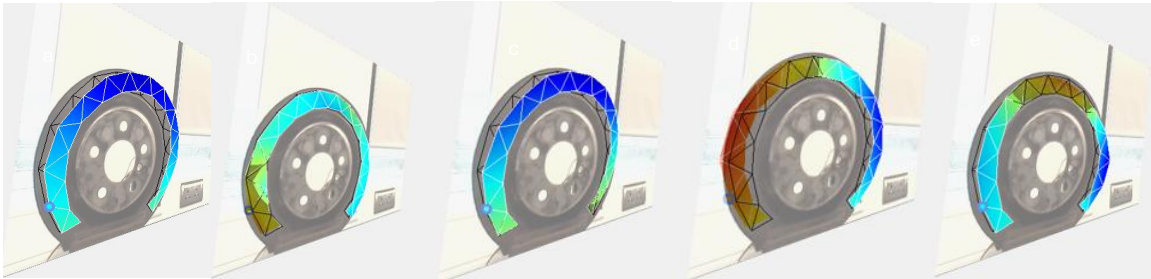


Figure 19.5 Highest Peaks found in the first scan, showing different bending and torsional modes where a) Bending, b) Bending & Torsion, c) Bending, d) Torsion, e) Torsion

The images (a to e) represent distinct mode shapes, with color gradients indicating deformation intensity—blue regions experience minimal displacement, while red/yellow areas undergo significant movement. These visualizations provide crucial insight into how different frequencies excite specific vibrational behaviors in the brake disc.

Table 3 Showing which mode from 1-5 (a-e) is undergoing which type of stress of movement from SCAN 1

Mode	Bending & Torsional - Degree - SCAN 1		
	Bending	Torsion	Description
1	Yes	No	1st degree Bending
2	Yes	Yes	1st degree Bending & Torsion
3	Yes	No	1st degree Bending
4	No	Yes	1st degree
5	No	Yes	2nd degree Torsion

The table on the right categorizes the identified modes based on their bending and torsional characteristics. Modes 1 and 3 exhibit pure bending, which generally leads to

compressive and tensile stresses along the disc's surface. Mode 2 is a mixed bending-torsional mode, indicating both out-of-plane deflection and twisting deformation. In contrast, Modes 4 and 5 display pure torsional behavior, where the disc undergoes rotational stress without significant bending displacement. Notably, Mode 5 represents a second-degree torsional mode, meaning it involves a more complex twisting pattern than Mode 4. This classification is critical for determining the disc's stress distribution, as bending stresses typically lead to material fatigue, while torsional stresses influence shear resistance and rotational stability.

5.1.2 SCAN 2

The second scan (5 kHz bandwidth) identified eight distinct vibrational modes where the brake disc resonated with significant intensity. These peak frequencies represent the dominant modal responses of the structure and are crucial for understanding its dynamic behavior.

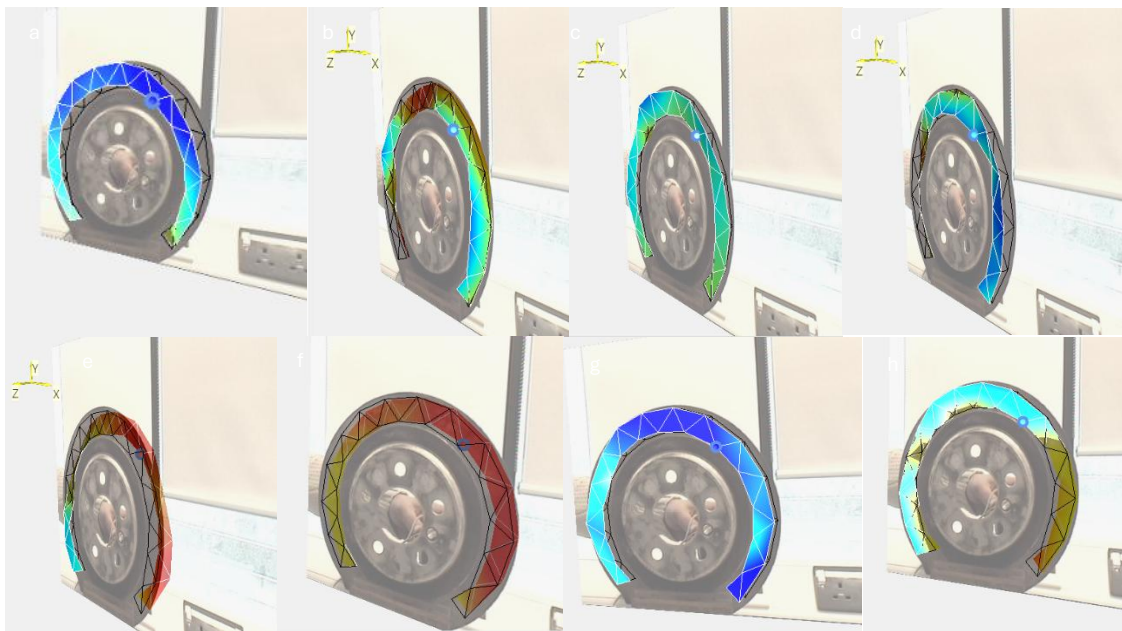


Figure 20 Illustrates the modes 1-8 (a to h), each corresponding to a unique frequency at which resonance occurs

As seen in for SCAN 1 the modal deformations vary across modes and in this case for SCAN 2 there are eight detected modes, with some exhibiting pure bending, others pure torsion, and a few displaying a combination of both behaviors.

Table 4 provides the corresponding frequencies for each mode, confirming the presence of first-degree and second-degree bending and torsional modes. Modes 1, 5, 6, and 8 display pure bending, while Modes 2 and 4 exhibit torsional characteristics. Notably, Mode 7 combines both bending and second-degree torsion, making it particularly relevant for structural integrity analysis.

Table 4 Showing which mode from 1-8 (a-h) is undergoing which type of stress of movement from SCAN 2

Bending & Torsional - Degree - SCAN 2			
Mode	Bending	Torsion	Description
1	Yes	No	1st degree Bending
2	No	Yes	2nd degree Torsion
3	Yes	Yes	2st degree Bending & Torsion
4	No	Yes	2nd degree Torsion
5	Yes	Yes	1st degree Bending
6	Yes	No	1st degree Bending
7	Yes	Yes	1st degree Bending & 2nd degree Torsion
8	Yes	No	1st degree Bending

5.2 Harmonic Frequencies

In SCAN 1, no harmonic frequencies were identified, as there was no consistent pattern in the peak frequencies that indicated a harmonic relationship. The resonant frequencies appeared irregularly distributed, suggesting that the brake disc's vibrational response was influenced by complex structural and material properties, rather than following a straightforward harmonic sequence. This lack of harmonics was clearly visible in the frequency spectrum, where the peaks did not align in multiples of a fundamental frequency.

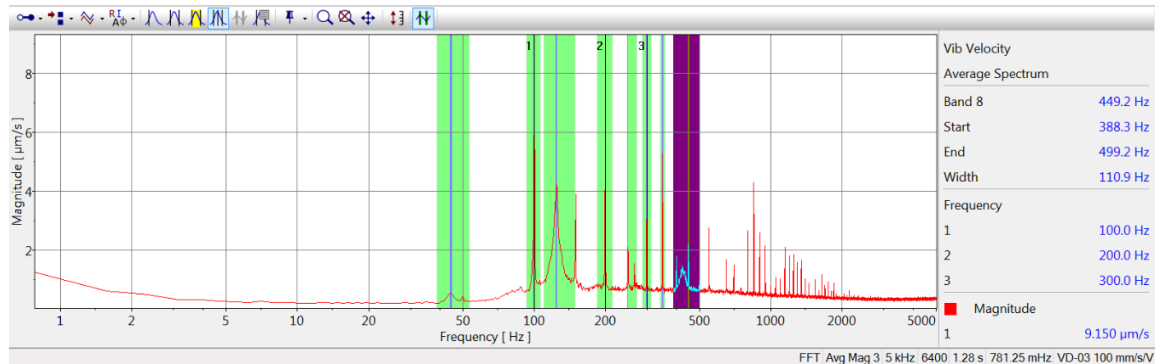


Figure 21 Peak frequencies of SCAN 2 and their natural frequencies in the dark blue box

However, in SCAN 2, which used a 5 kHz bandwidth, the presence of harmonic frequencies was observed at 100 Hz, 200 Hz, and 300 Hz. These frequencies correspond to Mode 2 (100 Hz), Mode 4 (200 Hz), and Mode 6 (300 Hz), forming a harmonic pattern where each successive peak aligns as a multiple of the fundamental frequency (100 Hz). This suggests that, at higher bandwidths, the brake disc exhibits harmonic resonance, likely due to repetitive structural excitation patterns that reinforce specific vibrational modes.

The identification of harmonic peaks is significant, as it indicates that certain modes can be excited more easily under repeated loading conditions, which could contribute to vibration-induced fatigue over time. These findings highlight the importance of higher-bandwidth modal analysis, as lower-frequency scans (such as SCAN 1) may not always reveal harmonic resonance patterns critical for evaluating the long-term durability and performance of the brake disc.

6. Limitations of the Study

One of the primary limitations of this study is the variability in actuator positioning between SCAN 1 and SCAN 2. The solenoid actuator applied excitation at different sections of the brake disc in each scan, which may have influenced the vibrational response and introduced uncertainty in the mode shapes and resonance frequencies detected. Since the excitation force was not applied at the exact same location, variations in local material properties, boundary conditions, and contact points could have contributed to inconsistencies in the identified modal patterns.

Additionally, external noise factors and environmental conditions during the experiment may have affected data accuracy. The magnitude of these variations cannot be precisely determined within the scope of this study, and future tests should implement controlled excitation positioning and repeatability tests to reduce uncertainty.

7. Conclusion

This study successfully characterized the modal response of a brake disc using Laser Doppler Vibrometry (LDV), identifying distinct bending and torsional mode shapes under two different bandwidth conditions. SCAN 1 (2 kHz bandwidth) captured five primary vibrational modes, whereas SCAN 2 (5 kHz bandwidth) identified eight modes, including harmonic frequencies at 100 Hz, 200 Hz, and 300 Hz, which were absent in SCAN 1. The presence of harmonics in SCAN 2 suggests a structured modal distribution, influenced by higher excitation bandwidths and increased resolution.

Despite these findings, inconsistencies in excitation positioning between the two scans introduce potential uncertainties in direct mode-to-mode comparisons. Future studies should focus on standardizing excitation application, ensuring precise actuator placement, and performing repeatability trials to establish a stronger correlation between the results of different scans.

Additionally, increasing the scan resolution and incorporating Finite Element Analysis (FEA) validation could further enhance the understanding of the brake disc's dynamic response. By refining experimental procedures and expanding modal testing conditions, future research can develop a more robust relationship between mode shapes, excitation bandwidths, and harmonic frequency patterns, ultimately improving brake disc design and durability analysis.

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