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Laser Doppler Vibrometer – Brake Disc Modal Analysis

Structural Integrity & Materials Evaluation

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1 Abstract

Work presented within this report outlines an experiment using Laser Doppler Vibrometry (LDV) to analyse a vehicle brake disc to determine resonant frequency modes and shapes wherever possible. A solenoid actuator was used to excite the brake disc in multiple different locations while a Polytec PSV-400 vibrometer was used to scan the surface of the brake disc. Results were analysed using PSV presentation software and collected for presentation within this report.

The report follows the methodology used, results obtained and their meaning, comparisons drawn to similar experiments using varying methods, and conclusions that could be drawn from the experiment. There are also some error estimates and suggested potential sources of error that have been included which could potentially be solved if the experiment was to be repeated in future.

2 Apparatus

Apparatus required to complete the modal analysis can be seen listed below:

- Polytec PSV-400 Vibrometer (Including tripod and computer system)
- Car brake disc test sample
- Bench vice
- Solenoid actuator
- Tape measure/1m ruler
- Tape (to secure solenoid actuator location)
- Blocks of varying height (to adjust solenoid actuator height)

3 Introduction and Method

Non-contact measurement techniques are used widely across all engineering disciplines, commonly in mechanical and automotive/motorsport engineering contexts to conduct modal analysis on components. Laser Doppler Vibrometry (LDV) was used for this experiment to conduct a modal analysis on the surface of a car brake disc. Resonant frequency modes and shapes (bending/torsional) were observed. A solenoid actuator controlled by the LDV function generator was used to excite the brake disc, creating movement that was detected by the scanning head.

A Polytec PSV-400 Vibrometer ("Laser-Vibrometer Polytec PSV-400 | UseScience," n.d.) was used. A high-power laser hits the brake disc surface, which is then reflected to the scanning head, where a high precision interferometer detects frequency shifts from the back scattered laser light from the test sample. The interferometer splits this light into two parts. A 'reference' beam is directed to a photo detector, and a 'measurement' beam is incident on the test sample where laser light is scattered from the moving surface of the brake disc surface. Dependant on velocity and displacement, the back scattered laser light changes in frequency and phase. These changes are retained in the back scattered light and are identified by the photo detector within the scanning head. The system creates a modulated detector output signal which reveals the Doppler shift in frequency. (Polytec, 2021)

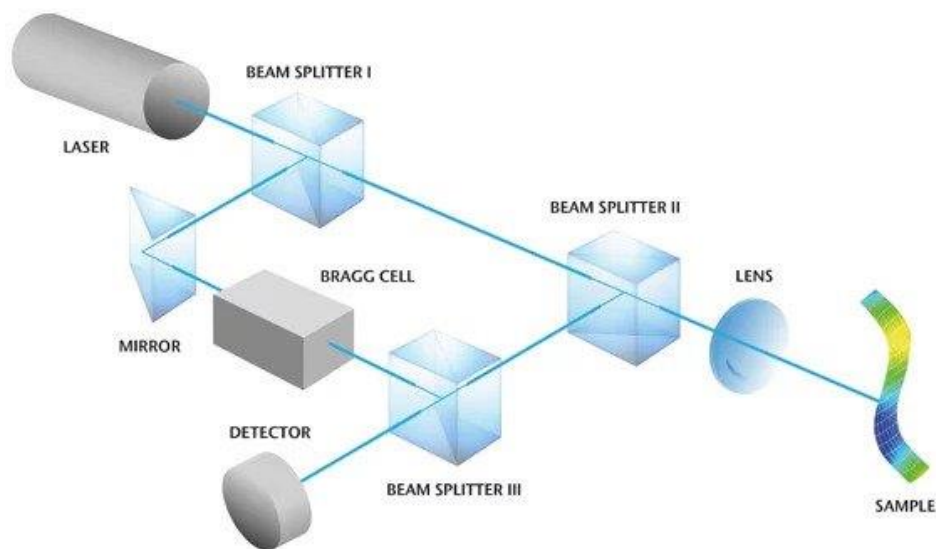


Figure 1 - Fundamentals of LDV. (Laser Doppler Vibrometry - Polytec, n.d.)

3.1 Method

The following steps should be followed to complete modal analysis of the brake disc effectively to achieve suitable results. This experiment was carried out using Polytec PSV acquisition and presentation software.

1. Collect all apparatus as listed in section two of this report and set up in an area with enough space to carry out the analysis safely. A bench/tabletop was necessary for setting the bench vice, solenoid actuator and test sample on.

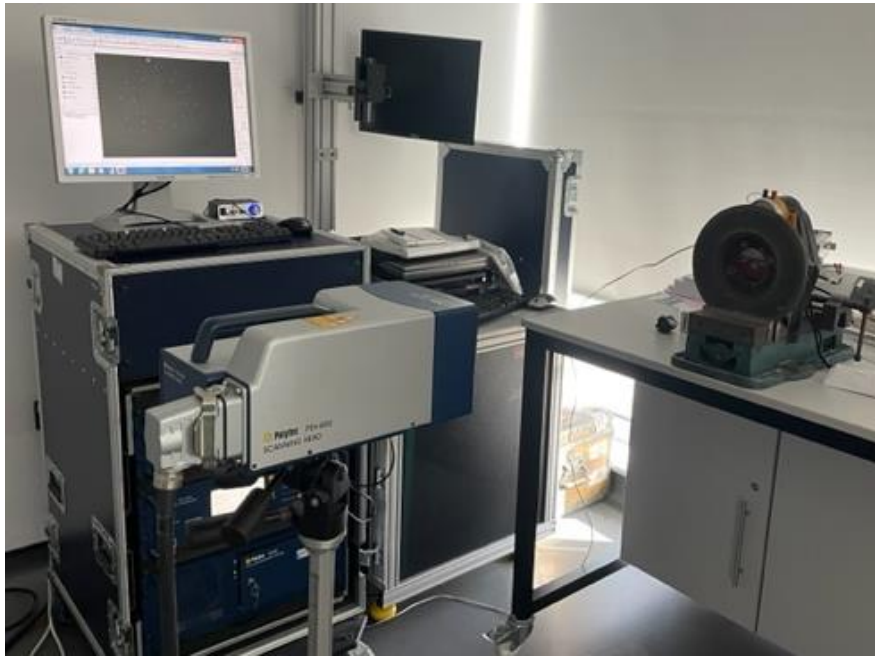


Figure 2 - LDV analysis setup.

2. Ensure that the solenoid actuator was positioned so that it made solid contact with the test sample and that it couldn't move upon hitting the sample. An audible ringing sound could be heard when the solenoid actuator was making good contact with the sample. In this analysis, industrial tape was used to secure the solenoid actuator in position.



Figure 3 - Solenoid actuator secured in position.

3. Using PSV acquisition software relevant to the Polytec scanning head, the laser was focussed using the auto-focus feature. This ensured that the laser was focussed correctly on the test sample in relation to the distance between the test sample and the scanning head, which in this case was 0.79m.

- Using the 2D alignment feature, a series of alignment points were defined on the brake disc surface. It was recommended to use a minimum of 5 alignment points.

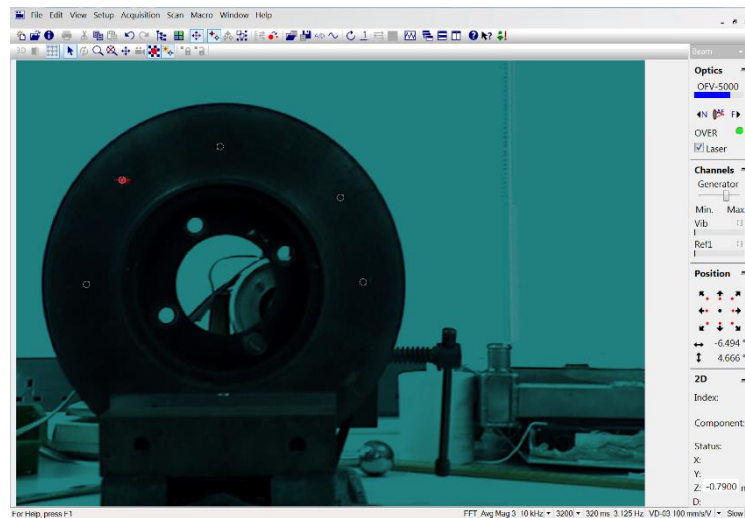


Figure 4 - 2D alignment points on the brake disc surface.

- With 2D alignment points specified, it was possible to define scan points that would be used to generate a mesh that the laser would follow on the brake disc surface to obtain results.

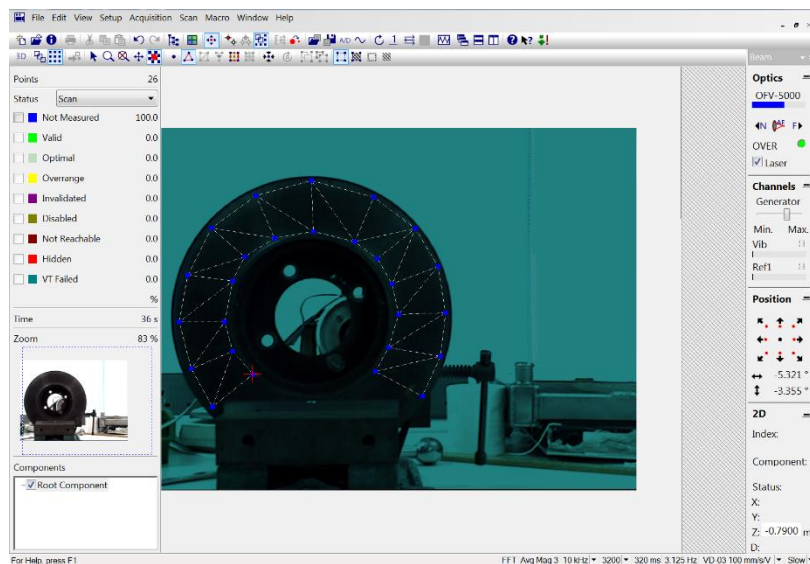


Figure 5 - Scan points.

- With previous steps followed, it was then possible to start the scan and allow the laser to analyse the defined points when it was excited by the solenoid actuator. Upon completion of the scan, a colour was allocated to each scan point which highlighted the success of the scan.

Status	Scan	
☐ Not Measured	100.0	
☐ Valid	0.0	
☐ Optimal	0.0	
☐ Overrange	0.0	
☐ Invalidated	0.0	
☐ Disabled	0.0	
☐ Not Reachable	0.0	
☐ Hidden	0.0	
☐ VT Failed	0.0	
	%	

Figure 6 - Scan points status legend.

For this analysis, points returned as either 'Valid' or 'Optimal' were acceptable and were taken as successful.

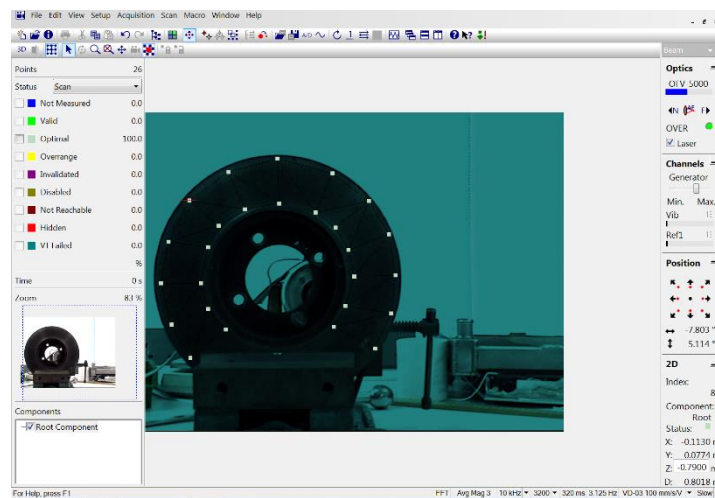


Figure 7 - Scan complete. All points returned as 'Optimal'.

- Results were viewed and analysed using PSV presentation software. Results are shown in following sections of this report.

4 Measurements and Results

4.1 Test Location on Test Sample Surface

To obtain a comprehensive set of results that could be compared, three separate tests were conducted. Each test was conducted with the solenoid actuator in a different position on the brake disc surface. Figure 8 below shows locations of each test, numbered 1, 2, and 3.

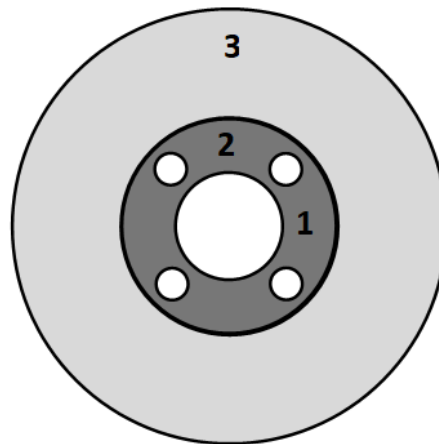


Figure 8 - Locations of each test numbered 1, 2, and 3.

4.2 Scanning Head Distance to Test Sample

As previously mentioned in the method, it was important to determine the distance at which the scanning head was from the test sample. This value was implemented within the PSV acquisition software and was kept the same throughout all tests for repeatability and accuracy purposes.

The distance was measured using a 1m rule and was kept at 0.79m (790mm) for all tests.

4.3 Obtaining Results

To view results correctly, the pre-defined graph in PSV presentation was auto scaled to show all bands occurring in each test on a suitable scale.

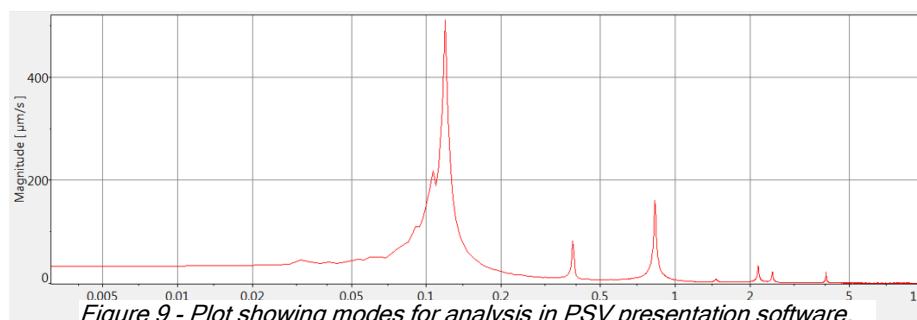


Figure 9 - Plot showing modes for analysis in PSV presentation software from scan number 3.

Using the plot shown in figure 9, it was possible to define each peak as a band that would be assigned to a particular frequency value which could then be analysed further. This was done simply by clicking and dragging the mouse cursor over each individual band.

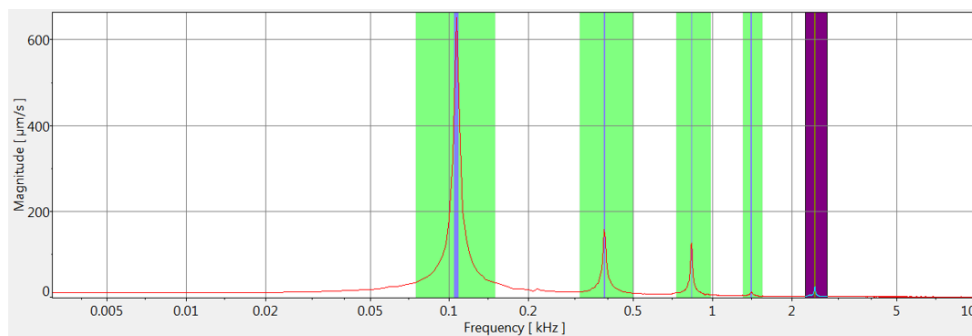


Figure 10 - Band definition from scan number 1.

No.	Start	End	Peak	Bandwidth	Unit
1	75	146.875	106.25	71.875	Hz
2	312.5	496.875	387.5	184.375	Hz
3	725	984.375	831.25	259.375	Hz
4	1296.875	1550	1400	253.125	Hz
5	2246.875	2718.75	2440.625	471.875	Hz

Figure 11 - Band definition table from scan number 1 relevant to figure 10.

Figures 10 and 11 show five bands that have been defined from scan number 1 with the solenoid actuator positioned in position number 1 as shown in figure 8. Each of those bands could then be analysed to determine their resonant frequency modes and shapes of the brake disc.

This process was carried out in the same way for each scan.

Brake discs are subject to many forces during their operation, with vibration being a major contributor. (*Vibration Analysis of a Brake Disc - Isi-Sys*, n.d.). Torsional and bending moments were observed on each set of results and an example of each will be shown below.

4.4 Bending and Torsional Moments

Below are some examples of results that showed bending and torsional moments occurring on the brake disc. Further explanation and discussion on this will be provided within section 5 of the report. This section is purely to display bending and torsional moments that were observed during the tests.

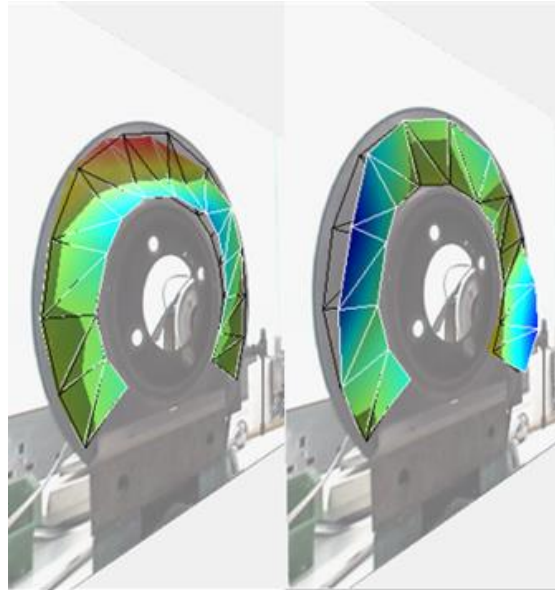


Figure 12 - Scan 1 comparison of bending moment (left) and torsional moment (right).

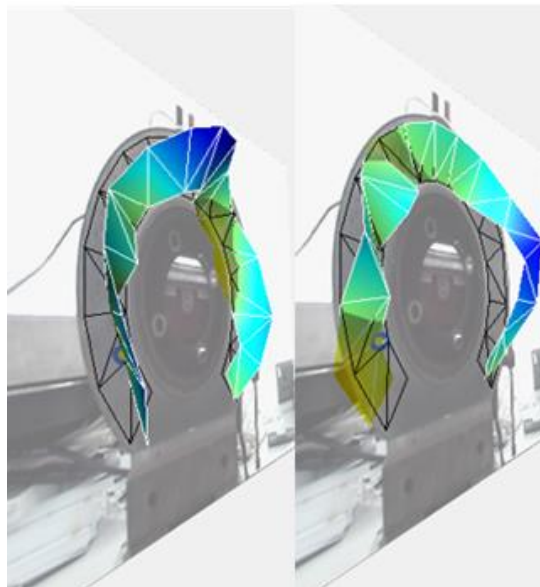


Figure 13 - Scan 3 comparison of bending moment (left) and torsional moment (right), results are up-scaled for display purposes.

5 Error Estimates

There are some aspects of the experiment that could be improved to improve the overall quality of the results obtained. Securing the solenoid actuator in this experiment was achieved using industrial tape, which held the solenoid actuator in its set position adequately. However it was observed that when the solenoid actuator made contact with the brake disc, there was some movement. Although the solenoid actuator didn't move backwards or rotate from the position it was secured in, the movement that was observed however could have impacted the quality of contact that the solenoid actuator made with the brake disc.

To reduce this potential error, a custom version of the bench vice used could be designed so that it could house the test sample as well as the solenoid actuator within a metal surround so that it was solid in its set position. As a mean of adjusting the position of the solenoid actuator with this proposed solution, a set of turn screws could be used to move the solenoid actuator forwards and backwards, and side to side.

When adjusting the height of the solenoid actuator, various items were used that were readily available at the workspace where the experiment was conducted. Some items were perfectly adequate however some items were less suitable as they weren't 100% sturdy, requiring industrial tape to solidify them. To prevent this in future, solid blocks of aluminium of varying thickness could be machined to offer further refinement in terms of the solenoid actuator height.



Figure 14 - Solenoid actuator setup that could have contributed to potential error.

6 Results and Discussion

Results obtained were adequate for the purpose of this experiment. They provided valuable information to define the resonant frequency modes and shapes that were occurring on the brake disc when it was excited by a solenoid actuator.

It was clear to see that both bending and torsional moments were occurring throughout these tests. Torsional moments are experienced when the brake disc tries to twist around its transverse axis due to torque (*Twisting Moments (Torques) and Torsional Stiffness*, n.d.), whereas bending moments occur when the disc tries to bend about the longitudinal axis of the brake disc (*Torsional Force - Definition, Formula, Effect and Examples*, n.d.). This becomes clear when observing figures 12 and 13 respectively.

Various modal analysis experiments have been carried out using varying methods. (*Modal Analysis of Train Brake Disc Using EDM Modal*, n.d.) conducts a modal analysis on a train brake disc using EDM (Engineering Data Management) Modal software (*Modal Testing & Modal Analysis*, n.d.). The experiment differed to the one within this report, in that it used

different acquisition and presentation software, as well as a Crystal Instruments Spider-80Xi modular acquisition device rather than the PSV-400 scanning head used within this report. To excite the test sample, a PCB 086C03 modal impact hammer was used.

(Xiaowei et al., n.d.) conduct a full modal analysis on an automobile brake disc by using a much more mathematical/Finite Element Analysis (FEA) approach. 3D modelling software CATIA (*Shape the World We Live in* / CATIA – Dassault Systèmes, n.d.) was used to model the brake disc. Ansys-workbench (*Ansys Workbench* / *Simulation Integration Platform*, n.d.) was used to conduct the FEA analysis.

Both methods above have been shown to provide adequate results when compared with the LDV method used within this report. Thus, suggesting that there are multiple methods to conduct a modal analysis of a brake disc to achieve suitable results. The following figures display results each scan conducted within the experiment.

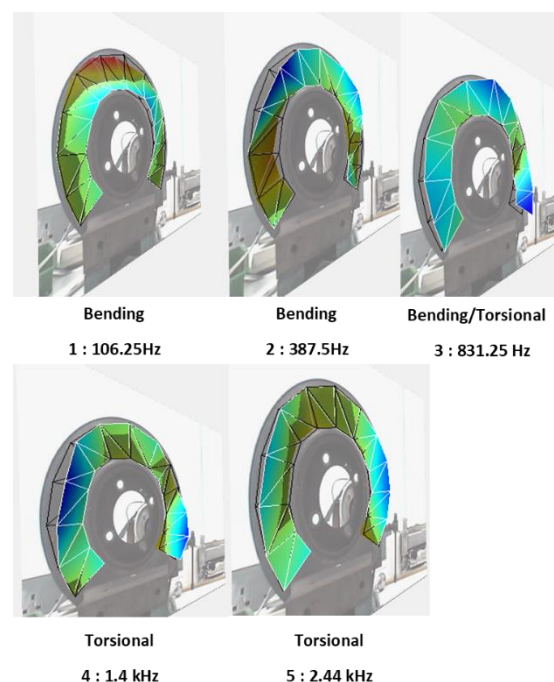


Figure 15 - Comparison of results gathered from scan number one.

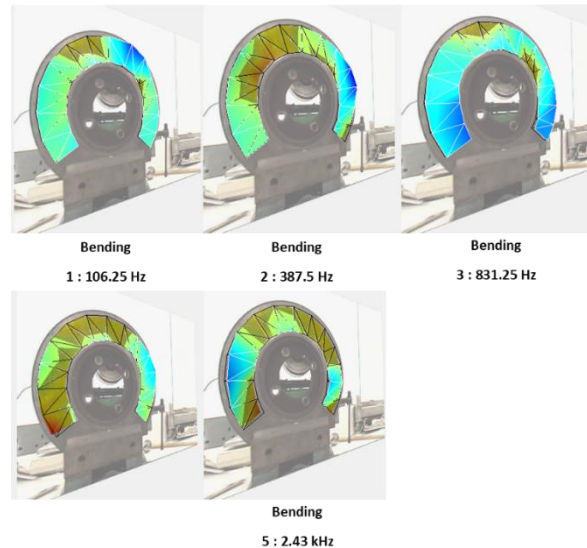


Figure 16 - Comparison of results gathered from scan number two.

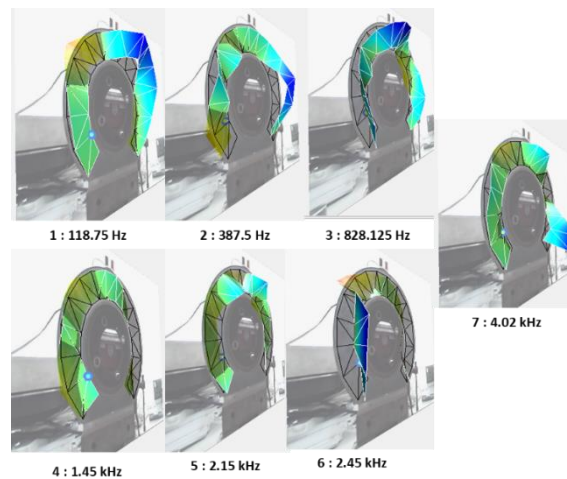


Figure 17 - Comparison of results gathered from scan number three, results here have been upscaled for display purposes.

A paper published by (Pagan & Lake, 2018) perfectly demonstrates the use of LDV to validate an FEA simulation of a motorcycle swing arm. LDV was used in a comparable manor to how it has been within this report. The swingarm was excited from multiple different locations by a solenoid actuator to demonstrate resonant frequency modes and to replicate as accurately as possible how the component would be subjected to force when in use. This is accurate to the way in which testing on the brake disc was conducted. As explained, three test locations were used to evaluate how the brake disc would behave as if it were mounted to a vehicle.

Of course, there are differences that it is important should be drawn out, a significant difference in component design and general characteristic would almost definitely lead to a difference in results. However, it is reassuring to know that the methods conducted within this report have been able to achieve results that are consistent and show clearly how the brake disc behaves when excited from various positions.

7 Conclusion

Results gathered within this experiment are valid and have shown resonant modes and shapes wherever possible on the brake disc examined. Methods and results have been compared to pre-existing literature available to the author, although some comparisons were made to results gathered using alternative methods.

The test sample used within this report was a solid brake disc as shown, with no holes or slots drilled. If future work was to be conducted then drilling holes or slots into the brake disc to observe how results would differ could be beneficial. As the brake disc would have less material, it would predictably behave differently when excited when compared to the solid disc used for this experiment.

It was reassuring to discover that after consulting the papers referenced within this report, results were perfectly reasonable and show how the brake disc would behave when excited from the positions shown. It is also important that multiple tests were conducted at different locations on the disc, so that a wider, more accurate scope of results could be obtained.

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