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Laser Doppler Vibrometer – Brake Disc Modal Analysis

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Abstract – *In this report, a modal analysis of a standard automotive brake disc was conducted. Using a Laser Doppler Vibrometer (LDV) and accompanying software, the components main harmonic resonant modes were identified. The complete experimental procedure has been described during the report along with a complete appendix with all the data produced where a solenoid actuator taped the brake disc, and then the LDV measured these vibrations and analysed the harmonic modes produced.*

Two locations for solenoid actuator were used, one on the right side of the disc, and the second, at the top of the brake disc, labeled test 1 and test 2 respectively. The results calculated showed 5 main harmonic modes occurred during test one and 7 in test two. In both tests, at lower frequencies the disc vibrated with common nodes and anti-nodes, however at higher frequencies, the brake disc

appeared to follow a torsional and then uniform ripple shape.

Overall, it was concluded that test 2 produced more accurate results, with the location of the solenoid reducing the amount the vibrations were damped, as this was seen in the shapes produced by the software during the analysis phase. Looking at previous research also validated the results found in this investigation, with similar resonant shapes being produced using comparable equipment and experimental procedure.

1. APPARATUS

- PolyTec Scanning Laser Doppler Vibrometer (LDV)
- Solenoid Actuator
- Tape measure
- Windows PC

2. INTRODUCTION

Laser doppler Vibrometers (LDV) allow for the detection and analysis of components vibration

modes. These modes signify how a component will vibrate when a force or load is applied. This will then show how the material is likely to behave within its specified use case, and therefore can allow Engineers to identify potential failures and design the component accordingly. This technology is a form of Non-Destructive Testing (NDT), therefore components can be removed from their application and then reinstalled after the investigation, whilst still providing an accurate understanding of the mechanical properties. Using light as a sensor does not influence the sample, it allows for small and lightweight structures to be analysed (PolyTec, n.d.). This allows the user to measure the mechanical vibrations of a sample with extremely high precision in terms of frequency, sensitivity and range (Optomet, n.d.).

All materials have a natural frequency, which is the a certain frequency that the component will

vibrate when tapped or disturbed (Cadence PCB, n.d.). Following on from this, a resonance frequency can occur, which is the highest amplitude of the natural frequency which can naturally occur. This is a function of the sound velocity, material characteristic and component geometry (Babak Khodabandeloo, 2014). When a material encounters the resonance frequency, this can put high torsional strain through the component, in a manner which had not been accounted for during the design process, initiating a crack and ultimately causing a failure (Inspectioneering, n.d.).

The PolyTec LDV works off the doppler effect in order to understand a materials vibration response. Light in the form of a laser is projected towards the component, as the component moves, the frequency in the backscattered light changes and the LDV measures these minute changes. This is done by splitting the light before measuring, creating an incident and reference

beam. The incident beam then hits the object and is backscattered back towards this laser, which then uses the superposition of the backscattered light alongside the reference beam to measure changes in frequency and phase (doppler shift). Signal processing and computer analysis use this information to calculate the frequency modes of the component (PolyTec, n.d.). Figure 1 shows a diagram of how the light is split and the path for the backscattered light.

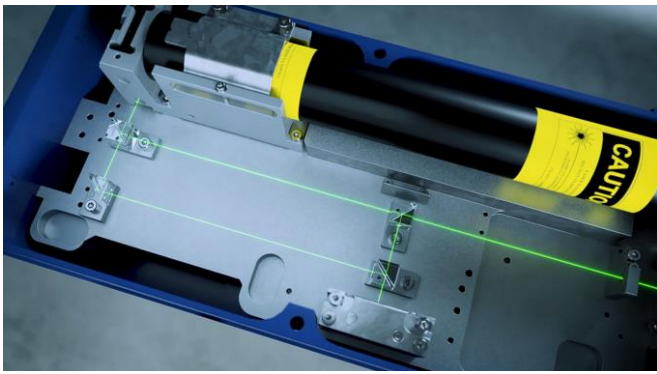


Figure 1: Laser Light Path within the LDV (PolyTec, n.d.)

For this investigation, the vibration modes of a standard brake disc were analysed. The brake disc, when clamped into a vice, with the LDV positioned approximately 70cm away. We then set up the solenoid actuator in two different locations, propped up and secured at the back of

the brake disc on top of the brake disc. The two locations where one was on the right hand side of the brake disc, the second position, up top, 90 degrees to the first position defined as Test 1 and Test 2. The software was then setup, identifying all the points where measurements will be taken from, the frequency of the light and the number of taps produced from the actuator. This setup allows for two different sets of results for comparison.

The LDV system can often be used in conjunction with or to validate finite element analysis (FEA) investigations. This is necessary as the FEA is a computer simulation, calculating what would happen if the physical test was conducted. In a Journal Paper from 2017, (Xiaowei, Bojun, & Dejian, 2017), when analysing an automotive brake disc to the one in this investigation, it was found that the two methods produced very similar results, with a maximum error result of 4.5%. They found that errors occurred from the

software using an ideal, but unrealistic material quality and noises and vibrations from the environment, causing some disturbances. Looking at this paper, this is a factor which should be considered when analysing the results for the experiment in this report.

Similarly, a comparison between digital image correlation (DIC) and LDV was investigated in 2016, (Phillip L. Reu; Daniel P. Rohe; Laura D. Jacobs, 2016). It was found that LDV remained to have the better out of plane resolution when analysing a flat 7-inch diagonal metal plate using pseudorandom excitation. However, the authors did notice that DIC produces more accurate strain calculations and provides a competitive approach to modal and vibration analysis. Whilst strain calculations aren't featured within the scope of this investigation, it is important to note this if the project was to be continued. When looking at the data, any area which doesn't move is a node, and

the areas with maximum displacement are the anti-nodes (Jones, 2021).

3. METHOD AND PROCEDURE.

To conduct the experiments, the brake disc needed to be mounted to a secure place. This was done by clamping it within a vice mounted to a work bench. This held the brake disc at the bottom, where we scanned the upper three quarters of the brake disc. Excitation of the disc came from a solenoid actuator, controlled to the software. This was securely placed at the right hand side for Test 1 and at the top in the centre for the Test 2. The solenoid needed to be placed at the correct distance, to tap the disc with

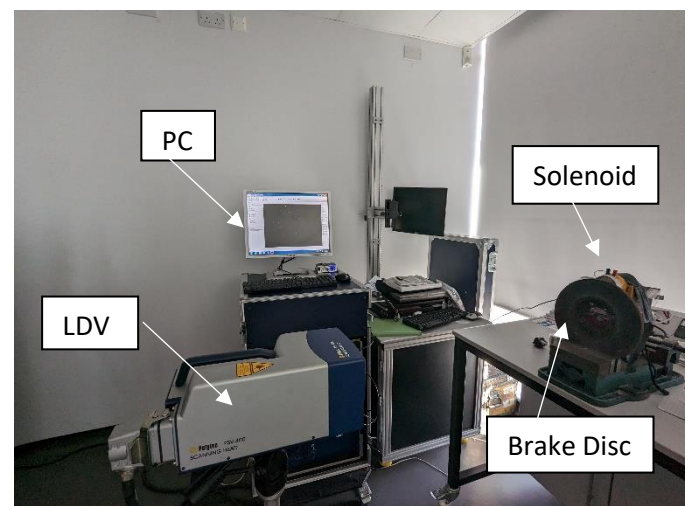


Figure 2: Setup used for investigation.

enough force, but not to damp the oscillations. The LDV scanner was then placed approximately 70cm away, providing suitable signal strength.

Figure 2 shows the setup used.

To run the test, software called PSV 9.3 Acquisition was used and the PSV 9.3 Presentation was used to view the data collected. When opening PSV 9.3 Acquisition it was required to firstly set the correct parameters, where the only variable changed for the run was the band width and number of FFT lines. In turn this changed the frequency and resolution. For

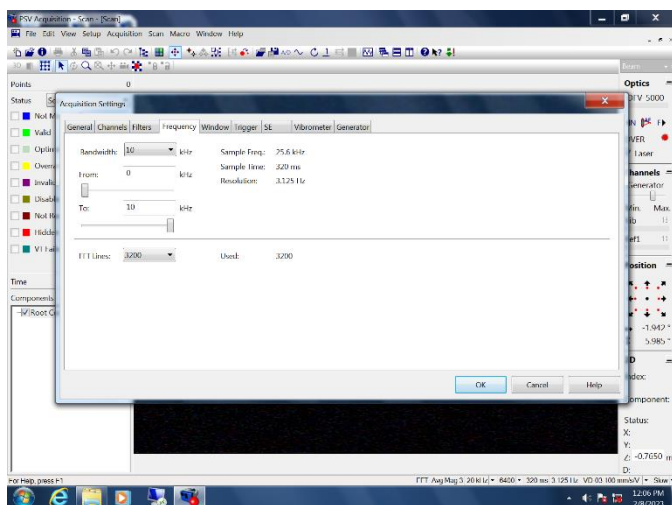


Figure 3: Acquisition Settings

the two experiments in this investigation, a bandwidth of 10 kHz and FFT line of 3200 was used (see Figure 3).

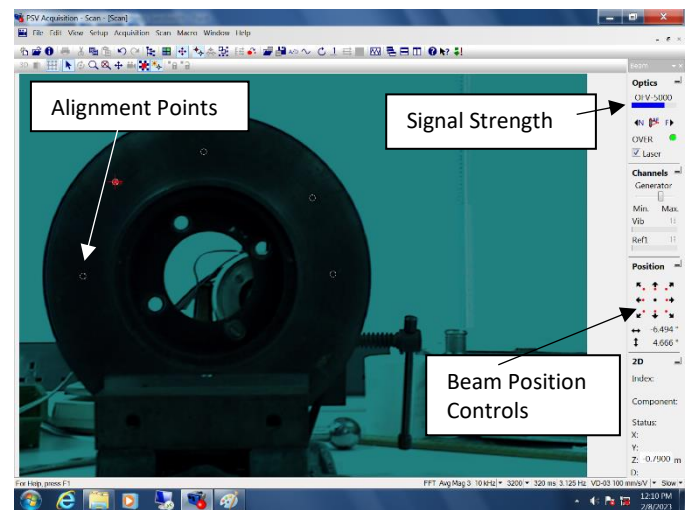


Figure 4: Alignment points

Once the system settings have been set up, a 2-D alignment of the scanning head is required. This essentially defined where the sample is in relation to the scanning device and ensures the signal strength is strong enough for the test. This is done by the menu, setup -> 2D Alignment. Using the arrows on screen, the laser can be moved, and clicked using the mouse to define the alignment point. It is recommended that this is done approximately five times for accuracy, as seen in Figure 4.

To finish this process, the scan points for the test need to be defined. This is done by Setup -> Define Scan Points. This can either be done by drawing a primitive shape, and then selecting a density for the number of points based on this shape. This is the quickest method, however for complex geometry parts like this brake disc, the preferred method is to manually select each point and then connect them together to define the whole area. For this method, use the icon symboling a 3x3 grid, and then use the cursor icon to drag the laser to where each point will be, then clicking on that point will select it as a scan point. Each point will then be joined together

using the triangle icon along the same banner. Defined points will appear blue and figure 5 shows the result before the test can begin.

A scan was ready to be run once these scan points have been defined. This is located under Acquisition -> Scan. The scan will then run, and on the left hand side a coloured scale of how well each scan performed, where the computer will decide if any points need to be rescanned, depending on the quality. A complete scan is show in figure 6 and the results can now be viewed within the PSV 9.3 Presentation software.

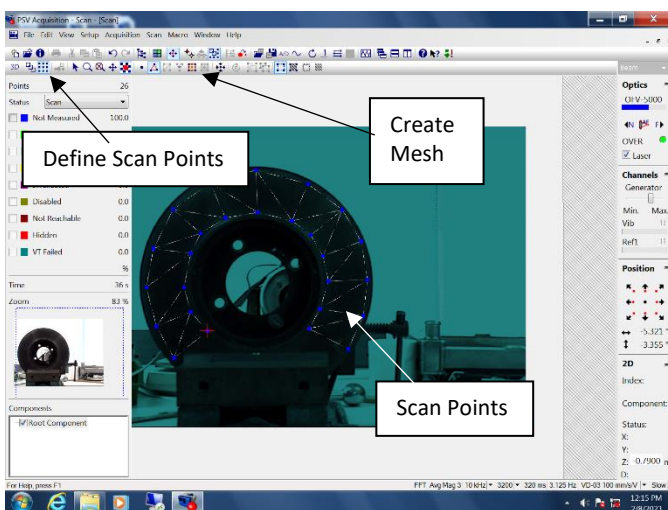


Figure 5: Define Scan Points

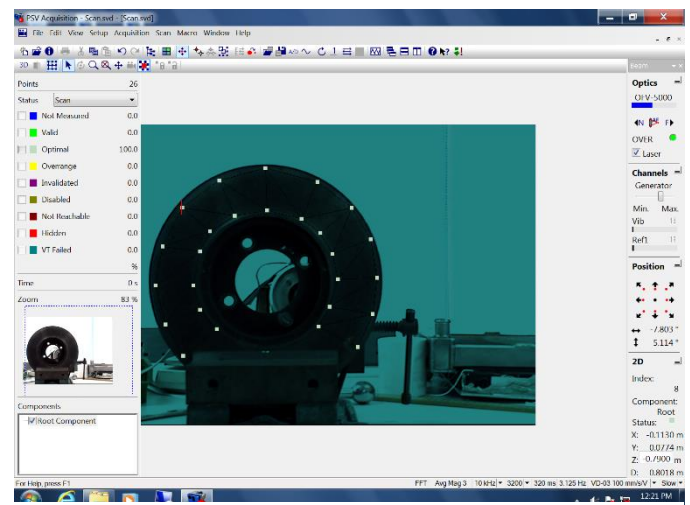


Figure 6: Completed Scan

4. MEASUREMENTS AND CALCULATIONS

Due to the experiment being entirely computer software driven, the only specific measurement that was taken was the distance between the brake disc and LDV device, 0.70m. Within the software, the primary calculation that occurred was when transforming the time based response (figure 7) to a frequency based response by using a Fourier transform, with all the calculations being done by the PSV Acquisition software.

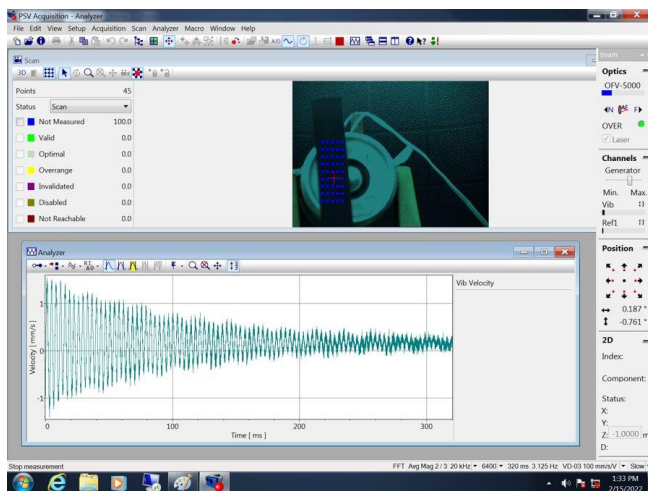


Figure 7: Time Based Frequency Response (Charlton, 2023)

5. RESULTS AND DISSCIUSION

The main results which will be compared are each component's harmonic resonant modes, and the vibrational shapes these modes produced. Data

from both the runs will be compared, which will suggest how the different locations of the actuator effects the vibration of the brake disc. These results will allow understanding of how a brake disc will vibrate, which can then in turn be used for brake disc vibration analysis when mounted to the car during typical use. Before analysing the results, it is important to note that the disc has been clamped at the lower section, which could dampen some of the vibrations and their path. This is entirely different to how it would be mounted and damped in use, which would be through the centre along the axle of the car.

Table 1: Mode Peaks for Test 1 and 2

Modes	Peaks (Hz)		Difference
	Test 1	Test 2	
1	106.25	118.75	12.5
2	387.5	387.5	0
3	831.25	828.125	-3.125
4	1400	1459.375	59.375
5	2440.625	2153.125	-287.5
6	N/A	2453.125	N/A
7	N/A	4028.125	N/A

Table 1 shows the peaks for each modal frequency calculated by the software. Test 1 indicated the test where the actuator was positioned to the left

and test 2 represents the test when the actuator was positioned at the top. Initially, clearly there are more modes for test 2. The largest difference for comparable peaks is at the fourth mode, with a difference of 287.5 Hz.

5.1 Test 1

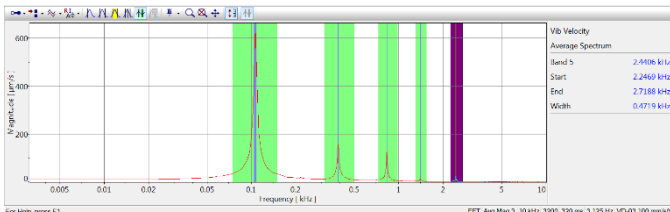


Figure 8: Bands for Test 1

Figure 8 shows the individual mode bands for each of the frequencies during test 1. The magnitude of each peak and band width decreases from mode 1 to 5. The highest magnitude shows the maximum velocity at which the sample will vibrate at. For example, table 1 shows that at 106Hz, the oscillations occur at approximately 620µm/s.

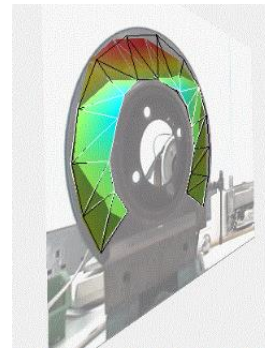


Figure 9: Test 1 Band 1

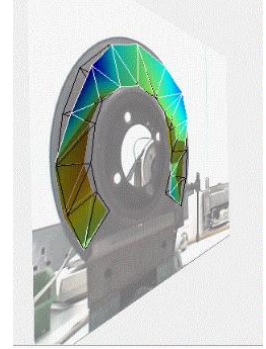


Figure 10: Test 1 Band 2

Comparing Figure 9 and 10, it is clear of the differences which can occur between two different frequency modes. Figure 9, which shows band 1 (106.25Hz); the top of the disc appears to oscillate the most, indicated by the red colour (anti-node). In contrast to this, Figure 10, Band 2 (387.5 Hz) which oscillates more towards the top corners, and more deformation towards the right and left edges, the main node now being the top of the brake disc.

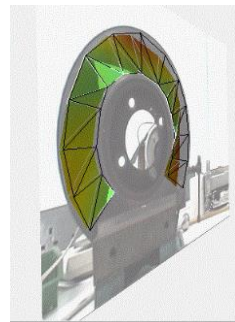


Figure 11: Test 1 Band 3

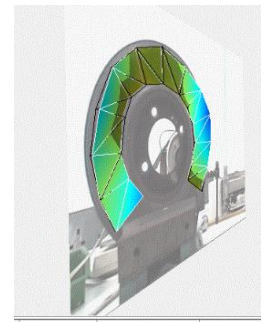


Figure 12: Test 1 Band 5

Figures 11 and 12 show the vibration modes from bands 3 (831.25Hz) and 5 (1400Hz) during test 1. Looking at figure 11, the vibration occurs uniformly across the whole of the brake disc surface, rather than having one area moving in the opposite direction. Comparing this to band 5 in figure 12 shows a completely different mode, a torsional wave like shape across the plane of the disc, which moves around the centre. Band 4 has not been shown as it looks similar to band 5, just less exaggerated.

5.2 Test 2

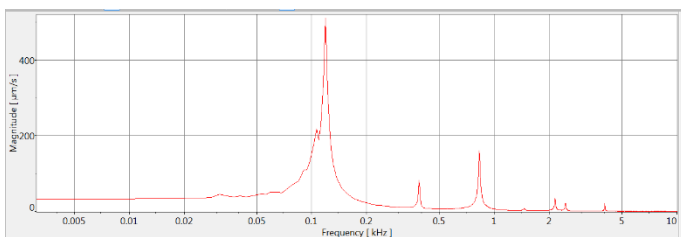


Figure 13: Bands for Test 2

Figure 13 shows the bands detected from Test 2 where the solenoid was placed at the top, in line with the centre of the brake disc. This test has clearly produced more vibration bands compared to test 1, which indicates there was less damping

within the brake disc, suggesting with the solenoid placed more centrally, the vibrations were able to propagate out more freely, providing a more accurate representation of the brake discs vibration modes.

A larger frequency range in band 1 is seen during test 2 compared to test 1, indicating a wider range of frequencies can cause this harmonic mode to appear. However, looking at the rest of the bands, they appear relatively similar between the two tests, with the only other noticeable difference being the magnitude peaks between bands 2 and 3. With a higher magnitude recorded, this indicates the vibrations occur with more velocity and therefore force.

The images for the vibration patterns for Test 1 are referred to in the Appendix 6.2 for reference. Comparing band 1 during Test 1 and Test 2, the pattern is roughly similar, however the movement in Test 2 occurs more towards the top

corners rather than in the centre, as the vibration occurs from the centre. They will then propagate outwards, rather than from right to left as shown in Test 1. However, it also appears that the left and right vibration directions follow an opposite and torsional wave form, more like band 2 in Test 2.

Band 2 in Test 2 appears to follow a ripple motion, which resembles band 5 in Test 1. Looking at bands 3 and 4 in Test 2, they appear very similar to each other and to band 3 in Test 1. Again, bands 5, 6 and 7 show a ripple formation with band 7 being the most pronounced, with all these formations being equivalent to band 5 in Test 1.

Comparing the results from Test 1 and Test 2, the main difference which can be seen is the number of resonant bands which have been recorded. This suggests by taping the disc in a central position shown in Test 2 allows for the brake disc

to vibrate more freely, rather than being damped, the further the vibrations travel around the disc. Similarly, the amount the vibrations were damped by being held in the vice appears to lessen during Test 2, which can only be caused by the location of the solenoid actuator.

Test 1 creates five main resonant bands, compared to Test 2 which creates seven. This indicates that Test 2 provides a more accurate representation of the harmonic frequencies which the brake disc can produce. However, whilst Test 2 has been concluded to produce the most accurate results, there are some limitations within the investigation which need to be noted. For example, during use, the brake disc will be clamped to the wheel hub within the centre, held in place with two or three bolts, therefore the damping which occurs would be different compared to how it occurs in the tests in this report where it was clamped at the bottom. To improve the testing, the brake disc should have

been held in place in an identical manner to how it would be on a car.

Similarly, for a true understanding of the resonant modes, it would be useful to hold the brake disc freely. For example, hanging it from the ceiling, or using a frame construction and then using a flexible and elastic cord to hold it in place, stiff enough to hold the disc still whilst still allowing vibrations to occur. To validate the results found in this experiment, comparisons need to be made to previous published literature.

Looking at a journal paper from 2013

(Mohammed & Rahim, 2013) analysing the cause of brake disc squeal, it was found that a brake disc will vibrate around the disc in an uniform manner; similar to what was found looking at band 5 in Test 1 and bands 5, 6 and 7 in Test 2. They also found that the disc would vibrate transversely with diametral nodes, similar to band 1 in Test and Test 2.

6. CONCLUSIONS

Overall, using a Laser Doppler Vibrometer, the main harmonic resonant modes and vibration shapes for a standard automotive brake disc have been investigated. The experiment was split into two tests where the location of the solenoid actuator was changed., This provided two sets of results allowing for comparisons to be made and the most accurate location to be concluded. For Test 1 with the actuator placed on the right hand side of the disc, five harmonic resonant modes (bands) were found.

Comparing this to Test 2 where the actuator was placed centrally at the top of the disc, seven different harmonic modes were found. The peaks for both Test 1 and Test 2 are shown in Table 1. For the first five peaks in each test, they were relatively similar, showing consistency within the testing. However, when looking at the shapes created (as seen in Appendix 8.1 and 8.2) the vibration patterns were more pronounced for

Test 2. Therefore, it has been concluded that Test 2 produced more accurate results, which was likely due to the solenoid placement and the level of damping which followed. However due to the way the disc was held, the experiment would benefit from running the tests again, with the disc being held from the centre which is more comparable to how it would be held when placed on a car.

7. REFERENCES

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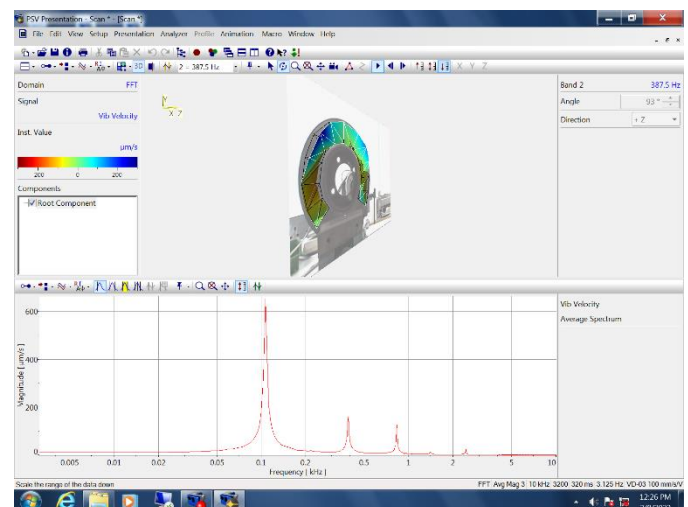
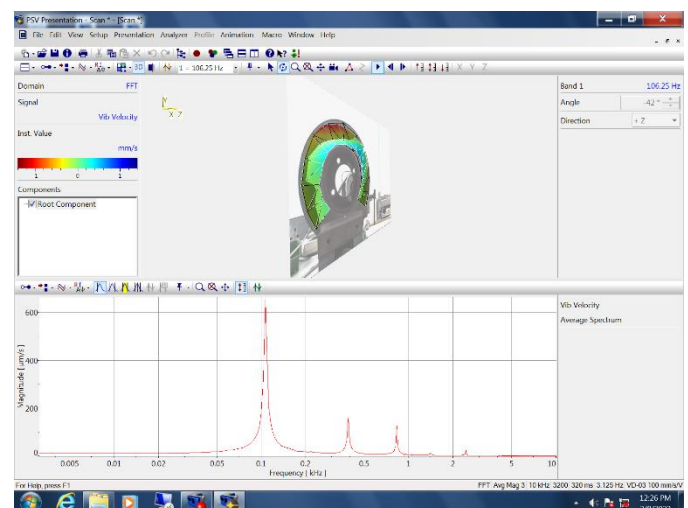
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8. APPENDIX

8.1 Harmonic Modes from Test 1



8.2 Harmonic Modes from Test 1

