

LASER DOPPLER VIBROMETER-

BRAKE DISC MODAL ANALYSIS

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1. ABSTRACT

In this experiment report, a Laser Doppler Vibrometer- brake disc modal analysis is carried out. For this, a Laser Doppler Vibrometer (LDV) is used to scan the surface of a brake disc for vibrations. The vibrations in the brake disc is generated using a solenoid actuator that is driven by the LDV function generator. The brake disc is clamped onto a mount holding it at the bottom. PSV Acquisition and PSV Presentation programmes are used to do the scanning and analysing of the brake disc. The experiment was carried out for three different bandwidth frequencies with different excitation points. The lower resonant frequency modes are similar for all the three scans but the higher resonant frequency modes for the scans at thicker inner excitation point is discovered to be higher compared to the thinner outer excitation point on the brake disc. For the same excitation point, the increase in resonant frequency modes for the scan with higher bandwidth frequency is much higher. Lastly, the scan with the lowest bandwidth frequency has very high noise and disturbance with very close resonant frequency modes.

2. APPARATUS

The apparatus used to complete this experiment were:

1. PolyTec scanning laser doppler vibrometer (LDV)
2. Solenoid actuator
3. Measuring ruler
4. Computer

3. INTRODUCTION

A laser doppler vibrometer is an instrument that emits a beam of laser on a vibrating surface in order to make non-contact vibration measurements of the surface. It extracts the parameters such as frequency and amplitude of the vibrating surface from the doppler shift in the laser beam frequency of the reflected beam which is caused by the motion of the surface. The working principle of the laser doppler vibrometer is that it divides the laser beam into two parts, a reference beam and a measurement beam. The reference beam point directly to the photodetector in the LDV while the measurement beam is incident on the vibrating object. The vibration causes the backscattered light to change in phase and frequency. This reflected light is then directed to the photodetector as well and the superposition of this light with the reference beam creates an output signal that reveals the doppler shift in frequency. As a result, this gives us the vibrational velocity and displacement of the object.

In this experiment, we aim to determine the resonant frequency modes and shapes of a brake disc using the PolyTec Scanning Laser Doppler Vibrometer (LDV).

4. LITERATURE REVIEW

Rothberg et al. (2017) discuss the laser doppler technique and use of laser doppler vibrometer and its applications and developments. They discuss the use of scanning laser doppler vibrometer for modal analysis and also its application in different fields such as structural health monitoring and MEMS, rotor vibrations etc.

MacPherson et al. (2007) emphasise on the need for measuring vibrational phase along with the vibrational amplitude to understand vibrations. They discuss a multipoint laser vibrometer that is capable of measuring 256 point simultaneously at up to 80kHz and its application on a squealing rotating disc brake.

lordache et al. (2017) discuss a braking system's modal behaviour in noise and vibration analysis. They performed finite elements analysis of the modal behaviour and validated it by experimental investigation. The resonant frequency modes obtained in the process were in the range of 1150 Hz to 2740 Hz.

Zeng et al. (1998) describe the application of non-linear regressive model for the determination of position and orientation of scanning laser doppler vibrometer with respect to a structural coordinate system for use in the automotive industry. Six parameters were used to achieve the same and the parameters were estimated using least-square technique.

Batel (2008) explains the use of laser doppler vibrometer and the methodologies used by automotive NVH test & CAE engineers for better noise and vibration quality with mass reduction constraints. They also discuss a new laser scanning technique with high precision and rapidity that uses a 3D robot.

Schell et al. (2006) discuss the use of a 3D scanning LDV with three different scanning LDV measurement heads. The different measurement heads measure the vibration at a point from three different directions simultaneously. They used this to measure vibrations in the full car body and compared the results obtained to finite element data.

Johansmann et al. (2011) discuss the use of a scanning LDV for automotive parts in a rotating coordinate system by using a derotator. This is used on an object with a rotating optical unit in order to achieve a stationary image of the object. In this paper, the authors measure the Operational Deflection Shape (ODS) of a rotating disc with and without derotator, to analyze the differences in results.

5. PROCEDURE

Firstly, the brake disc whose resonant frequency modes and shapes to be determined is clamped properly onto a mount along with the solenoid actuator as shown in Fig. 1. The PolyTec Scanning Laser Doppler Vibrometer (LDV) is then placed in front of the brake disc. The same is shown in Fig. 2. When in front of the laser doppler vibrometer, it is important to remember that the shutter should always be placed in front of the LDV as looking directly into the laser beam may cause permanent damage to the eyes. Once the setup is done, the distance between the LDV and the brake disc is measured.

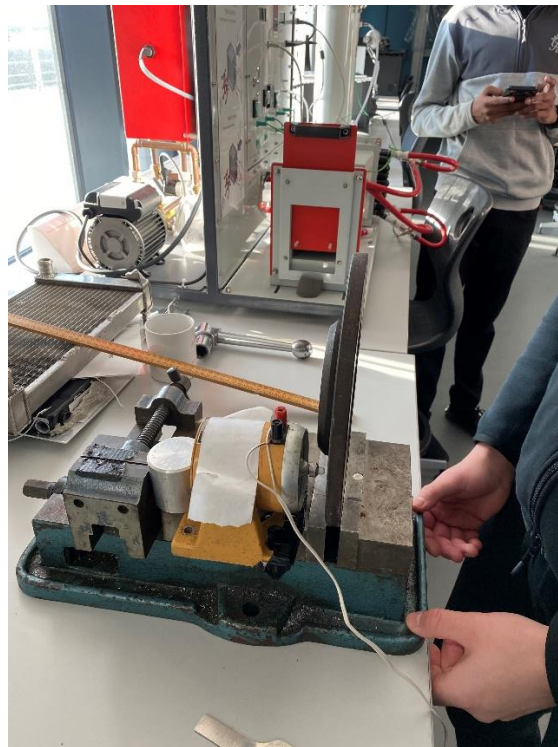


Fig. 1: Brake Disc Clamped with the Solenoid Actuator



Fig. 2: PolyTec Scanning Laser Doppler Vibrometer Placed in Front of the Brake Disc

Next, moving on to the computer, there are two applications that need to be used here, namely, PSV Acquisition and PSV Presentation. The PSV Acquisition application is used to set up and perform the analysis. The PSV Presentation application is used to carry out the modal analysis once the data has been acquired.

Once the PSV Acquisition application is started, settings is opened from the acquisition menu. This allows us to select and set up the system parameters such as measurement mode, frequency bandwidth, trigger source etc. The following are the settings used for undertaking the modal analysis.

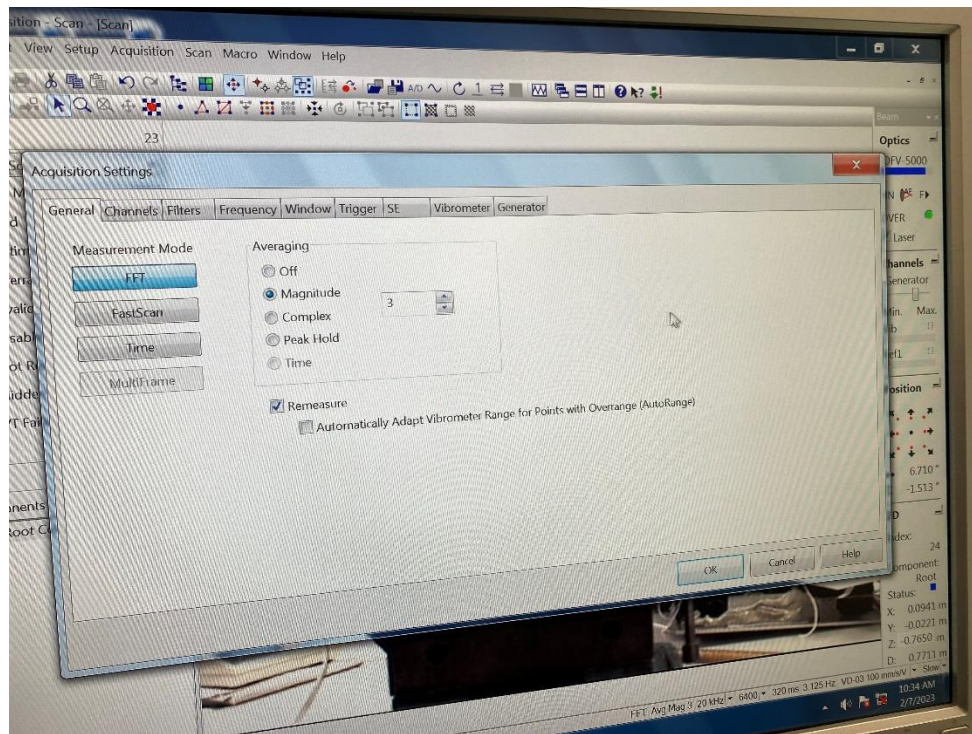


Fig. 3: Acquisition Settings- General

In general, the measuring mode is set to FFT with averaging magnitude of 3, as shown in Fig.

3.

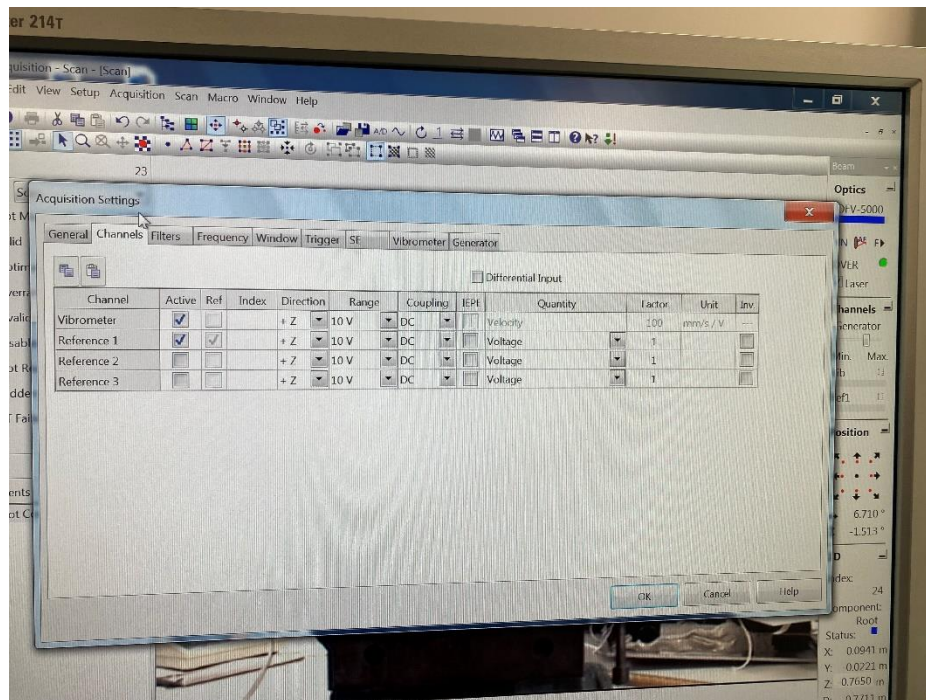


Fig. 4: Acquisition Settings- Channels

Fig. 4 shows the channels vibrometer and reference 1 being active.

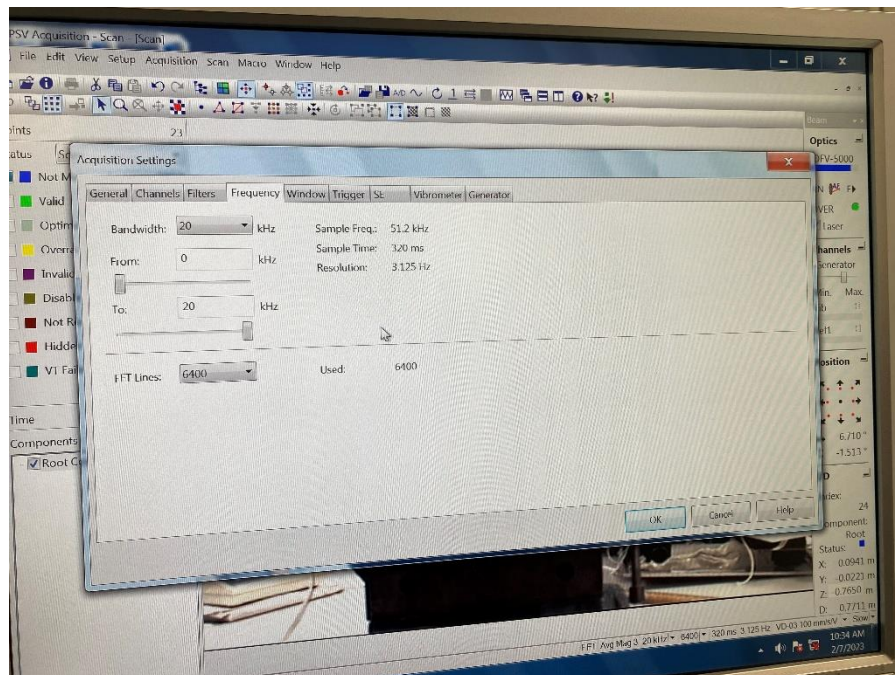


Fig. 5: Acquisition Settings- Frequency

Fig. 5 shows the FFT lines set to 6400 and the frequency bandwidth from 0 to 20 kHz. This experiment was carried out with three different frequency bandwidth, the details of which are mentioned later below.

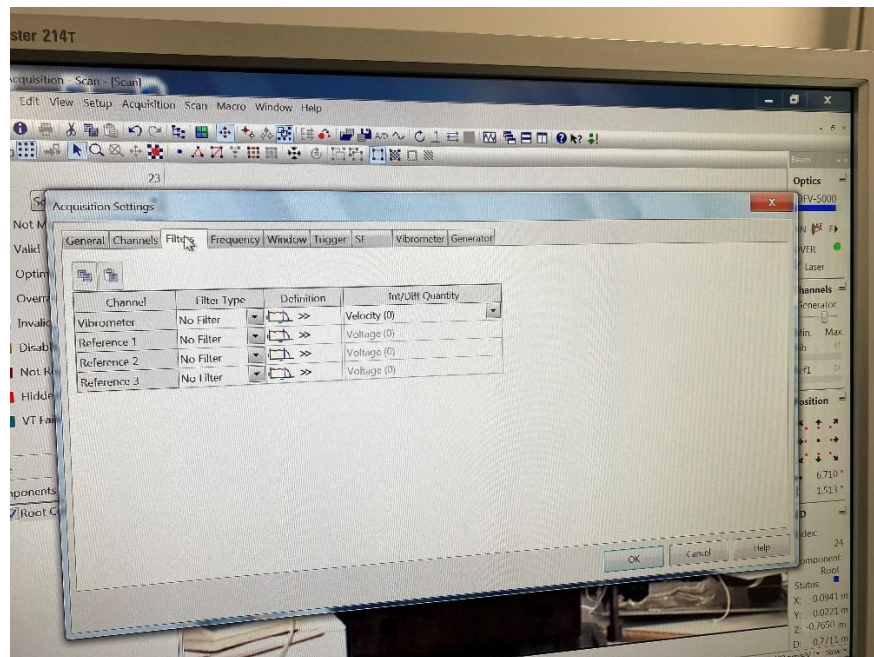


Fig. 6: Acquisition Settings- Filters

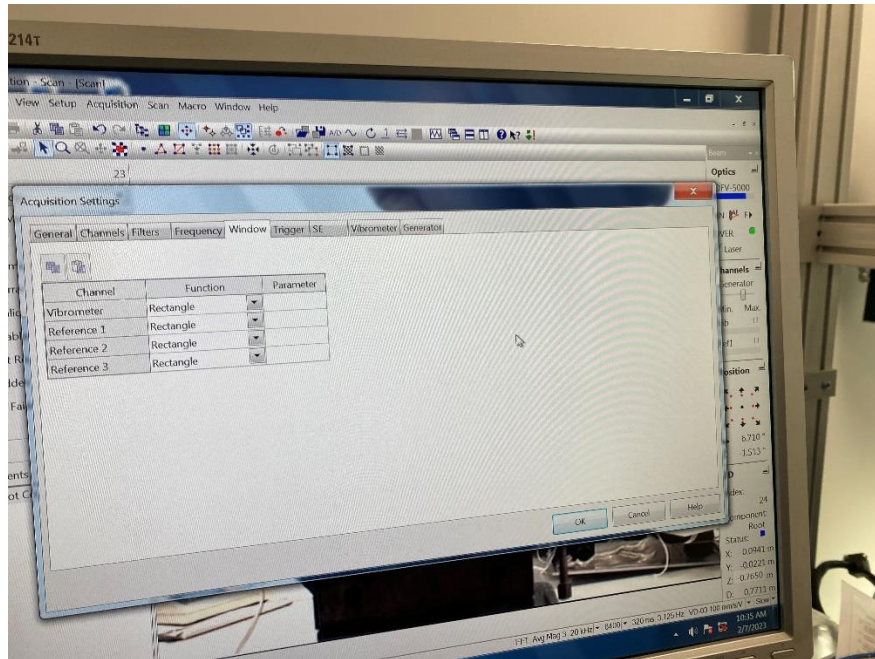


Fig. 7: Acquisition Settings- Windows

The filters are set to no filter and functions are set to rectangle, as shown in Fig.6 and Fig. 7 respectively.

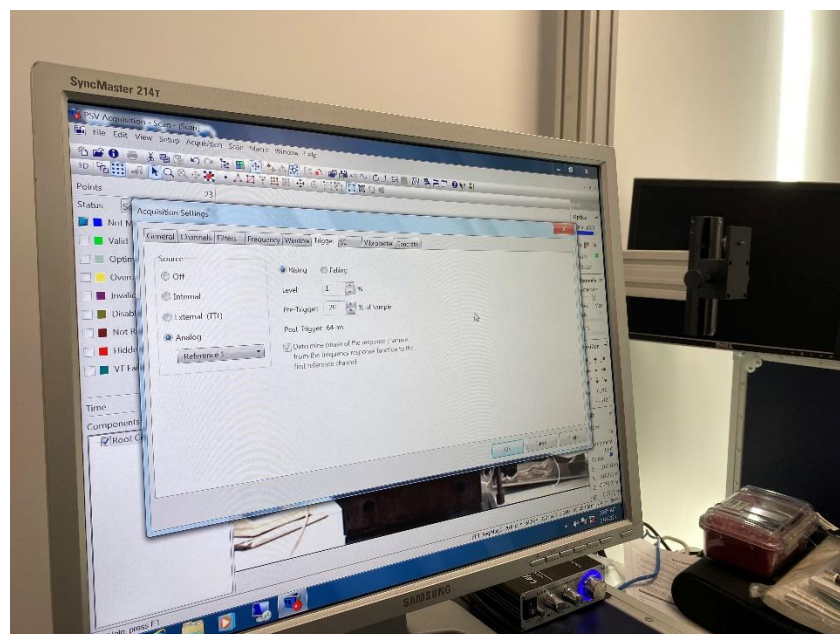


Fig. 8: Acquisition Settings- Trigger

In the trigger section, the source is set to analog and reference 1 along with rising, level 1% and pre-trigger of -20% of sample, as shown in Fig. 8.

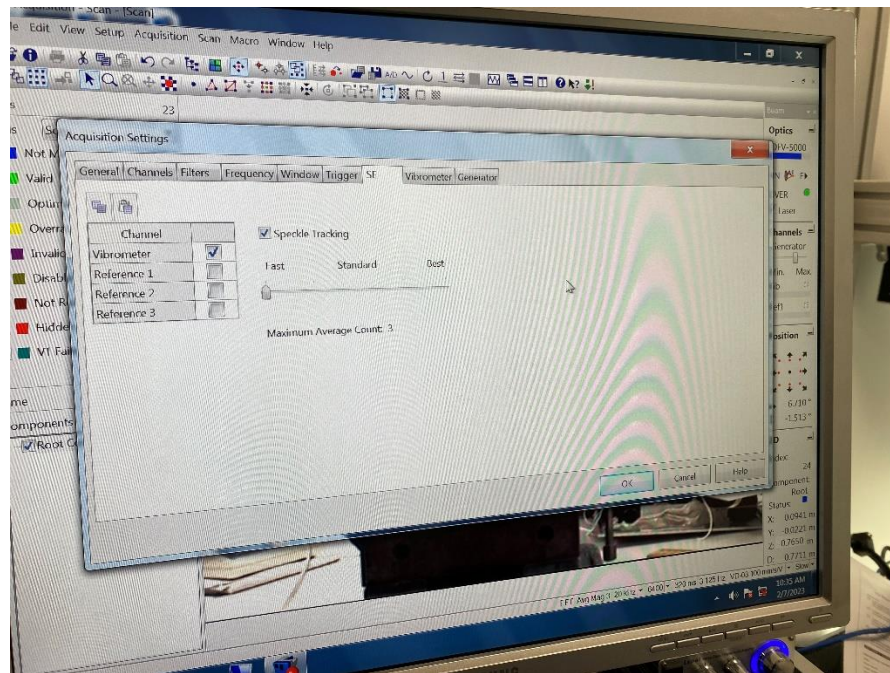


Fig. 9: Acquisition Settings- SE

Fig. 9 shows channel set to vibrometer along with speckle tracking on and fast setting.

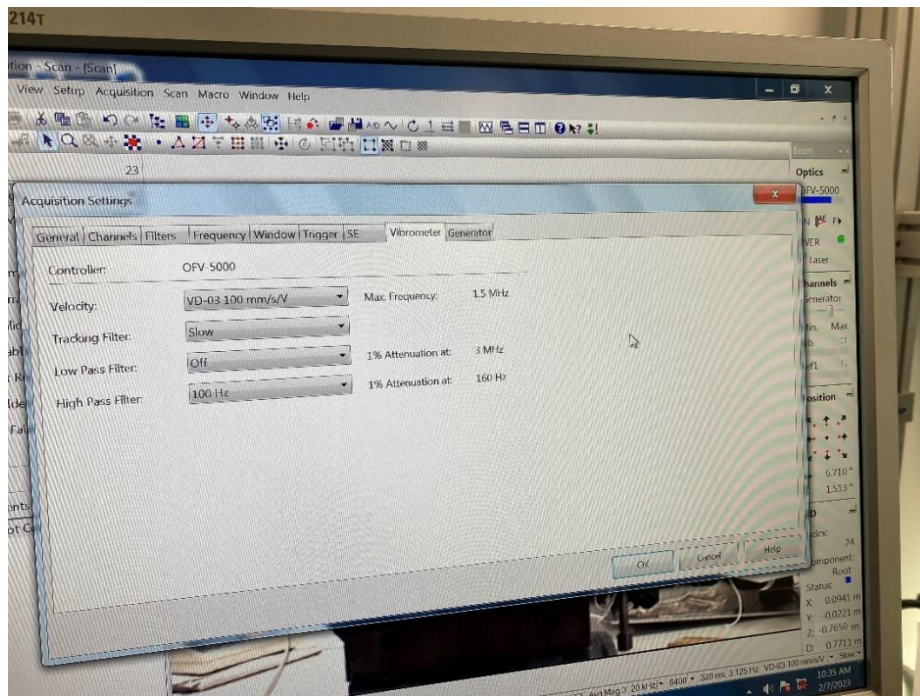


Fig. 10: Acquisition Settings- Vibrometer

Fig. 10 shows velocity, tracking filter, low pass filter and high pass filter set to VD-03 100 mm/s/V, slow, off and 100 Hz respectively.

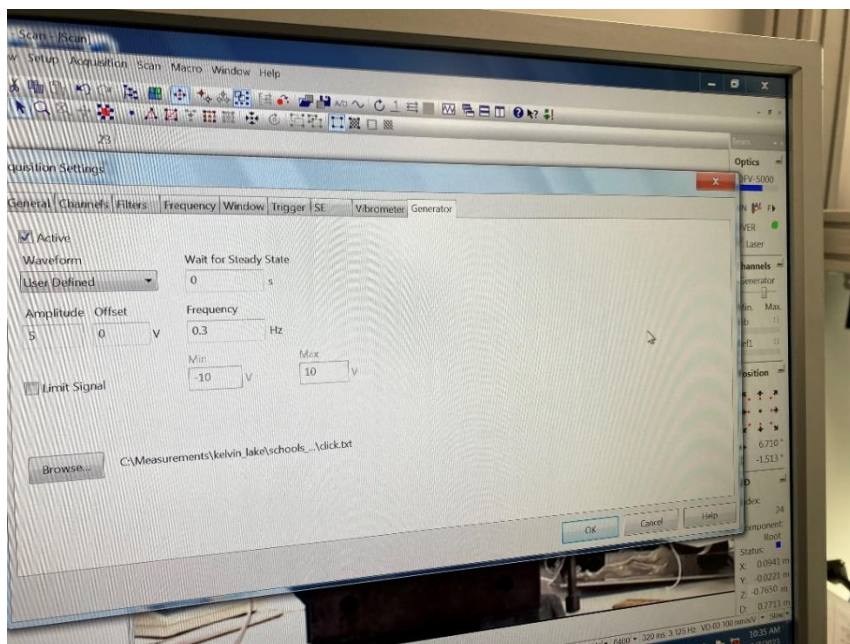


Fig. 11: Acquisition Settings- Generator

Lastly, fig. 11 shows the active box checked, waveform set to user defined, wait for steady state at 0 s, amplitude and offset at 5 V and 0 V and frequency at 0.3 Hz. The generator output is defined by the text file shown at the bottom.

The next step is to set up a 2-D alignment of the scanning head. For this, the 2-D alignment menu is opened up from the setup menu. Once it is opened up, there might be predefined alignment points already. These predefined points are then deleted.

Next, it is checked if there is a signal being indicated on the optics beam window. If the signal is detected, the autofocus button is clicked for the laser to be able to focus on the brake disc.

Once the laser focuses, the distance between the scanning head and the brake disc, which is defined by z , is specified under the 2D section of the beam window. For this experiment, the value of z was set to 0.77 m.

The next step is to define the alignment points. There are two ways to do this. It can either be done by using the position arrows to move the laser which can be found under the beam window or by directly dragging the laser to the parts of the brake disc where we want to place the alignment points. After positioning the laser, the point must be clicked every time to define the point. This is done to create multiple points which are necessary to perform the 2D LDV scan.

Next, the scan points are defined. This is done by using the triangular mesh option to create the required mesh. A picture of the same can be seen in Fig. 12 below.

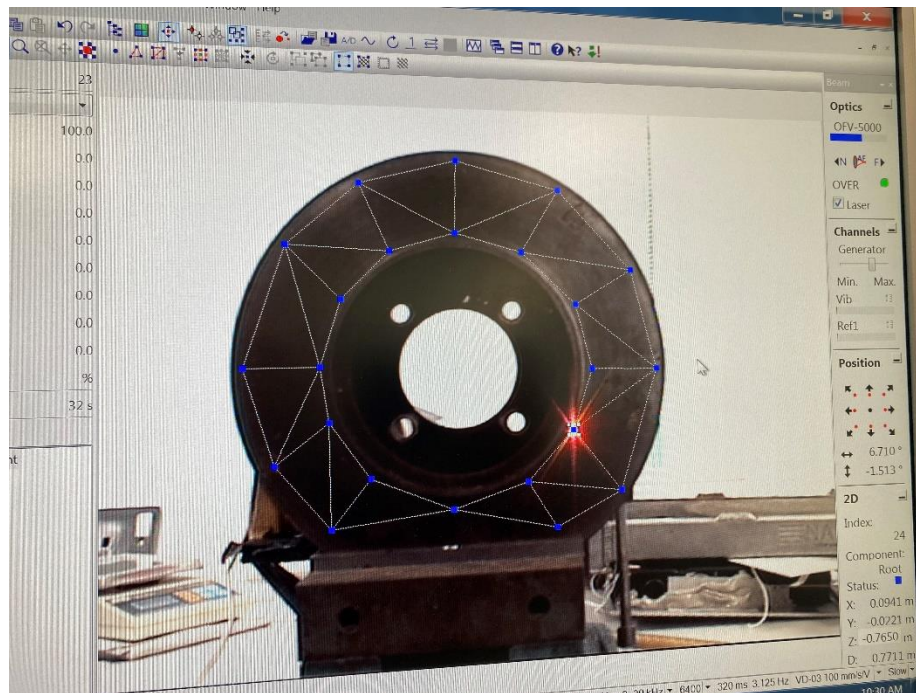


Fig. 12: Defining the 2D Scan Points and Generating the Mesh

Lastly, before undertaking the scan, the type of analysis display needs to be chosen under the analyzer window. The most commonly used options are time and FFT. Here, we use the FFT option.

Finally, the scan is started by clicking the scan button under the acquisition menu or pressing the F9 key. Upon doing this, we are prompted with a save as file name option. This saved file is used to define the results file that is generated after the scan is completed.

Once the scanning process begins, the scanning points turn green one by one which defines that the points were accepted. Once the data is collected from all the scan points and all the points turn green, the scan is completed.

This is where the use of PSV Acquisition application ends. Next, in order to analyse the scan results, the PSV Presentation application is used.

To open a scan result file, the file menu is used which contains a set of recent scan files.

Once the file opens, it shows a mode shape based upon the entire bandwidth on the default analysis window.

The next step is to specify the frequency bands. This can be done by opening up the frequency bands option from the setup menu. This gives us a graph of magnitude of velocity in m/s vs frequency in Hz. But the magnitude of velocity is in order of micrometres per second. Hence the graph appears to be one flat line. With is rectified by right clicking the mouse over the vertical axis of the graph and choosing the auto scale option of the vertical axis of the analyser display. The same can is shown below in Fig. 13.

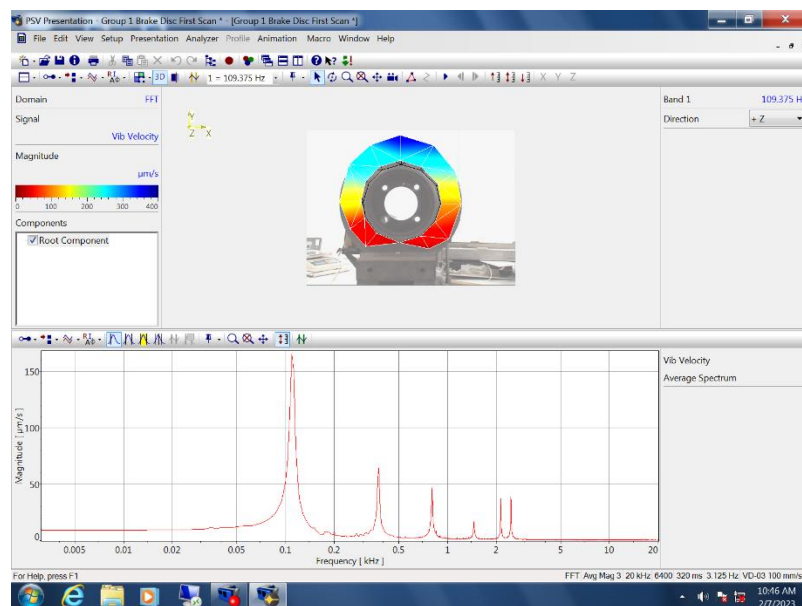


Fig. 13: General Frequency Page

Next, the relevant bands of peaks in the frequency domain are chosen using the select bands icon, that allows to highlight the desired areas of the band. This is done by clicking and

dragging over each peak. Upon selecting each band, they are highlighted and listed in the frequency band definition table as shown in Fig. 14.

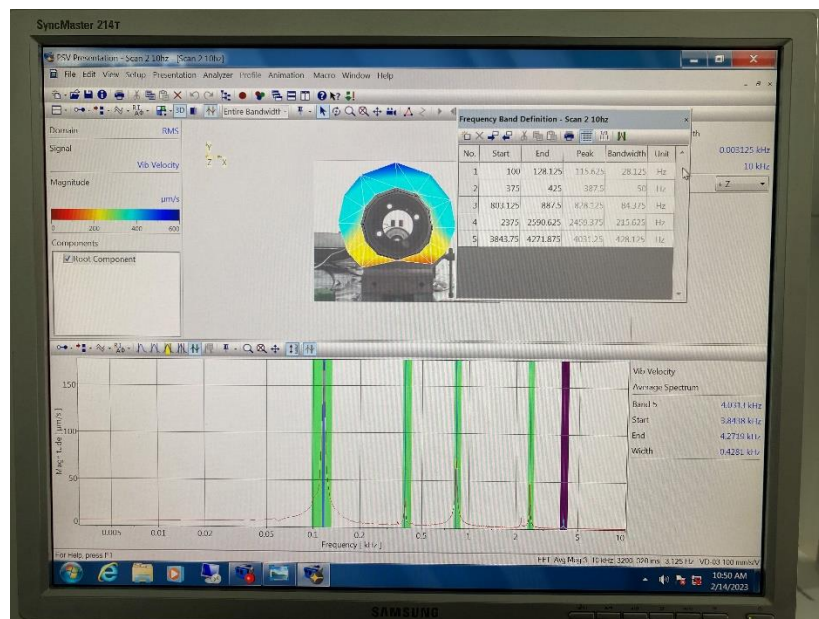


Fig. 14: Highlighted and Listed Frequency Bands

To complete the frequency band selection, the select bands option is clicked again. This results to give a prompt saying recalculate frequency bands, where the yes option is chosen. Lastly, now each frequency band can be seen individually to view the resulting vibration modes. For each frequency band, the start/stop animation button can be used to visualise the vibration of the object. The rotate button can also be used to rotate the image of the vibration for better visualisation.

This experiment was carried out three times. For the first scan, the solenoid actuator was positioned to hit the brake disc at the thinner outer part, as shown in Fig. 1. For this, the frequency bandwidth was set to 20 kHz. For the second and the third scans, the solenoid

actuator was positioned to hit the brake disc at the thicker inner part, as visible through the brake disc in Fig. 14. The frequency bandwidths for the latter two scans were set to 5 kHz and 10 kHz, as shown in Table 1.

Table 1: Frequency Bandwidth for Each Scan

SCAN	FREQUENCY BANDWIDTH
Scan 1	20 kHz
Scan 2	50 kHz
Scan 3	10 kHz

6. CALCULATIONS, ERROR ESTIMATES AND LIMITATIONS

6.1 Calculations

Since the entire experiment was completely software aided, there are no calculation to be done specifically. All the calculations are done directly in the PSV Acquisition. Here, the data acquired from the laser is in the form of time based response, as shown in Fig. 15 below. By using fourier transform, the time based response is converted to frequency based response. That being said, there was one measurement that was needed to be carried out, i.e., the distance between the laser doppler vibrometer head and the brake disc. This was calculated to be 0.77m.

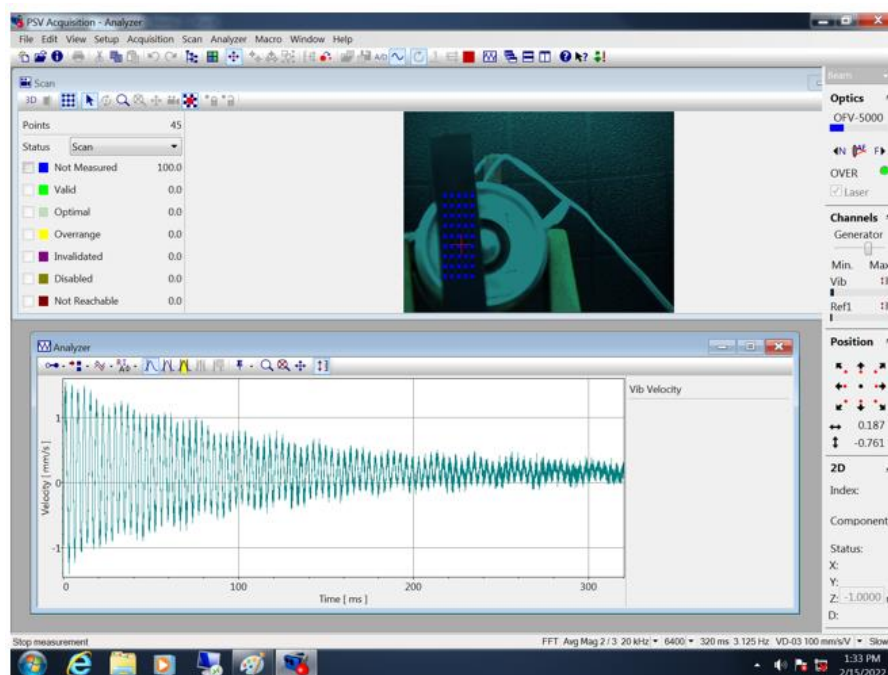


Fig. 15: Graph of Time based Response (Structural Integrity and Material Evaluation Module, 2022-23)

6.2 Errors Estimates and Limitations

While trying to scan a brake disc using a PolyTec Scanning Laser Doppler Vibrometer, there might be multiple sources of error. Most of them are very likely to be human errors. Firstly, there might be error in measuring the distance between the laser doppler vibrometer head and the brake disc. There might also be error in fastening the brake disc to the clamp mount. If the brake disc is not mounted tightly enough, it might result to give higher vibrations and hence different results to what could be normally expected. Also, the solenoid actuator might not be close enough to the brake disc or might not be hitting the brake disc hard enough to obtain the necessary frequency modes.

Also, the first scan was carried out on a separate day compared to the second and third scans. As a result, the brake disc was removed from the clamp after the first scan and remounted for the latter two scans. Even though there were efforts to replicate the exact same position of the brake disc on the mount, it is highly likely that there were some minute variation in its position. Not only that, in the real world, the brake disc would be mounted on the axle centrally and all the vibrations it experiences would travel through the axle. So, clamping it would not give the appropriate modal analysis compared to how the brake disc would respond during actual use.

There might also be error during choosing the alignment point positions. Since we always want to attain the vibratory motion of the entire brake disc during the scan, the alignment points are usually placed very close to the edges of the brake disc. It is possible to while trying to get close to the edge, some points might be placed right on the edge, not giving us the desired results as a result.

7. RESULTS AND DISCUSSIONS

After all the scans are completed, the frequency modes obtained for each scan are shown in Table 2.

Table 2: Frequency Modes

Scan 1 (20 kHz)	Scan 2 (5 kHz)	Scan 3 (10 kHz)
109.375 Hz	100 Hz	115.625 Hz
375 Hz	115.625 Hz	387.5 Hz
803.125 Hz	200 Hz	828.125 Hz
1456.25 Hz	250 Hz	2459.375 Hz
2134.375 Hz	300 Hz	4013.25 Hz
2465.625 Hz	350 Hz	-
-	851.5625 Hz	-

The animation stills from Scan 1 are shown in Fig. 16.

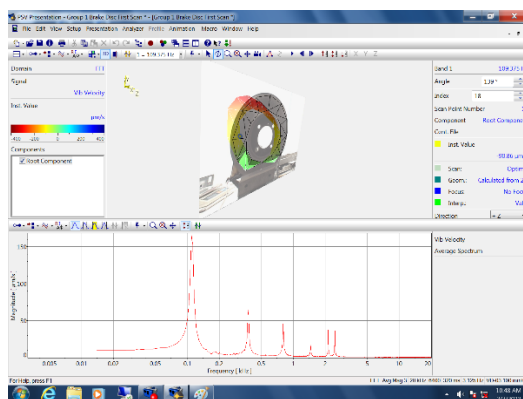


Fig. 16 (a) 109.375 Hz

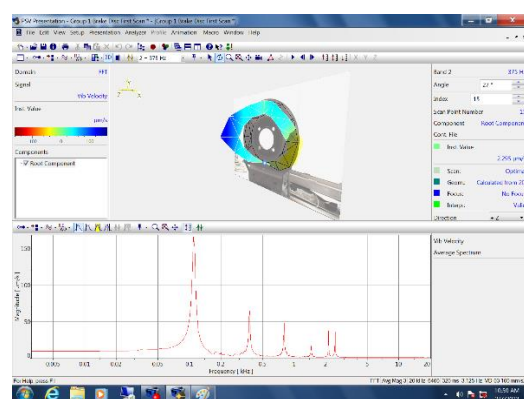


Fig. 16 (b) 375 Hz

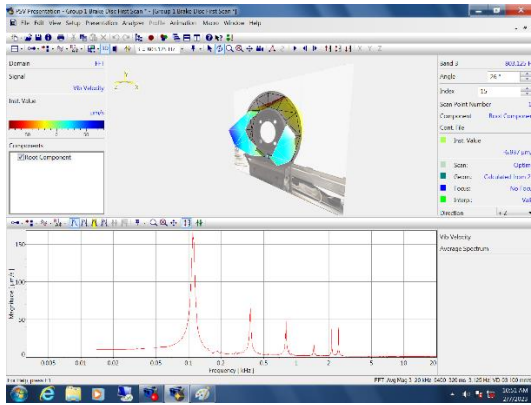


Fig. 16 (c) 803.125 Hz

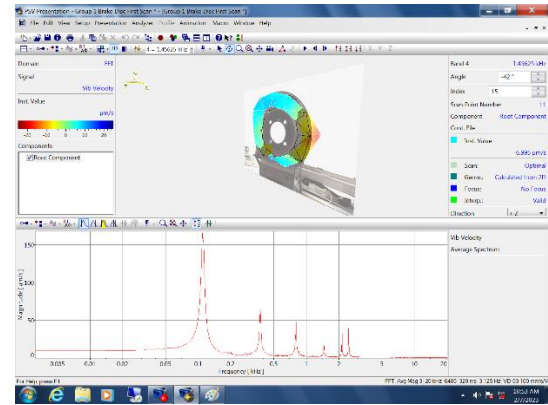


Fig. 16 (d) 1456.25 Hz

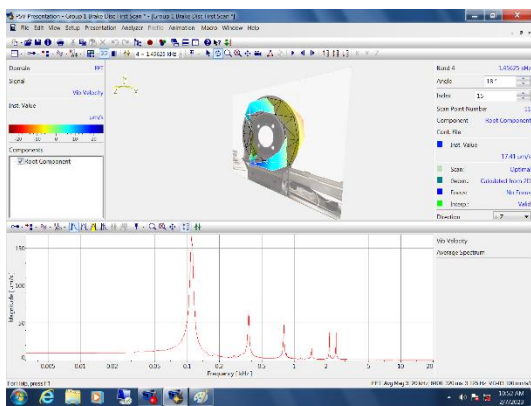


Fig. 16 (e) 2134.375 Hz

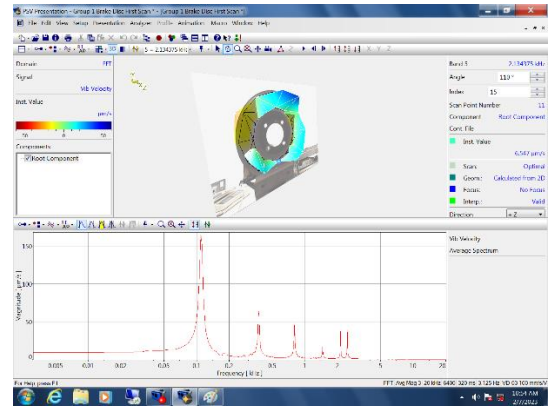


Fig. 16 (f) 2465.625 Hz

The animation stills from Scan 2 are shown in Fig. 17.

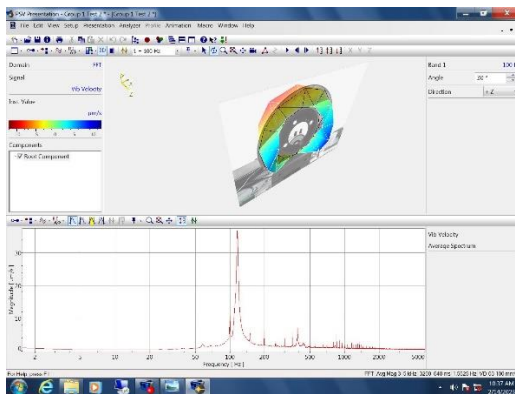


Fig. 17 (a) 100 Hz

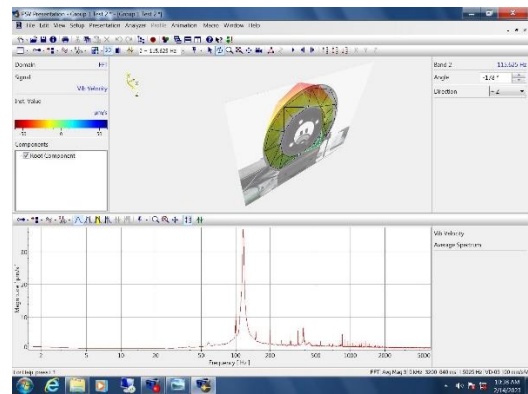


Fig. 17 (b) 115.625 Hz

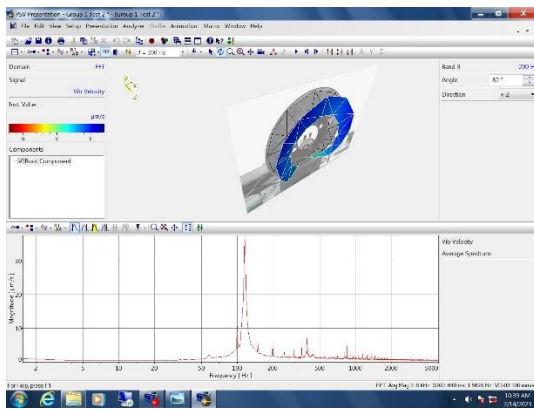


Fig. 17 (c) 200 Hz

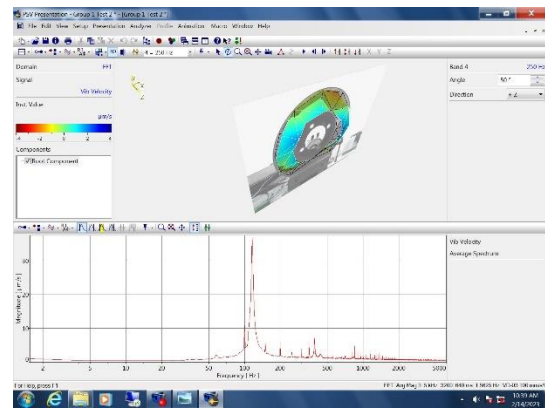


Fig. 17 (d) 250 Hz

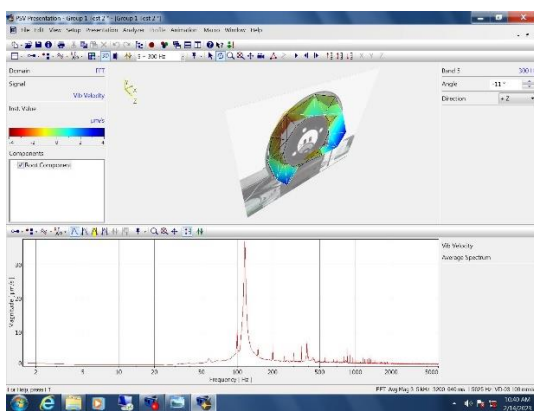


Fig. 17 (e) 300 Hz

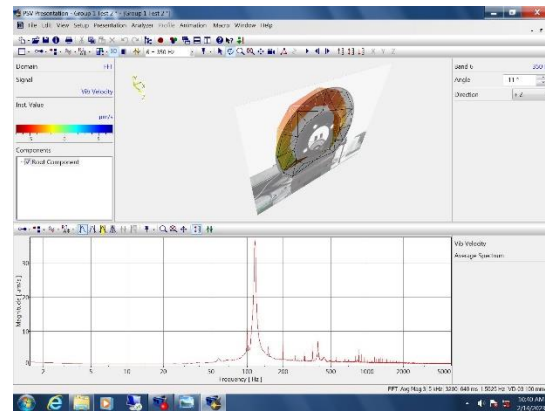


Fig. 17 (f) 350 Hz

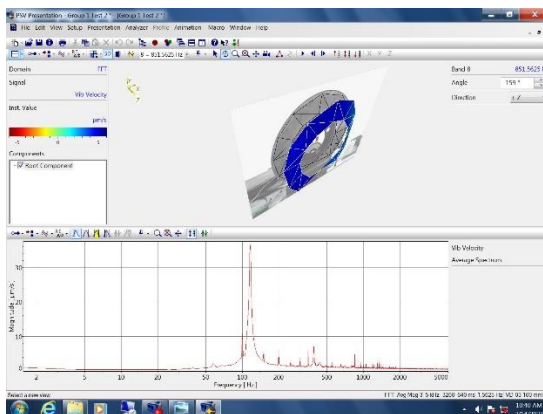


Fig. 17 (g) 851.5625 Hz

The animation stills from Scan 3 are shown in Fig. 18.

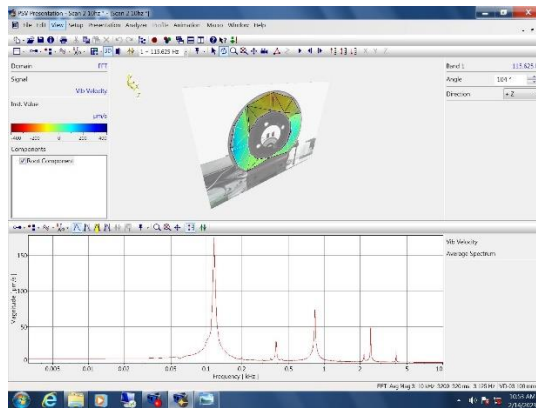


Fig. 18 (a) 115.625 Hz

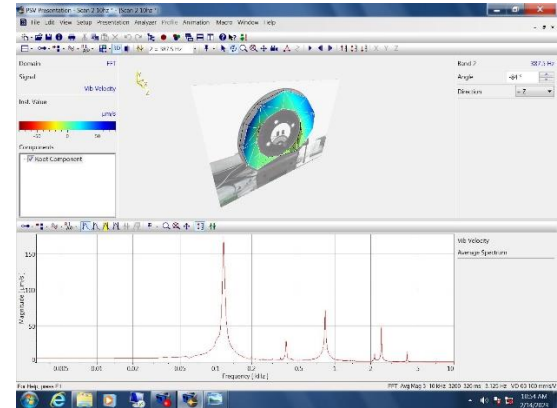


Fig. 18 (b) 387.5 Hz

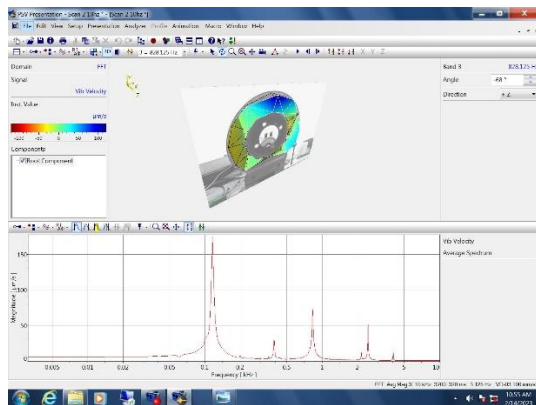


Fig. 18 (c) 828.125 Hz

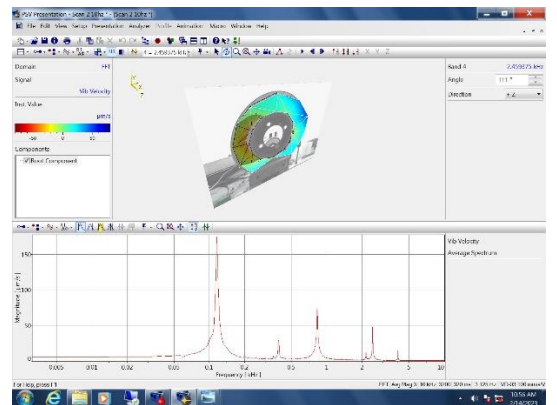


Fig. 18 (d) 2459.375 Hz

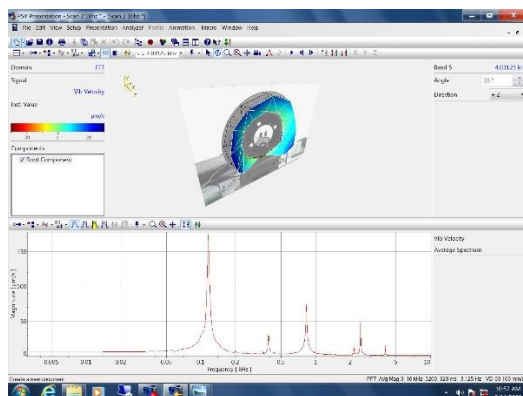


Fig. 18 (e) 4013.25 Hz

The first thing that can be observed from Table 2 is that Scan 2 with a low frequency bandwidth of 5 kHz has much more noise, giving repeatedly close peaks as visible in Fig. 17 (a)-(g).

At the lower frequency modes, the values for all the three scans are very similar. But as we move to higher frequency modes of around 800-900 Hz, it is observed that Scan 1 has the lowest frequency mode of 803.125 Hz compared to 828.125 Hz and 851.5625 Hz even though it has the highest frequency bandwidth. The reason for this can be that for Scan 1 the solenoid actuator taps the thinner outer part of the brake disc compared to the thicker inner part in Scan 2 and Scan 3.

Lastly, when comparing Scan 1 and Scan 3, it can be seen that the increase in consecutive frequency modes in Scan 3 is much higher compared to that of Scan 1.

8. CONCLUSIONS

In this experiment, we monitored and determined the resonant frequency modes and shapes of a brake disc. For this, we used a PolyTec Scanning Laser Doppler Vibrometer (LDV) and a solenoid actuator as the excitation source, that is driven from the LDV function generator. The experiment was carried out three times for different excitation points and bandwidth frequencies. Scan 1 was carried out with a bandwidth frequency of 20 kHz and the excitation point was on the thinner outer part of the brake disc. Scan 2 and Scan 3 were carried out on the thicker inner part of the brake disc and had bandwidth frequencies of 5 kHz and 10 kHz respectively. Upon completing the scans, it was discovered that Scan 2 with the lowest bandwidth frequency has a lot of noise and disturbance with very close resonant frequency modes. The lower resonant frequency modes were similar for all the three scans but the higher resonant frequency modes for the scans at thicker inner excitation point was discovered to be higher compared to the thinner outer excitation point on the brake disc. Also, when comparing the scans with the same excitation point, the increase in resonant frequency modes for the scan with higher bandwidth frequency was much higher.

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