



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

Laser Doppler Vibrometer -Brake Disc Modal Analysis

ACEA0713: Structural Integrity & Material Evaluation

MSc Automotive Engineering

Lecturer: Peter Charlton

Student: 2109787 (J V. Navadiya)

Date: 12 March 2023



Abstract

This report presents a study on use of Laser Doppler Vibrometer to modal analysis of brake disc. Brake vibrations are common issues in the automotive braking system, and understanding the vibrations of brake is important for improving performance, reducing wear and tear and noise during braking. In this study, the resonance frequency of a brake disc was determined using laser doppler vibrometer (LDV), which is non-contact technique for measure vibration velocity and displacement at a specific point on the surface. The brake disk is clamped on bench vise and use a solenoid actuator driven from the LDV function generator to disturb a brake disc. Due to disturbance, a brake disc vibrates, and scanner scan the reflected laser beam from a brake disc. From reflected laser beam, multiple frequencies of the higher vibration can be obtained. Magnitude of vibration velocity and displacement and behavior of a brake disc can be predicted by analyzing the different obtained frequencies.

Content

1. Apparatus.....	4
2. Introduction.....	6
2.1 Application of laser doppler vibrometer in automotive.....	6
3. Working principle.....	7
4. Experiment set-up.....	9
5. Methodology.....	10
6. Graph.....	12
7. Result and Discussion.....	15
8. Conclusion.....	15
9. Bibliography.....	16

1. Apparatus

Junction Box

The Junction Box is shown in the *figure 1*. This device is used in conjunction with Polytec Scanning Laser Doppler Vibrometers to enable the acquisition of simultaneous and synchronized data from multiple LDV heads.



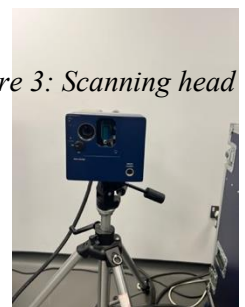
Velocity Controller

The velocity controller is shown in the *figure 2*. This system is used to control and synchronize the movement of the scanning mirrors in the LDV heads. The controller allows the LDV head to scan the laser beams over a surface, measuring the vibration at each point to build up a complete picture of the object's vibration behavior.



Scanning head

The scanning head shown in *figure 3*. It contains a two-axis galvanometer scanning mirror that scans the laser beam over the target surface, allowing the measurement of vibration at multiple points on the surface.



Solenoid Actuator Controller

A solenoid actuator controller is a device used to control the operation of solenoid actuators, which are electromechanical devices used to produce linear or rotary motion by converting electrical energy into mechanical energy.

Solenoid Actuator

A solenoid actuator is shown in *figure 4*. It creates a hit generated by the generator every finite second that can be set manually on PSV acquisition software where an analog signal is transferred.



Figure 4: Solenoid actuator with a brake disc

Brake Disc

An automotive brake disc is an experimental component which natural frequency is measured in this experiment. A brake disc is shown in the *figure 4*.

The schematic diagram of all these components is shown in the *figure 5*. The experimental set up of these components are shown in the *figure 6*.

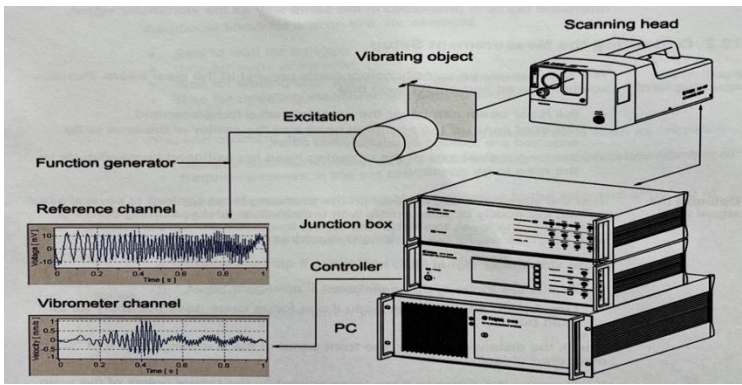


Figure 5: Schematic diagram for data measuring equipment setup

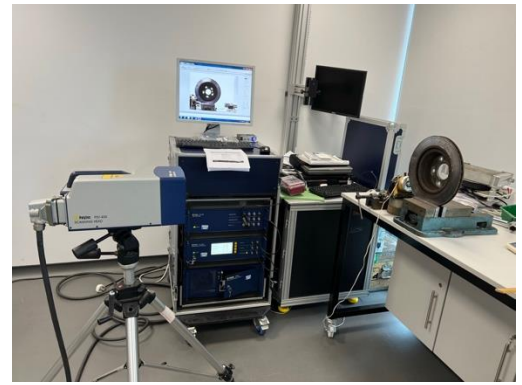


Figure 6: Experimental setup of LDV components

2. Introduction

Laser Doppler vibrometer (LDV) is a non-contact measurement technique with ability to measure vibration without contacting the surface being measured. LDV is based on the Doppler effect, which is the shift in frequency of light waves that occurs when the source of the waves is moving relative to the observer. In LDV, a laser beam is directed at the surface being measured, and the motion of the surface causes the laser light to be shifted in frequency. This shift in frequency is measured by a detector and used to calculate the velocity of the surface vibration. Modal analysis is a technique used to determine the natural frequencies and mode shapes of a structure. In brake disc modal analysis, the natural frequencies of the brake disc are determined by measuring the vibration frequencies using laser Doppler vibrometer, which is a non-contact technique for measuring vibration velocities at a specific point on a surface. *Li et al. (2019)* highlighted the advantages of LDV over traditional contact-based techniques, such as accelerometers, including the ability to measure vibration without contacting the surface, and the ability to measure both in-plane and out-of-plane motion.

2.1 Application of laser doppler vibrometer in automotive

Demanding tasks such as automotive parts and bodies vibration measured by laser doppler vibrometer. This method is very precious and used optical transducer to measure displacement and velocity at a point by frequency shift and phase variation of back scattered laser beam from vibrating object. *Pagano et al. (2015)*

used LDV to measure the vibration characteristics of the swingarm to determine its natural frequencies and mode shapes. The authors found that LDV was an effective technique for measuring the vibration of the swingarm and that the measured results were in good agreement with those obtained using traditional contact-based measurement techniques. The authors also noted that the use of carbon fiber reinforced polymer (CFRP) in the swingarm resulted in a significant increase in the natural frequencies compared to a swingarm made of aluminum. This increase in natural frequencies can improve the dynamic behavior of the motorcycle and enhance its performance. *Karadogan et al. (2021)* used LDV to perform modal analysis on a vehicle's suspension system. They found that LDV was an effective technique for measuring the vibration of the suspension system and identifying its natural frequencies. The results of the study can help improve the performance and ride comfort of the vehicle. In a study by *Kang et al. (2020)*, LDV was used to measure the vibration characteristics of an engine mount system. The authors found that LDV was an accurate and reliable technique for measuring the dynamic behavior of the engine mount system, which can help improve the durability and noise, vibration, and harshness (NVH) characteristics of the vehicle. In another study, *Yu et al. (2020)* used LDV to measure the vibration characteristics of a tire and wheel assembly in a vehicle. The authors found that LDV was an effective technique for measuring the dynamic behavior of the tire and wheel assembly, which can help improve the handling and ride comfort of the vehicle.

Overall, the literature suggests that LDV is a valuable technique for measuring the vibration characteristics of various components in vehicles, including suspension systems, engine mounts, brake systems, body, and tire and wheel assemblies. LDV can help improve the performance, durability, and NVH characteristics of vehicles.

3. Working principle.

Laser Doppler Vibrometer (LDV) is working on principle of Doppler Effect. When a laser beam is traveled towards vibrating or say moving object which we want to examine, laser beam will reflect by this object. Due to the subject vibrating, the frequency of reflected beam will be change due to displacement of the object. This

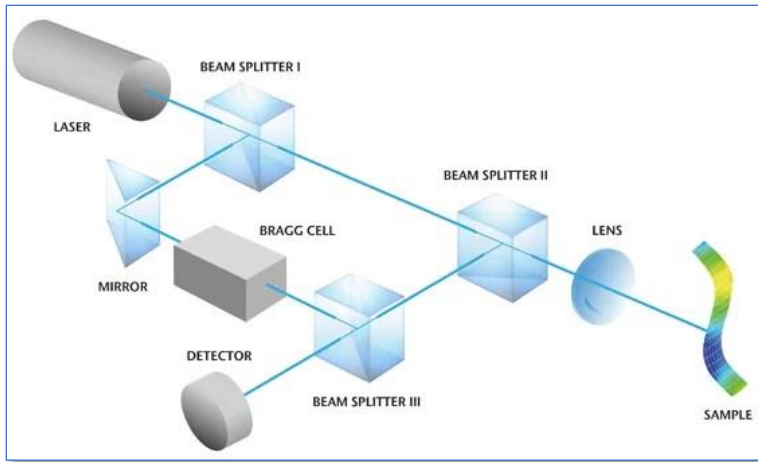


Figure 7: Working principle of Laser Doppler Vibrometer (AZO sensors)

induced beam is linearly proportional to the velocity component in the laser beam direction. The frequency of the reflected laser beam is very small compared to the laser fundamental frequency, typically 1 part out of 10⁸ (Esposito, E. 2014). So, the only way to eliminate such a small quantity is to use interferometer, which combines high frequency called base frequency to

the reflected frequency from the workpiece.

The laser light from the laser source split into reference beam and measured beam by the beam splitter 1. Then measured beam from beam splitter 1 passes through beam splitter 2 and finally through focal lens and impact on the vibrating surface. After impacting, this reflected beam passes through beam splitter 2, where it diverts the beam to the beam splitter 3. Beam splitter 3 combine measured beam with reference beam and finally passes through photo detector where optical signal converts into electrical signal. Vibrometer usually used He-Ne lasers, so we have doppler shift frequency about 3.18 kHz for each mm/s. The output signal at the operational amplifier is given by equation (1),

$$s(t) \propto A^2 \cos(2\pi f_D t) \dots \dots \dots (1)$$

where A is the amplitude of the laser beam.

We also know that frequency of the reflected beam is directly proportional to the displacement rate or velocity of vibrating surface. So, the wave's measured frequency shift can be expressed by the question (2).

$$\Delta f_D = \frac{2v}{\lambda} \dots \dots \dots (2)$$

Where, v is velocity of object,

λ is wavelength of emitted wave.

The significant limitation of laser doppler vibrometer is that it can only measure the response at one point at a time. For the small size object, it will be considerable but for the very large components like automobile bodies, ships engines, plane parts, buildings it will take much longer to scan. So, for the large size bodies components this method is time consuming. The other limitation of the LDV is that the shining surface may be less accurate because the shining surface scattered the laser beam and gives weak reflection of the laser beam.

4. Experimental setup

A typical experimental set up and main components for the Laser Doppler Vibrometer (LDV) PSV is shown in *figure (7)*.

- An Excitation will produce vibrations in an object.
- A measuring beam from the interferometer in a scanning head is positioned on an object through mirrors and it reflects to a scanning head.
- The backscattered laser beam will interfere with reference light beam in a scanning head.
- A photo decoder will record the interference.
- The decoder in a controller will generate voltage which is proportional to velocity of a vibrating object.
- The voltage is then digitized and converted into signal form and shown on a screen.

A disc brake mounted on a fixed bench wise and used solenoid actuator driven from the LDV function generator excitation for produce vibrations in a disc brake. A distance between a disc brake and a scanning head is 110 cm (about 3.61 ft) fixed throughout the experiment. An experiment disc brake and solenoid actuator are set up as shown in *Figure 4*.

In this experiment a actuator gives periodic jerks to a brake and a brake will vibrate. The laser scanning system generates a laser light beam and hits the front surface of a brake. A brake reflects a laser light beam and records on the interferometer in a laser scanning device. Interferometers generate voltage proportional to the velocity

and displacement of a disk brake and decode this signal into digital signal. The output of this experiment is a displacement v/s frequency graph which gives visual effect as well as graphical representation.

5. Methodology

This experiment used two different software namely PSV Acquisition and PSV presentation. PAV acquisition is used to set up the exam like set up the laser, object set up, excitation on off. On the other hand, PSV presentation allows us to present the analysis on the base of data which acquired from the Acquisition software. This software shows graphical and animation presentation.

To perform this experiment there are five steps through which we need to pass.

- Acquisition setting
- 2D alignment
- Grid definition
- Assign focus values
- measurement

An experiment started with Acquisition software. First, needed to set the acquisition setting.

In acquisition setting, only needed to change in **general**. Used FFT measurement mode so that can get results in form of frequencies. In averaging box, chose magnitude because we were only interested in this experiment is displacement of the disk during vibration. Used an average number as 3, higher values can take more time to scan. Remeasure box was ticked ON, which helps software to increase average point values if signal is not strong enough. All other remaining setting sections are same as inbuilt and no needed to any changes.

The second step is to set up 2D alignment using 2D alignment tool under SETUP. Chose 14 2D alignment points at same distance on the disk. These points will define a plane. 2D alignment point selection shown in the *figure 8*.



Figure 8: 2D surface define.

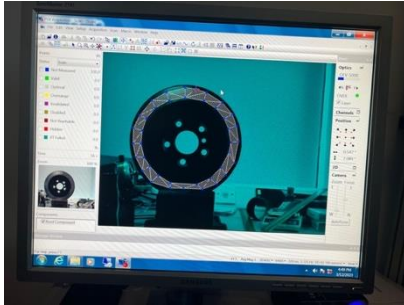


Figure 9: Scan point selection and mesh

The third step is defining component surface scan points using define scan tool under SETUP. Triangular shape meshing shape had been chosen as shown in *figure 9*.

The fourth step is to start actuator. An actuator continuously jerks to a disk brake and so brake vibrates. At same time, laser scans the defining points and measure values of an objects like displacement and/or velocity whatever is selected in setting and finally plots a displacement rate into graph. After completing a scanning process data will Analyse in a PSV analyzing software.

Next step is to open the data in the analyzer. Where choose different frequencies based on peaks and through bandwidth. Analyzer represents this data into graphical 2D as well as 3D animation representations. Analyzer allows to simulate all Signal data.

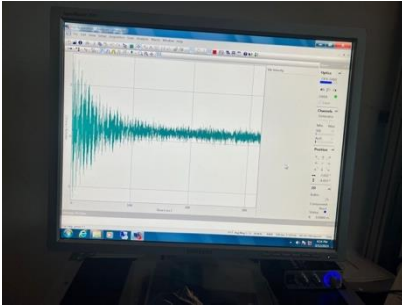
In this experiment 13 frequencies measured which are more significant and can produce high vibration in a disk brake. The frequency peak and bandwidth are shown in the *table 1*. In this experiment, FFT (Fast Fourier Transform) domain used which computes time and converts into frequency domain.

No.	Start	End	Peak	Bandwidth	Unit
1	68.75	71.875	71.875	3.125	Hz
2	75	81.25	78.125	6.25	Hz
3	103.125	115.625	109.375	12.5	Hz
4	171.875	190.625	184.375	18.75	Hz
5	196.875	206.25	200	9.375	Hz
6	225	246.875	231.25	21.875	Hz
7	287.5	493.75	300	206.25	Hz
8	575	628.125	606.25	53.125	Hz
9	1025	1115.625	1071.875	90.625	Hz
10	1415.625	1500	1475	84.375	Hz
11	1575	1646.875	1578.125	71.875	Hz
12	1712.5	1803.125	1746.875	90.625	Hz
13	2018.75	2896.875	2475	878.125	Hz

Table 1: Frequency peak and bandwidth

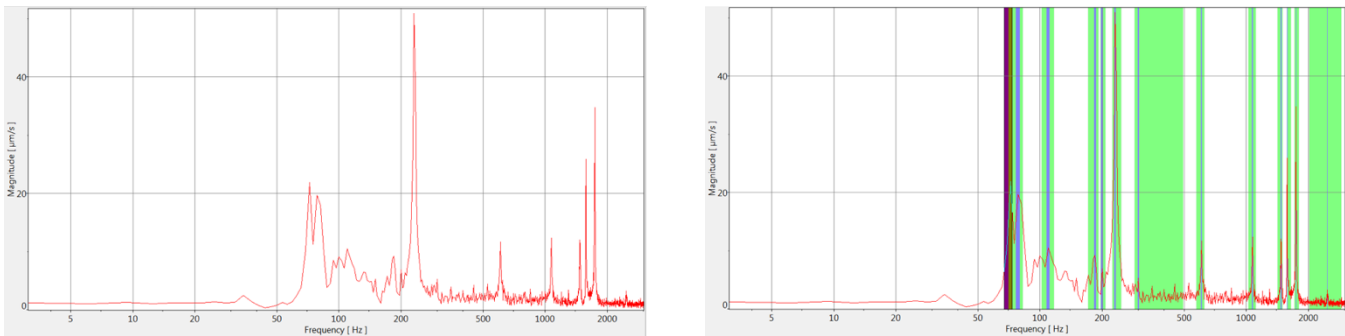
6. Graph

The live time domain vibrational signal of velocity graph generated from analyzer which is shown in *graph 1*.



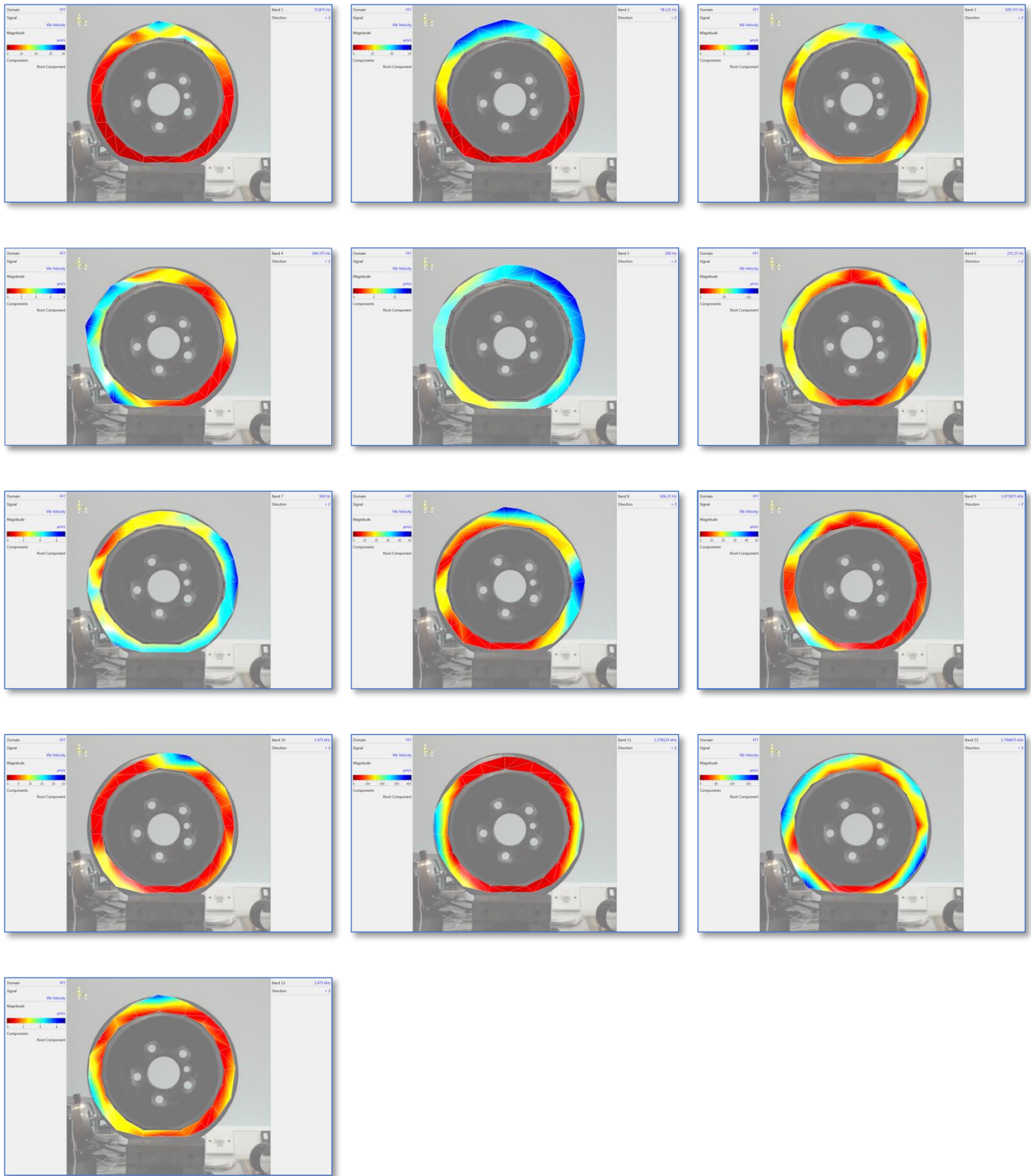
Graph 1: Velocity live spectrum

A following *Graph 2* represents the frequency (Hz) v/s displacement rate or velocity of vibration ($\mu\text{m/s}$) of a disk brake (FFT domain).



Graph 2: Frequency peak and bandwidth after completion of a brake disc scanning

According to the selection of the frequency, PSV Analyzation software create color representation of a brake disc for every single frequency. The color spectrum 2-Dimensional graphical representation of scan point over every single scan point selection are shown in *Graph 3*. 3D graphical representation of surface vibration over all the frequencies are shown in *graph 4*. The 2D representation use to analyze bending vibration in a disc while 3D representation uses to analyze torsional and axial vibration in a brake disc. A red and blue color represent the maximum negative and positive magnitude of velocity which is $\mu\text{m/s}$.



Graph 3: 2-dimensional graphical presentation of a brake disc



Graph 4: 3-dimensional graphical presentation of a brake disc

7. Result and Discussion

The study using laser doppler vibrometer (LDV) perform computational study of dynamic behavior of a brake disc. Due to external excitation on a circumference of a brake disc by solenoid actuator produce vibration in a brake disc. After scanning a brake disc, 13 different frequencies of vibration is examined. From analyzing the data, the maximum vibration speed is observed on 1.578125 kHz, which is almost 400 $\mu\text{m/s}$. On this frequency, bending vibration is observed and maximum bending found on the horizontal outer point of a brake disc. The vertical upper free point is remained steady and there is minimum vibration. The maximum axial vibration is experienced at 200Hz, and maximum axial vibration velocity is 15 $\mu\text{m/s}$. There is also found that brake disc experiences more vibration on an outer circumference surface as compared to inner circumference surface. The vibration of the surface is higher towards the edge of the component leading to bending- oriented results throughout the component. This is because due to the constrained rotor with vertical mounting.

From analyzing the data, the natural frequency of this brake disc for particularly this specific design and material, is 1.578125 kHz.

8. Conclusion

The Laser Doppler Vibrometer (LDV) is a powerful tool for investigating the vibrational characteristics of automotive components, such as brake discs. LDV offers non-contact and high accuracy measurements that make it an ideal tool for automotive research and development. To perform vibrational analysis of brake discs using LDV, it is important to properly mount the brake disc and position the LDV at an appropriate distance. The LDV system should be calibrated and set up properly to ensure accurate measurement. LDV measurements may be affected by environmental factors such as air turbulence or vibrations in the surrounding environment. This can introduce errors into the measurement and reduce the accuracy of the results. The result of this study has errors due to mounting of actuator and a brake disc.

9. References

- Li, Y., Huang, J., Chen, J., & Ma, Y. (2019). Non-contact measurement techniques for brake system vibration characteristics: A review. *Mechanical Systems and Signal Processing*, 117, 155-179. doi: 10.1016/j.ymssp.2018.07.033
- Luca Pagano, K. L., 2017. Modal Analysis - A comparison between Finite Element Analysis (FEA) and practical Laser Doppler Vibrometer (LDV) testing. *International conference on computer modelling and simulation*.
- Karadogan, A., Ersan, E. A., & Gokasan, M. (2021). Modal analysis of a vehicle's suspension system using a laser Doppler vibrometer. *Journal of Vibration Engineering & Technologies*, 9(1), 41-51. doi: 10.1007/s42417-020-00322-x
- Kang, J., Yoo, W. S., & Han, J. (2020). Non-contact measurement of the dynamic characteristics of an engine mount system using laser Doppler vibrometry. *Journal of Mechanical Science and Technology*, 34(2), 841-850. doi: 10.1007/s12206-019-1213-5
- Yu, Y., Feng, Z., Zhang, D., & Ma, S. (2020). Experimental research on vibration characteristics of tire and wheel assembly based on non-contact measurement. *Measurement*, 168, 108298. doi: 10.1016/j.measurement.2020.108298
- Esposito, E. (2014). *Laser Doppler Vibrometry*. CRC Press.
- Polytec. (2019). Laser Doppler Vibrometer User's Guide. Retrieved from https://www.polytec.com/fileadmin/user_upload/polytec/downloads/manuals/laser_vibrometer/UM_LDV_en.pdf
- <https://www.azosensors.com/article.aspx?ArticleID=717>

Appendix

Figure 1: Junction box

Figure 2: Velocity controller

Figure 3: Scanning head

Figure 4: Solenoid actuator with a brake disc

Figure 5: Schematic diagram for data measuring equipment setup

Figure 6: Experimental setup of LDV components

Figure 7: Working principle of Laser Doppler Vibrometer (AZO sensors)

Figure 8: 2D surface define.

Figure 9: Scan point selection and mesh

Graph 1: Velocity live spectrum

Graph 2: Frequency peak and bandwidth after completion of a brake disc scanning

Graph 3: 2-dimensional graphical presentation of a brake disc

Graph 4: 3-dimensional graphical presentation of a brake disc

Table 1: Frequency peak and bandwidth