

UNIVERSITY OF WALES TRINITY SAINT DAVID
WALES INSTITUTE OF SCIENCE AND ART



Laser Doppler Vibrometer – Brake Disc Modal Analysis
STRUCTURAL INTEGRITY AND MATERIALS EVALUATION
(ACEA7013)

Mr Vishnuvardhan Reddy Kesavarapu
2215387
Automotive Engineering
University of Wales Trinity Saint David, Swansea, SA1 8PH

Abstract

Modal analysis is a strong approach used to examine the vibrational characteristics of mechanical systems. It can be utilised to look at the modal behaviour of brake discs in the context of automobile braking systems. For this kind of modal analysis, laser doppler vibrometry is a non-contact measurement method that works exceptionally well. In this article, we offer a study on the application of laser Doppler vibrometry to brake disc modal analysis. The trials were conducted utilising a commercial laser Doppler vibrometer and a brake disc. performance. Overall, this work shows that laser Doppler vibrometry has the potential to be an important technique for modal investigation of brake discs. The method can precisely pinpoint the brake disc's native frequencies and mode shapes under diverse operating circumstances. The performance of the brake system can be enhanced by using this information to adjust the design of the brake disc. Overall, this work shows that laser Doppler vibrometry has the potential to be an important technique for modal investigation of brake discs.

Table of Contents

Apparatus.....	5
Introduction/Method/Procedure.....	6
Background	6
Method	6
Procedure	11
Measurements and Graphs of Raw measurements	13
Calculations and error estimates	16
Results and Discussion.....	17
Experimental-based model for analysis with model testing	17
Application of the modal analysis	18
Structural and health monitoring	19
Vibrational Frequency analysis	20
Scope for improvement.....	21
Physical implications	22
Conclusion	22
References	24

Figures and Tables:

Figure 1.....	5
Figure 2.....	7
Figure 3.....	8
Figure 4.....	9
Figure 5.....	9
Figure 6.....	10
Figure 7.....	11
Figure 8.....	12
Figure 9.....	13
Figure 10.....	14
Figure 11.....	14
Figure 12.....	18
Figure 13.....	19
Figure 14.....	21
Table 1.....	15

Apparatus

The first apparatus is the PSV Acquisition 9.3 which has helped in the data integration around the scope of the project. On the other hand, PSV presentation 9.3 is the second apparatus that has helped in terms of animation and result in visualization.



Figure 1 : Laser Doppler Vibrometer Equipment

The apparatus required in this experiment were:

- 1.Laser Doppler Vibrometer
- 2.Optical components
- 3.Signal Processing unit
- 4.Mounting System
- 5.Control Software

Introduction/Method/Procedure

Background

One important feature of this project is laser doppler vibrometry (LDV), which uses doppler effects to monitor vibration. LDV is utilised for testing and damage detection in aerospace and automotive industries. One of the key concepts in the LDV is the detection of the frequency of the light that is dispersed by minuscule particles as it passes through the interference. Finite element elements can be used to solve the vibration issue with a car brake disc while braking. So, it is essential to take this issue into account when analysing the system.

The brake disc is one of the main components of the vehicle braking system. The performance of the vehicle braking is the optimal safety factor within a vehicle. It should be mentioned that when the automobile is applying the brake, the “excitation frequency is close to the natural frequency of the brake disc” (Schwarz *et al.* 2020). Now, the application of braking usually causes resonance, vibration, and noise. Also, it should be mentioned that braking has a direct impact on riding comfort as well. Thus, it is essential in terms of analysing the modal characteristics of the vehicle brake disc. In this project, in order to perform the modal analysis, PSV acquisition has been used for the purpose.

Method

The method of modal analysis has been implemented in terms of studying the dynamic properties of the brake disc. PolyTec Scanning Laser Doppler Vibrometer (LDV) has been significantly useful in terms of monitoring as well as determining the effective resonant frequency modes and shapes of a vehicle brake disc. It should be mentioned that modal analysis is one of the critical aspects that determines the vibration characteristics of the component (Ma *et al.* 021). Under the

pretext of various dynamic loading conditions for instance the use of electrostatic actuators can display the movement of different parts of the brake disc. Thus, it can be said that Modal analysis on a brake disc component can drive valuable as well as significant insight into the effective dynamic characteristic within the structure.

Here, in this project, two particular model analysis applications such as “PSV Acquisition and PSV presentation” have been used. In this regard, it should be mentioned that this specific comprehensive software package has allowed faster as well as sample acquisition of the vibration measurement data (Otto and Ostermeyer, 2019). It is also critical to mention that full-field as well as dynamic characterization of “microscopic and macroscopic” samples have allowed the better display of the structure-borne vibrations.

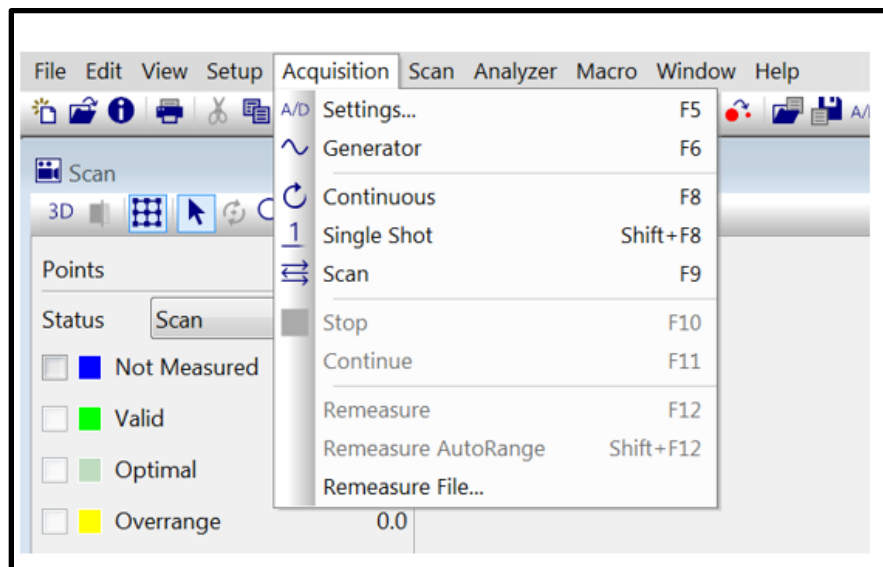


Figure 2: Acquisition

(Source: Acquired from PSV Acquisition)

The above image is defining that from the menu ribbon of the PSV software, acquisition can be selected. Once the acquisition app is running it is important to select the acquisition menu and select settings.

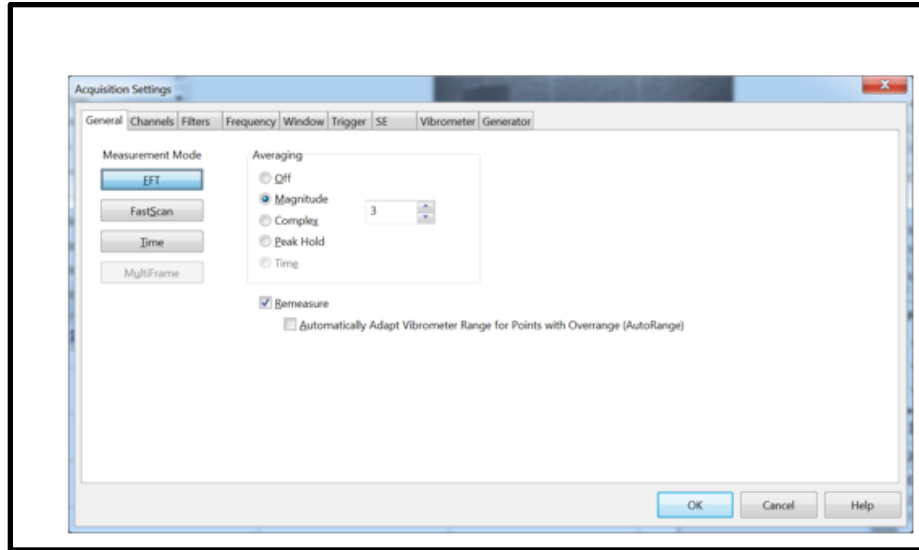


Figure 3: Setting

(Source: Acquired from PSV Acquisition)

It can be seen from the above figure that the acquisition settings have allowed the selection of the system parameters. The measurement mode has been selected as EFT whereas averaging can be seen as magnitude. With the help of such a setting, system components that can be analysed have been done.

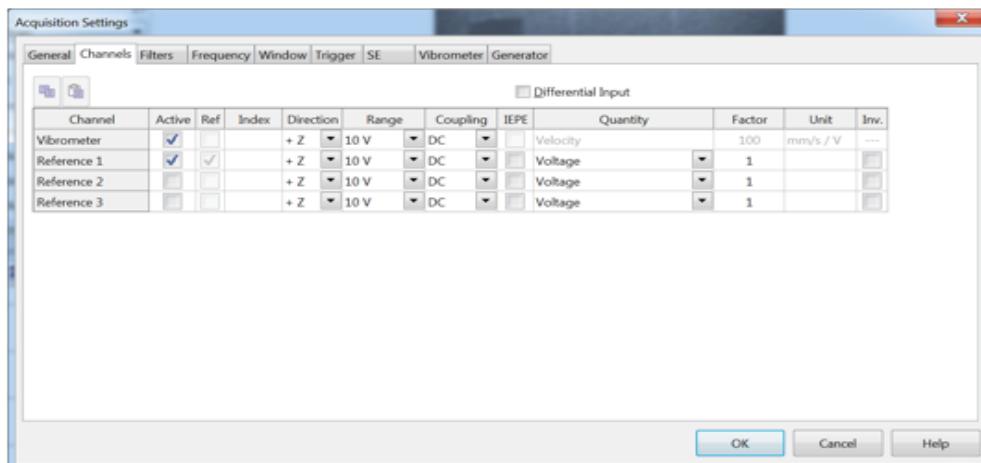


Figure 4: Acquisition setting

(Source: Acquired from PSV Acquisition)

It can be seen from the above figure that the range of the vibrometer has been selected as 10v and the factor has been given as 1.

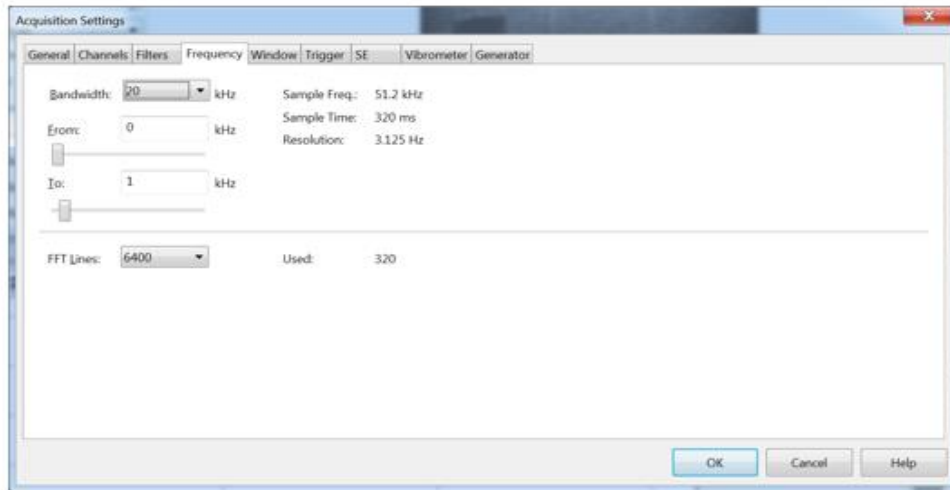


Figure 5: Frequency selection

(Source: Acquired from PSV Acquisition)

It can be seen from the above figure that the frequency range for the modal analysis has been done with the help of the following setting. The frequency bandwidth can be seen as 20hz with a sampling frequency of 512khz.

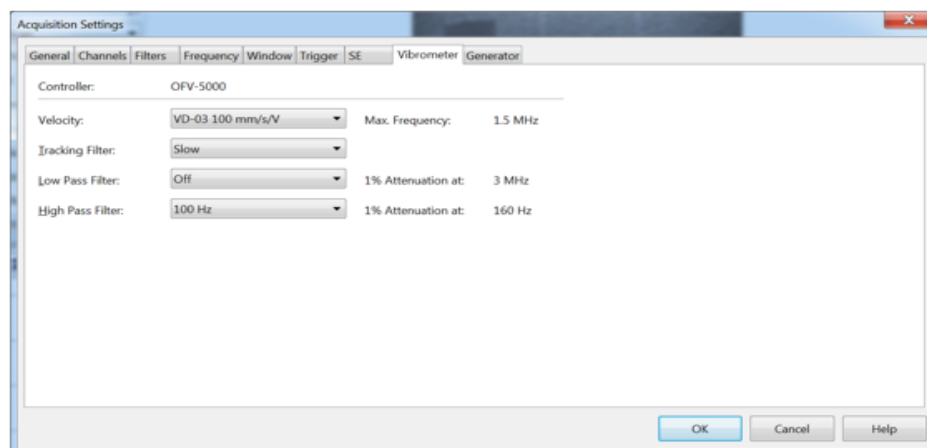


Figure 6: Vibrometer setting

(Source: Acquired from PSV Acquisition)

It can be seen from the above figure that vibrometer settings have been selected through this method.

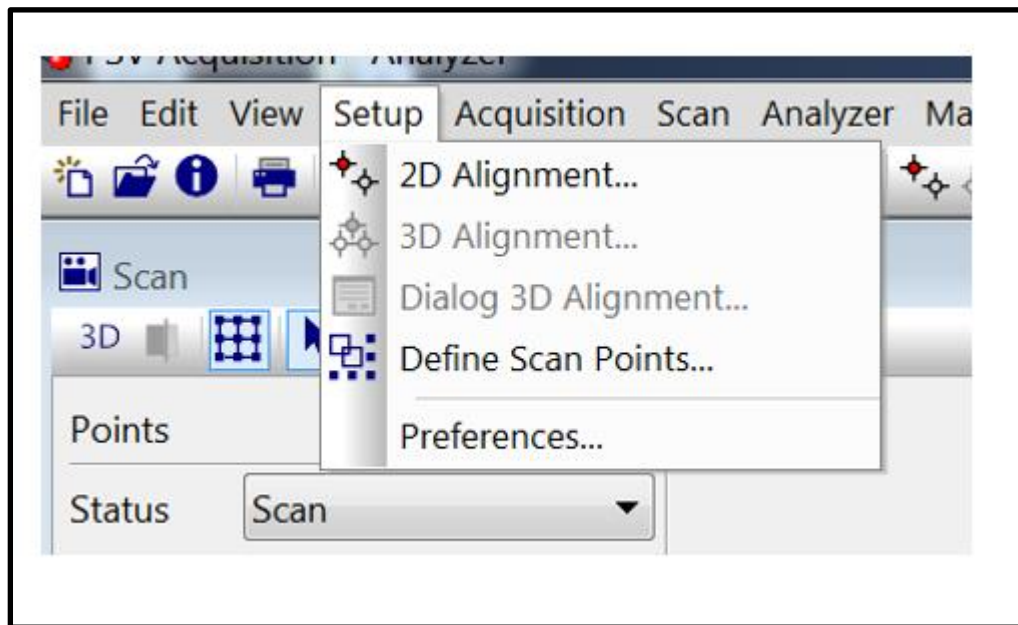


Figure 7: Set up a 2D alignment

(Source: Acquired from PSV Acquisition)

It can be seen from the figure that the setting up of the 2D alignment has been done with the help of the following method. This is achieved through the 2D alignment set-up in the menu option. Defining the scan point within the menu option should be directly finishing with the 2D alignment select the Setup. Henceforth, through this method, a modal analysis of the PSV acquisition has been done.

Procedure

It is critical to mention that differential vibrometry can describe the measurement of vibration at two points. These two points are directly associated with effective modal analysis. At the two points, one point directly gets vibration in relation to another. In such a case, two specific measurement methods are commonly used. For instance, with the first method, the procedure of

measuring vibration can be directly associated with the recognition of the optical path. However, this process is significantly ideal for higher frequency (Chen and Zhu, 2021). On the other hand, vibration measurement through the second process is directly associated with laser beam scanning on the brake disc through the use of various single-point measurements. The light gets scattered from the brake disc which is a moving object thus changing the frequency at a significant rate. The measurement beam gets incident on the test subject which is the vehicle braking disc.

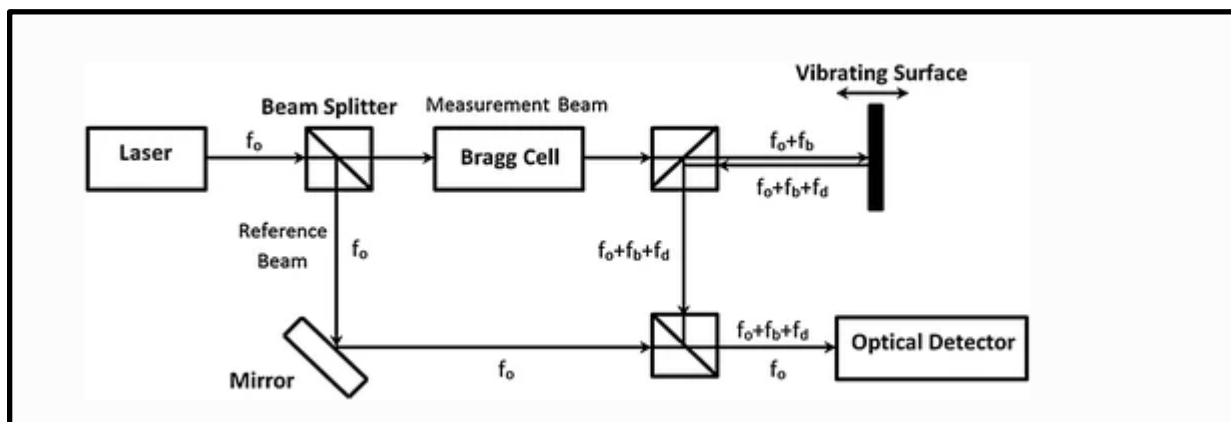


Figure 8: LDV procedure

(Source: Stamm *et al.* 2020)

It is critical to mention that depending on the velocity as well as displacement, the scattered light usually changes its frequency (Stamm *et al.* 2020). The above figure is suggesting on the procedure of the LDV where the laser beam splits into a reference beam and measurement beam. The figure is also suggesting that the measurement beam with the f_0 frequency is focused on the vibrating surface. On the contrary, the reference beam can be seen as experiencing a frequency shift that is significantly proportional to the velocity of the vehicle braking disc. Thus, through the help of LDV and these procedure steps, squealing brakes, engine noise, and rattles have been measured accurately.

Measurements and Graphs of Raw measurements

The SLDV has been applied in terms of measuring the vibration of the vehicle component that is moving. Measurement of vibration has been done under the pretext of relative motion. It should be mentioned that out-of-plane vibration of braking discs uses a curricular scanning approach. Now, it should be mentioned that the SLDV scanning approach provides response measurements for the vibration at a single-input frequency (Schmid *et al.* 2019). In this regard, it is critical to measure the frequency and vibration magnitude at a specific point in time. Thus, it can be said that the magnitude and frequency are the two specific measurement parameters that have been used for the modal analysis purpose.

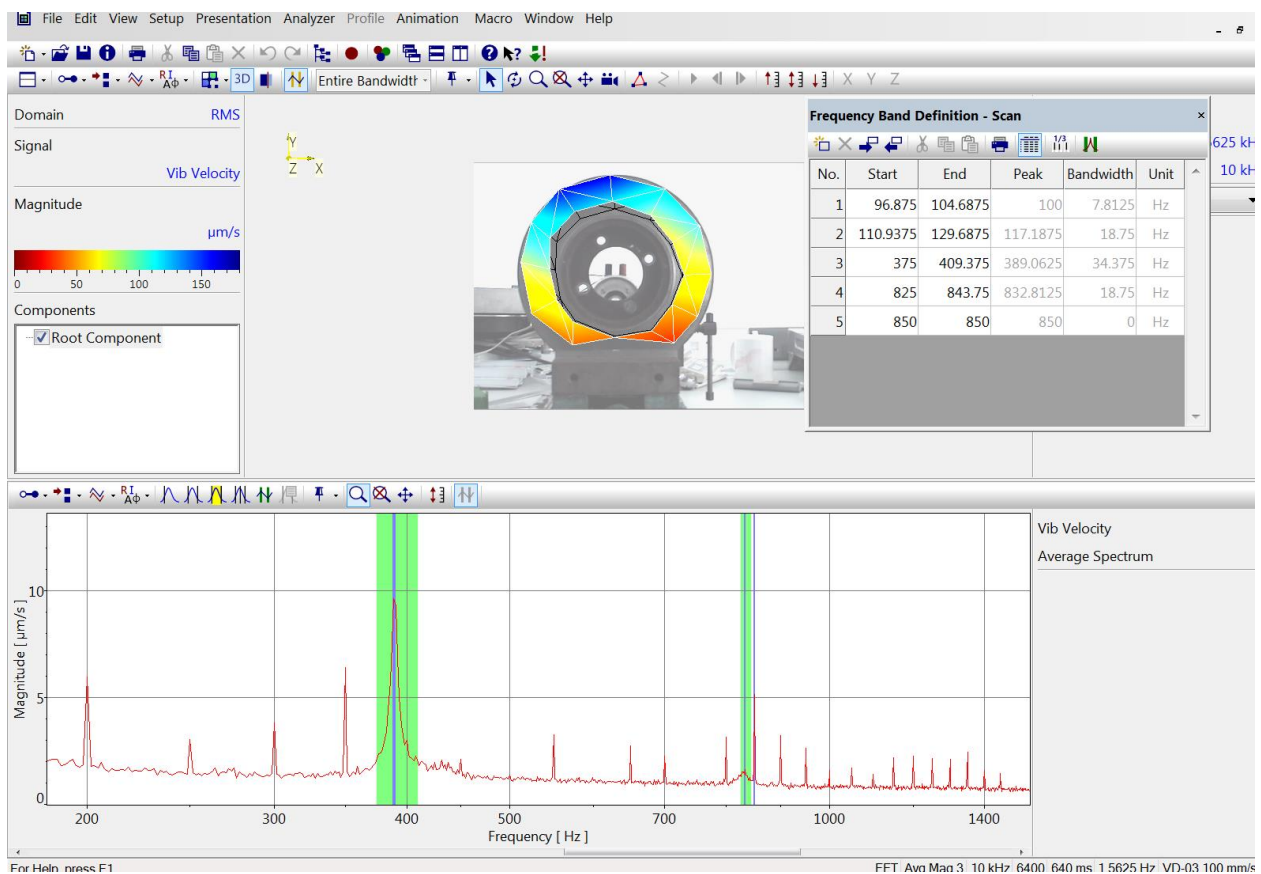


Figure 9: Full frequency responses

(Source: Acquired from PSV Acquisition)

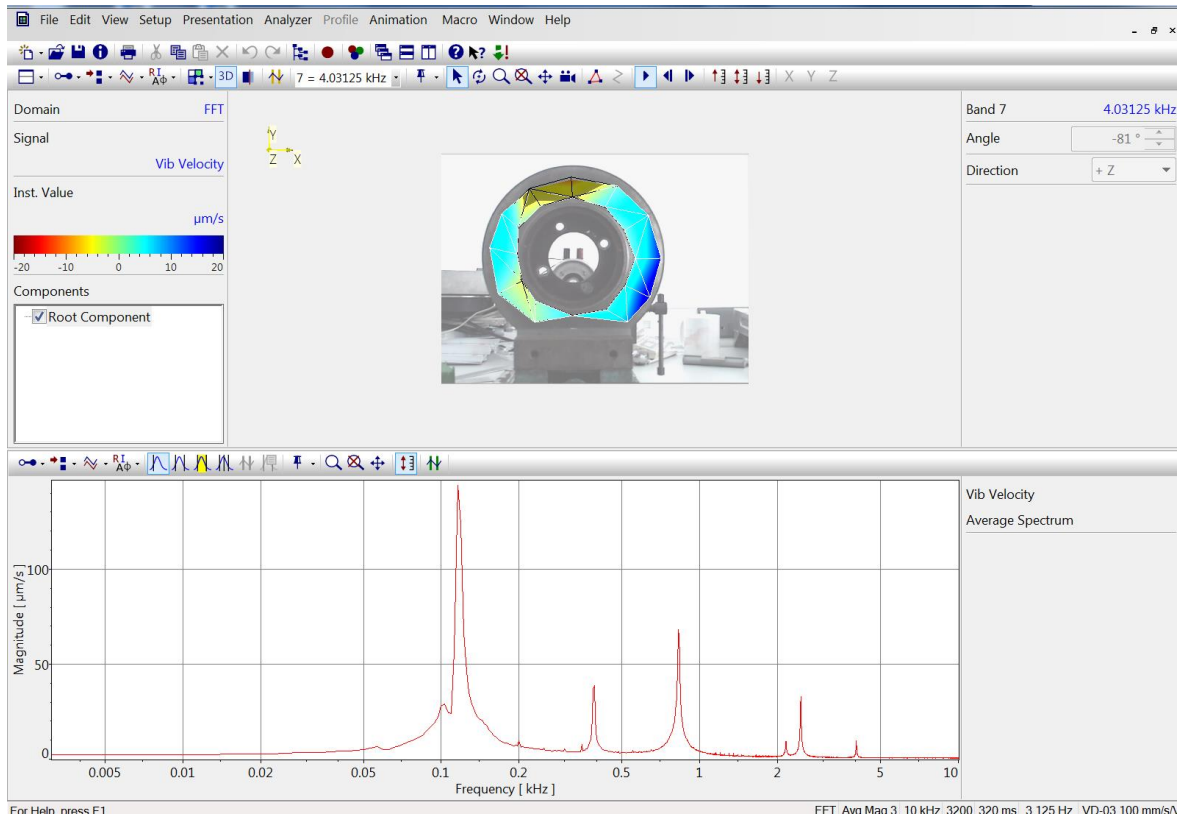


Figure 10: Full frequency responses 3200 bins

(Source: Acquired from PSV Acquisition)

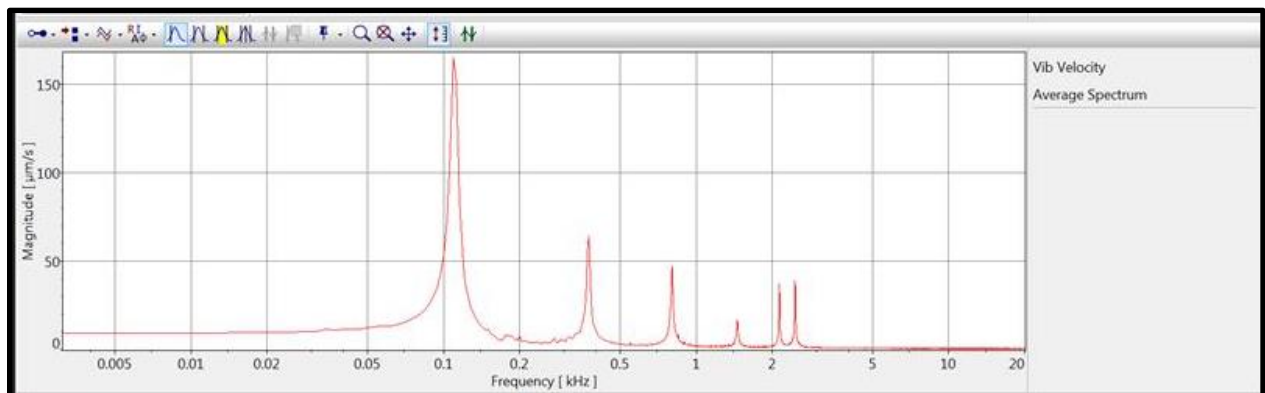


Figure 11: Frequency vs magnitude graph

(Source: Acquired from PSV Acquisition)

The above illustration is suggesting the Frequency vs magnitude graph generated from the software package. It can be seen that the magnitude of vibration has directly increased at critical frequency point. The following table provides a definitive overview of the system measurement.

Frequency	Magnitude
0.005 kHz	3 $\mu\text{m/s}$
0.01 kHz	4 $\mu\text{m/s}$
0.02kHz	6 $\mu\text{m/s}$
0.05 kHz	10 $\mu\text{m/s}$
0.1 kHz	160 $\mu\text{m/s}$
0.2 kHz	6 $\mu\text{m/s}$
0.5 kHz	4 $\mu\text{m/s}$
1 kHz	2 $\mu\text{m/s}$
2 kHz	1 $\mu\text{m/s}$

Table 1: Calculation of frequency and magnitude

It can be seen from the above table 1 that magnitude of the vibration is highest at 0.1 frequency. Apart from that, the magnitude of the vibration has not increased significantly at all. Thus, it can be said that the modal analysis of the vehicle disc brake has been done with the help of the

following parameters. However, it should be mentioned that data generated through this approach is significantly small.

Calculations and error estimates

Issues and sources of uncertainty are looked into from both a theoretical and then an experimental standpoint. Several calibration evaluations are carried out, and guidelines for how to design an ideal calibration are made. Multimodal analysis is employed in the second section of the research to solve these accuracy issues in a case study. To showcase the changes in the derived modal parameters caused by the scanner system calibrated and by the laser spot placement errors, two modal studies on a wind turbine are conducted with two different scanner calibrations, and the outcomes are contrasted.

It is shown that poor scanner calibrating precision may lead to ambiguity inside the collection of the modal properties, making applying SLDV possibly incorrect (Ma *et al.* 2021). Early on in the creation of LDV, it was realized that it could potentially be possible to remotely control the movement of laser light by applying optical components (usually a combination of two orthogonally placed galvanometer-based mirrors in scanning the point through a building). Specific applications started to develop around the automobile and aeronautical parts of the economy. Although SLDV continues to offer vibration testing in general, it has made the greatest effects in the context of Experiential based various essential Modal Analysis (EMA). The usefulness of CSLDV for modal testing is that it substitutes the purely time approach with one that lays a great deal more emphasis on the significant spatial of the structure's modern portfolio theory met. Although this can significantly allow faster modal testing, the measurement calls for specialized processing algorithms point has always been shifting. The third figure shows a single-frequency excitation area scan on a car panel.

The unlimited range is the result of several horizontal and vertical scanning frequencies, and it comprises the various Fourier-based components that are attached with coefficients mainly in their polynomial-based equation for its various deflected-based patterns (Stamm *et al.* 2020). Thus, the more often complicated formation of shape needed some higher order of essential polynomial-based coefficient that is used for the accuracy of the reconstruction hence the accuracy regarding CSLDV area could be set up by the different harmonics mainly above the corresponding noise floor mainly in their desired spectrum estimated. This could also limit the thrust of various signal-based dropouts, mainly related to the basic surfaces-based quality as well as the speckle of noises, particularly at the high scanning speeds.

Results and Discussion

Experimental-based model for analysis with model testing

The model-based analysis processes to explain the vibration of structure mainly on the basis of their natural related characteristic that is the resonance frequency, mode shapes along with damping factors. The dynamics-based properties are used for setting up the experimentally based model testing that is often required for some sensor-based technology that is the force, transducer, some accelerometers, and camera with non-contact the laser vibrometers. The various data acquisition along with the computer utilizes for the various monitoring as well as the analyzation of the various estimated data such as DAQ.

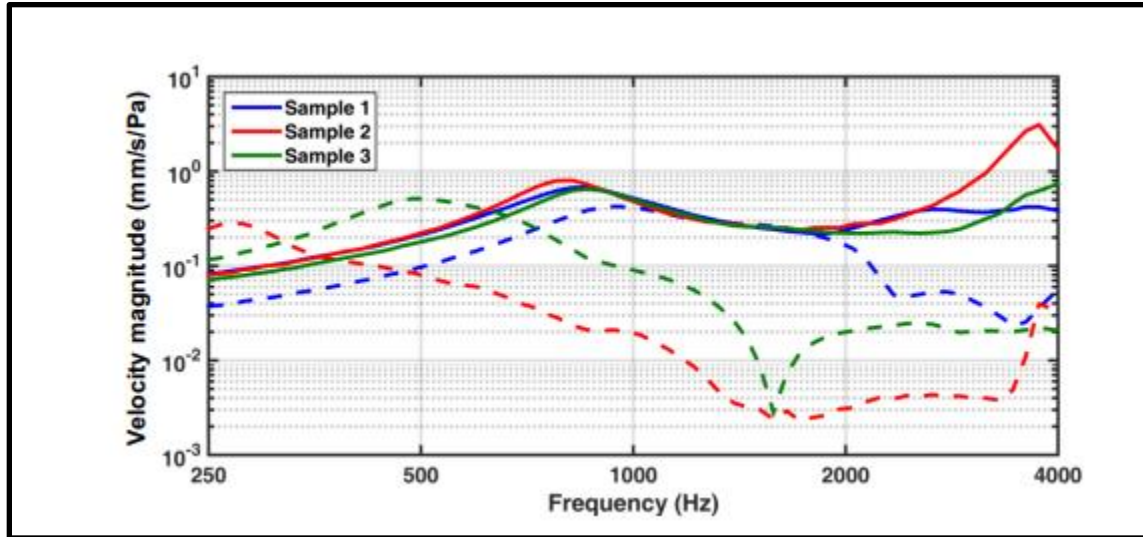


Figure 12: Graph of frequency vs velocity magnitude for resonance analysis

(Source: Chen *et al.* 2021)

Application of the modal analysis

While executing the experimental based model testing the very first step is to measure the frequency of the vibration-based responses. Thus, the excitation must be spectrally classified as braid for exiting the various natural based frequencies. Hence, the significantly based excitation of the spectrum is thus acquired to transfer the various functions such as FRFs for the responses and input-basedforce must be recorded.

Then the prepared estimated FRFs is the curve that is then fitted mainly to some mathematical based model that comprises the coherent-based modes for the structures mainly under the proper tests (Chen *et al.* 2021).

Structural and health monitoring

LDV is proved as a very efficient based diagnostic relevant tool mainly in the various forms of damage detection that occur on structures since it has the capability to prepare the non-contact form of measurement through the dense form grid-based points. Thus, the various composite materials are then attracted but the principle that has been employed here is to evaluate the detachment for the different landmines-baseddetections (Stamet *al.* 2020). The severe location of the detections would have been recognized effectively mainly by the analyzation of certain wave-based propagation and model responses by the operation-based deflection of their shapes.

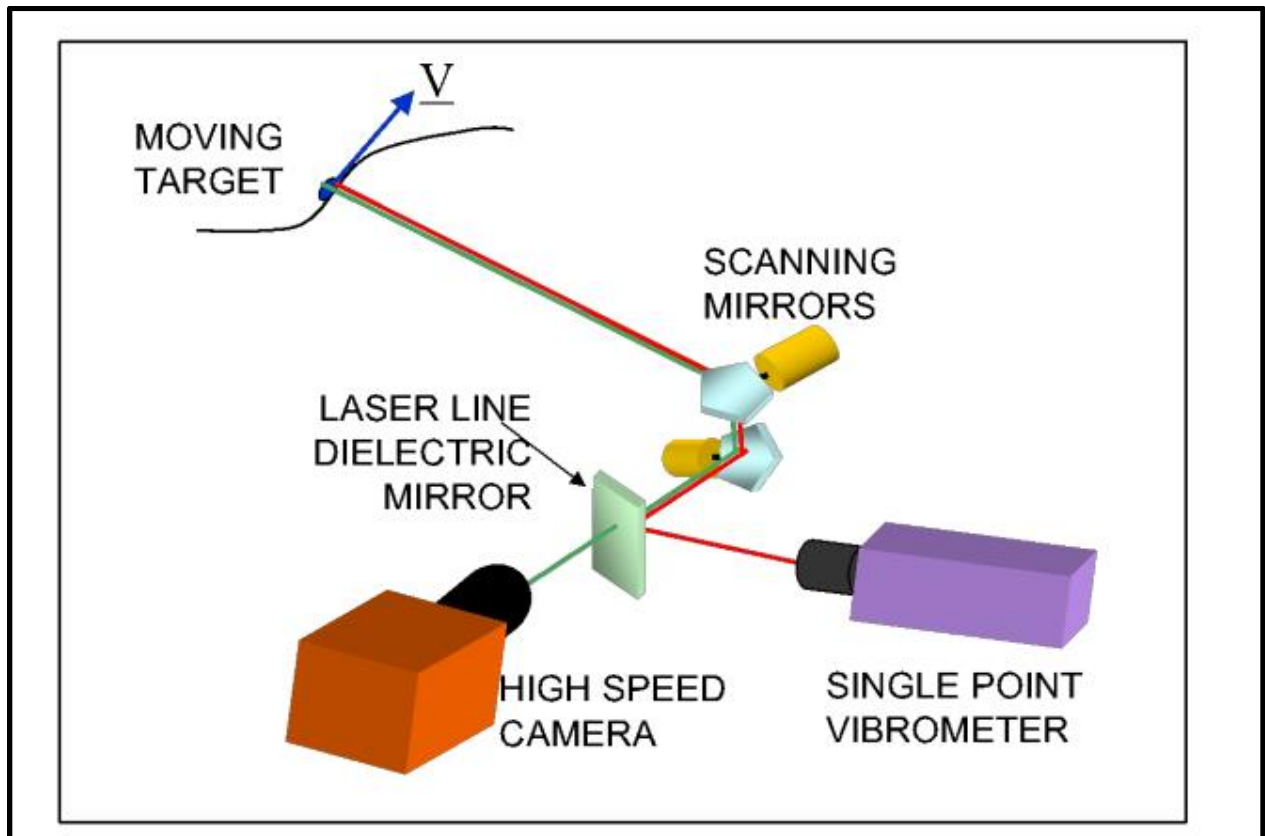


Figure 13: Layout of the image-based Tracking for LDV

(Source: Stamm *et al.* 2020)

But the exact location for detecting is found mainly in such studies, the various text structures are also relatively very often simple. The ODS based analysis are also based on the certain spectral firm of sidebands in which all the CSLDV-based measurement along with designatory for particular IDS are provided. The monitoring of its sideband must be sufficient mainly for diagnosing the various emerging-based effects but outgoing, requiring the overall ODS-based processing (Duvigneau *et al.* 2019). The step-based sine of excitation is also suitable for the finding of the severe frequency and their range which are most seriously affected by the various damages.

Vibrational Frequency analysis

This study deals with the behaviour for certain braking systems mainly in the noises as well as analysis of vibration because of its complexity, various numerical-based models depending on the finite element-based model analysis have been used. Thus, the dynamo-based structure characteristics for the brakes system and its component is strongly attached to their modal baked behaviour (Karamoozianet *al.*2020). This modal analysis might be efficient in predicting the vibrational based model for system-based various components. Thus, model frequency along with the vibrational modes is critical particularly in the design phases since this must provide information about the component's behaviours in the various dynamic related conditions. Thus, the model successfully applied the validation of the design specification for complex as well as mechanical structures which are at higher for the corresponding front vehicular based operations.

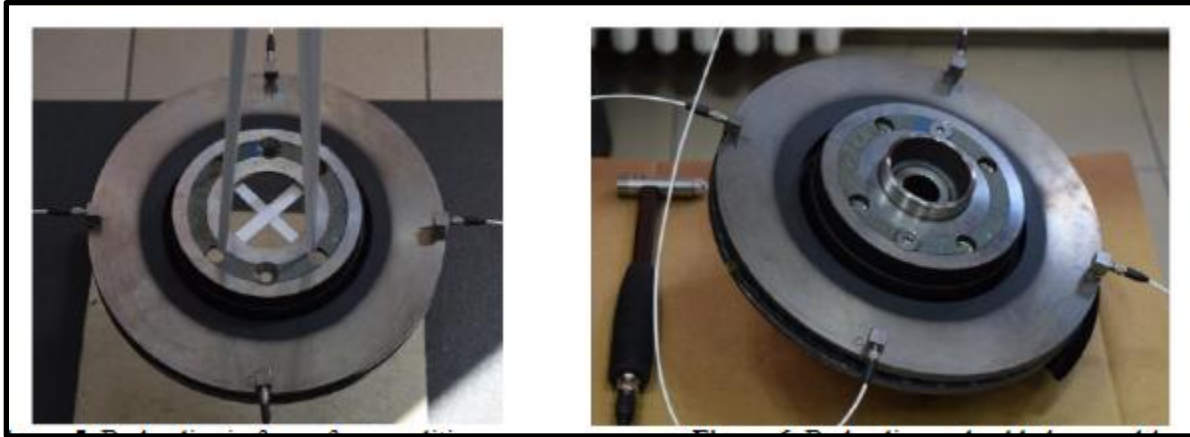


Figure 14: Brake disc modal-based analysis

(Source:Duvigneau *et al.* 2019)

The resonance harmonics are determined through testing using an impact hammer. The energy stimulus's amplitude and frequency contents are supplied by the force sensor with a piezoelectric sensor in the hammer to the test object. Direct stimulation in the in-plane direction was provided using the impact hammer. Hammer points enable the impulse's energy content to be adjusted to satisfy the requirements of a test object. The hard tip is chosen for this type of material and for this frequency range to supply sufficient energy for high frequencies. To establish an unrestricted situation that enables the structure to vibrate autonomously, a disc is elastic deformation suspended.

Scope for improvement

The responses are then captured mainly by the four essential accelerometers further converted into the signal-based conditioner mainly into the various forms of electrical-based signals. This signal generated from all of the accelerometers along with the impulsive hammer is acquired and then processed in the LabVIEW-based software. This natural frequency is obtained by applying the frequency-based analysis. The impulse developed by the impact of hammers would be having

the quick type damping during the accelerometer eyes would be holding the record of the various disc forms of vibrations.

Brake squeal seems to be the name for friction-induced oscillations that can emerge during frequency screens such a high. The pad, rotor, brake assembly material, or geometry have every impact just on the frequency range that determines how sensitively a human ear screeches. Together with surface characteristics, contact surface bulk qualities also influence brake squeal (Karamoozian *et al.* 2020).

Physical implications

By focusing on changes such as caliper tension, attachment brackets, and rotor geometry, braking squealing noise created by driving can be decreased. Another approach for analysing CSLDV data is referred to as "*lifting*", which groups together the responses from each incremental site along the laser path and treats them as if they were the outputs from a set of sensors fixed at such places even if the answers are not measured working in unison. These reconstructed replies have such a temporal increment equal to the scan period, thus aliasing is possible (Srivastava *et al.* 2020). It was demonstrated that the scan frequency must be greater than twice the greatest frequencies of interest in a study that used the lifting approach to recover the natural frequencies of the mass-normalized mode forms of an unrestricted beam under impact stimulation.

Conclusion

Therefore, it can be said from the analysis that modal testing is one of the major aspects that can be used for the vibration testing of the vehicle disc. The raw data suggests that modal analysis of the element through LDV has generated adequate results. Thus, it can be also said that the

physical implication of such a test can be directly associated with the safety of the vehicle. In other words, through the help of this LDV testing on the vehicle components, ensuring safety can be achieved. In this regard, it is evident that the safety of the vehicle is directly associated with the effective modal analysis of the components. Identification of the component's "main harmonic resonant modes and shapes" has directly helped in the further decision-making around braking disc design. With the help of frequency and magnitude detection, it is possible to perform a modal analysis on vehicle components. Henceforth, this particular data can be directly used in terms of increasing safety and delivery of better vehicle components.

The scan frequency might be adjusted in cases where this is not possible to make sure the method of addressing the issue is inadequate. The finite element approach is now commonly used to analyse a wide variety of building and thermal brake system issues. Using a was before complex modal analysis can reduce squeal is used on the brake disc to study the significance of friction effects that lead to instability. Quasi-contract analysis serves as the foundation for this modal solution approach. This enables the early diagnosis of designs that result in grating brake squeal.

References

- Chen, D.M. and Zhu, W.D., 2021. Investigation of three-dimensional vibration measurement by three scanning laser Doppler vibrometers in a continuously and synchronously scanning mode. *Journal of Sound and Vibration*, 498, p.115950.
- Duvigneau, F., Daniel, C., Koch, S. and Woschke, E., 2019. NVH in Electric Mobility-Vibration Analysis Using a Derotator. *ATZ worldwide*, 121(6), pp.66-71.
- Hasheminejad, N., Vuye, C., Margaritis, A., Van den Bergh, W., Dirckx, J. and Vanlanduit, S., 2019. Characterizing the complex modulus of asphalt concrete using a scanning laser doppler vibrometer. *Materials*, 12(21), p.3542.
- Karamoozian, A., Jiang, H., Tan, C.A., Wang, L. and Wang, Y., 2020. An integrated approach for instability analysis of lattice brake systems using contact pressure sensitivity. *IEEE Access*, 8, pp.19948-19969.
- Li, Y., Dieussaert, E. and Baets, R., 2022. Miniaturization of laser Doppler vibrometers—a review. *Sensors*, 22(13), p.4735.
- Ma, X., Li, M., Yu, K., Ye, L., Yang, Y., Ma, X. and Song, Y., 2021. Review of Development and Application for Laser Doppler Vibrometer. *Forest Chemicals Review*, pp.1194-1213.
- Otto, J. and Ostermeyer, G.P., 2019. High-frequency vibrations in the contact of brake systems. *Facta Universitatis, Series: Mechanical Engineering*, 17(2), pp.103-112.
- Otto, J. and Ostermeyer, G.P., 2019. High-frequency vibrations in the contact of brake systems. *Facta Universitatis, Series: Mechanical Engineering*, 17(2), pp.103-112.
- Rohe, D.P. and Reu, P.L., 2021. Experimental modal analysis using phase quantities from phase-based motion processing and motion magnification. *Experimental Techniques*, 45, pp.297-312.

Schmid, D., Sessner, V., Gräbner, N., von Wagner, U. and Weidenmann, K.A., 2019. Parameter identification of brake pad shims for complex eigenvalue analysis. *PAMM*, 19(1), p.e201900306.

Schwarz, S., Hartmann, B., Sauer, J., Burgkart, R., Sudhop, S., Rixen, D.J. and Clausen-Schaumann, H., 2020. Contactless vibrational analysis of transparent hydrogel structures using laser-Doppler vibrometry. *Experimental Mechanics*, 60, pp.1067-1078.

Srivastava, R., Kumar, R. and Bhattacharya, B., 2020, September. Vibration response studies of a bi-morph sma hybrid composite using 3d laser doppler vibrometer. In *Smart Materials, Adaptive Structures and Intelligent Systems* (Vol. 84027, p. V001T03A003). American Society of Mechanical Engineers.

Stamm, M., Schlemme-Weber, S., Appl, S., Köser, J. and Pfeiffer, H., 2020, September. Fast loose rivet detection by using scanning laser doppler vibrometry. In *Proceedings of the ISMA2020 and USD2020—29th International Conference on Noise and Vibration Engineering, Leuven, Belgium* (pp. 7-9).