MATLAB Application in Vibration Study

*Neel Suratwala, #Mahesh Kulkarni

*PG Student, #Assistant Professor, School of Mechanical Engineering, Dr. Vishwanath Karad MIT – World Peace University, Pune, India, *aero.neel@gmail.com, #mahesh.kulkarni@mitwpu.edu.in

Abstract **Vibration are harmful in number of ways to machines and equipment. To control vibration, study and analysis is pivotal. Vibration protecting mechanisms or Vibration Isolators are designed based on analysis of vibration behaviour. MATLAB computer program is used in this research to fulfil the design and analysis goals. A Mathematical Model is developed, which defines system and provides output in terms of isolator properties based on input signal. MATLAB is known for its applications in all of engineering fields. A script in MATLAB is used for input signal processing and equation solving and another Simulink model is used for simulation and comparison of optimized solution. In this research mechanical theories, mathematics, calculus, signal processing tools and knowledge of MATLAB program are applied.**

Keywords — **MATLAB, Vibration, Isolation, Frequency Spectrum, Signal Processing**

I. Introduction

Vibration is generated in any machine that has moving components. Everyone who has worked in industrial field knows, there are very less possibility to design a machine without any vibrations. It comes under design goals to reduce them from disturbing its own machine and surroundings. Vibration reduction has number of benefits: increase of lifetime, reduction in the downtime or maintenance time, better quality output. Therefore, mounting machine using vibration isolator is very important. To design mounts that can isolate or reduce significant vibration, Vibration Analysis (VA) is done. VA saves lot of time in finding fault in machines without dissembling every part and checking each one for fault, in other way it reduces the total cost. In VA, vibration data collected from an equipment or a foundation cannot be studied in time domain. Therefore, frequency domain transformation is required. For the purpose of transformation, Fast Fourier Transform (FFT) is applied on data. Before transformation, data needs to be filtered out for error reduction. As data captured using probes like accelerometer also captures errors, some trend or offset, shift, noise, etc. Therefore, filtering out errors is very important. The vibration study, design and analysis include number of concepts from mechanical theories, calculus and signal processing.

In Industries, machines or equipment are attached with mounts that can provide high stability as foundation. Mounts are manufactured from one single material as single product and they can also be made out of assembly of multiple components, which is known as Vibration Protecting System (VPS). For specific purpose equipment where precision, accuracy and measurements are required at high level, selection of mount plays very important role [1]. Vibration Isolator's (V.I.) types: 1. Active, 2. Passive. Active vibration isolators required high number of components and it is expensive and complicated. While passive V.I. is affordable and simple, but the accuracy and effectiveness are less than active ones. To study, design and analyse concept of Transmissibility is primary base. In common practice, single degree of freedom system is used. According to theory for $\boldsymbol{f_{operating}} > \sqrt{\boldsymbol{2}}\boldsymbol{f_{resonance}}$ the transmissibility is less than one ($T_r < 1$). Increasing damping ratio reduce the transmissibility at resonance but also reduce the isolation effect at higher frequencies [2].

II. Literature Review

A. Review Stage

Performance degradation, malfunctioning, short life time, etc. are issues faced by machines and the primary reason is vibration [3]. Based on mechanical vibration theory, it is known that high amplification at resonance leads to better isolation in high operating frequency zone; and while high damping at resonance increase transmission comparatively in high operating frequency zone. So technically, it is a trade-off between these two, so according to priority of performance and operating speed range, objectives of Isolator's design are defined. Dae-Oen Lee et. al. did study various passive vibration isolators and concluded a comparison of transmissibility of useful mechanisms. Dynamic forces and torques occurring on machines are studied and analysed for identifying the isolator or mounting requirement. Dynamic Vibration Absorber (DVA) is one of the widely used isolator for [4], as they are affordable and simple. For defining exact real-life behaviour of components, some of studies implemented non-linear terms, which is difficult to solve and anlayse. In this, number of studies are done but one of the research studies shown a

 DOI : 10.35291/2454-9150.2022.0204

method that is easy and simple [5]. Various studies have been carried out for non-linearity in stiffness of system [6] [7] [8] [9] [10], as it solves issues of simple linear system and provide higher isolation. Rubber mounts also behave non-linearly and are widely implemented in industry for vibration reduction as they are cheap and easy to produce. Detailed study of design and application of elastomer mounts were done [11] [12]. Apart from elastomer mounts, pneumatic springs are also used with adaptive system for better vibration reduction with accuracy and over wide range of frequency [13]. Wire rope isolators are very effective as they protect equipment from vibration as well as shock, also they can provide vibration isolation in three degrees of freedom: vertical, rolling and lateral [14]. The damping in WRI is done through friction between wires. Wire rope isolators (WRI) are made of high strength wire and it has number of turns, which leads to high load carrying capacity with good isolation. Vibration signals are measured using various probes. Accelerometer is the most common electronic probe used in study, which measures the acceleration. Therefore, many times to change metrics from acceleration to velocity or displacement an appropriate processing is required. Sangbo Han's study regarding this shows some valuable points like error generation, frequency dependency, DC component involvement, curve fitting, etc [15].

B. *Research Gap*

In all research studies till now, there has not been a research where entire vibration study is combined together and defined a mathematical model. A self-developed mathematical model of vibration study using computer application – MATLAB, that can work on signal processing, mechanical vibration, calculus, mathematics is the novelty of this study.

III. METHODOLOGY

Methodology in Figure 1 describes, the process for vibration isolator design and analysis. A methodology describing different steps of design process in vibration isolation are shown. It begins with defining objective. In that allowable transmissibility, operating frequency, critical frequencies, mass, etc. are defined. Once the vibration data is captured, it is used as an input signal of mathematical model in MATLAB. Mathematical model is a program which describes the system and its behaviour in mathematical terminologies and equations. The data is edited and filtered for error reduction using various signal processing tools. There are number of filters that are used during signal processing. Butterworth, Elliptic, Chebyshev, Bessel are most commonly used filters. They are defined by transfer functions. Probes like accelerometer sometimes pick up noise from surroundings like ultrasonic equipment, electrical noise due to electromagnetic induction, etc. These frequencies are required to be eliminated from signal. Signal processing applies low-pass, high-pass or band-pass filter as per objective defines correct faulty signal. Corrected data is then transformed into frequency domain. Fast Fourier Transform (FFT) is an algorithm that computes the Discrete Fourier Transform (DFT) of a data, which is written as equation (1). Through FFT concept, frequency spectrum is estimated and plotted. FFT is also used to estimate Power Spectral Density (PSD), which is much more effective tool for analysis as it explains significance of power with respect to different frequencies. Power spectral density reduces the power from noise. From the frequency spectrum in PSD, dominant frequencies are selected.

Dominating frequencies are values with high power in vibration signal. Vibration signal has more than one frequency in it. All frequency weighs different in signal. In frequency domain, the data reveal more than one disturbing frequency and for design purpose one value of frequency as critical one needs to be chosen. For systems with low operating frequencies compared to disturbing frequencies, the critical frequency is chosen to be higher value, so difference between operating frequency and resonance gets as high as possible. While for a condition, where operating speed is higher than disturbing frequencies, the small value is chosen so the resonance condition gets as far as possible.

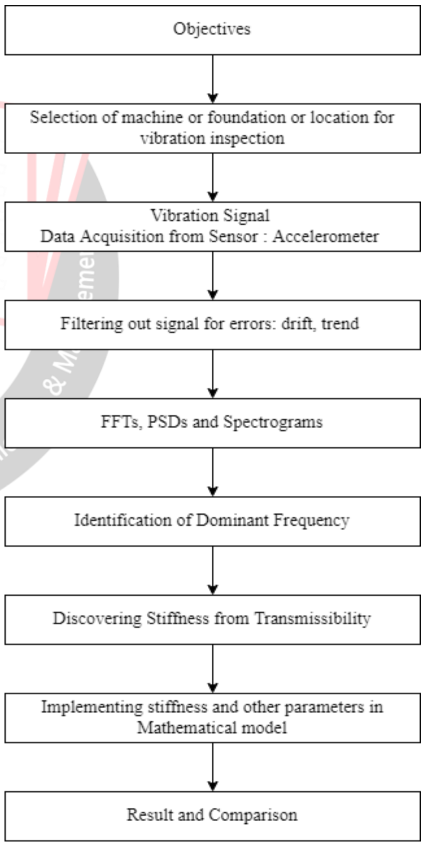

Figure 1 Methodology Process

DOI : 10.35291/2454-9150.2022.0204

From PSD, we can analyse in which frequency zone, the vibration has least power and simultaneously it should not be around operating zone. By following this method, dominating frequency can be kept far. According to above optimization, a frequency zone is predicted which leads to a condition for deriving stiffness and damping is achieved.

For linear vibration isolation, transmissibility equation is written in equation (2). Transmissibility equation can be in non-linear form. In MATLAB, values of stiffness and damping for design of mount is calculated. Based on values collected from program, a set of solution is stored in database for cross-verification. A Simulink model is developed which describes the vibration isolation system. Vibration signal is taken as input with mount properties stored in database and it predicts the response. This Simulink model previews the comparison between input signal and output signal after implementation of designed mount. RMS values are calculated and frequency spectrum of both signals are also compared to review the results.

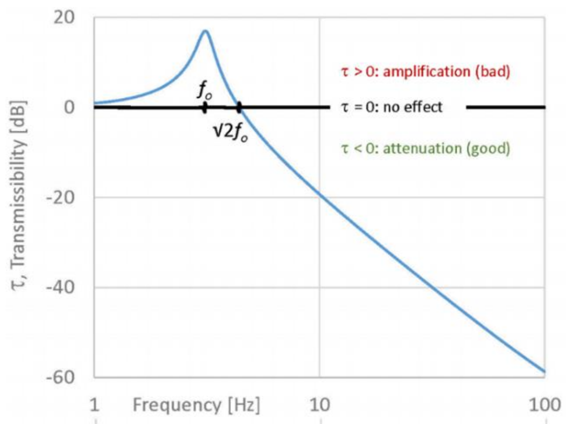

Figure 2 Transmissibility Curve

Figure 2 is a transmissibility curve shown for an example. It has horizontal axis as frequency values and transmissibility on vertical axis. The plot is in logarithmic form. The curve crosses transmissibility of one, in plot horizontal line of zero at $f = \sqrt{2}f_0$, means $\sqrt{2}$ times resonating frequency. The peak at resonance can be reduce by increasing damping, but it will also increase transmissibility beyond $\sqrt{2}f_0$. Commonly, damping ratio of any system is less than 0.1, unless a designed damping component is added to it. In real life experiment, transmissibility curve shows multiple peaks. In machines with number of rotating components, dominating force frequency is due to unbalance. The vibration signal has number of metrics, used for study: Velocity RMS, Acceleration Peak, Crest Factor, Acceleration RMS, Standard Deviation of Acceleration, Frequency of Peak Pseudo Velocity Displacement RMS, Peak Frequency, Acceleration RMS, Peak Pseudo Velocity. Each of this metric is used in vibration analysis for different purposes.

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-i2\pi ft}dt \qquad (1)$$

$$T_r = \left[\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}\right]^{\frac{1}{2}} \qquad (2)$$

where, ζ = damping ratio = $\frac{c}{c_{critical}}$

r = frequency ratio = $\frac{f}{f_{natural}}$

IV. Analytical Experimentation

For experimentation, a set of data is used as input signal to mathematical model in MATLAB. It is in time domain; therefore data must be in a way that first column consists of time and second column of measured values. This signal has data of 5 seconds with sampling rate of approximately 1024 Hz meaning approximately 1024 times values are measured during one second of time in almost equal interval. Therefore, there are more than 5000 data points. Figure 3 is graphical presentation of Time History data. Generally, when sampling rate is in power of 2 (= 2^n) like: 256, 512, 1024, 2048, etc., it is easier for calculations. From plot, it is impossible to understand how many frequencies are involved and how much amplitude of them. To operate, this data is first of all passed through filtering process of error reduction. Using trend removal and noise elimination tool from signal processing toolbox. Not just error removal but many times data consist of known frequencies which are unavoidable or useful, so it also eliminates those frequencies' involvement. Such process requires frequency filters based on transfer function. Filtered data is forwarded to be analysed in frequency domain.

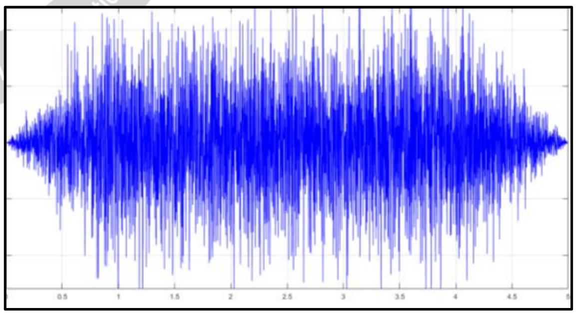

Figure 3 Input Vibration Signal

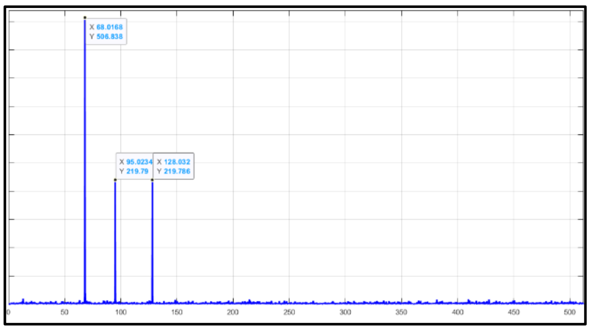

Figure 4 PSD plot

 DOI : 10.35291/2454-9150.2022.0204

Use of FFT as per mentioned in methodology section III, will be done for transformation. FFT and PSD will be calculated. Fast Fourier Transformation changes domain from time (sec) to frequency (Hz). Yet it still has noise of small involvement, and it needs to be reduced or eliminated for easy analysis. Therefore FFT is forwarded to PSD. PSD is plotted in Figure 4. Horizontal axis is of Frequency (Hz) and vertical axis is of Power (g^2/Hz). Our data sampling rate is 1024 Hz, so the frequency domain data will be calculated upto Nyquist frequency of 512 Hz. Frequency spectrum leads to analysis of comparison between noise, dominating frequencies and critical frequency. There are 3 frequencies, which shows peaks meaning they are dominating vibration signal. By comparison of respective power values, frequency dominance is decided. This data has following frequency involvement 68, 95 and 128 Hz in descending order of their power value. Higher frequencies might have high involvement in some cases because power depends on amplitude and frequency, both factors. For further processing, critical frequency needs to be chosen from 3 dominating. The smallest frequency 65 Hz is chosen to be the critical frequency as it holds high-power and by reducing vibration at this point, vibration due to frequencies higher than 65 Hz also damps out. From experimental observation, the mass of system mounted on it is around 15 Kg.

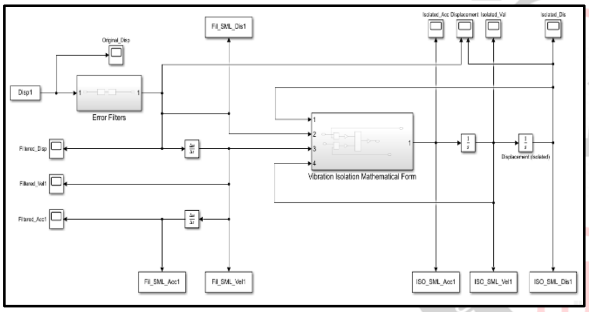

Figure 5 Simulink Model

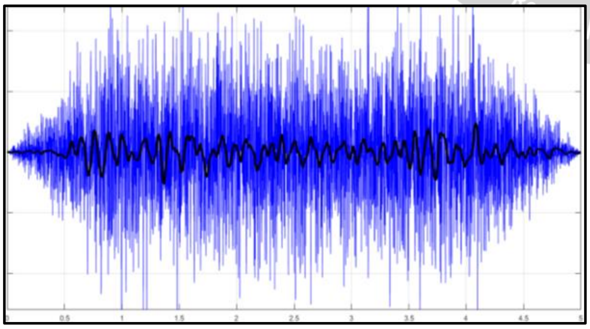

Figure 6 Output Simulation with comparison

From transmissibility curve and equation stiffness comes around 35.208 N/mm and damping co-efficient 1449.715 $N \cdot s/m$. These values are stored in database of MATLAB. Current, script is defined for linear vibration transmission behavior. For cross-verification of result, another model for running a comparative analysis is required. The second model is a Simulink program for simulation of result. Simulink model is a feature in MATLAB application, where user can define Mathematical operations using blocks and defines operations based on their parameters. This Simulink model is developed such that it filters data at first for useful information, afterwards according to sequence of mathematics, calculus and transfer functions blocks, signal is passed through. This model is directly implemented into the MATLAB script, so it will run once all the data is acquired. The original input signal of vibration is also used with found values of stiffness and damping directly from database. The sampling rate in Simulink also needs to be same otherwise it will run into errors. The Figure 5 is the Simulink model's preview. Simulink model is based on equations of motion of spring-damper of SDOF. The model includes input block from database, blocks of transfer function, mathematical operations, calculus, output to main database for collection of data and scope.

Simulink model runs and predicts an output signal once estimated stiffness and damping properties are used. The output of run comes in time domain. Figure 6 is a comparative representation of output and input signal. Black color signal is prediction of Simulink while blue signal is the original signal. To verify the dominance of frequency comparatively, FFT is used again. A comparison of FFT between both signal is plotted. The Figure 7 previews the comparison. In figure, the black data is of FFT of predicted response signal and blue is of original signal. The comparison proves that, the vibration is reduced on entire frequency axis and the small peak in initial frequency zone is significantly small compare to original signal. The later signal's Power is significantly less than original signal, due to that plot of PSD comparison shows almost a horizontal line close to frequency axis. The black data points curve also looks similar to transmissibility curve shown in Figure 2. The input vibration signal has 3 different dominating frequency values, while the predicted final output shows only one small frequency dominance and even that is small comparison. Therefore, frequency domain data also suggests that the estimated values must be able damp out vibration significantly.

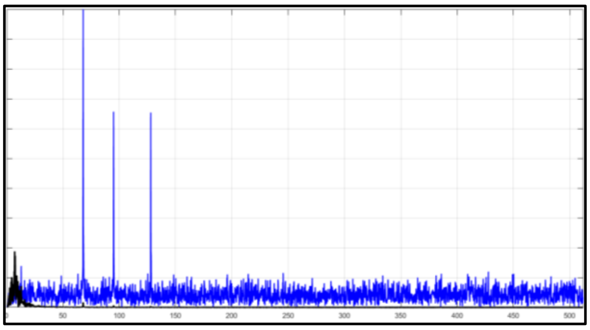

Figure 7 FFT Response comparison

V. CONCLUSION

MATLAB software is very beneficial computer application, as it can do large calculations very easily and accurately. Mathematical model defined in this research is based on single degree of freedom. For much complex

 DOI : 10.35291/2454-9150.2022.0204

system with high degree of freedom and non-linear parameters, it only requires to update the equations accordingly. This Mathematical Model not only solves equations but using other features of MATLAB it eliminates errors from faulty data easily. In analytical experiment, input vibration data has number of high amplitudes. Data processed using MATLAB eliminates error which provides advantage in improved accuracy after transformation to frequency domain. As our data has sampling rate of 1024 Hz during capture, the frequency spectrum and analysis done upto Nyquist Frequency of 512 Hz. And according to selection of critical frequency from spectrum, a stiffness and damping properties are estimated using linear transmissibility curve. The same input data with acquired solution is when directly simulated in Simulink, the prediction of output data showed good amount of damping and reduction in amplitudes. The Simulink model is linked directly to script, so verification of analysis and result becomes quick. Approximate reduction in percentage and previews of comparison between two signals in time domain and simultaneously in frequency domain, helps understand the amount of reduction in vibration. Overall conclusion is that this research proved to be effective as model defined using MATLAB does number of tasks in very less amount of time, even for highly complicated vibration data. The greater advantage of this study is, number of user defined task which takes time to manually one by one can be easily defined in MATLAB like computer application and provides result quickly. The visual presentation of frequency spectrum, comparison of vibration data in time and frequency domain helps user understand the effectiveness of result.

VI. ACKNOWLEDGEMENT

This research is done with support of Shivam Setia – Engineer at Fatigue and Material Excellence Centre of the Automotive Research Association of India, Pune. Authors are grateful of Mr. Setia for his support.

VII. REFERENCES

[1] P. Bointon, L. Todhunter, A. Clare and R. Leach, "Performance Verification of a Flexible Vibration Monitoring System," *Machines*, vol. 8, no. 3, 2020.

[2] S. S. Rao, Mechanical Vibrations, Pearson Prentice Hall.

[3] H. Huang, H. Ouyang, H. Gao, L. Guo, D. Li and J. Wen, "A Feature Extraction Method for Vibration Signal of Bearing Incipient Degradation," *Measurement Science Review*, vol. 16, pp. 149-159, 2016.

[4] Y. Du, R. A. Burdisso and E. Nikolaidis, "Control of internal resonances in vibration isolators using passive and hybrid dynamic vibration absorbers," *Journal of Sound and Vibration*, vol. 286, no. 4-5, pp. 697-727, 2005.

[5] Y. K. Cheung, S. H. Chen and S. L. Lau, "Application of the incremental harmonic method to cubic non-linearity systems," *Journal of Sound and Vibration*, vol. 140, no. 2, pp. 273-286, 1990.

[6] Z. Lu, M. J. Brennan and L.-Q. Chen, "On the transmissibilities of nonlinear vibration isolation system," *Journal of Sound and Vibration*, vol. 375, pp. 28-37, 2016.

[7] Y. Liu, L. Xu, C. Song, H. Gu and W. Ji, "Dynamic characteristics of a qausi-zero stiffness vibration isolator with nonlinear stiffness and damping," *Archives of Applied Mechanics*, vol. 89, pp. 1743-1759, 2019.

[8] I. Kovacic, M. J. Brennan and T. P. Waters, "A study of a nonlinear vibration isolator with a quasi-zero stiffness characteristics," *Journal of Sound and Vibration*, vol. 315, no. 3, pp. 700-711, 2008.

[9] A. Carrella, M. J. Brennan, T. P. Waters and V. Lopes Jr., "Force and displacement transmissibility of a nonlinear isolator with high-static-low-dynamic-stiffness," *International Journal of Mechanical Sciences*, vol. 55, no. 1, pp. 22-29, 2012.

[10] X. Yang, J. Zheng, J. Xu, W. Li, Y. Wang and M. Fan, "Structural design and isolation characteristic analysis of new quasi-zero-stiffness," *Journal of Vibration Engineering & Technologies*, vol. 8, pp. 47-58, 2020.

[11] A. Valeev, A. Zotov and S. Kharisov, "Designing of Compact Low Frequency Vibration Isolator with Quasi-Zero-Stiffness," *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 34, no. 4, pp. 459-473, 2015.

[12] A. Valeev and S. Kharisov, "Application of Vibration Isolators with a Low Stiffness for the Strongly Vibrating Equipment," *Procedia Engineering*, vol. 150, pp. 641-646, 2016.

[13] H. Pu, X. Luo and X. Chen, "Modeling and analysis of dual-chamber pneumatic spring with adjustable damping for precision vibration isolation," *Journal of Sound and Vibration*, no. 330, pp. 3578-3590, 2011.

[14] P. S. Balaji, L. Moussa, M. E. Rahaman, P. L. Y. Tiong, L. H. Ho and A. Adnan, "Performance study of Wire Rope Isolators for vibration isolation equipment and structures," *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 18, pp. 11036-11042, 2016.

[15] S. Han, "Measuring displacement signal with an accelerometer," *Journal of Mechanical Science and Technology*, vol. 24, no. 6, pp. 1329-1355, 2011.

 DOI : 10.35291/2454-9150.2022.0204