CHAPTER 3

ROTATING MACHINERY VIBRATION ANALYSIS AND ENERGY LOSS CALCULATION USING LabVIEW

3.1 INTRODUCTION

Vibration analysis is one the prominent approaches in predictive maintenance. Rotating machines experience the vibration from the start, run and shut down of the machinery. This chapter illustrates the virtual instrument based vibration analyzer with designated hardware with mathematical model. Compatibility of the virtual instrument system is compared with a conventional instrument and results are presented.

Vibration signals are studied by using various methods and designated hardware. Vibration textures and signatures are studied using different mathematical models and analysis techniques in time and frequency domain.

3.2 DESIGN REQUIREMENT

Based on the development by Chanting Wang and Robert Gao (2000), a LabVIEW based bearing condition monitoring system, as a user and engineer friendly integrated system, was studied.

A Virtual Instrument design with single channel algorithm is found and decided to enhance in the proposed research.

Haider and Koronios et al (2006) delineated different technological advances including vibration analysis for the condition monitoring so as to improve the performance of manufacturing industries. In this work, e-intelligent integrated condition monitoring was studied and the interface with sensors and interface also discussed about communicating the result with Machine Interface System to provide indications and exact location of the failure condition developing. Based on this work a need for web enabled measurement analysis system was identified.

Jose De Jesus et al (2010) described an FPGA based vibration analyser as a full custom IC design machine monitoring with FFT and DWT analysis to decompose the frequency band with certain sampling frequency. An instrumentation system with basic sensory unit without reconfigurability was studied. Hence the need for reconfigurable and stand alone executable instrument system was understood and proposed in this section with relevant data acquisition system.

3.3 PROPOSED METHODOLOGY

Rotating machine vibration is to be monitored periodically to avoid machine damage and the cost involved. Laggan et al (1999) narrated about vibration monitoring. Srinivas et al (2004) discussed about vibration analysis of motor due to bearing, housing and rotor. Condition monitoring helps to identify the power consumption due to vibration, higher operating speed, improved efficiency and to avoid occupational hazards.

In the proposed method, Spectral analysis is found to be the suitable methodology for estimation to understand the cause for vibration. Analytical method and texture analysis will be helpful for finding energy loss and to evolve recommendations. The proposed method describes the network based remote server configuration for the estimation of vibration profile. LabVIEW has been selected as the graphic environment for developing the proposed virtual vibration analyser.

3.4 DESIGN FORMULATION AND SIGNAL FLOW ALGORITHM

The following are the virtual instrument based vibration analysis signal flow algorithm:

1. A mathematical model has been formulated with vibration analysis Methods.
2. Correlation of design environment has been identified.
3. Signal interface was designed for signal flow.
4. Design requirements based on the section 4.2 was realized with suitable tools in the selected environment.
5. Study has been carried out for compatibility of the instrument design.
6. Secured signal transmission has been designed with VI server concept.

Each section of the above signal flow is involved the software model and signal interface development. For the design and development of the proposed design, LabVIEW has been selected as the graphic environment. It has been depicted in Figure 3.1

3.5 SIGNAL FLOW CHART FOR PROPOSED VIRTUAL VIBRATION ANALYSER

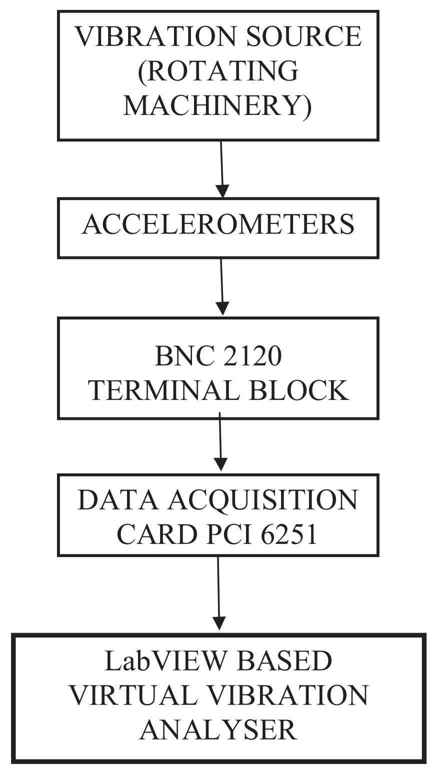

Figure 3.1 Signal Flow chart of Proposed Workbench

3.6 LabVIEW FEATURES FOR PROPOSED INSTRUMENT DESIGN

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a 'G' programming (graphical programming) environment to configure a Virtual Instrument, shortly called as VI. A VI is the combination of software and hardware based instrument system onto the industry standard computer technologies. The importance of LabVIEW environment and design for data acquisition and signal processing system of mechanical vibration was clearly explained Zhao Hua (2011).

The following are the effective features of LabVIEW environment for fulfilling the design requirement based on the previous literature:

1. Graphical programming environment for User interface and Source code.
2. Faster development time, upto 4 to 10 times reduction than text based programming.
3. Easily modularized programme structure with interlinked execution.
4. User defined and Reconfigurable instrument system.
5. Standalone executables for the operating environment.

3.7 OTHER EQUIVALENT ENVIRONMENTS

There are few related software environments for carrying out the same functionality as listed below:

MATLAB - Allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces and interfacing with programs written in other languages. But signal interfaces are not available with MATLAB as compared to LabVIEW

TESTSTAND- Ready-to-run test management software that is designed to help develop automated test and validation systems faster. But mathematical tools and signal processing tools are very versatile with LabVIEW.

3.8 ROTATING MACHINERY VIBRATION ANALYSIS METHODS

Vibration has static and dynamic characteristic where on the firmly fixed heavy machines and rotating machinery. Davis et al (1993) explained about comparison of methods and analysis of vibration measurement. Amati et al (2001) explained vibration condition monitoring of induction motors with a specified method. Amei Li et al (2003) presented a method for vibration condition monitoring during hard disk spacing variation. A few mathematical methods illustrate the analysis of single and multi- level systems. The helps to find the fundamental frequency in order to study the resonance.

3.8.1 Rayleigh Method

The fundamental frequency of multi-DOF system is often of greater interest than its higher natural frequencies because it is forced response and in many cases it is the largest. Rayleigh method was introduced to obtain a better estimate of the fundamental frequency of the systems that contained flexible elements such as springs and beams.

3.8.1.1 Potential energy, kinetic energy and fundamental frequency estimation

Using Rayleigh, a vibration signal is understood by its displacement, velocity and acceleration measurement. This helps to estimate fundamental frequency and to relate potential and kinetic energies. Assume M and K as the mass and stiffness matrices respectively, and X the displacement vector for the amplitude of vibration. Then for harmonic motion, the maximum kinetic and potential energies can be written as

$$T_{max} = \frac{1}{2}\omega^2 X^T M X \tag{3.1}$$

and

$$U_{max} = \frac{1}{2} X^T K X \tag{3.2}$$

Equating the Equations (3.1) and (3.2) and solving for ω^2, Rayleigh quotient is obtained as:

$$\omega^2 = \frac{XTKX}{XTMX} \tag{3.3}$$

This quotient mentioned in Equation (3.3) approaches the lowest natural frequency, called as fundamental frequency, from the high side and its value is somewhat insensitive to the choice of the assumed amplitudes. This analysis shows that if the exact fundamental deflection (or mode) X_1 is assumed and hence the fundamental frequency is found by this method. If greater accuracy is desired, the approximate curve can be repeatedly improved. Daan Rabijns et al (2004) narrated about spectrum analysis of periodical signals. Ohashi et al (2005) and Oviedo et al (2011) discussed about machinery vibration analysis and energy involved.

The potential energy was determined by the work done by the static weights in the assumed deformation. This work is, of course, stored in the flexible manner as strain energy. Let M be the bending movement and θ the slope of the elastic curve, the strain energy stored in an infinitesimal element is given by Equation (3.4)

$$dU = \frac{1}{2} M d\theta \tag{3.4}$$

The kinetic energy is given in Equation (3.5)

$$T_{max} = \frac{1}{2}\int \dot{y}^2\, dm = \frac{1}{2}\,\omega^2 \int y^2\, dm \tag{3.5}$$

where y is the assumed deflection curve. Thus, by equating Equations (3.4) and (3.5) the kinetic and potential energy, an alternative equation for the fundamental frequency is indicated in Equation (3.6)

$$\omega^2 = \int EI\,(\,d^2y/dx^2\,)^2\, dx \,/\, \int y^2\, dm \tag{3.6}$$

This method provides fundamental frequency, potential and kinetic energy of the vibration.

3.8.2 Accuracy of the Integral Method Over Differentiation

In using Rayleigh's method for determining the fundamental frequency, a curve is assumed. Although the deviation of this assumed deflection curve compared to the exact curve may be slight, its derivative could be in error by a large amount and hence the strain energy is computed from the Equation (3.7)

$$U = \frac{1}{2}\int EI\,(\,d^2y/dx^2\,)^2\, dx \tag{3.7}$$

The resultant may be inaccurate. To avoid this difficulty, the following integral method for evaluating U is recommended for some problems.

The problem is overcome as mentioned in Equation (3.8) by the method of integral of the inertia loading $m\omega^2 y$ from the free end of the vibrating body as,

$$V(€) = \omega^2 \int_{€}^{l} m(€)y(€)d€ \tag{3.8}$$

Equation (3.9) shows the shear relation by using bending moment,

shear relation, $\frac{dM}{dx} = V$ (3.9)

The moment at x is found from integral as shown in Equation (3.10)

$$M(x) = V\int_{€}^{l}(€)d€ \tag{3.10}$$

The strain energy of the vibration segment is then found from (3.11) as.

$$U = \frac{1}{2}\int_{0}^{1} M(x)2/EI\ dx \tag{3.11}$$

which avoids any differentiation of the assumed deflection curve.

3.8.3 Lumped Masses

Rayleigh method can be used to determine the fundamental frequency of a beam or shaft represented by a series of lumped masses. At a first approximation, assume a static deflection curve due to loads M_1g, M_2g, M_3g and so on, with corresponding deflections y_1, y_2, y_3.... The strain energy stored in the beam is determined from the work done by these loads, and the maximum potential and kinetic energies becomes as U_{max}, as indicated in Equations (3.12) and (3.13)

$$U_{max} = \frac{1}{2}g(M_1y_1 + M_2y_2 + M_3y_3 + \ldots.) \tag{3.12}$$

$$T_{max} = \frac{1}{2}\omega^2(M_1y_1^2 + M_2y_2^2 + M_3y_3^2 + \ldots.) \tag{3.13}$$

By equating the Equations (3.12) and (3.13) the frequency equation is established as mentioned below in Equation (3.14).

$$\omega_1^2 = g\sum Miyi \ / \sum Miyi2 \tag{3.14}$$

3.8.4 Undamped Forced Vibrations with Harmonic Excitation

When a harmonic forcing function acts on a system, the solution consists of the transient part and the steady state part. In the steady state part the vibrations of any part in the system take place at the frequency equals any of the natural frequencies of the system. Ling Xiang et all (2008) and Luis Miguel et al (2010) discussed a method for time and frequency attributes of vibration signal.

Considering the system with exciting force F_o sinωt acting on mass m_1, the differential equation of motion for the two masses will be the same as Equations (3.15) and (3.16) except that the term F_o sinωt will not be introduced on the right hand side of the equations. On rearranging,

$$[m1\ddot{X}_1+(k_1+k_2)x_1]-[k_2x_2] = F_o \sin\omega t \tag{3.15}$$

$$[k_2x_1]-[m_2\ddot{X}_2+(k_2+k_3)x_2] = 0 \tag{3.16}$$

For the case of no damping in the system each mass will be either in phase or out of phase with exciting force. Then assume, for the steady state, the solutions is given as mentioned in Equations (3.17) and (3.18) with different amplitudes X_1 and X_2

$$x=X_1\sin\omega t \tag{3.17}$$

$$x=X_2\sin\omega t \tag{3.18}$$

Substituting the value of 'x' in Equations (3.15) and (3.16) and cancell out the common term sin ωt,

$$[-m_1\omega^2+(k_1+k_2)]X_1-k_2X_2=F_o \tag{3.19}$$

$$k_2x_1-[-m_2\omega^2+(k_2+k_3)x2]=0 \tag{3.20}$$

Solving for X_1 and X_2 from the above two equations,

$$X_1=\frac{[k2+k3-m2\omega 2]F_o}{[m1m2\omega 4-\{m1(k2+k3)+m2(k1+k2)\}\omega 2+\{k1k2+k2k3+k3k1\}]} \tag{3.21}$$

$$X_2=\frac{k2F_o}{[m1m2\omega 4-\{m1(k2+k3)+m2(k1+k2)\}\omega 2+\{k1k2+k2k3+k3k1\}]} \tag{3.22}$$

The above two Equations (3.21) and (3.22) give the steady state amplitude of vibration of the two masses respectively, as a function of ω. That means when the exciting frequencies are equal to any of the two natural frequencies, the denominators of equations vanish condition. Thus the system has two resonance frequencies, each corresponding to the one natural frequency of the system. At resonance, all the points in the system have infinite amplitude of vibration.

Experimental modal analysis, also known as modal analysis deals with the determination of natural frequencies, damping ratios and mode shapes through vibration testing. Two basic ideas are involved:

1. When a structure machine or any system is excited its response exhibits a sharp peak at resonance when the forcing frequency is equal to its natural frequency when damping is not large.
2. The phase of the response changes by 180^O as the forcing frequency crosses the natural frequency of the structure or machine and the phase will be 90^o at resonance.

This analysis necessitates a vibration exciter, transducer, signal condition unit and analyser. So the research focuses on developing the analyser using LabVIEW based Virtual environment and studing vibration signals.

3.9 MATHEMATICAL BACKGROUND FOR SELECTING A DATA ACQUISITION SYSTEM

Virtual instrument systems are the combination of software and hardware based reconfigurable instrument systems. In this research, necessary DAQ cards are used for signal processing. This section provides the mathematical background for selecting the analyser and signal processing elements. Gani et al (2002) discussed about LabVIEW based data acquisition system for vibration monitoring. Giovanni et al (2002) explained about DSP based FFT analyser fault diagnosis of rotating machine with vibration study. He Qing et al (2008) discussed about vibration measurement and dynamic balancing with NI DAQ cards. Vijayalakshmi et al (2011) presented about vibration textures.

The analyzer converts the analog time-domain signals, $x(t)$, into digital frequency domain data using Fourier series relations to facilitate digital computation. Thus the analyzer accepts the analog output signals of the accelerometers or force transducers, $x(t)$, and computes the spectral coefficients of these signals $a_o, a_i,$ and b_i . The process of converting analog signal into digital data by ADC is part of a digital analyzer. If N samples of $x(t)$are collected at discrete values of time, t_i, the data [$x_1(t_i)$, $x_2(t_i)$,…,$x_N(t_i)$] can be used to obtain the discrete form of Fourier transform as found in Equation (3.23).

$$x_j = x(t_j) = \frac{a_o}{2}\sum_{i=1}^{N/2}\left(a_i \cos\frac{2\pi i t_j}{T} + b_i \sin\frac{2\pi i t_j}{T}\right) \; ; j = 1,2,\ldots,N \tag{3.23}$$

where the digital spectral coefficients ao, ai, and bi are estimated as indicated in the Equations (3.24), (3.25) and (3.26)

$$a_o = \frac{1}{N}\sum_{j=1}^{N} x_j \tag{3.24}$$

$$a_i = \frac{1}{N}\sum_{j=1}^{N} x_j \cos\frac{2\pi i t_j}{T} \tag{3.25}$$

$$b_i = \frac{1}{N}\sum_{j=1}^{N} x_j \sin\frac{2\pi i t_j}{T} \tag{3.26}$$

with the number of samples N equals to some power of 2 (such as 256, 512, or 1024) which is fixed for a given analyzer. The above equations denote N algebraic equations for each of the N samples. The equations can be expressed in matrix form as,

$$\vec{X} = [A]\vec{d} \tag{3.27}$$

In equation (3.27), matrix $\vec{X} = \{x_1 , x_2 \ldots x_N\}^T$ is the vector of samples, $\vec{d} = \{ a_0\, a_1, a_2 \ldots a_{N/2} \;\; b_0\, b_1 b_2 \ldots b_{N/2} \}^T$ is the vector of spectral co-efficients, and [A] is the matrix composed of the coefficients $\cos\frac{2\pi i t_j}{T}$ and $\sin\frac{2\pi i t_j}{T}$. The frequency content of the signal or response of the system can be determined as per equation (3.28), from the solution:

$$\vec{d} = [A]^{-1}\vec{X} \tag{3.28}$$

where $[A]^{-1}$ is computed efficiently using Fast Fourier Transform (FFT) by the analyzer. The above equations are well correlated in this research with approach proposed by Toyota et al (1999) and Toozhy et al (2000).

3.10 SELECTION PARAMETERS FOR DATA ACQUISITION SYSTEM

Based on the mathematical background from section 3.3 Data Acquisition System is selected with the following selection criteria:

1. Sampling rate
2. Single or multiplexed channels
3. Resolution
4. Signal range (minimum and maximum voltage levels)
5. Compatible signal interface standard
6. Analog and Digital graphs
7. Counter and Timer functions
8. Acquire anywhere, Analyse anywhere and Present anywhere feature
9. Capability of developing a low cost data logger
10. Mathematical and Digital Signal Processing functions

LabVIEW Windows

Front panel - Serves as the user interface designed by using Controls palette.

Block diagram- Contains the graphical source code that defines the functionality of the VI designed by using Functions palette.

Icon and connector panel-Identifies the VI so that a VI can be used in another VI. A VI within another VI is called a subVI. A subVI corresponds to a subroutine in text-based programming languages.

3.11 OTHER EQUIVALENT ENVIRONMENTS

There are few related software environments for carrying out the same functionality as listed below:

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TESTSTAND - Ready-to-run test management software that is designed to help develop automated test and validation systems faster. But mathematical tools and signal processing tools are very versatile with LabVIEW.

3.12 OTHER COMMON METHODS FOR VIBRATION ANALYSIS

3.12.1 Speed Trials

Changes in vibration levels as a function of changing machine speeds or loads are normally analyzed using waterfall plots. The X-axis represents frequency, the Y-axis represents vibration amplitude and the Z-axis represents time or machine speed. Waterfalls are useful for the identification of resonances. The high energy levels of the rotating components excite structural resonances, as well as those of rolls and major components.

Changes in vibration as a function of changing machine speed are easily analyzed with this tool.

3.12.2 Speed Trial Data

Speed trial data will reveal the data related to resonance that is excited by multiples of vibration segments of rotational frequency with the 3rd harmonic being the most dominant source of vibration.

Vibration levels reached 0.8 in/s, which is generally considered to be very high and harmful. It contributes to component failure due to fatigue.

3.12.3 Impact Testing

The purpose of impact testing is to identify the natural frequencies of typically smaller components in the rotating machine, such as tube rolls, doctors, drive shafts, motor stands, showers etc. This complements the speed trial, because the speed trial and resultant waterfalls will show multiple excited natural frequencies and resonance.

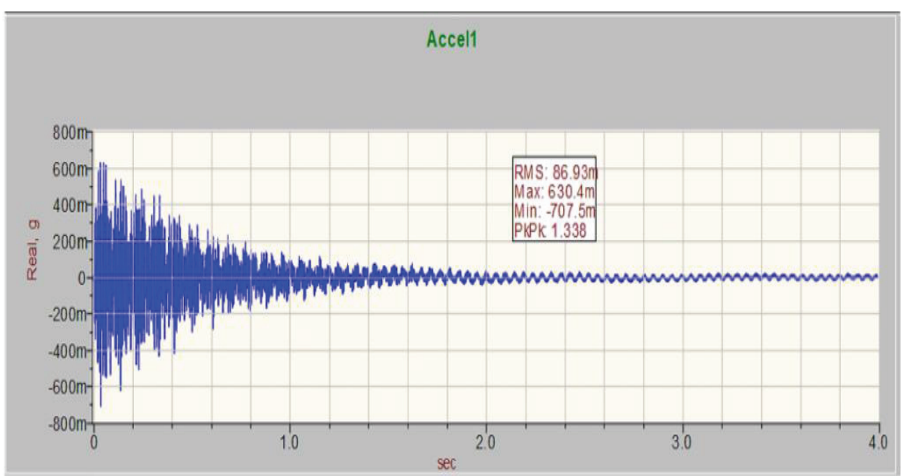


Figure 3.2 The time domain response of an Impact testing

The equipment consists of a modal hammer that contains a force sensor, and a conventional vibration sensor such as an accelerometer mounted on the component being measured and it is illustrated in Figure 3.2. The component is impacted by the hammer, which measures the force of impact. The accelerometer measures the response. The software then generates a transfer function in the frequency domain - the ratio of response to force. The peaks of the transfer function correspond to the natural frequencies of the component being measured. The amplitude tells the analyst the energy required to excite the mode.

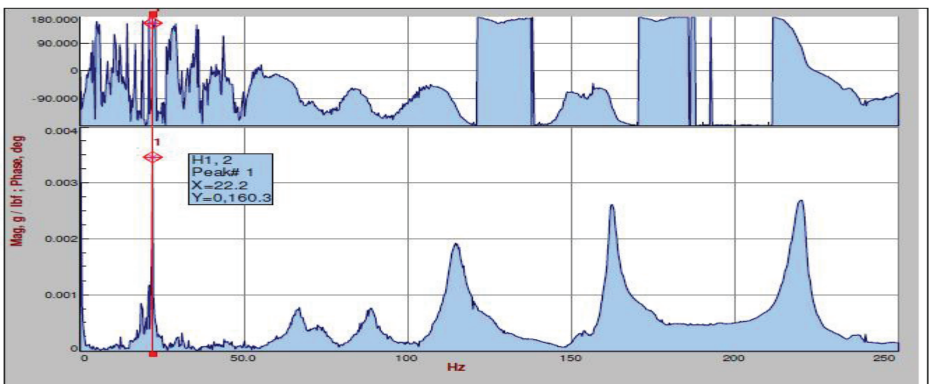


Figure 3.3 Response for impact testing on horizontal forces

Impact testing on the tension roll also revealed natural frequencies between 70 and 80 Hz, which correlated well with the ODS results are depicted in Figure 3.3

3.12.4 Synchronous Averaging

Synchronous averaging is used to isolate the contribution of vibration of a single rotating source. This is done by obtaining a tachometer trigger from a given roll or felt and then timing the data acquisition perfectly with the occurrence of the trigger. Averaging of a series of acquisitions then removes the vibration contribution of asynchronous components - leaving only that vibration which is synchronous with the trigger.

Time Synchronous Averaging is a fundamentally different process than the usual spectrum averaging that is generally used in FFT analysis. While the concept is similar, TSA results in a time domain signal with lower noise than would result with a single sample as indicated in Figure 3.4. An FFT can then be computed from the averaged time signal. The signal is sampled using a trigger that is synchronized with the signal. The averaging process gradually eliminates random noise because the random noise is not coherent with the trigger.

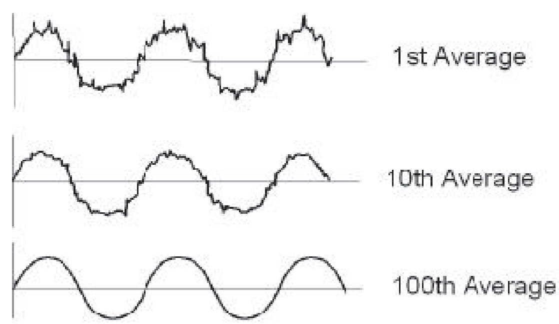


Figure 3.4 Illustration of the effect of Time Synchronous Averaging

Traditional spectrum based averaging records a frame of data in the time domain, computes the FFT and then adds the FFT spectrum to the averaged spectrum. The time signal is discarded and then the process is repeated until the averaging number is complete. Important application of time synchronous averaging is in the waveform analysis of machine vibration, especially in the case of rotating machinery drives. In this case, the trigger is derived from a tachometer that provides one pulse per revolution of a rotating machinery in the machine. This way, the time samples are synchronized in that they all begin at the same exact point related to the angular position of the rotating machinery. After performing a sufficient number of averages, spectrum peaks that are harmonics of the rotating machinery rotating speed will remain while non-synchronous peaks will be averaged out from the spectrum.

3.12.5 Operating Deflection Shape (ODS) Analysis

ODS analysis shows how a machine or structure moves in actual operation at specific frequencies of interest and helps determine the cause of the motion. If the data used in the ODS analysis is fit to natural frequencies of the system then the resultant model will show mode shapes instead. Knowing which modes are being excited and the positions of greatest movement allow for the most effective structural modifications. An ODS requires gathering vibration data in three directions at various points on a machine. The data is then processed on a personal computer to allow animation of a stick figure or 3D model representation, showing relative amplitude and phase between all measured points, at any selected frequency. The pictures are single frame shots from a movie that shows the motion of a press section at a 5 Hz natural frequency. The software can allow easy visualization from any angle of interest.

An operating deflection shape (ODS) is defined as any forced motion of two or more points on a structure. Specifying the motion of two or more points defines a shape.

3.12.6 Linear Spectrum

This frequency domain function is simply the FFT of a sampled time domain function. Phase is preserved in the Linear Spectrum, so in order to obtain operating deflection shapes from a set of Linear Spectra, either the measurement process must be repeatable, or the time domain signals must be simultaneously sampled. Since the Linear Spectrum is complex valued, the resulting operating deflection shapes will also contain magnitude and phase information.

3.12.7 Auto Power Spectrum

The APS is derived by taking the FFT of a sampled time domain function, and multiplying the resulting Linear Spectrum by the complex conjugate of the Linear Spectrum at each frequency. Phase is not preserved in the APS, so a set of these measurements need not be obtained by simultaneously sampling all of the time domain responses. Since phase is not retained in these measurements, operating deflection shapes derived from them will contain only magnitude, and no phase information.

3.12.8 Finite Element Analysis

Finite Element Analysis (FEA) involves the mathematical modeling of a physical system to predict the structural behavior of the system - involving geometry, material properties, boundary conditions, etc. The model is used to determine what the new natural frequencies of the system will be after structural modification is applied. The model can be as simple or extensive as required.

FEA consists of a computer model of a material or design that is stressed and analyzed for specific results. It is used in new product design, and existing product refinement.

Regions which will receive large amounts of stress usually have a higher node density than those which experience little or no stress. Points of interest may consist of: fracture point of previously tested material, fillets, corners, complex detail, and high stress areas. This web of vectors is what carries the material properties to the object, creating many elements.

3.13 SELECTING A TERMINAL BLOCK

Terminal blocks are normally selected based on the number of Analog and Digital input/output channels and other features specifically required for certain application.

3.14 DATA ACQUISITION SYSTEM FOR VIRTUAL VIBRATION ANALYSER

3.14.1 BNC-2120

The NI BNC-2120 is a shielded connector block with signal-labelled BNC connectors. One can use this connector block can be used with NI X Series, M Series, E Series, and S Series multifunction I/O data acquisition (DAQ) devices as well as analog output devices. The BNC-2120 simplifies the connection of analog signals, some digital signals, and two user-defined connections to the DAQ device while maintaining the integrity of measurements with a shielded enclosure.

- BNC connectors for I/O connections
- Interfaces to X Series, M Series, E Series, S Series, and NI 671x devices
- Shielded enclosure
- Function generator and quadrature encoder
- Temperature reference and thermocouple connector

3.14.2 DAQ specification

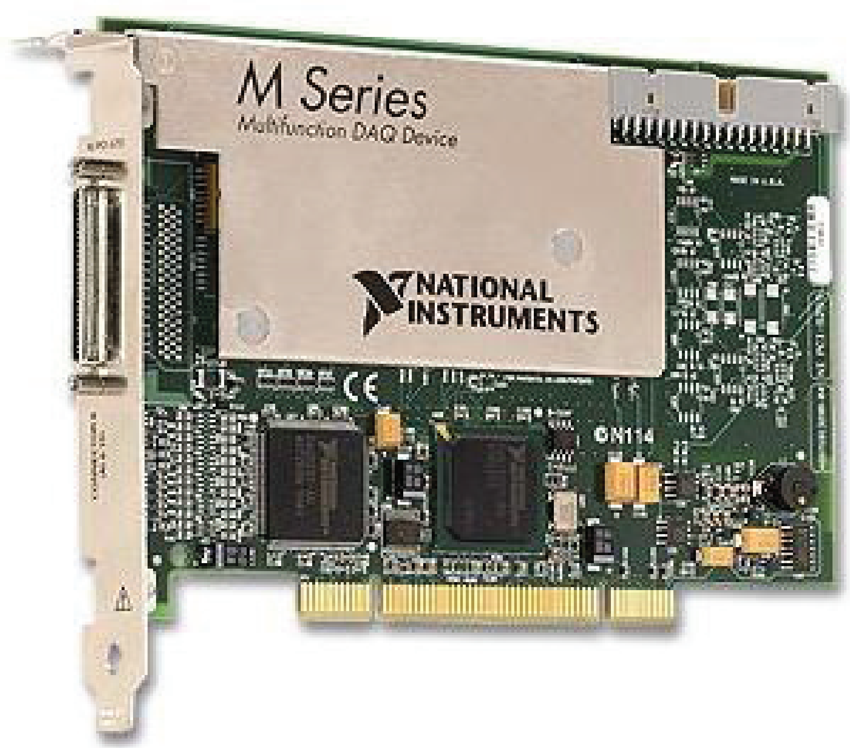


Figure 3.5 M Series PCI 6251 DAQ Card

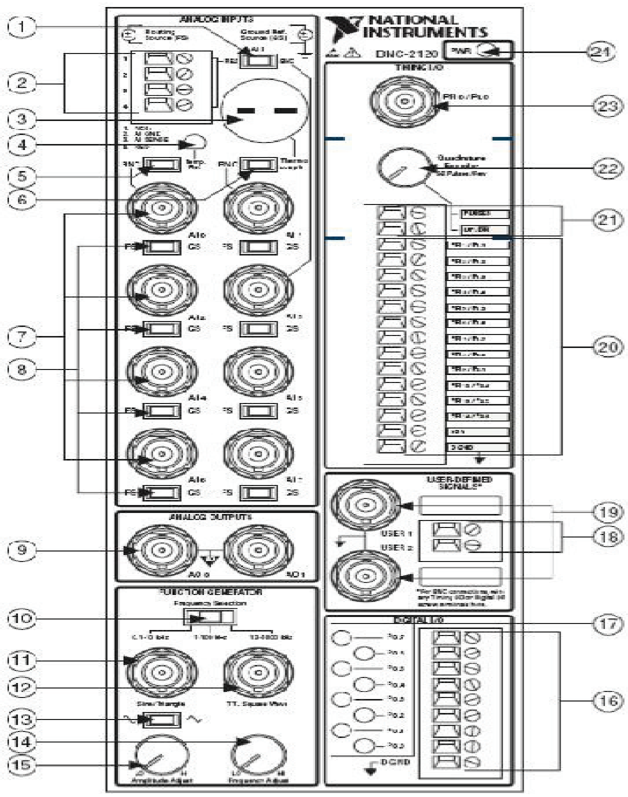
Figure 3.5 represents the High-speed M Series Multifunction DAQ - 16 Bit, up to 1.25 MS/s, upto 80 Analog Inputs

- NI recommends high-accuracy M Series for 5X more measurement sensitivity or industrial M Series for 10X better noise rejection.
- 16, 32, or 80 analog inputs at 16 bits.
- 1.25 MS/s (1 MS/s scanning 1)

- Up to 4 analog outputs at 16 bits, 2.8 MS/s (2 μs full-scale settling)
- 7 programmable input ranges (+100mv to +10 v & -100mv to -10 v)per channel.
- Up to 48 TTL/CMOS digital I/O lines (up to 32 hardware-timed at 10 MHz).
- Two 32 bit, 80 MHz counter/timers.
- Analog and digital triggering.
- NI-MCal calibration technology for improved measurement accuracy.
- 6 DMA channels for high-speed data throughput.
- X1, X2, or X4 quadrate encoder inputs.
- 2-year calibration interval.
- The platform to be used,
    - Windows Vista/XP/2000
    - MAC OS X
    - Linux

3.14.3 Connection of BNC-2120

Connect BNC-2120 accessory to M series device, connect one end of 68-position cable to M series device and the other end to the 68-position I/O connector on the BNC-2120. Figure 3.6 shows the BNC-2120 front panel.



1 RES/BNC Switch (AI 3)
2 Resistor Measurement Screw Terminals
3 Thermocouple Input Connector
4 Temperature Reference
5 BNC/Temp. Ref. Switch (AI 0)
6 BNC/Thermocouple Switch (AI 1)
7 Analog Input BNC Connectors
8 FS/GS Switches
9 Analog Output BNC Connector
10 Frequency Range Selection Switch
11 Sine/Triangle BNC Connector
12 TTL Square Wave BNC Connector
13 Sine/Triangle Waveform Switch
14 Frequency Adjust Knob
15 Amplitude Adjust Knob
16 Digital I/O Screw Terminals
17 Digital I/O LEDs
18 User-Defined Screw Terminals
19 User-Defined BNC Connectors
20 Timing I/O Screw Terminals
21 Quadrature Encoder Screw Terminals
22 Quadrature Encoder Knob
23 Timing I/O BNC Connector
24 Power Indicator LED

Figure 3.6 BNC 2120 terminal block

3.14.4 NI USB-6009

The NI USB-6008/6009 provides connection to eight single-ended Analog Input (AI) channels, two Analog Output (AO) channels, 12 Digital Input/Output (DIO) channels, and a 32-bit counter with a full-speed USB interface, as indicated in Figure 3.7.

AI resolution	:	14 bits differential
Maximum AI sample rate, single channel	:	48 kS/s
Maximum AI sample rate, multiple channels	:	48 kS/s
DIO configuration	:	Each channel is individually programmable as open collector or active drive.

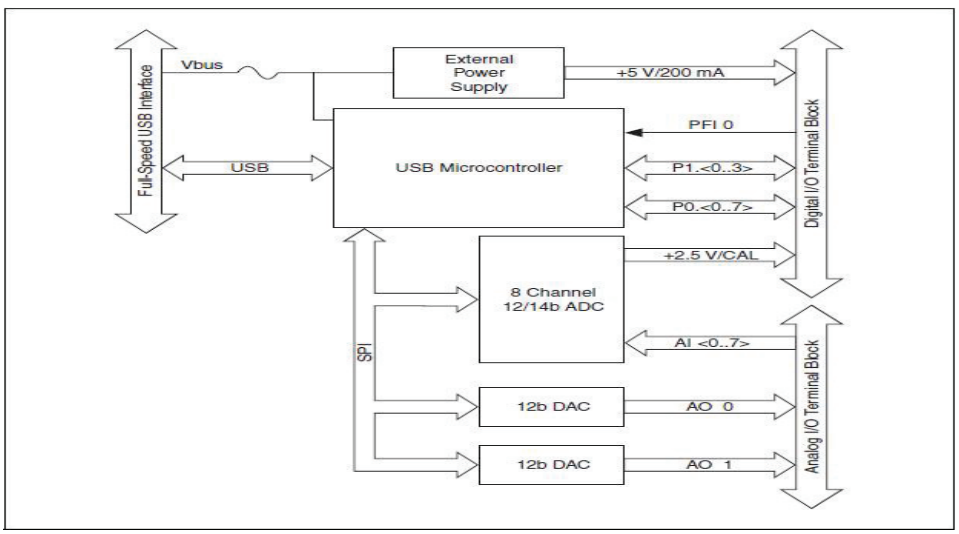


Figure 3.7 USB 6009 Functional block diagram

3.15 MATHEMATICAL BACKGROUND FOR THE SENSOR

Vibration has reciprocating or back-and-forth movement involving a continual interchange of kinetic energy and potential energy. It also involves an oscillation of repetitive motion around a mean equilibrium position. It is the combination of many oscillatory motions simultaneously.

Alessandro Depari et al (2007) discussed about sensor data processing in ANFIS network and Alberto Vallan et al (2010) described about vibration parameters measurement.

Amplitude describes the severity of vibration, and frequency describes the oscillation rate of vibration. The combined spectra will illustrate the root cause for vibration. Vibration is related to the size of the vibratory movement, speed and the force associated with the movement. Since vibration is a combination of multiple oscillatory motions, spectral analysis is being carried out for studying the individual frequencies at which a machine component vibrates, as well as the amplitudes corresponding to those frequencies, to get inferences on the condition of the machine. Vibration analysis involves data collection method, fast data collection, data processing and data display.

Since the paper addresses the instrumental method with virtual instrument technique selection criteria, sensors are significant. Piezoelectric transducers, which generate electrical charge when subjected to a mechanical stress, are suitable for vibration measurements.

The charge generated in the crystal due to a force is given by Equation (3.29).

$$Q = kF = kAp \tag{3.29}$$

where k is called the piezoelectric constant, A is the area on which the force F acts and p is the pressure due to F. The output voltage of the crystal 'E' is given in Equation (3.30),

$$E= vtp \tag{3.30}$$

where $\boldsymbol{v}$ is called the voltage sensitivity and t is the thickness of the crystal.

When a transducer is used in conjunction with another device to measure vibrations, as a vibration pick up has mass (m) spring (k) damper (c) as a system mounted on the vibration body, then the vibratory motion is measured by finding the displacement of the mass relative to the base on which it is mounted. The bottom ends spring and the dashpot will have the same motion as the cage and their vibration excites the suspended mass into motion. Then the displacement of the mass relative to the cage, z = x-y, where x denotes the vertical displacement of the suspended mass.

3.16 TYPES OF VIBRATIONAL EFFECTS

Vibration classification is required to position the sensor. Some basic classes of vibration include lateral, torsional and axial. Nowotny et al (1999) and McInerny et al (2003) discussed about some of the sensory effects.

Since mechanical stress causes charge development in the sensor, the sensor will experience the following effects viz. longitudinal, shear and traverse.

Longitudinal effect:

The size of the charge depends only on the force applied.

The only way to increase this charge is to connect several plates mechanically in series and electrically in parallel.

If this is done, the charge is found as in Equation (3.31):

$$Q_x = d_{11} \times F_x \times n \tag{3.31}$$

where d_{11} = piezoelectric coefficient (for quartz crystal). Its value is given in the Equation (3.32)

$$d_{11} = 2\ .30 pC/N \tag{3.32}$$

F = applied force,

n = number of crystal plates,

x = direction of applied force

Shear effect:

This effect, too, is independent of the size and shape of the piezoelectric element as well as of the charge distribution. The charge occurs at the surfaces under load; at n elements connected mechanically in series and electrically in series is:

The charge is expressed in Equation (3.33)

$$Q_x = 2 \times d_{11} \times F_x \times n \tag{3.33}$$

Transverse effect:

In this case, a force in the direction of one of the neutral axes produces a charge on the surfaces of the corresponding polar axis. The magnitude of the charge is dependent on the geometrical dimensions of the piezoelectric element.

Assuming dimensions a, b, and c, the charge is given as per Equation (3.34),

$$Q_y = d_{11} \times F_y \times b/a \tag{3.34}$$

where y = a neutral axis.

Equations (3.31), (3.32), (3.33) and (3.34) describe different and crystal constants.

The experimental set up of vibrational analysis where LabVIEW with relevant data acquisition unit will be integrated to perform vibration analysis instead of hardware based systems.

Accelerometer is mounted where the vibration is to be monitored as per the standards and signals transferred through a charge amplifier to the terminal block BNC 2120. which in turn connects to DAQ card PCI 6251 which is 250kS/s. It provides continuous signal to LabVIEW based analyser over the steady state vibration behavior. Various sensors are compared as shown Table 3.1 to select the suitable sensor.

Based on the mathematical model, the following sensors were compared and suitable accelerometer was selected for the experimental set up for the proposed virtual vibration analyzer. The sensors parameters comparison is found in Table 3.1.

Table 3.1 Sensor parameters comparison

Sensor	Sensitivity	Measure-ment Range	Broad band resolution	Frequency range	Wt.	Electri. Connector
General-Purpose, Ceramic Shear IEPE Accelerometer	(±10%): 10 mV/g (1.02 mV/(m/s²))	±500 g pk (±4900 m/s² pk)	(1 to 10,000 Hz): 0.0005 g rms (0.005 m/s² rms)	(±5%): 0.5 to 10,000 Hz	0.20 oz (5.8 g)	10 to 32 side connector
High-Sensitivity, Ceramic Shear IEPE Accelerometer	(±10%): 100 mV/g (10.2 mV/(m/s²))	±50 g pk (±490 m/s² pk)	(1 to 10,000 Hz): 0.00015 g rms (0.0015 m/s² ms)	(±5%): 0.5 to 10,000 Hz	0.20 oz (5.8 g)	10 to 32 side connector
General-Purpose, Industrial, 2-Pin Accelerometer	(±10%): 100 mV/g (10.2 mV/(m/s²))	(±3 dB):)	±50 g (±490 m/s²)	30 to 600,000 cpm (0.5 to 10,000 Hz		2-pin MIL-C-5015
Triaxial, Lightweight (1.0 g), Miniature, Ceramic Shear IEPE Accelerometer	(±20%): 5 mV/g (0.51 mV/(m/s²))	±1000 g pk (±9810 m/s² pk)	(1 to 10,000 Hz): 0.003 g rms (0.03 m/s² rms)	(±5%): (y or z axis) 2 to 8000 Hz	0.04 oz (1.0 g)	integral cable
General-Purpose Modal Analysis Impact Hammer	(±15%): 10 mV/lbf (2.25 mV/N)	±500 lbf pk (±2200 N pk)		8 kHz	0.34 lb (0.16 kg)	50 W BNC cable.

General purpose industrial 2 –pin accelerometer as been selected with an adequate care for the selection of sensor viz. natural frequency of accelerometer, frequency range, minimum and maximum amplitude of vibration, environmental conditions and mounting method. The sensor is a low G Micro-machined Accelerometer with a capacity for acquiring signals ranging from +40g to -40g. This is a capacitive and surface-micro-machined integrated-circuit accelerometer.

The device consists of a surface micro-machined capacitive sensing cell (g-cell) and a CMOS signal conditioning ASIC contained in a single integrated circuit package, as shown in Figure 3.8. The sensing element is sealed hermetically at the wafer level using a bulk micro-machined "cap" wafer. The movable beams can be deflected from their rest position by subjecting the system to acceleration.

Figure 3.8 Accelerometers and Charge amplifiers used in this research

The sensors are attached to the vibrating medium or instruments. Since vibration varies throughout the instrument, the single point measurement is less efficient. So six sensors are placed in six different parts of the instrument so that the vibration in all parts can be measured and analyzed. Each sensor has its own signal conditioning unit and the sensors are given to selector switch. The selector switch has the capability to allow all signals through it or only the selected sensor signal through it. Every sensor signal line is given to the analog input channel of the USB-6009. This will convert the analog signal into computer accepted signal.

The functional block diagram found in Figure 3.9, indicates the experimental set up with USB 6009 DAQ card.

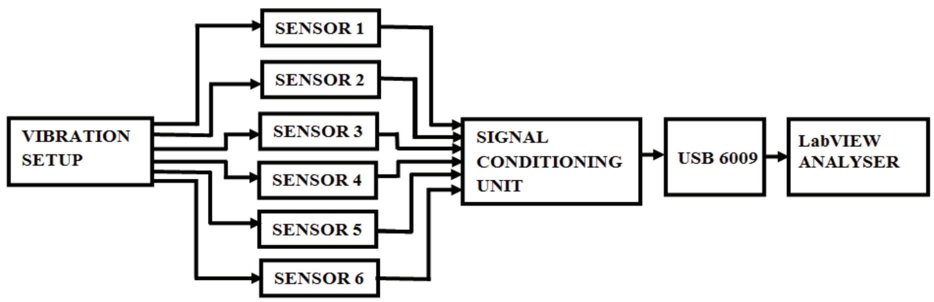


Figure 3.9 Functional block diagram of USB 6009 based vibration analyser

The USB-6009 is connected to the computer through USB. The signal is taken into the LabVIEW using DAQ Assistant. Then the frequency and amplitude of the signal for every 100ms is determined and tabulated. The frequency of the signal is taken to classify the level of vibration. A fuzzy logic controller is used to classify the signals. An artificial neural network is also built to identify the fault. Back propagation network is created and trained which will identify the fault based on the vibration signals.

3.17 PIEZOELECTRIC SENSOR

A piezoelectric sensor is a device, as found in Figure 3.10, that uses the piezoelectric effect to measure pressure, acceleration, strain or force by converting them to an electrical charge. Piezoelectric sensors evaluate the power potential due to the implementation mechanical pressure to some piezoelectric materials. Piezoelectric sensors for transforming minor oscillations and stress and anxiety of items within way of measuring into power signals using the piezoelectric effect of their elements uncover applications in various area.

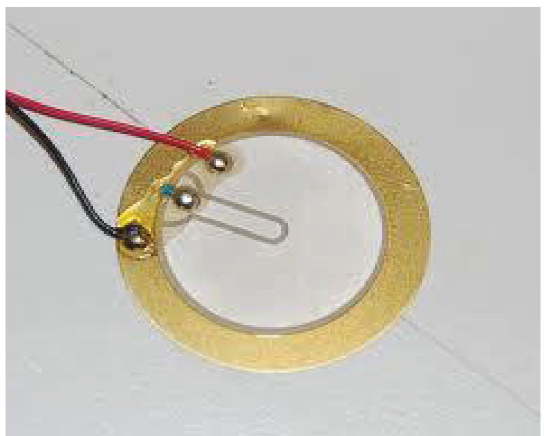


Figure 3.10 Piezoelectric Sensor

Piezoelectric pressure sensors involve all sensors, transducers and elements that produce an electric signal proportional to pressure or changes in stress. Primarily the piezoelectric pressure sensors are units that understand alterations in stress, and exchange this statistics to recorders or switches. The research study uses six sensors. Since the vibration varies from area to area in the same instrument, it is necessary to measure the vibration signals from various part of the instrument and analyse all the signals.

3.18 SIGNAL CONDITIONING UNIT

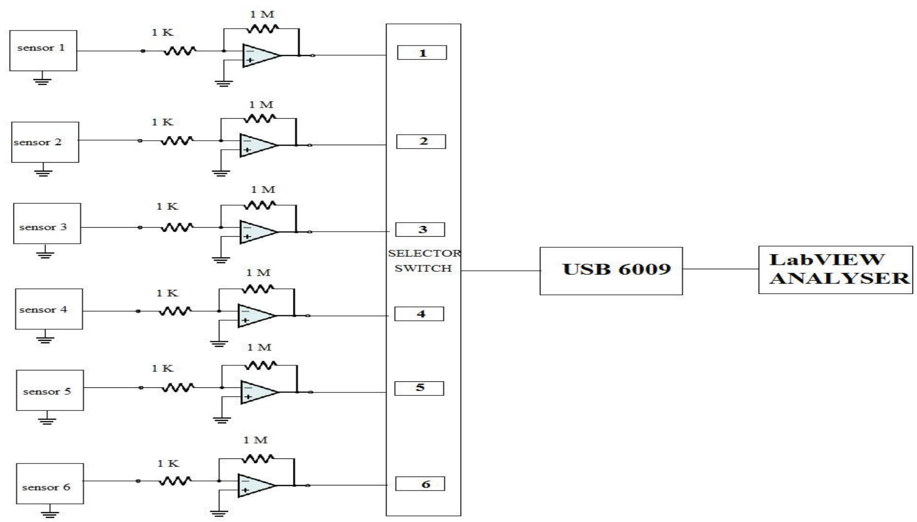


Figure 3.11 Signal conditioning Circuit Diagram

Signal conditioning means manipulating an analog signal in such a way that it meets the requirements of the next stage for further processing. IC 741 is an amplifier used in signal conditioning circuit, presented in Figure 3.11. The signal from the sensor is in mV and it has to be amplified into voltage using amplifier. For this purpose, a non-inverting amplifier is used. The signal from each sensor is amplified using the respective amplifier and the six voltage signals are given to a selector switch. The selector switch can select and decide which signal can pass through the switch.

3.19 LabVIEW AND DATA ACQUISITION SYSTEM ASSEMBLY

The mount assembly used for acquiring signals from the sensors is portrayed in Figure 3.12. Here, the DAQ card is PCI 6251, a higher sampling rate card than USB 6009. DAQ card is mounted on the PCI slot of the motherboard. A cable runs to connect DAQ card with Terminal block BNC 2120 which is to be connected with accelerometer signals.

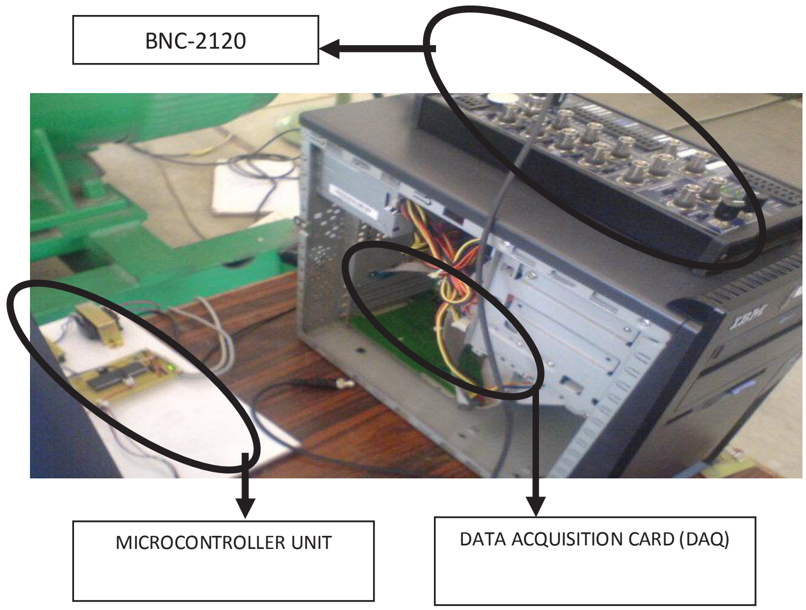


Figure 3.12 DAQ Card Connection and Signal Conditions Unit

PCI 6251 M series DAQ card has been used for interfacing. It has 8 Analog Input channels, 2 Analog Output channels, 8 Digital Input Output lines. It can be used as a port or individual lines. To monitor the ambient temperature, there is a built in temperature sensor provision. Thermocouple can be connected separately. For configuring Counter / Timer operations individual command lines are provided.

It is possible to channelize the signal through microcontroller based configuration and it serves the purpose when multiplexed channels are preferred. Front panel interface of the vibrobench is shown in Figure 3.13. It consists of four main sections like sensor section to prompt between different types of sensors, Operation type to select standardization, measurement and analysis and recording.

The graph section consists of four different graphs that illustrate the vibration parameters like displacement, velocity and acceleration. Power spectral analysis shows the frequency composition of vibrating segment which finds the magnitude and its reoccurrences during vibration.

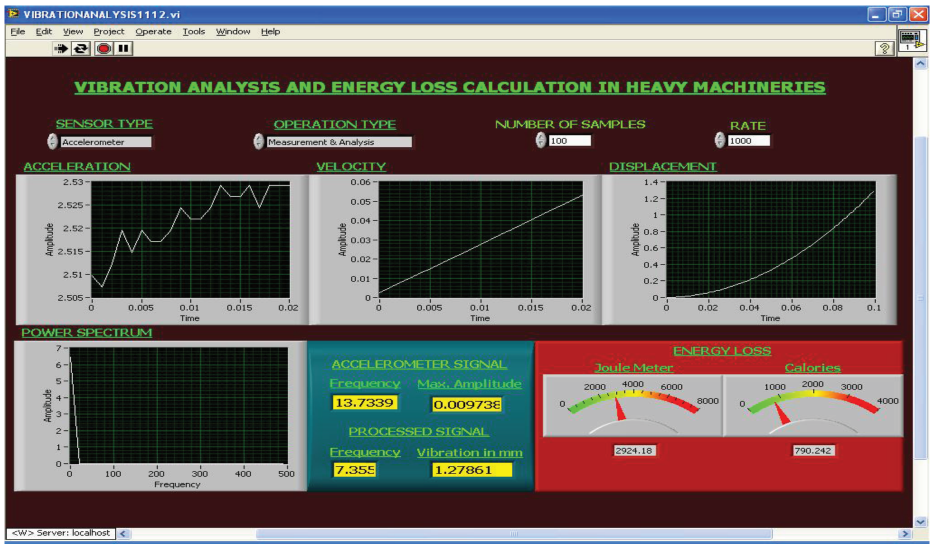


Figure 3.13 Front Panel of Proposed LabVIEW based Workbench

LabVIEW based virtual vibration analyser is shown in Figure 3.13. In the front panel, option for selecting sensor, option for selecting operations such as measurement and analysis or energy loss calculation are provided. For instantaneously configuring the DAQ card, the number of channels and sampling rate can be adjusted.

The graph section displays plots for acceleration, velocity, displacement and power spectrum of the vibration signal. Signal strength is displayed in frequency and amplitude. Ferrero et al (2011) have mentioned a mathematical method for the evaluation of frequency and amplitude of spectral component. In the energy loss section, energy is calculated for momentrical values.

Figure 3.14 Hardware set up with LabVIEW based testing unit

In the above mentioned hardware set up shown in Figure 3.14, a 1 hp, 230V, single phase induction motor was taken as the rotating machinery for the vibration study. In its mechanical power transmission shaft two accelerometers were mounted with required charge amplifiers. Since accelerometers have crystal, it produces rate of change of charges with respect to the vibration in the rotating machinery. It is given to charge amplifier to convert them into electrical signal in terms of mV. Through a BNC cable these signals are interfaced with DAQ card PCI 6251, residing in the PCI slot of the PC, via a recommended terminal block BNC 2120.

In the VI front panel, the interfaced signal is displayed and respective displacement, velocity and acceleration are calculated and plotted. Energy loss is calculated in a separate module so as to continuously monitor and performs the analysis.

3.20 ENERGY LOSS CALCULATION

Energy loss in a machine means a decrease in efficiency of that machine. Energy loss can occur in many ways. Sadoughi et al (2006) discussed about auto correlation of energy signals in vibrations due to bearings. Amin karami et al (2011) experimentally verified of vibration of some structures. The energy loss may be due to sound, vibration, heat, friction etc. Here, the energy loss is calculated by taking vibration into consideration.

The rate of change of energy with time (dW/dt) is given in Equation (3.35) and Equation (3.36)

$$\begin{aligned} dW/dt &= \text{force x velocity} \\ &= Fv \\ &= -c\,v^2 \\ &= -c\,(dx/dt)^2 \end{aligned} \qquad (3.35)$$

Or

$$\begin{aligned} \Delta E &= \int F_D\,(dx/dt)\,dt \\ &= \int F_D\,X\,\omega\,\cos\omega t\,dt \end{aligned} \qquad (3.36)$$

The negative denotes that energy dissipates with time. Considering a motion as $x(t) = X \sin\omega_d t$, where X is the amplitude of the motion, the energy dissipated in a complete cycle is given in the Equation (3.37)

$$\begin{aligned} \Delta W &= \int c\,(dx/dt)^2\,dt \\ &= \int cX^2\,\omega_d \cos^2\omega_d t\,.\,d(\omega_d t) \\ &= \Pi\,c\,\omega_d\,X^2 \end{aligned} \qquad (3.37)$$

This shows that the energy dissipated is proportional to the square of the amplitude of motion. Energy loss occurs due to the damping given to the machine.

The frequency of damped vibration is given in Equation (3.38)

$$\omega_d = (\sqrt{1 - \zeta^2})\ \omega_n \tag{3.38}$$

The logarithmic decrement is given by,

$\Delta = 2\ \Pi\ \zeta = 2.32\ X$

For a sample reading during the experimentation, energy loss is calculated as below:

$X = 1.2615$ mm, $c = 79$, $\omega_d = 8.51$ Hz

According to the formula,

$\Delta W = \Pi\ c\ \omega_d\ X^2 = 3.14 \times 79 \times 8.51 \times (1.2615)^2$

$= 3363.53$ Joule

and if it is converted Joule to calories then the value of energy loss will be

1 Joule = 0.2388 Calorie

3363.53 Joule = 0.2388 x 3363.53 Calorie = 803.21 Calorie.

3.21 EFFICIENCY OF THE PROPOSED METHOD

By considering the methods of evaluation to compute energy loss, the proposed method has been compared. The results are enumerated in Table 3.2 and it proves the proposed method is more efficient.

Table 3.2 Comparison of proposed method with previous methods

S.No	Method	Energy loss calculated (in J)	Efficiency (in %)	Remarks
1	Rayleigh Method	3058.8	87.39	Mathematical Methods
2	Integral Method	3195.66	91.3	
3	Ruqiang Yan et al (2009)	3200	91.4	Different wavelets used
4	Dane Quinn et al (2011)	3105	88.7	Energy harvester with impulse loading
5	Proposed Method	3363.53	96.1	VI and DAQ based system

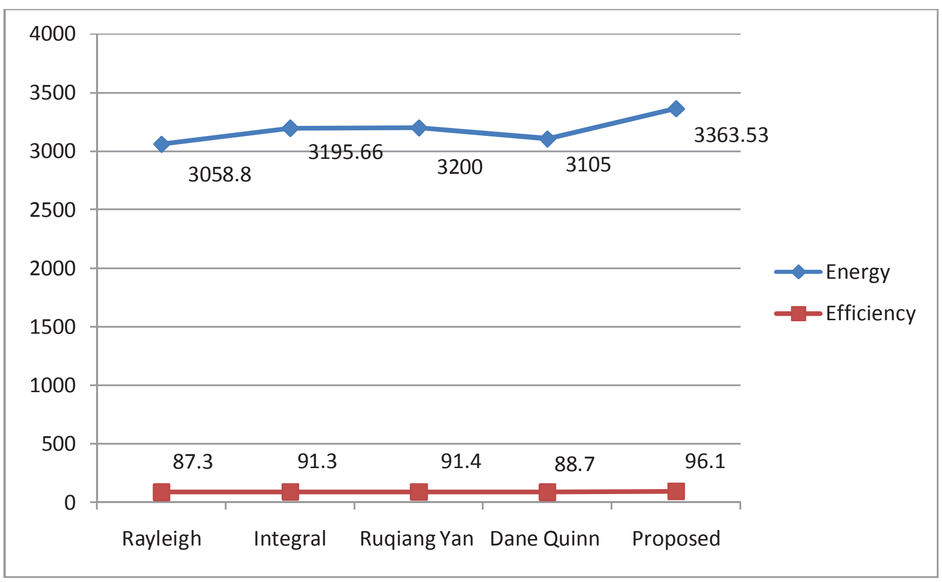


Figure 3.15 Comparison of Energy loss calculation methods

From the results tabulated and graphically shown in Figure 3.15 in efficiency of energy loss calculation has increase more than the previous methods. It is closely calculated upto 96.1% than 91.4 stated by Ruqiang Yan et al (2009). Comparatively it is observed to be good during the analysis and calculation.

3.22 WEB PUBLISHING AND COMPARISON

The web publishing tool is yet another feature of LabVIEW. It allows the user to acquire readings remotely. The user can view and control a VI front panel remotely, either from within LabVIEW or from within a Web browser, by connecting to the LabVIEW built-in Web Server.

The use of this application helps the users to locate their rotating machinery anywhere over the network and to keep analyzing. In this connection, the network based analysis is a commonly preferred feature for computer based instrumentation systems. It is supported by a common network layer and application layer protocols.

In this proposed virtual vibration analyser, a VI server has been configured for sharing the instrument over the network. When the user opens a front panel remotely from a client, the Web Server sends the front panel to the client, as shown in Figure 3.16. But the block diagram, as shown in Figure 3.17 and all the sub VIs remain on the server computer .

The user can interact with the front panel in the same way as if the VIs were running on the client, except the block diagram executes on the server. This feature to used to publish entire front panels or to control remote applications safely, easily and quickly.

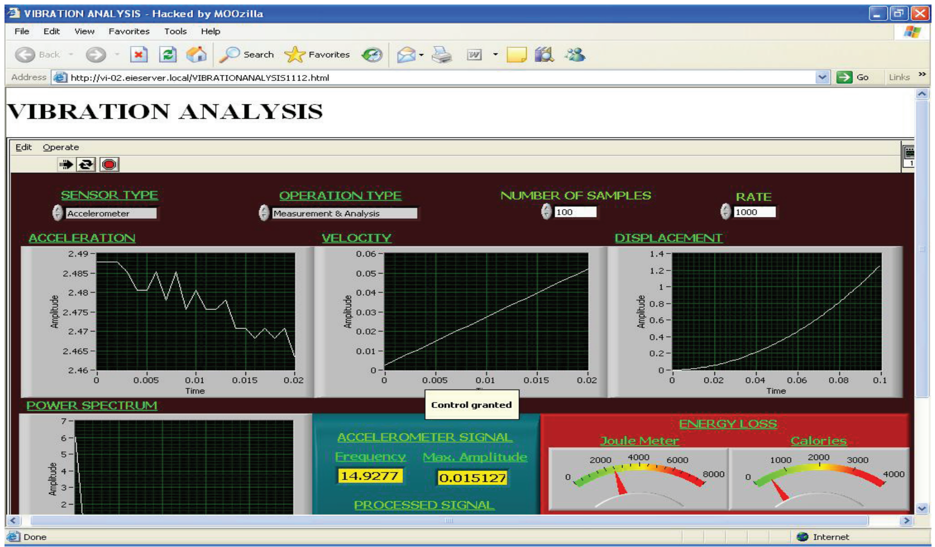


Figure 3.16 Web published Front Panel as VI Server

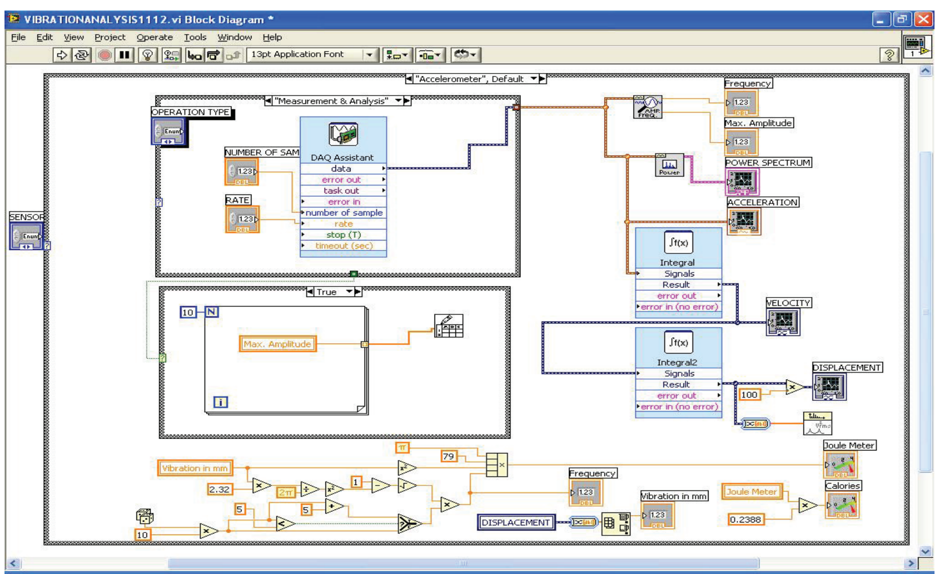


Figure 3.17 LabVIEW Source Code

3.23 HARDWARE IMPLEMENTATION

The Figure 3.18 that follows depicts another hardware set up used in this research with different DAQ card USB 6009. This card facilitates the signal interface through USB port with a required sampling rate of 48kS /s. As shown in the block diagram, the card is supported by signal condition unit for accelerometer interface. Signal conditioning unit has one selector switch to select the one accelerometer among all. When these accelerometers are fixed on the vibrating segment of the rotating machinery, the signals are interfaced with the LabVIEW based vibration analyser through SCU and DAQ card.

Figure 3.18 Hardware set up for vibration study

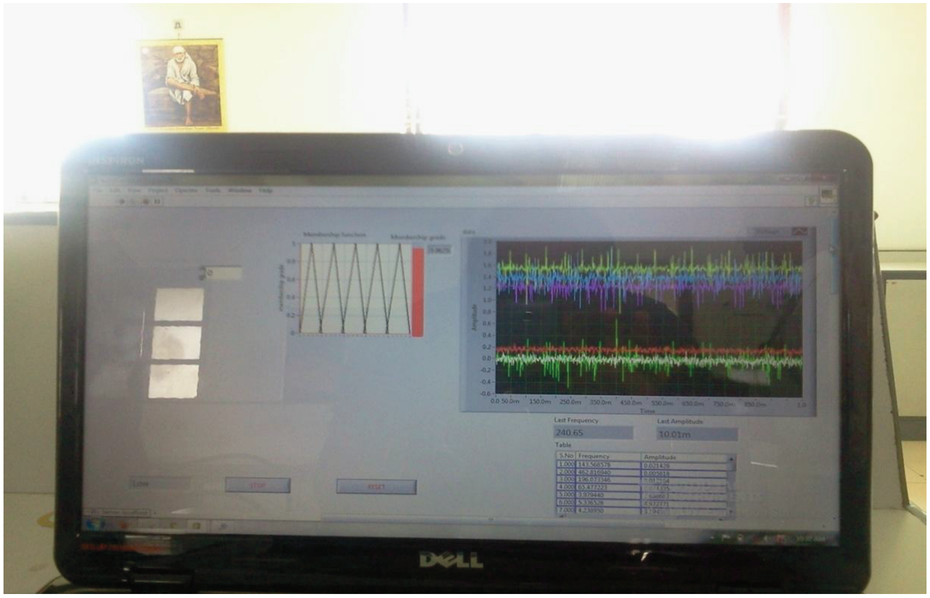


Figure 3.19 Signal on the LabVIEW Front panel

Figure 3.19 portrays the snapshot of the PC screen which acquires and displays the vibration signals. Relevant calculations and fuzzy functions are also seen as LabVIEW front panel or user interface.

Figure 3.20 represents the source code in the LabVIEW for the signal acquisition and processing. It has the DAQ Assistant function to configure the DAQ card for required sampling rate, N samples or continuous along with mode of connections of signal wires. It can be configured either directly or through Measurement and Automation Explorer wizard.

Tone extraction feature helps to extract single or multi tone information of the interfaced signal. With this output proposed spectrum analysis and parameters estimation for displacement, velocity and acceleration can be done.

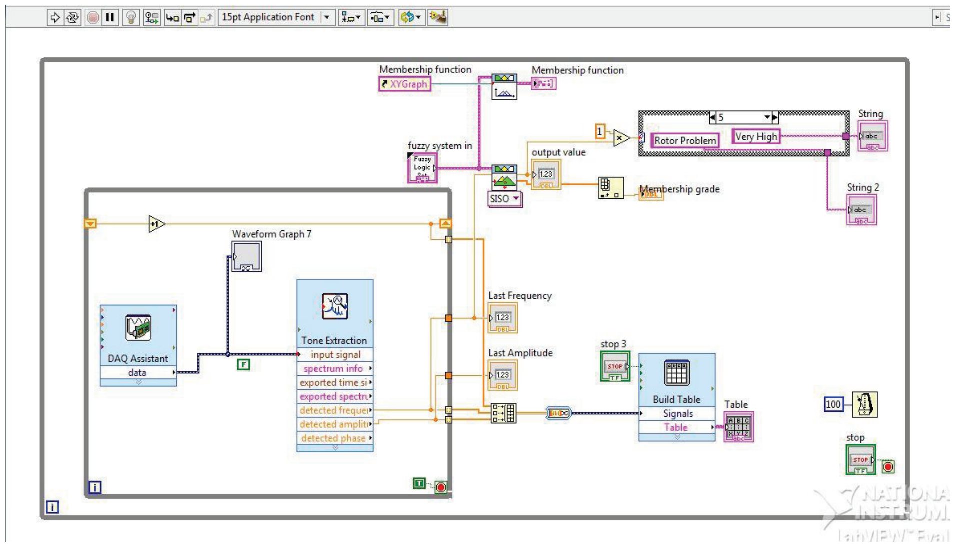


Figure 3.20 LabVIEW block diagram for Signal acquisition

The photograph seen in Figure 3.21 shows the rotating machinery under study, USB 6009 DAQ card, signal conditioning unit and virtual vibration analyser on the PC as per the proposed design and signal flow algorithm.

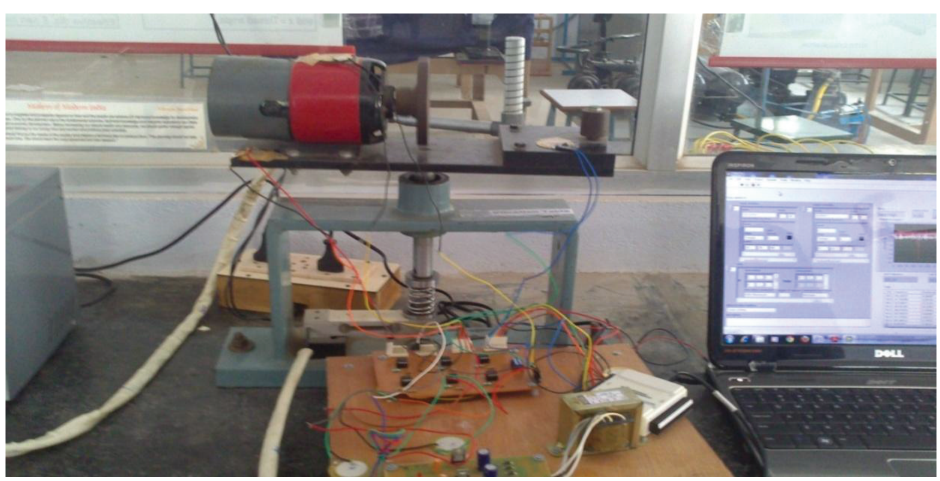


Figure 3.21 LabVIEW and DAQ set up interface with Rotating Machinery

3.24 RESULTS AND DISCUSSION

This section depicts the development of new instrument system compatible with conventional mode of measurements by its compatibility, signal interface and other display parameters.

The readings of a conventional Vibration System are shown in below Table 3.3 and the corresponding plot is shown in Figure 3.22 for the vibration parameters. These readings appear on the front panel of virtual vibration analyzer continuously as the motor runs. Individual charts for acceleration, velocity and displacement have been given to view the history of reading. From the panel, a set of samples is tabulated as in Table 3.3.

Table 3.3 Conventional vibration system values

S.No	Frequency (Hz)	Displacement (mm)	Velocity (mm/sec)	Acceleration (mm/sec^2)
1	5	1.5	40	16
2	6	1.48	41	22
3	7	1.46	38	28
4	8	1.42	40	30
5	9	1.4	36	30
6	10	1.38	40	30

Table 3.3 shows sample readings observed during the vibration analysis using a standalone hardware based vibration analyzer. It has the power amplifier unit and analyser unit in which displacement, velocity and acceleration are being calculated. There is no specific algorithm or provision for calculating energy loss during the operation. It has been configured in the proposed virtual vibration analyser.

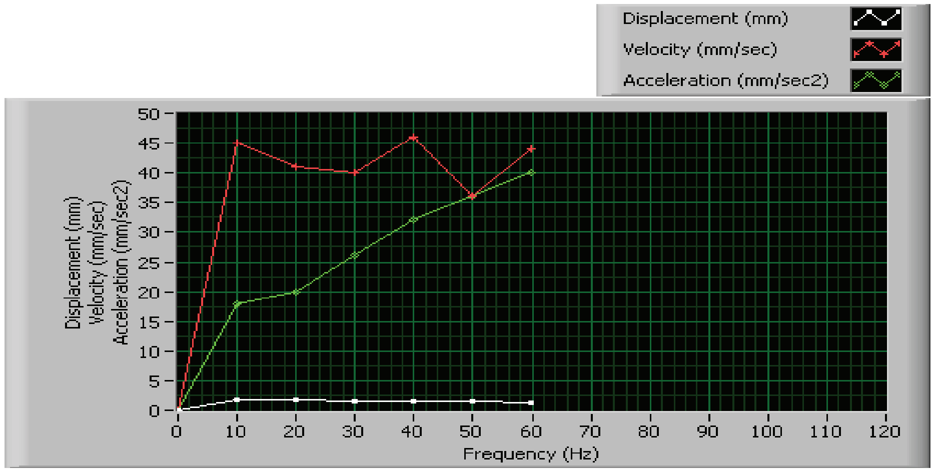


Figure 3.22 Vibration parameters in conventional instruments

Virtual Instrumentation based Vibration System readings are illustrated in Table 3.4 and the graph in Figure 3.23.

Table 3.4 has a the set of readings taken in the same context as it has been done in the standalone hardware based vibration analyser. It shows the compatible mapping of reading on the same experiment. These readings are verified with set vibrations and it has been graphically plotted for analysis.

Vibration analysers will normally have single sensor for signal acquisition. For industrial mounting and verification, tri-axial sensors are being used. In the proposed research six sensors have been used along with a selector switch. For acquiring vibration and verifying them over the time, more number of sensors are preferred.

All these sensors are configured with DAQ card through Measurement and automation explorer. Sensors are configured for Analog Voltage, since from charge amplifier the signal is in the form of mV only. Thus vibration signal is transduced into electrical signal by preserving the signal conditioning norms.

Table 3.4 VI based Vibration System Values

S.No	Frequency (Hz)	Displacement (mm)	Velocity (mm/sec)	Acceleration (mm/sec^2)
1	5	1.8	45	16
2	6	1.7	41	22
3	7	1.5	40	28
4	8	1.6	46	30
5	9	1.4	36	32
6	10	1.2	44	36

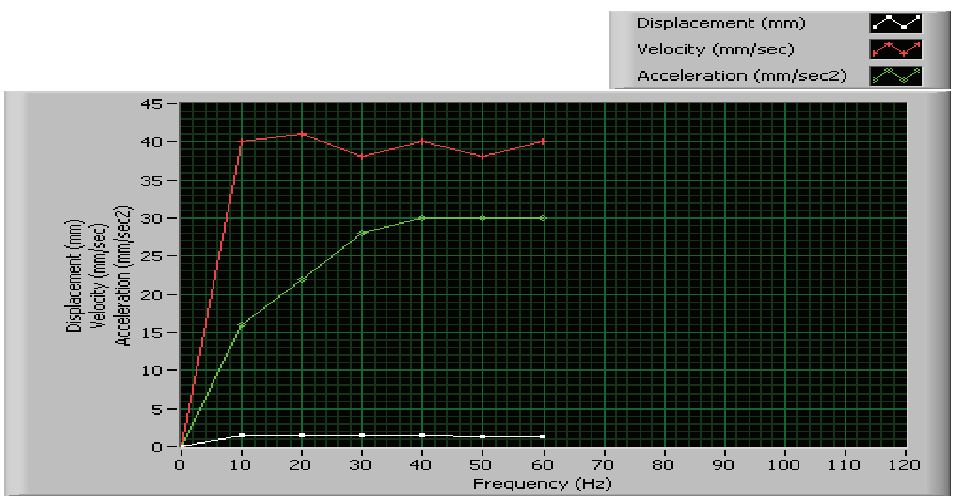


Figure 3.23 Vibration Parameters in Virtual Instruments

Based on the readings acquired it can be concluded that in accordance with the standard readings the VI based system is much more accurate, reliable and efficient than the conventional system.

3.25 SUMMARY

This technique provides a new instrumental approach to analyze vibration in heavy machinery. The proposed system is user friendly and cost effective over the conventional system and it can be efficiently to implement for remote system analysis. Interactive front panel and graphic source code lead to faster development in time and graphic displays of different parameters involved. Spectral analysis leads to evolve recommendations over the energy lost, machine to machine with VI server enabled for network based automation.