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# Vibration Faults Simulation System (VFSS): A Lab Equipment to aid Teaching of Mechatronics Courses*

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*VFSS is an example of a mechatronics system which involves data acquisition and analysis using LabVIEW-based virtual instrument technology. This system can serve as teaching equipment for mechatronics students in the area of data acquisition, sensors and actuators, signal processing and vibration monitoring to aid students' understanding on these subjects. Since vibration fault signals and their causes are important for fault detection and diagnosis, a vibration faults simulation system is developed to gain good understanding of such signals. To achieve this a vibration faults simulation rig (VFSR) is designed and developed to simulate and study most common vibration fault signatures encountered in rotating machines. A LabVIEW-based data acquisition system is used to acquire and analyze the fault signals. The complete system has been developed and tested and the fault signals were compared with normal signals so as to ascertain the condition of the machine under investigation. VFSS has been successfully used to demonstrate some vital concepts in the teaching of DSP, sensor and actuators and mechanical vibration since data are acquired from the physical system and are analyzed to derive information on the system under investigation. This approach further allows students to gain insight into effects of noise on measurements and how such effects can be combated.*

## INTRODUCTION

ADEQUATE ATTENTION and planning as well as appropriate equipment must be available for the teaching of mechatronics engineering courses because of their multidisciplinary nature and the overall need to enhance the hands-on skills of the students. In addition, necessary experiments must be designed so that students are thoroughly drilled to understand the basic components of mechatronics systems and their integration. Equipment for achieving these objectives in the traditional laboratory are limited both in number and their functionality, hence the need to design and fabricate customized equipment that can enhance students' knowledge and skills. VFSS is one example of such equipment which has been produced at our university for use in the teaching of courses such as signal systems, sensors and actuators, applied digital signal processing, mechanical vibration, electronics instrumentation and measurement, and this list could continue.

VFSS is developed to study signatures for most common rotating machinery faults. An understanding of fault signals will guide us to implement suitable maintenance procedures. VFSS has been designed to enable students to physically study the vibration signal to perform condition monitoring. This is in contrast to learning maintenance procedures based on simulation studies alone. Here, students will be exposed to the techniques of acquiring signals from sensors using LabVIEW and this will be processed using modern signal processing techniques so as to acquire the desired information from the system. Furthermore in using this system students will be exposed to selection of sensor, sensor mounting techniques, optimal sensors positioning and the effects of noise on measurements.

Vibration analysis is an important procedure for determining machinery condition. This is accepted as the most effective method used in predictive maintenance, see Fig. 1 for the commonly-used maintenance strategies. Since this is a practical procedure, sufficient training is necessary to familiarize the students with this operation before it can be effectively applied.

Vibration monitoring has been extensively and successfully applied to rotating machinery. Vibration measurements are superior indicators of potential failure, they are relatively easy to obtain via suitable transducers and offer the advantage of simple, reliable interpretation over other methods. As machine conditions change the vibration characteristics will also change. The vibration signals can be represented either as a time series, and/or frequency spectrum. In addition, further processing may also be undertaken to indicate the condition of machine and diagnose potential failures. The condition monitoring of machinery can significantly reduce the costs of maintenance since it allows:

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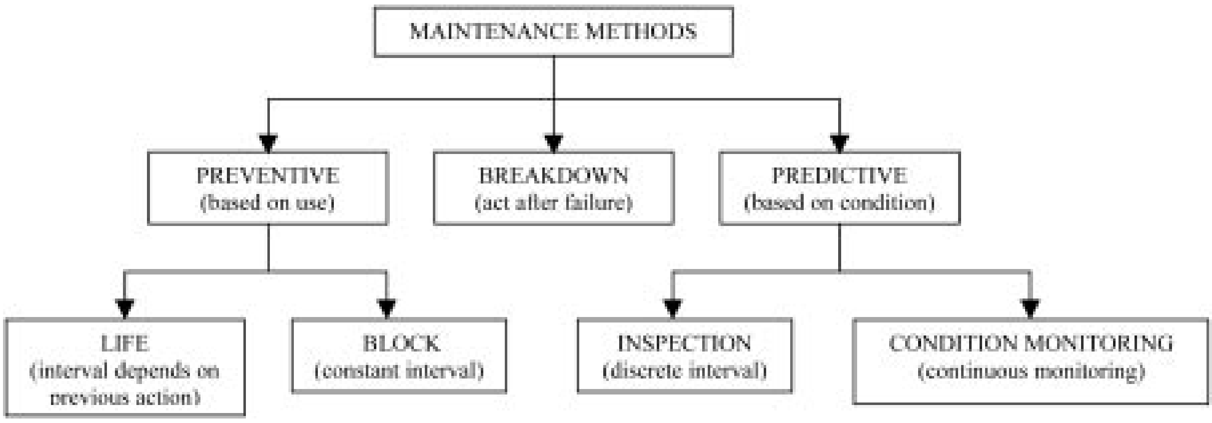


Fig. 1. Maintenance methods.

- the early detection of potentially catastrophic faults, which could be extremely expensive to repair;
- the implementation of a condition-based maintenance rather than preventive or breakdown-based maintenance.

## VIBRATION ANALYSIS

Most equipment encountered in the industry is subjected to vibration in one form or another. Hence there is a need to monitor vibration. In actual sense, vibration of mechanical equipment is generally not good for its operation. It causes [1, 2]:

- excessive wear of bearings;
- cracking;
- fasteners to become loose;
- electric relays to malfunction;
- electronic malfunctions through the fracture of solder joints;
- abrade insulation around electrical conductors causing shorts;
- noise that is generally uncomfortable for humans.

Vibration itself is usually a bad situation, but it is also a symptom of an internal defect. Specifically, it is a very sensitive and an early predictor of developing defects. Catastrophic failures are usually preceded by a change in vibration, sometimes months before the actual failure [3]. Consequently, there is a need to develop equipment that can be used in teaching students on monitoring vibration.

The main objective of vibration analysis is to determine how the internal forces in machines are changing with time and accelerating the breakdown of components. Changes in force within the machine might reflect direct changes in work process as well as the changes in the properties of the machine elements. Vibration is the best indicator of overall mechanical condition and an earlier indicator of developing defects. Table 1 shows vibration and other parameters related to machinery failures [4].

The two analysis techniques as shown in Fig. 2, available for determining the components of vibration are time domain, which provides insight into the physical nature of the vibration and frequency domain, which is ideal to recognize the signal components [5, 6].

## EXPERIMENTAL RIG DESIGN

A VFSR has been designed and fabricated in order to demonstrate some of the most commonly found faults in rotating machinery. The following faults can be illustrated using VFSS: misalignment (parallel and angular), imbalance, mechanical looseness, bent shaft, bearing fault, gear fault, eccentric pulley, electric motor fault, vane passing frequency and missing blade.

Table 1. Vibration as the best indicator of machine health

| Failures | Temperature | Pressure | Flow | Oil analysis | Vibration |
|---|---|---|---|---|---|
| Out of balance | | | | | × |
| Misalignment shaft | × | | | | × |
| Damaged rolling element bearings | × | | | × | × |
| Damaged journal bearings | × | × | × | × | × |
| Damaged or worn gears | | | | × | × |
| Mechanical looseness | | | | | × |
| Noise | | | | | × |
| Cracking | | | | | × |

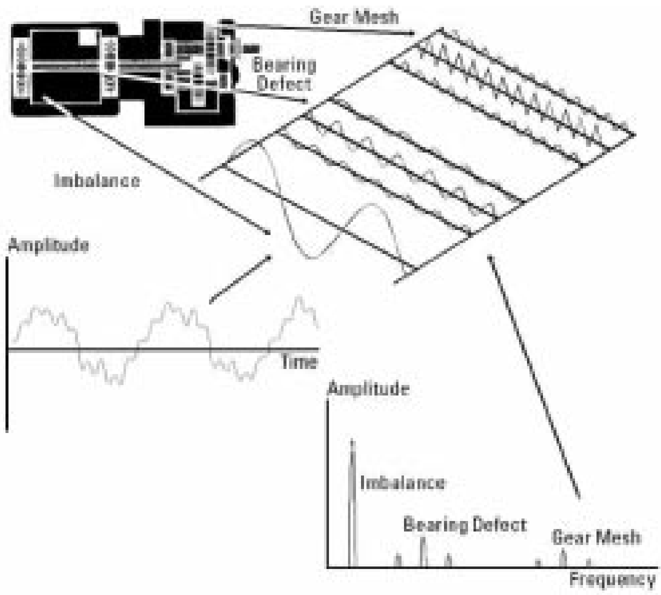


Fig. 2. Machinery vibration viewed in the time and frequency domains [7].

Some of the advantages of VFSS are to:

- demonstrate various vibration faults in any rotating machine.
- demonstrate the understanding of simple but cost effective tool for machine diagnosis.
- illustrate computer based data acquisition and monitoring system.
- provide basic understanding of sensor selection for desired application.
- demonstrate various signal analysis techniques such as correlation, FFT, filtering and even some advanced signal processing techniques.
- show the effects of signal conditioning and sampling on the acquired data.

The rig consists of the following components:

1. Three stainless steel shafts of 10 mm diameter are fabricated. Two are good shaft and the remaining one is a bent shaft for simulating shaft fault.
2. Rotor disc is designed to simulate imbalance in rotating shaft without stopping it.
3. Balancing disc is used to study single plane and dual plane balancing stainless steel flywheel is designed for use together with bent shaft system, which acts as load, thereby increases the magnitude of the fault signal.
4. Five aluminum pulleys (shaft pulley eccentric, pulley and pinion pulley with different diameters).
5. Fan blade to simulate vane passing frequency and missing blade. All blades in the fan are adjustable so as to create different slanting angle of blades. The blades are long enough to apply aerodynamic forces on the wind block when it rotates.
6. The bearing used here comes together with detachable aluminum pillow block. One of the bearings is ground at outer race to create the bearing outer race fault
7. The gearbox is designed for gear fault simulation. It has two pinions and one gear. The ratio of the matching gears is 30:20. One of the two pinions is damaged to simulate gear fault.

Other components produced for this rig are wind block, flexible coupling, bearing stand, track, motor base plate, and sensor mounting stud.

## EXPERIMENTAL SETUP

The faults are simulated and studied with five different systems. The summary of these systems and simulated faults are given in Table 2 whilst the different setups for demonstrating the faults are shown in Figure 3.

## ANALYSIS SOFTWARE AND INSTRUMENTATION

A spectrum analyzer shown in Fig. 4, is designed and developed using LabVIEW. Laboratory

Table 2. Simulation Systems

| System | Analyzed vibration signature |
|---|---|
| Main shaft | Imbalance, Parallel and Angular misalignments, Mechanical looseness, Vane passing frequency, Electric motor fault, Missing blade and Bearing fault |
| Gear box | Gear fault |
| Eccentric pulley | Eccentric pulley |
| Bent shaft | Bent shaft |
| Balancing discs | Static, dynamic and couple imbalance |

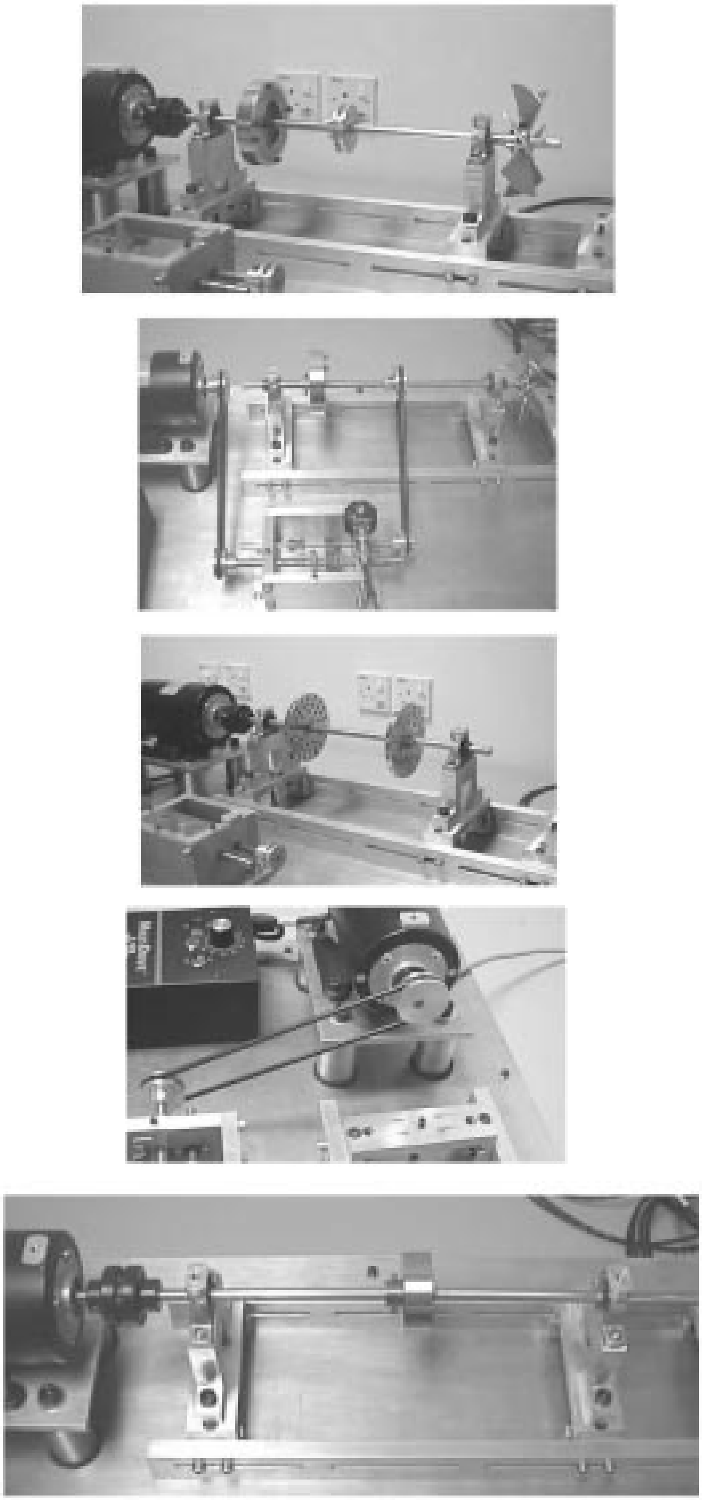

Fig. 3. Various faults simulation systems

**V**irtual **I**nstrumentation **E**ngineering **W**orkbench (LabVIEW) is a graphical programming environment based on the concept of data flow programming [8]. This programming paradigm has been widely used for data acquisition and instrument control software [9]. LabVIEW features an easy-to-use graphical programming environment, which covers data acquisition, data analysis and data visualizations.

This analyzer can perform the following function: acquire analog input from different channels, apply various types of filters and windows, and display both time domain signals and their spectra The spectrum analyzer has three different settings as described below:

**Filter setting**: This panel allows the user to select various designs of filters. The filters are:

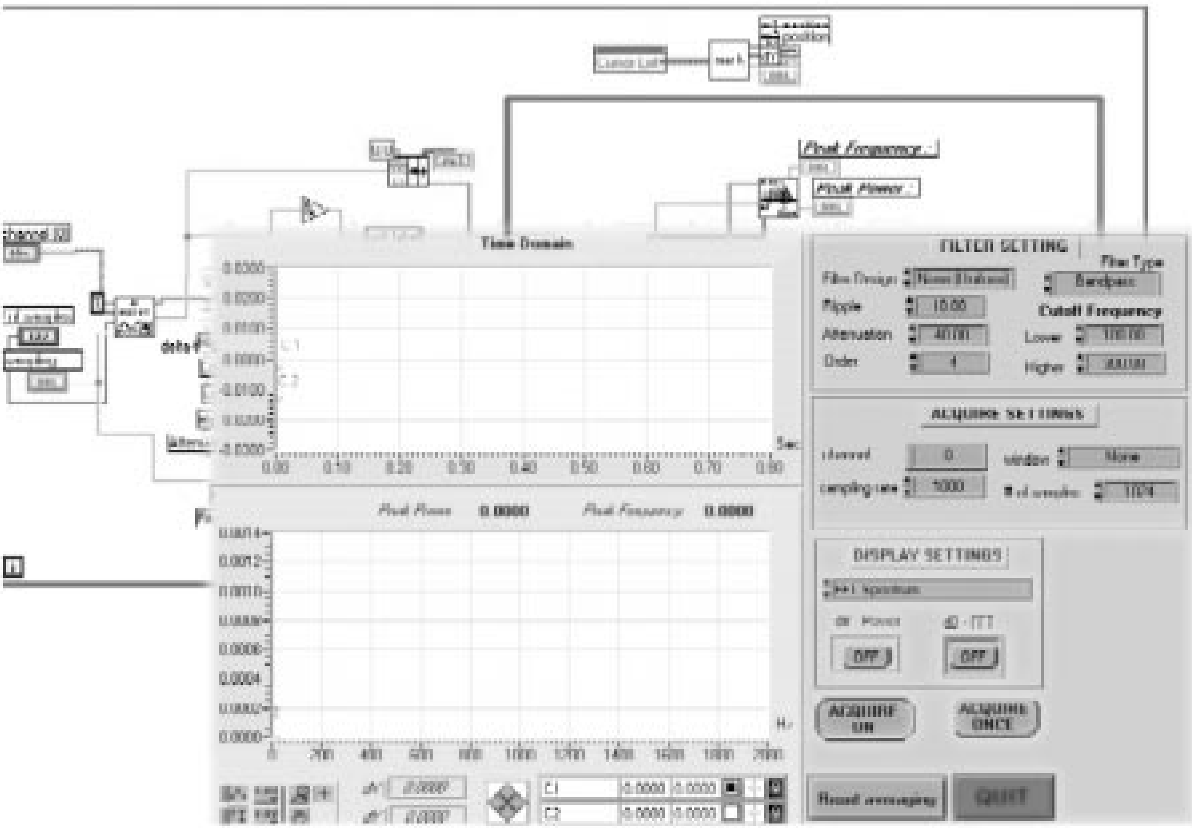


Fig. 4. Spectrum analyzer: front panel and block diagram.


Fig. 5. DAQ board.

Fig. 6. Single and triaxial accelerometers.

Butterworth, Chebychev, Inverse Chebychev, Elliptic and Bessel. For each the user can set the cut off frequency and select one of their four types, namely lowpass, highpass, bandpass, and bandstop.

2. **Spectrum setting**: the spectrum setting allows the user to select channel, sampling rate, number of samples, and different types of windows.
3. **Display setting**: allows types of spectrum (FFT, averaged FFT, Power and averaged Power), and display unit (dB or rms value).

The hardware components include:

- **Data Acquisition (DAQ) Board**: A 16-bit, National Instruments PCI E series DAQ board shown in Fig. 5, is used to acquire analog inputs form accelerometers. The board model is PCI-MIO-16XE-10. It has 16 single-ended or 8 differential mode software selectable channels. The maximum sampling rate of the board is 100kS/s and voltage range is $\pm 10\,V$.
- **Accelerometers**: Two (one single axis and one triaxial) Piezoelectric (PE) general purpose accelerometers as shown in Fig. 6, are used with VFSS. Triaxial sensor measures vibration in mutually perpendicular x, y and z-axes using three sensing elements in one compact case [10].
- **Tachometer**: A hand held digital tachometer is used in this system to measure the rotating speed of the motor and shafts.

Table 3. Position of accelerometers

| Position | Fault to detect |
|---|---|
| MA1 | Electric motor and eccentric pulley |
| BA1 | Imbalance, Parallel misalignment, Angular misalignment, Mechanical looseness, Bent shaft and Bearing fault |
| BA2 | Missing blade |
| WBA | Vane passing frequency |
| GBA | Gear fault |

Accelerometers are mounted using stud and the locations with their respective faults to be detected are described in Table 3. Figure 7 shows the schematic diagram of the accelerometer mounting positions and Fig. 8 shows the complete VFSS.

## DEMONSTRATION OF THE VFSS

In this section, only two out of ten simulated faults are discussed, namely mechanical looseness and bearing faults. Other faults that can be simulated are misalignment (parallel and angular), imbalance, bent shaft, gear fault, eccentric pulley, electric motor fault, vane passing frequency and missing blade.

*Mechanical looseness*

Mechanical looseness can be categorized into structural looseness such as mounting base and rotating element looseness. Mounting base looseness will result in relative motion between the machine foot and base plate. This fault is simulated with motor speed of 1800 RPM which is equivalent to fundamental frequency of 30 Hz. Accelerometer is mounted at BA1. Good and faulty spectra are shown in Fig. 9. Harmonics of running speed frequency 30 Hz shows up in faulty system. This signature characteristic corresponds to the mechanical looseness. The truncated time wave in the mechanical looseness system (shown in Fig. 10) contributes to the harmonics in the frequency domain.

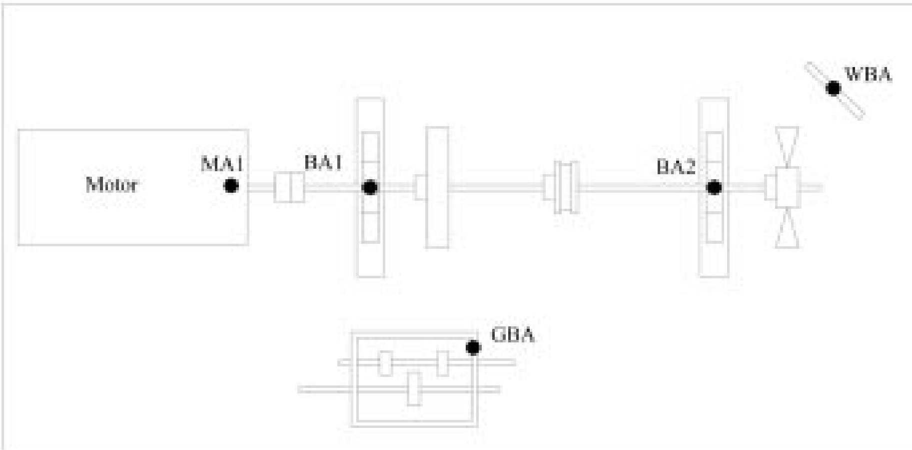


Fig. 7. Accelerometer mounting positions.

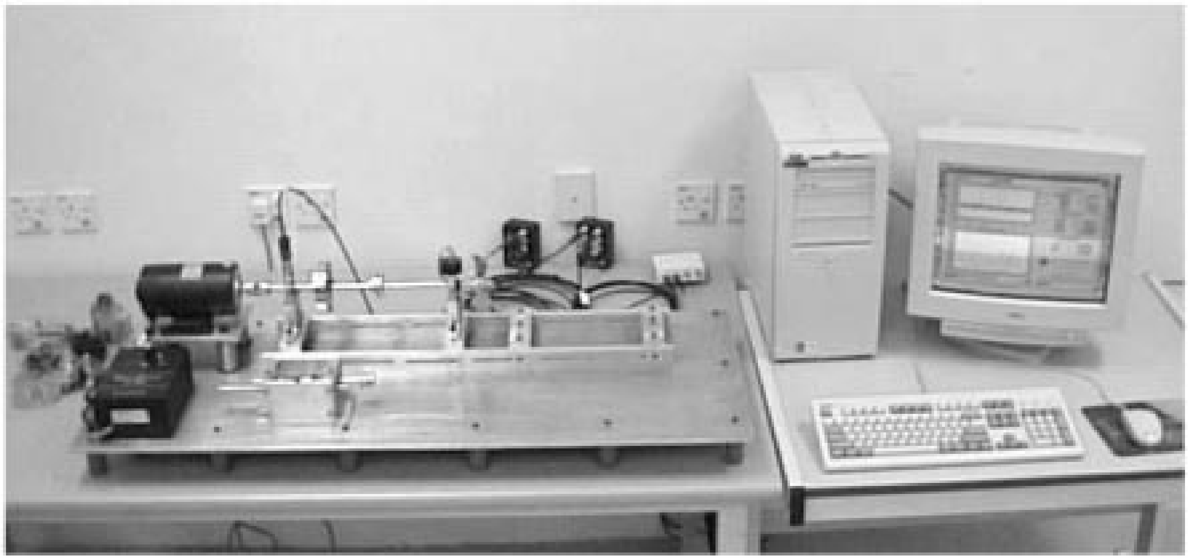

Fig. 8. The vibration analysis instruments and the VFSR.

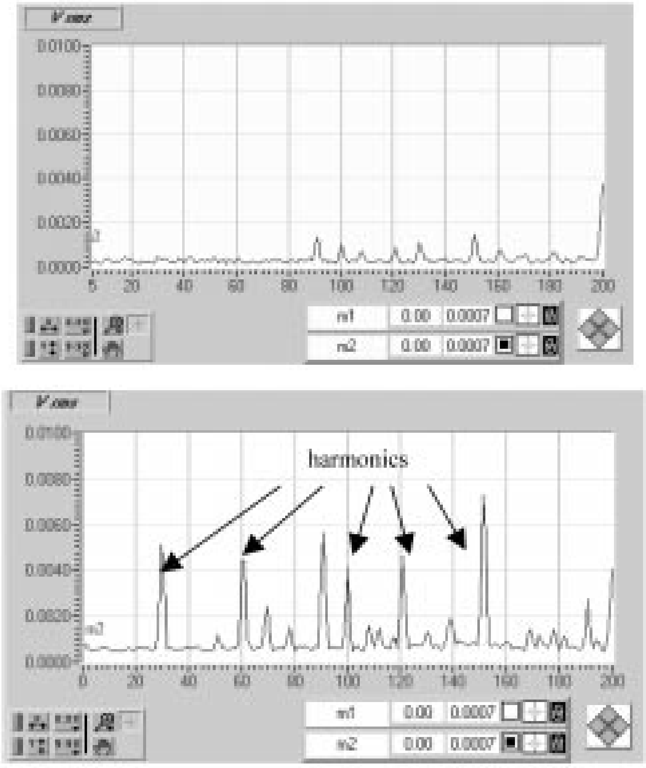


Fig. 9. Good and faulty spectrum for mechanical looseness.

*Bearing fault*

This fault is simulated on bearing with outer race fault. Initial spectrum is acquired using a good bearing and the bearing is replaced with faulty bearing to acquire bearing fault signature. The motor speed is maintained at 1800 RPM. The ball bearing related frequencies for the used ball bearing in this system are given in Table 4, where N = number of balls, Bd = ball diameter, Pd = pitch diameter and rps = revolution per second.

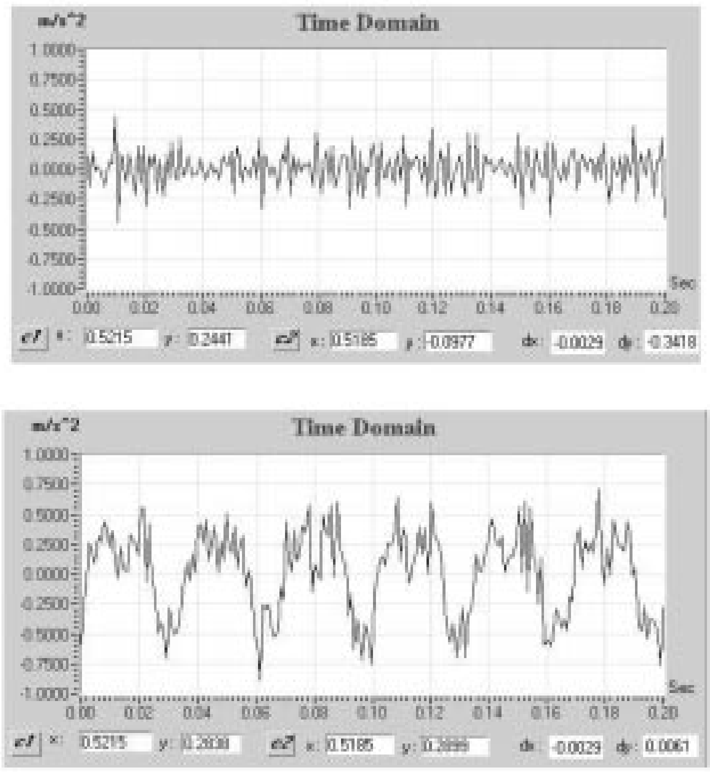


Fig. 10. Time domain signals for mechanical looseness.

Table 4. Ball bearing related frequencies

| | Formula | Frequency (Hz) |
|---|---|---|
| Fundamental train frequency (FTF) | $FTF = \frac{rps}{2}\left[1 - \frac{Bd}{Pd}\cos\phi\right]$ | 11 |
| Ball spin frequency (BS) | $BS = \frac{Pd}{2Bd}(rps)\left[1 - \left(\frac{Bd}{Pd}\right)^2\cos^2\phi\right]$ | 52.25 |
| Outer race frequency (OR) | $OR = N(FTF)$ | 77 |
| Inner race frequency (IR) | $IR = N(rps - FTF)$ | 133 |

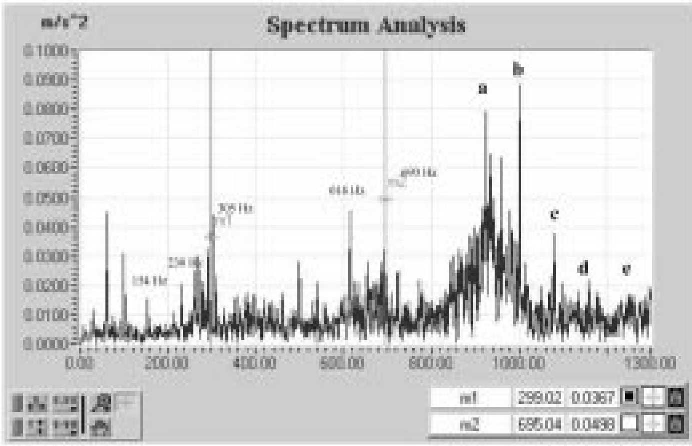


Fig. 11. Faulty bearing system.

Figure 11 is obtained for a system with bearing fault. It shows high peaks at OR frequency harmonics, which are 155 Hz ($2 \times$ OR), 230 Hz ($3 \times$ OR), 305 Hz (4x OR) 616 Hz ($8 \times$ OR) and 693 Hz ($9 \times$ OR). Respectively, at higher frequency, the sidebands with interval of 75 Hz to 79 Hz also appear. These side band frequencies and peaks are shown in Table 5, which gives an average interval of 76.75 Hz, which is about 77. The 77 Hz is the OR of the faulty bearing. This analysis confirms the used outer race fault bearing. Hence the vibration signature for bearing fault is that side band frequencies will appear at ball bearing faulty frequency as shown in Table 4.

## CONCLUSION

This paper has demonstrated how vibration monitoring and analysis can be studied to understand system performance for both teaching purposes and industrial needs. Since vibration monitoring and analysis is a practical oriented procedure, there is the need for students to acquire hands-on training in this area so as to effectively learn and understand this technique. A VFSR is designed and developed to serve this purpose by providing fault signals from a real physical system which can be used to bridge the gap between theory and practical knowledge. This VFSR has been successfully used in simulating most common machinery faults such as: imbalance, gear fault, misalignment, eccentric pulley, mechanical looseness, electric motor fault, bent shaft, vane passing, bearing fault and missing blade. The VFSR is also capable of providing field balancing training of rotating equipments. The simulated faulty vibration signatures characteristics are valuable sources to form a database needed in developing a self-diagnosis or intelligent based system. The intelligent based system should have the capability of identifying possible faults from the change in the vibration spectra and to send alarm to the user. Consequently when such system is fully developed it will be a very valuable training kit for teaching undergraduate students as well as to train maintenance staff in the industry. In this paper it has been shown how a combination of signal processing and sensor can also be used to perform faults analysis for predictive maintenance. VFSS has been developed and used in our department for demonstrating some DSP concepts to the students.

Table 5, Bearing fault side bands analysis

| Peak | Frequency (Hz) | Interval (Hz) | Amplitude (g) |
|---|---|---|---|
| a | 925 | – | 0.079 |
| b | 1003 | 76 | 0.0881 |
| c | 1080 | 77 | 0.0376 |
| d | 1159 | 79 | 0.0215 |
| e | 1234 | 75 | 0.0094 |
| | Average | 76.75 | |

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