9.2.4.2 Disadvantages of Overall Level Monitoring:

a) It is only a crude overall measurement.

b) No frequency related information is available.

c) Its capability to identify defects is limited because of the absence of frequency formation.

d) The author's experience has shown that if an RMS vibration level is composed of say three frequencies of similar amplitudes, the machine will subjectively appear "better" than would a vibration level of the same RMS value but composed only of say a fundamental shaft rotation frequency. This means, in effect that monitoring RMS levels and ignoring frequency information can be misleading particularly when one is trying to assess the rate of deterioration of continuously operating plant.

9.2.5 Bandwidth RMS Trending

This technique introduces the frequency aspect of trending, to a limited extent. An FFT analyser is interfaced to a desktop computer. Software was developed by the author whereby bandwidth RMS values of certain discrete frequencies of interest, such as at the fundamental speed, twice fundamental and any other higher order harmonics were obtained. See the flowchart in Figure 9.7.

This technique operates as follows: Since the energy of a discrete frequency component is spread over approximately three bandwidths or cells, it is more representative to obtain RMS values of the cell containing the running speed
WHERE: \( x_2, x_1 \) & \( x_3 \) represents the velocity values of the cell containing the 1x RPM component, one cell to the left and right respectively.

\( x_{bv} \) bandwidth trending value for the 1x RPM component.
say, and a cell to the left and right of that. This is illustrated in Figure 9.7.

If the speed, load, flowrate or pressure of a machine changes slightly between measurements, the results obtained will still be representative of the condition at the particular frequency of interest. This only applies if the speed variation is of the order of 1 or 2 Hz for a frequency range of 500 Hz and a window containing 400 cells. Example, if we were to find the bandwidth RMS value of a frequency component at 25 Hz, we would take the value in cells 19, 20 (25 Hz) and 21, square and add them and then take the square root. Say the speed of the machine drops to 23 Hz the energy will be spread over cell numbers 18, 19 and 20, with the majority of the energy in cell 19. The software developed for this method takes fixed cells each time, i.e. 19, 20 and 21 in this case. So even with small changes in speed this method of trending is representative of the energy present in a discrete frequency component. Spurious results would be obtained if only one cell was used and the speed varied.

If computerised data logging is used a tremendous saving in storage requirement is achieved. A disadvantage of using this technique is that a previously unseen fault might occur at frequencies or orders other than those being monitored, and the fault could be missed.
9.2.6 Setting Alarm and Trip Levels for Discrete Frequencies

Three methods exist for setting alarm and trip levels. The most crude of these is to set one alarm and trip level over the full frequency range, as shown in Figure 9.8 below.

The main disadvantage of this method is that alarm and trip levels are only set for the fundamental rotational frequency. The reason for this is that the amplitudes of the higher order harmonics are unlikely to exceed that of the fundamental rotational frequency.

The second method sets different alarm levels over fixed frequency ranges. Three alarm levels are set over the frequency range chosen. The first alarm level is set from zero Hz to 0.8 times the fundamental rotational frequency.
The second alarm level is set from 0.8 times to 1.2 times the fundamental rotational frequency. The third alarm level is set from 1.2 times the fundamental rotational frequency to the end of the frequency range. The main advantage of this method is that not only can the fundamental rotational frequency be trended but also sub-harmonics and harmonics of this frequency. This method is illustrated in Figure 9.9.

The third method involves setting different alarm and trip levels for any number of discrete frequencies. This method is illustrated in Figure 9.10. The main advantage of this method is that discrete frequencies of importance can be individually monitored according to their own unique alarm and trip levels. It is the author's view that the last method is the best in terms of overall protection against catastrophic failure. This method also gives immediate indication of the source of the problem, by identifying which frequency has exceeded the alarm level. The more individual alarm and trip levels that are set for discrete frequencies the more difficult it is to set levels that avert false alarms and unnecessary trips. The alarm and trip levels must be set so as to allow enough lead time between these levels for the machine to be rectified before it is tripped.

9.2.7 Spectrum Cascade Trending

This method employs a technique whereby frequency spectra, taken at different times, are represented on a three-dimensional plot. The emergence of discrete frequencies can immediately be detected on this plot. The main advantage of such a plot is that the vibration history of a machine is represented on one compact plot with frequency information available. A spectrum cascade trend plot can be seen in Figure 9.11.
ALARM & TRIP LEVELS FOR DISCRETE FREQUENCIES

WHERE $X = \frac{1}{60} \cdot \text{RPM}$ (Hz)

FIGURE 9.9

FIGURE 9.10
SPECTRUM CASCADE TRENDING

FIGURE 9.11
9.2.8 Phase Trending

Steady state phase trending is important to detect vectorial changes. The propagation of a crack in a rotor manifests itself as a vector change.

9.2.9 Other Important Aspects of Trending

1) An important aspect to remember about trending is that a graphical record is easier to interpret than a tabulation of the same values. The advantage of displaying data graphically is that the trend of a machine's condition can be determined at a glance.

2) The time interval between taking vibration measurements must be such that a sufficient lead time is allowed before failure. This is illustrated in Figure 9.12.

9.3 MANUAL AND COMPUTERISED LOGGING

9.3.1 Manual Data Logging

Manual data logging has three major disadvantages:

1) It is time consuming to log data manually.

2) Another disadvantage of manual detailed data logging is evident when we attempt to review all of the data after they are logged. Because of time restrictions not all points can be plotted manually or even carefully reviewed. Further cross-correlations cannot be made easily.
THE REGULAR MONITORING OF DETERIORATION TO GIVE ADVANCED WARNING OF FAILURE
3) Another major disadvantage of manual detailed data logging relates to personnel. All too often, management fails to understand the importance of designating specific personnel to the machinery-monitoring task. The greatest asset to any machinery monitoring programme is personnel who are well trained and experienced enough to understand exactly what is being logged.

9.3.2 Computerised Data Logging

A well designed computer logging system can overcome some of the inherent limitations of manual data logging listed above. For example time to take data and data trending. Computers will usually not solve the personnel problem. On the contrary, computers require highly trained people to use them efficiently and keep them running.

The main advantage of computerised data logging is that once the data has been stored, it can then be transcribed to include the following:

1) Cross-correlation.

2) Statistical analysis such as Kurtosis so that the condition of roller and bail bearings can be monitored.

3) Statistical algorithms for anomaly detection.

4) Normalisation of data.

Another advantage of a computerised based monitoring system is its ability to store a large quantity of data and then rapidly recall and present them in a convenient format. This
eliminates the need for strip chart recorders and the time consuming process of manually sorting rolls of chart paper when looking for a particular event.

The overall objective of such a system would be to:

1) Continuously monitor vibration levels of critical rotating equipment.

2) Automatically analyse, store and update vibration information for trouble shooting purposes.

3) Generate alarms that would indicate the source of trouble if anomalies develop.
9.4 CONSIDERATIONS CONCERNING THE PURCHASING OF PERIODIC VIBRATION MONITORING EQUIPMENT FOR RECENTLY COMMISSIONED AND FUTURE ESCOM POWER STATIONS

9.4.1 Introduction

In its simplest form periodic vibration monitoring involves the acquisition of vibration data using a hand held vibration meter and manually logging the data for trending purposes. Manual data logging routines have one major, inherent fault - time. With the advent of computerised data logging and storing systems large volumes of vibration data generated from machines can be handled efficiently.

The trend today is to opt for a computerised data logging system. This is only economically feasible if a large number of machines are to be monitored. With a computerised system a fully portable, microprocessor-based data collector greatly simplifies the task of gathering information. Once the steady state vibration data from various machines have been stored in the portable data collector's memory, this data is then down loaded into the host computer where the data is stored, updated and trended on a floppy disk or hard disk.

An important prerequisite is that the equipment must be simple to use, (a semi-skilled labourer must be able to operate it), as well as allow for more detailed diagnostic analysis to be performed when necessitated by impending problems.

Technological advances in the development of software and hardware used for periodic vibration monitoring equipment make it increasingly difficult to choose a system that will
not be obsolete by the time you get around to use it. Stewart (52) estimates that 90% of all condition monitoring equipment bought over the past 10 years now lies idle for reasons either of basic unsuitability or simple obsolescence. Periodic vibration monitoring equipment must therefore offer versatility to cater for technological advancements and increased plant size.

9.4.2 Software

After conducting an extensive market survey into periodic vibration monitoring software packages and examining the possibilities of developing "in-house" software it was soon comprehended by the author that a compromise between the following had to be reached:

a) If an "off-the-shelf" computer package were to be purchased it would not completely satisfy ESCOM's needs regarding an efficient and rational vibration monitoring programme.

b) If "in-house" software were to be developed this would fulfil ESCOM's needs but it would not be cost and time effective. Also, the necessary hardware for the acquisition of the dynamic vibration data would have to be developed.

After serious consideration of the above predicament it was concluded by the author that the purchasing of an "off-the-shelf" computer package to cater for most of ESCOM's periodic vibration monitoring needs, would be more cost effective, efficient and less time consuming than to develop "in-house" software.
9.4.3 Software requirements

1) The software must be well structured and designed in terms of ease of operation and user friendliness.

2) The quality of the documentation supplied concerning the operation of the system must be such that an operator, with no or very little or no computer experience, can operate the system within a short time.

3) The software must be updated regularly by the supplier to reflect changes in technology.

9.4.4 Requirements Concerning the Supplier of the Periodic Vibration Monitoring Equipment

1) The supplier must offer a reasonable after sales service, to cope with any software or hardware problems that might arise.

2) The supplier must be in a position to offer training should it be deemed necessary.

3) The supplier must be involved in vibration monitoring to an extent where he publishes application notes concerning case studies and applied research. This is to ensure that the supplier includes field and practical related experience and knowledge in the design of the software and portable vibration data collector.
9.4.5 System Requirements for Periodic Vibration Monitoring Equipment

It is the author's view that periodic vibration monitoring equipment should have the following requirements:

1) The data collector must be fully portable, i.e. battery operated.

2) The data collector's mass and size must be such that an operator will feel comfortable carrying the equipment around the plant for up to five hours.

3) The data collector must be robustly constructed to cope with the rugged field environment.

4) The data collector must have a non-volatile memory or bubble memory so that vital machine data is not lost due to low battery life or batteries being changed. If this feature is not available a method whereby stored data, in the data collector's memory, can be quickly transferred to a floppy disk must be provided in the event of low battery life.

5) If the data collector makes use of a volatile memory then it must include a feature whereby the operator is forewarned of low battery life.

6) The data collector must be capable of departing from a pre-determined route to collect measurements from equipment requiring immediate attention.
7) The data collector must be capable of displaying overall vibration levels. It should also display FFT frequency spectra graphically on the collector unit for field analysis. An over load light must be provided to indicate when spurious vibration data is being collected.

8) The ergonomics of the system must include the following:
   
a) The data collector's keyboard must minimise operator error.

b) When the operator is in the process of collecting data the equipment must allow him to have both or at least one hand free so that he can operate switches and move transducers. His hands should not be pre-occupied in holding the data collector.

9) The data collector must contain a softkey option so that notes describing vital observed conditions can be stored for later reference.

10) A semi-skilled labourer should be able to operate the data collector without any difficulty. At the same time the software must allow for more detailed diagnostic analysis to be performed when necessitated by impending problems.

11) Previously obtained data must be easily retrievable for diagnostic purposes.

12) The system must be able to monitor discrete frequencies such as blade passing frequencies which occur at several times fundamental rotational speed.
13) The system must include a feature whereby specific parameters, which are pertinent to the mechanical condition of the machine, can be trended, such as:

a) Overall RMS levels.
b) Discrete frequencies.
c) The full frequency spectrum.
d) Phase related information.

14) The system must include a feature whereby steady state vibration data can be compared to pre-determined alarm levels so that status reports can be generated.

15) As computerised logging is used it is not necessary to analyse page after page of spectra that contain nothing more than a low amplitude component at the running speed, followed by two or three lower amplitude multiples. As long as vibration amplitudes at different discrete frequencies are below some pre-established value and is stable, nothing more needs to be done. The software must include a feature whereby the operator is only notified of vibration amplitudes at discrete frequencies, when they have exceeded some pre-determined value.

16) The system must also include a feature whereby the amplitude scale in the frequency domain spectrum can either be logarithmic or linear.

17) A cursor must also be included in the frequency domain spectrum when displayed on the CRT of the computer. This is convenient for determining amplitudes and frequencies of discrete components.
18) The periodic vibration monitoring equipment that will be purchased by various new power stations must be standardised to ensure compatibility. The purpose of standardised equipment is twofold:

a) Power station personnel at various power stations will be able to share their knowledge with each other as well as solve common problems. This will lead to a greater proficiency of the system and equipment.

b) To ensure that the power station's vibration monitoring equipment is compatible with specialist groups such as Engineering Investigations and CMS.

19) All new power stations will have permanently installed transducers on critical machines. The data collector must accommodate outputs from both velocity, displacement and accelerometer transducers, so that full vibration spectra from these machines can be obtained via a buffered output.

9.5 CONSIDERATIONS CONCERNING THE PURCHASING OF CONTINUOUS ON-LINE VIBRATION MONITORING EQUIPMENT

On-line vibration monitoring equipment is used to continuously monitor the vibration levels from permanently installed transducers on critical machines that are subject to problems, or where problems can develop rapidly and have severe financial consequences.

Most on-line continuous monitoring systems consist of permanently installed sensors coupled to an indicator. These indicators take on three forms:-
a) Strip chart recorders which scan signals from various sensors.

b) Dedicated indicators for each sensor which display vibration levels in digital or analog form.

c) Computerised real-time systems with exceptionally high scan rates which can store both steady state and transient data.

The shortcomings of the abovementioned three indicators will now be discussed.

9.5.1 Strip Chart Recorders

This form of indicator is used to monitor vibration levels from permanently installed velocity transducers mounted on the turbo-generator's bearings. The system scans the vibration levels from the transducers and plots them in different colours on the strip recorder. Alarm levels are initiated when vibration levels exceed pre-set levels. The operator is normally notified by a bleeper and flashing indicator that an alarm level has been exceeded. If vibration levels exceed a preset trip level then the machine is tripped.

The main disadvantages of strip chart recorders are:

1) They can only record steady state data.

2) Their scanning rate is relatively slow and it is quite possible to miss a sudden increase in vibration levels during one of its scans.
3) No phase information is available so vector changes cannot be monitored to detect cracks and a sudden breakage of part of a blade.

4) The thickness of the pen used often exceeds the resolution, that is, only large variations in vibration levels are detected or noticeable.

5) Problems can often be overlooked or missed if the strip chart rolls are not promptly analysed after they have been replaced.

6) Unless the strip chart is continuously monitored by the operators, problems could be overlooked. This situation is further aggravated if poor communication exists between the operators of succeeding shifts concerning impending problems. Problems that have been noticed by one shift operator could result in catastrophic failure during the next shift if no mention of such a problem was made.

7) Only peak to peak vibration levels are monitored. No discrete frequencies are monitored.

9.5.2 Dedicated Indicators

This indicator operates on the same principle as the strip chart recorder, the only difference being that the vibration levels are displayed in digital or analog form. Dedicated indicators are normally installed on less critical machines, in FSGOM's case the draught group fans. In modern power stations the levels are displayed on the CRT in the control room, and are available as a hardcopy.
Disadvantages of dedicated indicators:

1) They can only display steady state data.

2) No phase information is available, so no vector changes can be monitored.

3) They only display overall RMS vibration levels.

4) No record of the continuous vibration levels in a form of a hardcopy is available.

5) Unless the levels from the monitors are recorded on a regular basis, the dedicated indicator only acts as an alarm and trip initiator.

9.5.3 Computerised Real-Time Systems

The overall objective of a computerised system is to:

1) Continuously monitor vibration levels of critical rotating machinery.

2) Automatically analyse, store and update vibration information for trouble shooting purposes.

3) Generate alarms that would indicate the source of trouble if problems develop.

The main advantage of a continuous on-line system is that a vast amount of vibration data can be stored and retrieved almost instantaneously and in a convenient format.
Other advantages include:

1) Steady state and transient data can be stored provided the scan rate is sufficiently high.

2) Discrete frequencies can be monitored such as, 1 x RPM, 2 x RPM and the blade passing frequency.

3) Vector changes can be monitored and trended provided a keyphasor and tracking filter are available.

4) Run-up and coastdown transient data are available after every general overall so that crack propagation can be detected.

9.5.4 Requirements of a Computerised Real-Time System

1) Real-time systems should perform statistical analysis so that any deviation from the baseline signature can be detected.

2) Since the alarm setting at each bearing might be different, the system should normalise the measured vibrations with respect to these so that the operator merely has to glance along a single line to see which bearings are approaching the desired levels.

3) The operator must be able to manually select a number of display formats. For example, frequency spectra, shaft orbits with phase information, eccentricities and trend plots.
4) Real-time systems should monitor discrete frequencies with regard to transient and steady state vibration data.

5) Should the machine reach 80% of its normal operating speed then the coastdown should be automatically stored, so that vibration data prior to an unexpected trip, is available.

6) The scan rate of the system must be sufficiently high to acquire data during the faster part of the run down.

9.5.5 Requirements for all On-Line Continuous Systems

1) The trip signal should have a time delay and trip multiplier facility to increase the preset trip level. This feature must be available so that the machine is not tripped as it passes or excites a shaft critical or resonance during the start up of the machine.

2) The monitors must have buffered outputs so that, in the case of strip chart recorders and dedicated monitors, detailed steady state and transient vibration data can be recorded for later analysis.

3) To ensure compatibility all these outputs should have standardised BNC connectors.
STANDARDISED RULES FOR MEASUREMENTS ON ROTATING MACHINERY

Several ESCOM power stations have embarked on vibration monitoring programmes. Since vibration specialist groups within ESCOM such as Engineering Investigations and Central Maintenance Services (CMS) are involved in these programmes it is important that compatibility and standardisation exists not only of equipment but also on rules of measurement.

The abovementioned specialist groups will be required to perform detailed diagnostic analysis when the maintenance personnel at the power station are unable to diagnose problems. It can be very difficult in certain circumstances to diagnose a vibration problem without knowing the maintenance history of the machine. Since computerised vibration trending and logging has been recommended, all the vibration machine history will be stored on a floppy disk. If a vibration problem arises at a power station, and the maintenance personnel cannot solve it, then a copy of the floppy disk containing the vibration history can be sent to the specialist groups. Having compatible equipment the specialist groups will be able to generate spectra and trend plots, and thus familiarise themselves with the vibration history of the machine.

In order to achieve this compatibility, it is desirable to standardise communication by means of a set of recommended practices defining:-

a) The polarity and phase referencing of transducers.
b) The orientation and location of transducers.
c) The presentation of vibration data.
d) The units defining vibration severity.
e) The method of identifying machinery using a four digit number.
a) Polarity and phase reference

Proximity Probes

Movement toward a transducer along its sensitive axis produces a positive signal of voltage or current. The polarity of a relative displacement transducer is easily tested by decreasing the gap as shown below in Figure 9.13:

![Graph showing relationship between gap and voltage](image)

**FIGURE 9.13**

GAP IN MICROMETERS

VOLTS

0 VOLTS

GAP DECREASE INCREASE
Velocity transducer and accelerometers

The polarity of velocity transducers and accelerometers is easily tested by means of an impact test. The impact test consists of lightly tapping the transducer in the sensitive axis. The resultant waveform, as shown below in Figure 9.14, is an initially positive going output signal when tapped toward the sensitive axis.

In the event of all three subjected to the same sinusoidal motion during calibration procedures, the velocity and acceleration signals lead displacement by $90^\circ$ and $180^\circ$ respectively.
h) Orientation and location of transducers

Normally velocity transducers and accelerometers are mounted either axially, horizontally and vertically on bearing housings. The orientation and location for a typical machine is shown below in Figure 9.15:

Proximity probes are usually mounted 90° to each other. Figure 9.16 below shows a typical vertical and horizontal orbit display using vertical and horizontal probes.
b) **Orientation and location of transducers**

Normally velocity transducers and accelerometers are mounted either axially, horizontally and vertically on bearing housings. The orientation and location for a typical machine is shown below in Figure 9.15:

Proximity probes are usually mounted 90° to each other. Figure 9.16 below shows a typical vertical and horizontal orbit display using vertical and horizontal probes.
When transducers are located off vertical and horizontal, typically 45° off vertical centreline, the 45° up left transducer is presented to the oscilloscope vertical input and the 45° up right transducer is presented to the horizontal input viewed from the drive-end of the machine. Both orbit and time displays for 45° mounted transducers are shown below in Figure 9.17:
Transducer orientation guidelines

Special care must be taken in identifying and labelling orthogonal pairs of proximity pairs to ensure that the orbits are properly displayed.

The following guidelines and conventions are recommended.

As viewed from the outboard end of the driver:

0 degrees = horizontal right (3 o'clock).
90 degrees = vertical up (12 o'clock).
180 degrees = horizontal left (9 o'clock).
270 degrees = vertical down (6 o'clock).

The "vertical" probe connects to "channel 1" and the "horizontal" probe connects to "channel 2".
American Petroleum Institute Standard API 670 (12) suggests that when viewed from one extreme end of the machine train, preferably the drive end, the Y-probe (vertical) shall be on the left side of the vertical centre and the X-probe (horizontal) shall be on the right side of the vertical centre.

c) **The presentation of vibration data**

When vibration data from various machines are collected at set intervals of time, it is normal to display this data as a trend plot. Trend plots can take the form of overall RMS versus time, or phase versus time or three dimensional frequency spectrum versus time plots.

A frequency domain spectrum is defined as a spectrum of amplitude versus frequency. A time domain spectrum is defined as a spectrum of amplitude versus time. Trend plots usually take the form of overall RMS versus time plots. Discrete frequencies such as the fundamental or blade passing frequency can also be individually trended. This is illustrated in Figure 9.18.

Phase trend plots are plots of phase versus time. The phase being the phase difference between the vibration component at the fundamental rotational speed or harmonic thereof obtained from a transducer and a pulse obtained from another transducer as it passes a fixed reference point like a keyway.

Three dimensional or cascade spectrum trending (CST) combines the frequency domain spectrums on the x-y axis with time on the z-axis.
Figure 9.18
Shaft orbits are normally displayed as $1 \times$ RPM, $2 \times$ RPM or $1/2 \times$ RPM filtered orbits at a particular speed, or as unfiltered orbits.

d) Units defining vibration severity

The three most common units of vibration are displacement in micrometers ($\mu$m), velocity in millimeters per second (mm/s) and acceleration in g's or meters per second squared (m/s$^2$).

It is recommended that the following units be used with ESCOM.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement in $\mu$m</td>
<td>peak to peak</td>
</tr>
<tr>
<td>Velocity in mm/s</td>
<td>RMS</td>
</tr>
<tr>
<td>Acceleration in m/s$^2$</td>
<td>Peak</td>
</tr>
</tbody>
</table>

e) The method of identifying machinery using a four digit number

The data collector that has been recommended uses a four digit identification number to distinguish between different measuring positions.

It is advantageous to standardise on the identification numbers so that improved communication can take place between the maintenance personnel, the specialist groups and between the various departments within the power station.

The numbering system can be such that a number for a particular machine bearing at one station will refer to
the same machine bearing at another station. Although some stations differ in design, it can still be possible to identify the machine train at any station given the four digit number.

The following numbering system is recommended. Assume the identification number to be represented by ABCD, where A, B, C and D are numbers from 0 to 9.

The first number A will distinguish between the various units i.e. if A = 1 then this will be referring to Unit 1.

The second number B will refer to specific items of plant.

B = 1 refers to the turbo-generator set
B = 2 refers to the electric and steam feedpumps
B = 3 refers to the extraction pumps
B = 4 refers to the condensation polish plant
B = 5 refers to the draught group fans
B = 6 refers to the mills
B = 7 refers to the cooling water pumps
B = 8 refers to the water purification plant
B = 9 refers to miscellaneous items of plant

The third and fourth numbers refer to specific bearing locations in the train. It is customary to start the numbering at the driver side. The numbering of the main turbo-generator set should start at the barring gear side. Although vertical and axial measurements are recommended for the turbo-generator set, and horizontal and axial measurements for the draught group fans, three
identification plates per bearing is recommended. It is also recommended that these plates be standardised. The identification numbers should also be engraved on the identification plates.

**Vibration Standards**

To ensure conformity within ESCOM it is recommended that ISO 3945(53) and ISO 2373 (54) be used. These standards are recommended because they are universal in the sense that they are a combination or summary of most of the other standards like VDI and API.