Condition Monitoring

At

Associated Pulp and Paper Mills

Wesley Vale, Tasmania.

By

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Abstract

This report describes the introduction of large scale Condition Monitoring by Associated Pulp and Paper Mills (A.P.P.M.) at Wesley Vale (W.V.), Tasmania. Some C.M. techniques have been in use for several years at the mill but without being part of an overall C.M. program. Two examples are:

- Dye-penetrant testing.
- Thermography.

The report includes a literature survey describing some of the different techniques available to the Condition Monitoring Engineer. The three basic principles of C.M., (*Detection*, *Diagnosis*, and *Prognosis*) are discussed, as are some of the more common techniques in use in other industries.

An introduction to vibration monitoring is presented to set the scene for the application of this technique in the Paper Mill and is discussed in more detail in the following chapters. Examples of the types of machine faults that can be detected by a vibration monitoring program are discussed along with some of the techniques available to process the vibration data. Included also is a discussion on the need for the selection of appropriate measuring points and transducers.

The history of C.M. at the W.V. paper mill, including dye-penetrant testing and Thermography, are discussed with case studies included.

The extension of the major time based maintenance intervals (annual shuts) from twelve months to eighteen months made the need for a condition based maintenance system more acute. This would be sustainable only if the progress of any developing fault could be monitored and preventative action taken before failure of the machine occurred.

The range of plant and equipment in use at W.V. is discussed along with some of the causes of break-downs commonly encountered with this machinery. The most common reason for plant downtime is due to bearing related faults. Vibration monitoring is selected as the most appropriate C.M. technique for W.V. given the types of machines in service and the kind of faults experienced.

The selection of the particular vibration monitoring hardware and software to be used in the vibration monitoring program is discussed. The decision on which equipment to use was based on the need to consider the following points:

- Cost.
- Compatibility with existing data.

- Ease of use.
- Availability of software upgrades.
- The ability to extract a slice of the database.

The C.S.I. hardware and software selected for use at W.V. is discussed along with the necessary support equipment such as computers, cables, and accelerometers.

Some of the practical problems encountered in getting the vibration monitoring program in place are discussed including the fitting of studs to machines and getting co-operation from the maintenance staff generally. The use of A4 size floor plans to assist in the identification and location of each machine to be monitored is discussed.

The monitoring program for the 4MW steam turbine at W.V. is discussed including both oil analysis and vibration monitoring. The balancing of the turbine rotors carried out in early 1991 and the problems encountered in this job are also outlined.

Results of the monitoring program are included after it had been in use for about eighteen months along with some case studies. Included is a discussion on the training of the maintenance staff and their place in the C.M. program.

The use of Computer based Maintenance Management Packages is discussed along with their interaction with the C.M. program in use at the mill. The need for good maintenance records is highlighted along with a proposal for upgrading the existing mill data collection system to give sufficiently accurate records to allow statistical analysis of breakdowns to be carried out when required.

The use of Expert Systems as an aid to C.M. is discussed with a pilot program being developed by the writer for future use at Wesley Vale.

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1.0 Introduction.

This report outlines the use of C.M. at the A.P.P.M. Wesley Vale paper mill in Tasmania. Particular attention was paid to the use of vibration monitoring, this being the most recent technique implemented, and because it is the most widely used C.M. technique on site.

Oil analysis is described in some detail because, while it has been in use in various forms for a number of years, it has not been set up in such a way as to get the greatest benefit from the results. It is expected that the use of oil analysis and vibration monitoring will be used to complement each other rather than as competing C.M. techniques.

1.0.1 Aim.

The aim of this report was to investigate the various condition monitoring techniques in common use within industry and to describe the application of one or more of these techniques to the Wesley Vale paper mill of A.P.P.M.

This report is also intended to meet the requirements of the Faculty of Engineering, University of Tasmania for a Master of Engineering Science Degree.

1.0.2 Scope.

This report covers the integration of condition monitoring with the planning and execution of maintenance at A.P.P.M. Wesley Vale Tasmania. The report discusses the use of complementary techniques including Oil analysis, Vibration Monitoring, and Thermography, all of which are now in use in varying degrees at the mill.

1.0.3 Limitations.

As the regular use of condition monitoring in maintenance is relatively new to the mill it is not possible to give any quantitative information on the long term benefits of this approach to maintenance beyond that given in the text. In time as this information becomes available it will be possible to review the C.M. program and refine these techniques.

The lack of any previous maintenance cost reporting system makes it impossible to give any quantitative measure of the cost benefits of implementing the overall C.M. program. Because of the lack of this reporting in previous years it is impossible to give a before-and-after comparison of maintenance practices.

1.1 Introduction to Condition Monitoring (C.M.).

Because of the increasing costs associated with downtime on plant and equipment, any technique that can be used to decrease this downtime has the potential to save a considerable amount of money for a company. Since machinery was first used on a large scale last century, operators have been applying C.M. in the form of looking for unusual signs, listening, etc. Any change from normal operation is interpreted as being an indication of some developing fault in the machine, and if detected early enough can help to prevent further damage.

As many process industries and manufacturing plants operate 24 hours a day, there will be two or more shifts responsible for the operation and maintenance of the plant and equipment. This can lead to a considerable variation between shifts in the ability of operators and maintenance personnel to recognise and correct developing faults in the equipment. One shift can assume that another shift is taking care of any faults that are known or alternatively little attention may be given to equipment as one shift competes with another for increased production targets. The net result of this lack of attention to equipment, and variation in ability to detect faults, is an increase in plant downtime and associated lost production.

A regular condition monitoring program using one or more of the techniques discussed in this paper would overcome the problems associated with the traditional methods mentioned above and permit the operators to concentrate on production. This can be achieved by :

(i) Reducing outside influences when assessing the machine condition and therefore make it easier to detect faults earlier.
(ii) Eliminating the human variability that can arise with having several people monitoring the machinery.

Condition Monitoring as an aid to planned maintenance has been in use for many years. The monitoring techniques used have varied from simple, periodic visual inspections of the equipment to fully integrated continuous monitoring systems that give automatic warning of a developing fault. Whichever monitoring technique is used in a particular application, there are some common advantages and disadvantages to condition monitoring generally :

Advantages

(i) Early warning of a developing fault.

(ii) Opportunity to plan maintenance work.

(iii) Reduction in damage to equipment due to a developing fault.

(iv) Reduction in potential hazards to workers.

(v) Reduction in unnecessary maintenance.

(vi) Increases life from equipment.

Disadvantages

(i) Cost to set up monitoring program.

(ii) Requires skilled staff to operate.

(iii) Requires an on-going commitment from management.

Traditionally the signs of an impending failure of a machine take one or more of the following forms :

(i) Increase in roughness.

(ii) Increase in noise level.

(iii) Increase in heat generated.

(iv) Increase in wear debris.

(v) Reduction in process efficiency.

(vi) Increase in power consumption.

A particular machine might show one or more of these symptoms as it deteriorates depending on the machine type and operating conditions. In practice it is often difficult for an operator to detect these warning signs early enough for them to be of use in preventing a breakdown. This can occur because of the environment in which the machine is being run. For example if the environment is noisy, a small increase in noise level or roughness of a single machine can be missed.

A rise in temperature generally manifests itself most noticably just prior to failure and therefore little time is available to take corrective action. If a regular wear debris monitoring program is not in place then the increase in wear debris that accompanies deterioration will be missed.

To reduce or eliminate unexpected failures in plant and equipment it is common in many industries to shut down the equipment and overhaul it on a regular basis. This is the case even for machines that were operating satisfactorily just prior to the shutdown. This form of maintenance has several drawbacks :

(i) Equipment not otherwise requiring overhaul is stripped unnecessarily.

(ii) This type of maintenance does nothing to detect or prevent random failures.

(iii) While the plant is shut down for periodic maintenance, production is suspended and this can lead to considerable financial loss for the company.

(iv) The length of time between maintenance shut-downs has to be a compromise that suits the plant as a whole rather than any particular machine. This can lead to the selection of a maintenance interval that is too long for some machines and too short for other machines. If the maintenance interval is longer than optimum for a particular machine, that machine is likely to suffer failures towards the end of the period. If the time period between shutdowns is shorter than optimum, then the machine is not run for as long as possible and thus maintenance costs for that machine are greater than would otherwise be necessary.

(v) Dismantling and re-assembling a machine that was running well before shutdown can reduce that machines reliability for some time after startup. This is because stripping a machine exposes it to poor assembly practices, the need for new parts to be run in etc. Figure 1.1 shows the characteristic curve for machine reliability as predicted by Weibull distribution. The characteristic curve is a composite of three individual curves that describe different stages in the machines life.

Early in the life of the machine the most likely cause of failure is due to what is known as Infant mortality. Infant mortality can be due to one or more of the following causes [11] :

(i) Poor design.

(ii) Poor quality components.

(iii) Incorrect assembly.

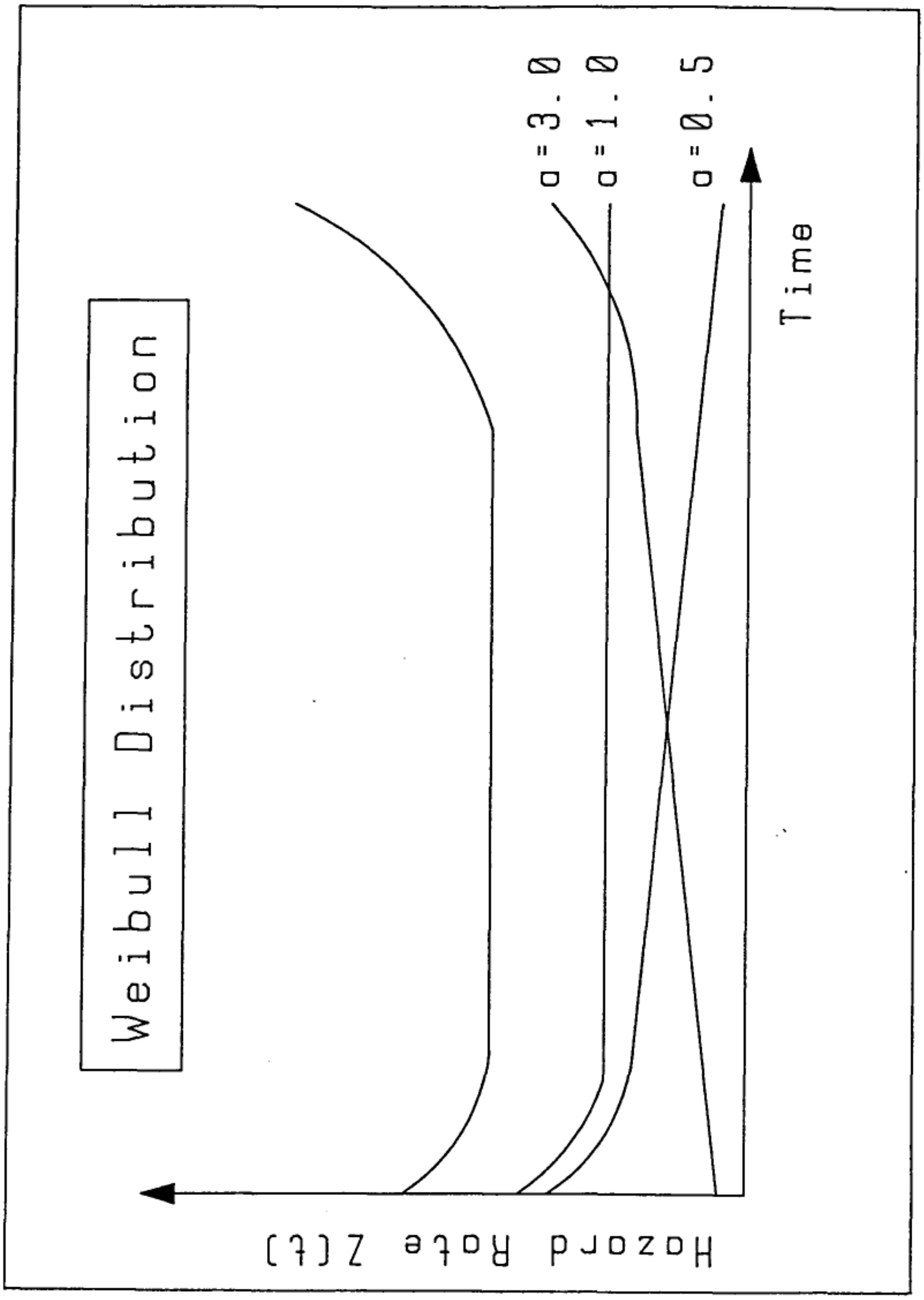


Fig. 1.1 Reliability curve for a typical machine.

These problems can be overcome to a large extent by careful attention to detail both at the design and assembly stages, and by using the most suitable components available.

During the normal life of the machine, failures are most often due to overstressing of the machine or due to using the machine in a manner for which it was not designed. This is quite common in industry and comes about due to increases in production levels over and above that for which the machine was designed. This can be difficult to allow for at the design stage as any advantage in increasing the machine size to allow for increased workloads in the future is offset by the increased capital cost of the installation. Therefore, the increase in machine capacity required to match an increase in production demand can lag the increase in production by a considerable time in some cases. In the intervening period the machine will have to be worked harder to meet the increased production demand, and all safety margins designed into the original installation will be reduced. The net result of this is to increase the probability of failure during the Useful Life Stage of the machine's life.

From the very moment that a machine is first operated, it begins to wear out. If the machine is properly designed for its application the rate of wear will be constant over most of its life, increasing rapidly as the machine reaches the wear out stage. Nothing can be done to prevent wear out but good operating and maintenance practice can delay it considerably.

The composite curve that results from the combination of these three curves is the traditional Bath-tub curve. Many excellent articles have been written on Weibull distribution and the Bath-tub curve in particular so no further detail will be given here [11,12,13,14].

The ideal method of performing maintenance work on plant and equipment is to work only on those machines that actually require maintenance and to perform that maintenance function just in time to prevent unacceptable operation or failure. This approach requires continuous or regular (periodic) monitoring of machine condition and early warning of any signs of deterioration of a component or of the machine as a whole. The proven technique to achieve this continuous or regular monitoring is to select and monitor variations in some parameter (e.g. vibration levels, temperature, process monitoring etc.) that is known to be a good indicator of machine condition.

Given the diversity of machines in a modern manufacturing or processing plant it is likely that more than one monitoring technique would be required to cover all machines of interest. In some instances different monitoring techniques can produce complementary information about a particular machine. For example a vibration monitoring program can be complemented by wear debris analysis in gearbox monitoring. The presence of increased wear debris supporting an increase in vibration level previously detected.

A significant advantage of On-condition maintenance is that the work load on the maintenance staff is considerably evened out over the year and not concentrated at one point during the annual shutdown. This saves the company a considerable amount of money (e.g. penalty rates, overtime rates etc.) that is likely to be required during a shut-down. Perhaps more significantly this can reduce production down-time and make more productive use of the workforce throughout the year.

For the above reasons there is a trend in industry towards extending the period between maintenance shutdowns. This is possible largely because of improvements in C.M. techniques over the last 10 years or so. Further improvements in technology will allow earlier detection of impending failures as well as more accurate diagnosis of the source of the failure.

The three basic steps involved in C.M., (regardless of the technique used) are :

(i) Detection.

(ii) Diagnosis.

(iii) Prognosis.

1.1.1 Detection.

Detection involves identifying the earliest possible sign of a component starting to wear or fail. This corresponds to the transition between useful life and wear out as shown in figure 1.1. By regular recording of the selected parameter (e.g. vibration level, wear debris quantity, temperature, changes in process indicator), and plotting this parameter, any trend that indicates a deterioration in condition will become evident (See fig. 1.2). For this reason the measured parameter should be selected to give the earliest and clearest warning of a developing fault.

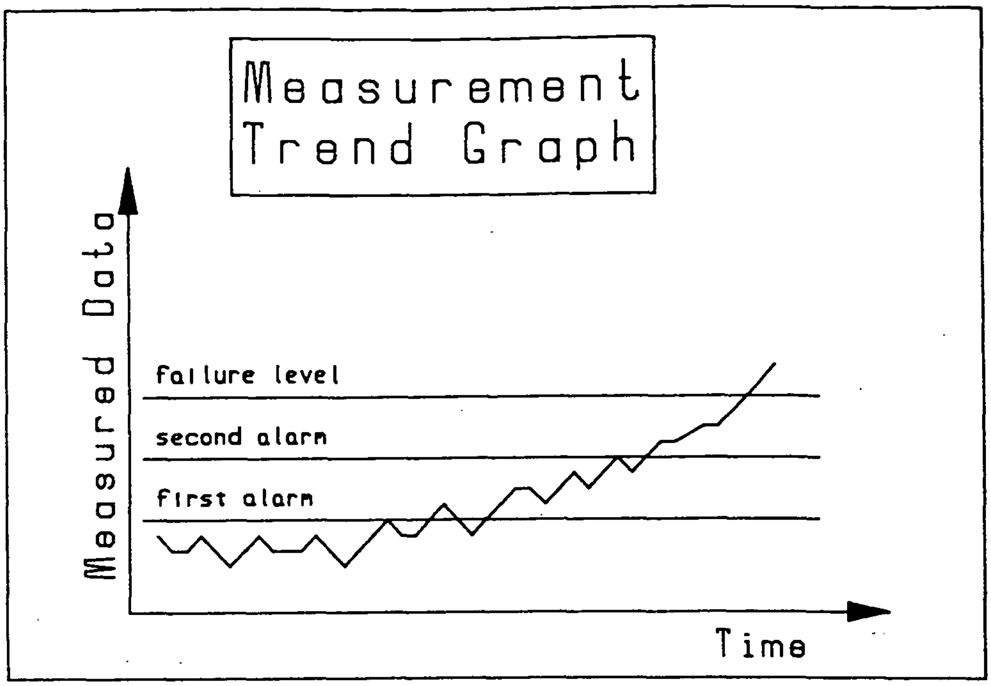


Fig. 1.2 Trending of a measured parameter.

The sooner this increase in the trend is detected the more time there is to take corrective action to prevent further damage. Because early detection allows planned maintenance of the machine, losses due to associated damage and production interruptions can be minimised or avoided.

It is often the case that a considerable amount of time elapses between detection of a fault and eventual failure. For example a vibration monitoring program can often detect the early signs of bearing failure months before the bearing becomes unservicable. Therefore a reliable reporting procedure is required to ensure that the maintenance department gets an initial report on the machine condition once the fault is detected, followed up by a reminder sometime before the repair is considered overdue.

1.1.2 <u>Diagnosis</u>.

Diagnosis involves determining the specific cause of an impending failure. That is identifying what component in a complex machine is actually failing. For example an overall increase in vibration level or in wear debris level, indicates that something is wrong with the machine but does not indicate the cause of the increase.

By detailed examination of the measured parameter it is possible to identify the specific component in the machine that has started to deteriorate. In the case of vibration monitoring, examination of the frequency spectrum can often indicate the component of interest if the operating frequencies of the major components are known.

Similarly with wear debris analysis, by examination of the material in the debris, and by comparing this with the known materials in the machine, it is possible to get a good idea of what is wearing excessively. For example if a significant increase in brass particles is detected in an oil sample from a gearbox, and the only brass in the gearbox is in the bearing cages, it is a good indication of bearing cage wear.

If more than one source exists for the particles that are detected, it can be difficult to determine which is the major contributor without stripping the machine.

1.1.3 Prognosis.

Prognosis involves estimating the remaining life of a machine before failure occurs. This is the least developed step in the C.M. of machines. This is because when a fault is detected and diagnosed, it is more than likely that the operating conditions will change as operators try to extend the life of the machine by reducing the load. For this reason it is not possible to say with any certainty how long the machine will last before failure.

1.1.4 Condition Monitoring Techniques.

There are many interesting techniques used in industry that can be used in C.M. some of which are discussed here. Of the many techniques available, vibration analysis and wear debris analysis are perhaps the most widely used in modern production facilities with special cases requiring different techniques.

Some of the more common techniques are [4,6,15] :

(i) Visual monitoring.

(ii) Vibration monitoring.

(iii) Wear debris analysis.

(iv) Thermography.

(v) Temperature monitoring.

(vi) Process monitoring.

It is usual practice to have more than one of these techniques in operation at any one time in a modern plant. This permits verification of doubtful cases by alternative means. In one application of a particular type of machine one technique may be superior to another, while in a different application of the same machine, an alternative monitoring technique may prove more suitable. For example, in two similar gearbox applications, one having a relatively high speed output shaft (500 RPM.), and the second application having a low speed output shaft (50 RPM.). The high speed output shaft application may lend itself to vibration monitoring and wear debris analysis as C.M. techniques whereas the low speed output shaft application might be more suitably monitored using wear debris analysis. This is because the vibration level is proportional to the square of the shaft speed (i.e. $a = -w^2xr$) [6]. For this reason at slow shaft speeds the vibration signal is often swamped by background vibration levels and by low frequency noise in the transducer [16].

In practice, the need to rationalise the C.M. equipment used can often mean that the equipment being used to monitor the machine condition may not always be the best for the task. For this reason it is important to realise the limitations of the equipment and know when the results are likely to be unreliable.

1.2 Vibration Analysis.

In all machines some of the input energy to the system (e.g. electricity to a motor, fuel to a diesel engine etc.) is dissipated as vibration. These vibrations exist even in a new, well designed machine, and generally increase as the machine wears out. This increase in vibration level over the life of the machine can be used as a practical indicator of the machines condition (See fig. 1.3). The total increase in energy and the energy at a particular frequency can both indicate deterioration of the machine.

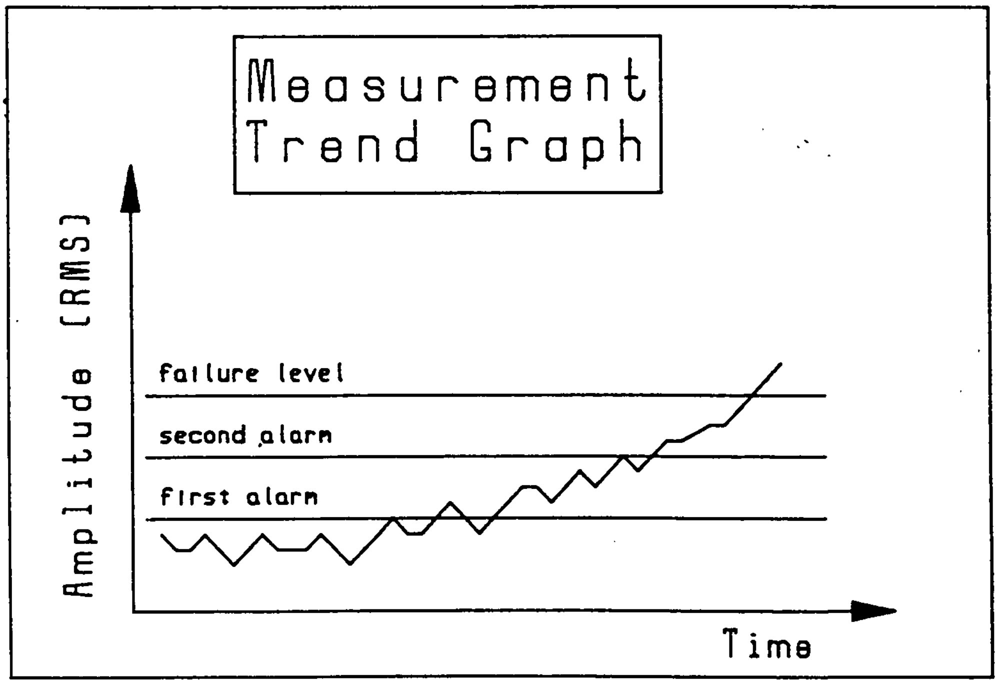


Fig. 1.3 Changes in vibration level over the life of a machine.

Vibration analysis can detect many different forms of machine defect particularly when used with a Fast Fourier Transform (F.F.T.) and spectrum analyzer. Some of these defects are [4] :

Shafts :
- Imbalance.
- Bent shaft.
- Loose components.
- Misalignment.
- Rubs.

Journals :
- Oil whirl.
- Journal/Bearing Contact.

Gears :
- Cracked teeth.
- Tooth mesh defects.
- Badly designed gears.
- Worn gears.

Rolling element bearings :
- Bearing surface pitting.
- Cage defects.
- Looseness.

Vibration in a machine occurs because of the dynamic forces created by the moving parts. The overall vibration level will increase as more power is fed into the system or as the system is operated at increasing speeds. The vibrations are transmitted through the machine as deflections in the 'less-than-perfectly-rigid' structure of the machine. Once these deflections get to the outside of the machine the moving surfaces set up pressure waves in the air, resulting in the sound typical of a particular piece of machinery. It is because of this link between machine vibration and machine sound that it is often possible for an experienced operator to detect the presence of some defect in a machine just by listening to it.

However because of the noisy surroundings in which many machines are operated, and because it is usually impossible to determine the source of the vibration just by listening to the sound coming from the machine, noise monitoring is not commonly used in Condition Monitoring. This is particularly so in modern process plant where many machines can be operating alongside each other on a 24 hour-a-day basis as it would be impossible to determine which machine was actually generating the noise without stopping all other machines in the surrounding area.

As a defect develops in a machine the overall vibration level increases and the vibration at the frequency of the damaged part also increases. By examining the amplitude of the vibration signal at the known significant frequencies for the machine, and comparing this amplitude with the signal taken when the machine was in good condition, it is often possible to say not only that some defect is developing in the machine, but what the source is.

A typical example of this type of detection and diagnosis is when a signature is taken of a machine in good condition and stored in a database as a baseline reading for future reference. If at some later time, (weeks or months), a further reading is taken under the same conditions and compared with the baseline reading, any increase detected can indicate a possible fault. By noting the frequency at which the amplitude increase occurred it is often possible to diagnose the cause of the increase in amplitude. The frequencies of significant components of the machine can be calculated beforehand and these are used to identify the component associated with a particular frequency.

Some examples of significant frequencies that can be calculated for a particular machine are :

(i) Shaft speed.

(ii) Ball pass frequency outer.

(iii) Ball pass frequency inner.

(iv) Cage rotational speed.

(v) Gear-mesh frequency.

(vi) Blade-pass frequency.

For example if the frequency corresponding with the increase in amplitude coincides with the outer ball pass frequency it indicates that a fault exists in the outer bearing race. These pits are fatigue induced and are quite common occurrences in bearings in industrial applications. Figure 1.4 shows some of the formulas used to calculate the frequencies of some common bearing faults [17].

Approximate Discrete Frequencies Expected from Roller Bearings.*

FREQUENCIES, in hertz	RELATIONSHIP TO OPERATION
$f = N/60$	Shaft rotational speed
$f = (N/120)(1 - [d/D] \cos\phi)$	Rotational speed of ball cage when outer race is stationary
$f = (N/120)(1 + [d/D] \cos\phi)$	Rotational speed of ball cage when inner race is stationary
$f = (N/120)(D/d)(1 - [d^2/D^2] \cos^2\phi)$	Rotational frequency of a roller element
$f = (nN/120)(1 - [d/D] \cos\phi)$	Frequency of contact between a fixed point on a stationary outer race and a rolling element
$f = (nN/120)(1 + [d/D] \cos\phi)$	Frequency of contact between a fixed point on a stationary inner race with a rolling element
$f = (N/60)(D/d)(1 - [d^2/D^2] \cos^2\phi)$	Contact frequency between a fixed point on a rolling element with the inner and outer races
$f = (N/60)[1 - \frac{1}{2}(1 - [d/D] \cos\phi)]$	Frequency of relative rotation between the cage and rotating inner race with stationary outer race
$f = (N/60)[1 - \frac{1}{2}(1 + [d/D] \cos\phi)]$	Frequency of relative rotation between the cage and rotating outer race with stationary inner race
$f = (nN/60)[1 - \frac{1}{2}(1 - [d/D] \cos\phi)]$	Frequency at which a rolling element contacts a fixed point on a rotating inner race with fixed outer race
$f = (nN/60)[1 - \frac{1}{2}(1 + [d/D] \cos\phi)]$	Frequency at which a rolling element contacts a fixed point on a rotating outer race with fixed inner race

*f = frequency, in hertz; N = shaft speed, in rpm; d = roller diameter; D = pitch diameter of bearing; η = number of rolling elements; ϕ = angle of contact between rolling element and raceway, in degrees ($\phi = 0°$ for a simple radial ball bearing).

Fig. 1.4 Formulas used to calculate some common frequencies.

The vibration reading is taken at the machine in either time, velocity, or acceleration units (or all three) at all the points considered significant for that machine. These points are decided upon by analyzing the machine and determining the directions that would give the most information for the least number of readings (See fig. 1.5).

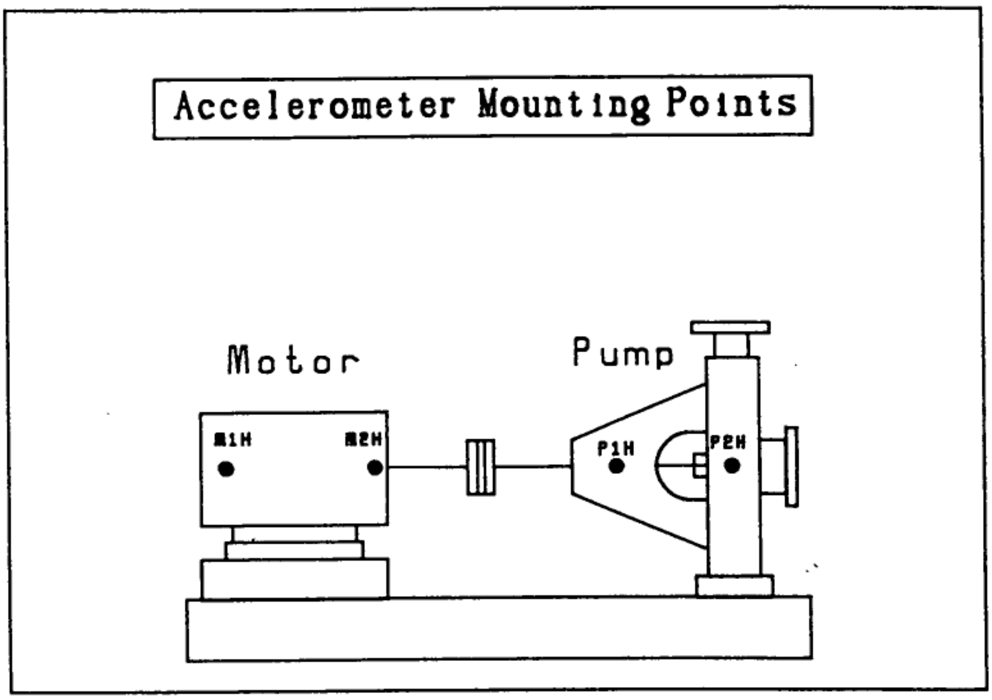


Fig. 1.5 Vibration monitoring points positioned to get the strongest signal.

The monitoring points at each end of the motor are used to detect bearing faults, loose bars, and unbalance in the motor. The point closest to the drive end of the pump is used to detect bearing faults in the pump, while the second pump point is used to determine if there is any unbalance in the impeller.

As the pump bearings are relatively close together, little can be gained by having a measuring point for each bearing. However if a vibration is detected in this area it helps if it is possible to determine if the impeller is the source or not. This configuration was suggested by the condition monitoring consultant from Tensor Systems and it is intended that this arrangement will be continued while it proves satisfactory.

In most instances these measurement points are located on or adjacent to the bearing housings, as all the forces generated in the moving components of the machine pass through the bearing housing (e.g. plumber block). If the bearing housing is not easily accessible a point on the machine housing (e.g. gearbox casing) having a solid uninterrupted path to the bearing, can be used. It is important to get as close as possible to the bearing being measured or at the very least be mechanically linked via. the casing. Attachment to light or un-supported points on the machine should be avoided as these sites can vibrate independently of the bearing of interest and no useful data is collected (See fig. 1.6).

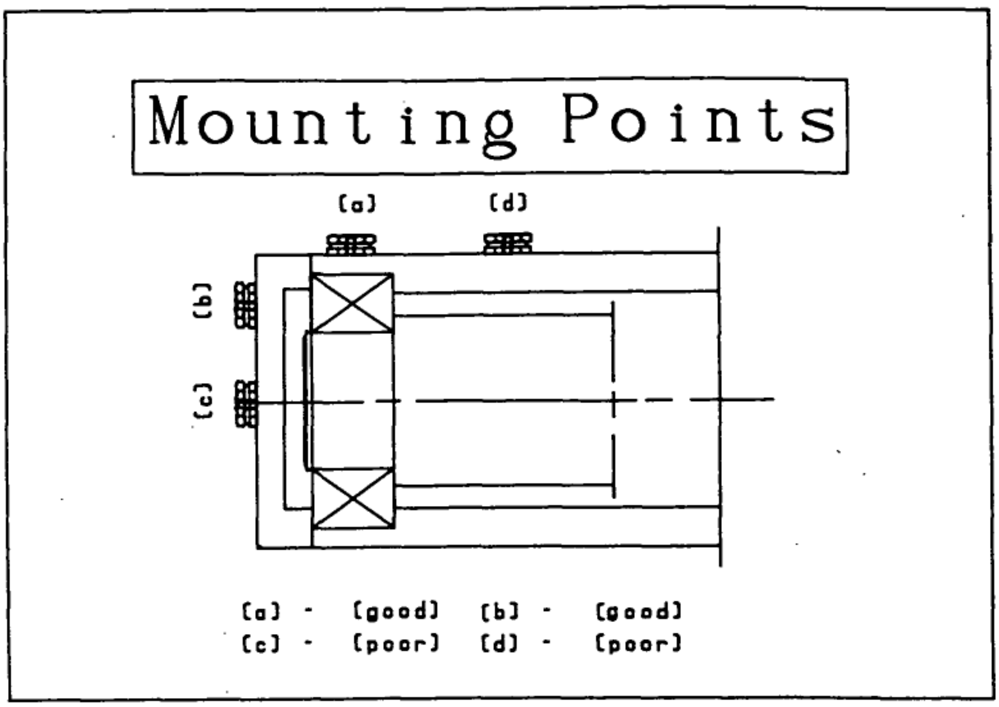


Fig. 1.6 This figure shows both good and bad transducer mounting points.

In most applications where axial forces are thought to be significant a reading in the axial direction should be taken (e.g. helical gears, fans, pumps, etc.). When only one point is to be used to record radial measurements it is best to locate the accelerometer in the radial direction that has the lowest machine stiffness.

To get the best repeatability of a vibration reading it is necessary to take successive readings at the same point on the machine. This can be achieved by marking the measurement points in such a way that they are easily identified and thereby ensuring that successive readings are taken at the same place and in the same direction each time.

For the best all round results, particularly where high frequency signals are to be collected, either a quick connect coupling or screwed fitting to attach the accelerometer is to be preferred. These quick connect couplings require an anchor to be fixed to each machine point. A typical quick connect coupling is shown in figure 1.7. This is the type of fitting installed on machines at A.P.P.M's Wesley Vale site.

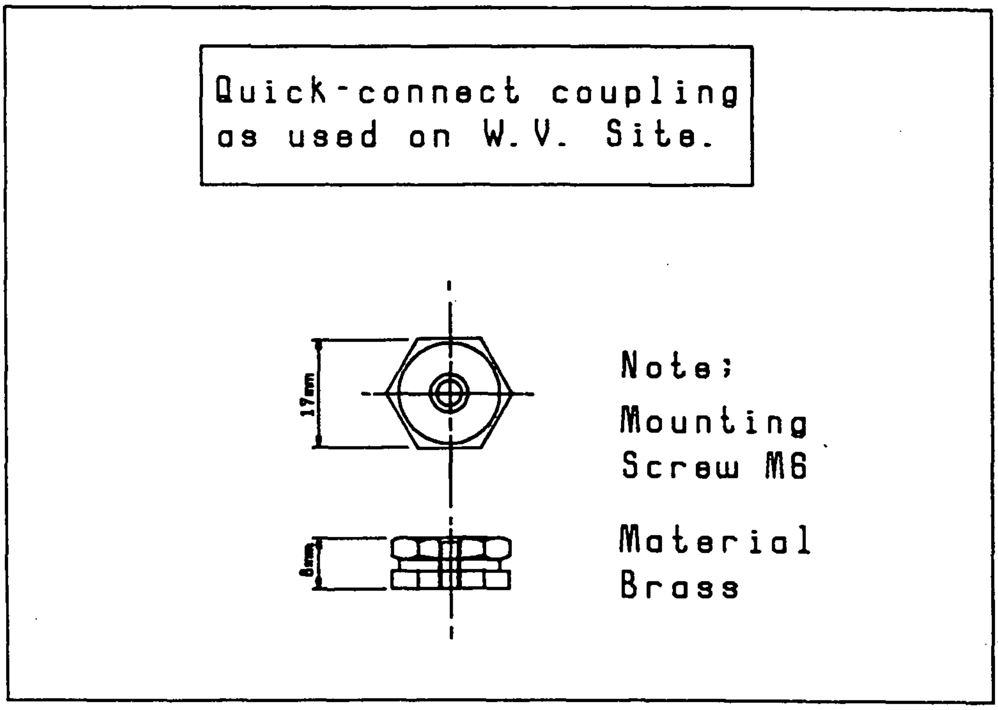


Fig. 1.7 Typical transducer mounting point as used at A.P.P.M's Wesley Vale mill.

These permanent anchors can be attached by a stud, by glue, or by securing under some convenient fastener already present on the machine. Consideration must be given, when fitting permanent attachment points, to any inconvenience they may create during maintenance work on the machinery. This can be a problem if it is necessary to disturb the attachment points during machine servicing as they can be put back in a different position or left off altogether. This has been a problem at A.P.P.M's Wesley Vale mill when bearings and caps are removed during a roll change on the paper machine and are subsequently replaced in a different position.

Another problem was experienced when these anchor points were glued onto the bearing blocks of the paper machine rolls and subjected to moisture. Over time the brass fittings would fall off after the glue became separated from the bearing block. In some cases the fittings were knocked off due to rough handling but this has not been a major problem.

The nature of a paper machine is such that the bearings being monitored are often removed from the machine along with the roll they are supporting due to routine roll changes. The roll changes can be necessary for reasons having nothing to do with the bearings, such as marking of the cover, imbalance etc. This means that when trending historical data it is important that the data relates to the same roll and bearing combination. If the roll and its bearings have been changed out recently, the bearings will be different and no trending will be possible. A computer based record system had been developed previously to keep track of roll changes and this system can be used as an information system for the condition monitoring program being developed at the Wesley Vale site.

So long as the frequency range is not too high for the point being measured (i.e. < 2kHz) a magnetic mount can be used to attach the accelerometer. This is not a solution of course for non-ferrous machine casings and an alternative solution must be sought, (e.g. glue a steel washer on to the machine/bearing to allow the use of a magnetic pickup). The use of hand held probes is to be discouraged except for very low frequency signals (i.e. < 500Hz). This is because the probe can not be kept in good contact by hand at higher frequencies. The quick connect coupling is restricted to about 15 kHz, and if the accelerometer is bolted to the machine the upper frequency limit is typically about 30 kHz at which stage the resonance frequency of the accelerometer has been reached. In many applications on machines operating at 'normal' speeds a magnetic attachment is both adequate and convenient.

A practical problem experienced at A.P.P.M. was that in taking readings around the dryer bearings, the quick connect coupling became quite hot to touch and in some cases it was necessary to allow time for the connector to cool down before it could be handled further. This is not to suggest that the accelerometer was in any danger of overheating, rather that the operator required some form of insulating glove to allow the continuous sampling of many points without the need to wait for the connector to cool. In all cases it is unlikely that the temperature reached by the connector would have exceeded 80^{o} (C) the typical upper operating temperature range for a modern accelerometer being 120^{o} (C). Higher temperature accelerometers are available, up to 260^{o} (C), but special high temperature cables are required for these applications.

When measuring vibrations it is generally possible to interpret the vibration severity as being proportional to [6] :

(i) Displacement. (for low frequencies)
(ii) Velocity. (for mid-range frequencies)
(iii) Acceleration. (for high frequencies)

Needless to say there is no discreet point where it can be said that vibration severity changes from being proportional to say displacement, to being proportional to velocity. These boundaries will be gradual rather than discreet and will alter from one machine to the next. Indeed one machine will have different transitions if operated at different speeds. However it is useful to visualise vibration in this way.

Analysis of vibration is conducted in one or all of three domains :

(i) Time domain.

(ii) Frequency domain.

(iii) Quefrency domain.

However the vibration signal is taken (e.g. time signal, velocity, or acceleration) it is in the form of raw data and will require further processing before it is suitable for interpretation and trending. Figure 1.8 shows a schematic representation of the data processing that is commonly performed in modern vibration analysis equipment.

The raw signal is collected by the transducer which is usually an accelerometer but can be velocity transducers or even proximity probes. The transducer used depends on the frequency range to be monitored. Some typical examples of these transducers are :

(i) Displacement tranducers are used for low amplitude, low frequency vibrations typically in the range 1 - 100 Hz. They are useful for measuring shaft motion within journal bearings, shaft run-out and variations in clearance in close running machinery.

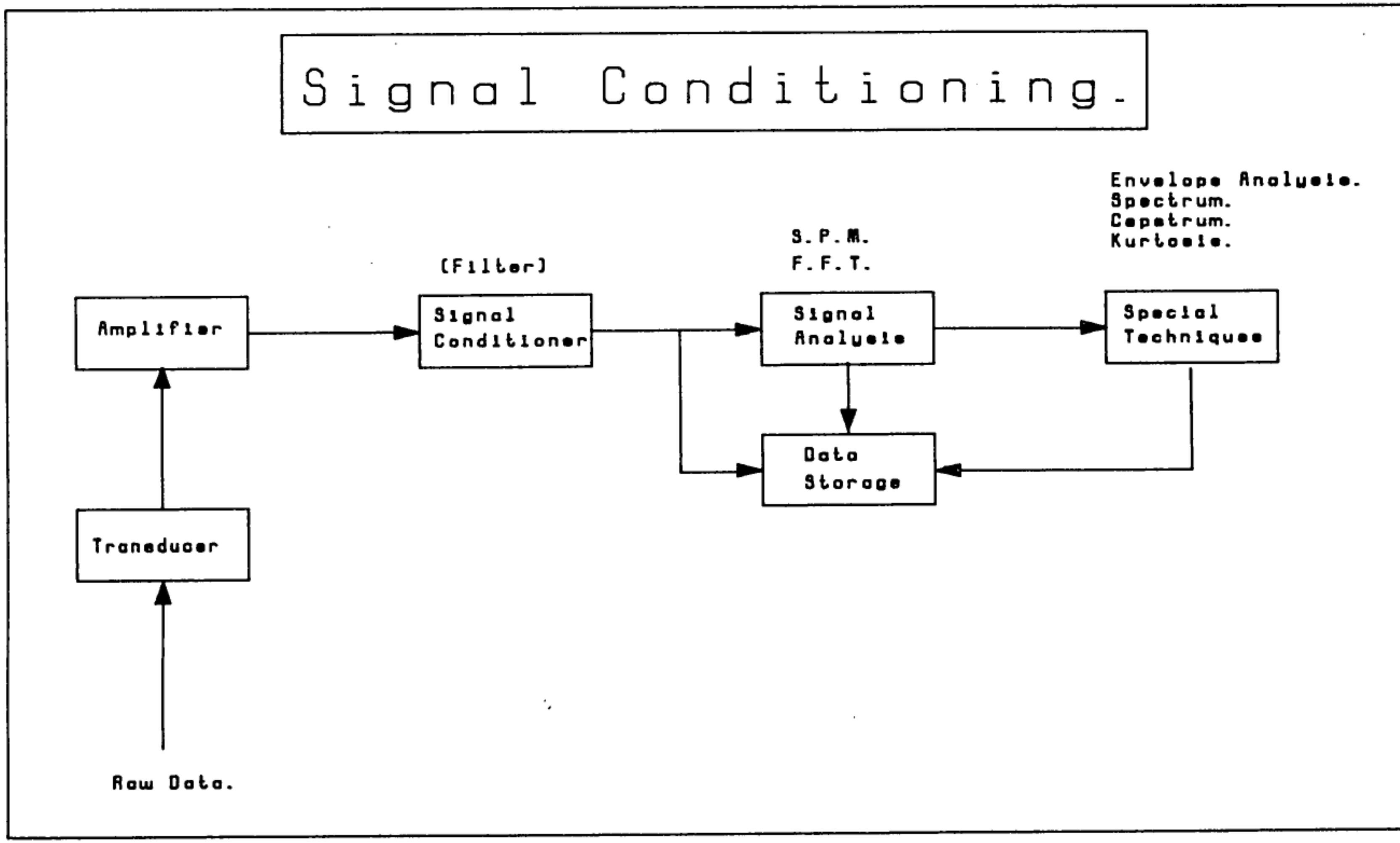


Fig. 1.8 Typical data processing flow chart.

(ii) Velocity transducers are used for medium to low frequency measurements in the range 1 - 1000 Hz. Because velocity transducers are most sensitive at the lower frequencies they tend to filter out the signals at the higher end of the frequency range. This makes them less sensitive to amplifier overloads that can reduce the signal quality at low amplitudes, and low frequencies [18]. Velocity transducers are best suited to the monitoring of slow (low frequency) machines and measurements of unbalance in balancing operations.

(iii) Accelerometers tend to be the most widely used transducer for vibration monitoring having a useful frequency range from 1 - 20,000 Hz. Accelerometers are smaller and more rugged than either displacement or velocity transducers and this makes them suitable for most industrial applications. Most modern accelerometers are constructed using piezoelectric sensors as they are unaffected by dirt, moisture, oil, and most chemicals. They are also capable of operating over a broad temperature range, e.g. -50^{o} (C) to $+120^{o}$ (C), and can resist shocks and vibrations very well. Figure 1.9 shows the velocity and displacement curves relative to acceleration.

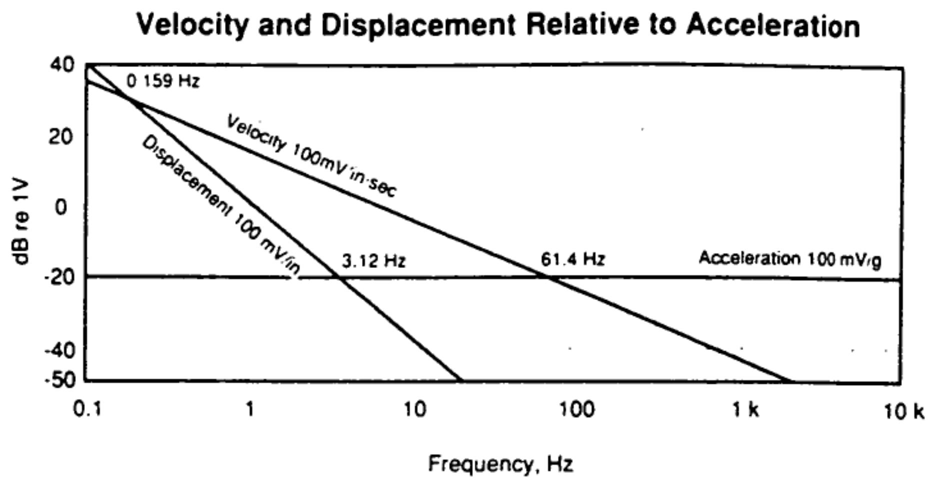


Fig. 1.9 Comparison of displacement and velocity curves relative to acceleration.

Selection of an appropriate transducer.

Because of the importance of the transducer in the vibration monitoring system it is vital that the most suitable transducer is selected. As most modern transducers used for industrial condition monitoring are piezoelectric accelerometers, only these will be considered here. Before selection is made the answers to the following questions must be known [18] :

(i) The expected maximum vibration level.

(ii) The frequency range of interest.

(iii) The operating temperature range.

(iv) Any chemicals that may be present.

(v) Any acoustic or electromagnetic fields.

(vi) Is the machine grounded or not.

(vii) Size of accelerometer.

(iix) Cable length required.

(ix) Power supply requirements.

Two principal, and to some extent conflicting, characteristics of piezoelectric accelerometers are sensitivity and frequency range. In general the higher the sensitivity the lower the frequency range [18]. The level of sensitivity required is dictated by the amplitude of the signal expected from the machine to be monitored. If the sensitivity is set too high it will detect the very low amplitude signals but will restrict the frequency range. If the sensitivity is set too low, the low amplitude signal will be lost in the background signal noise. While the frequency range will be extended, little use can be made of it if the low amplitude signal is the most important. From this it can be seen that selecting an accelerometer is mainly a compromise between desired sensitivity and usable frequency range. Figure 1.10 shows a generalized relationship between sensitivity and frequency range.

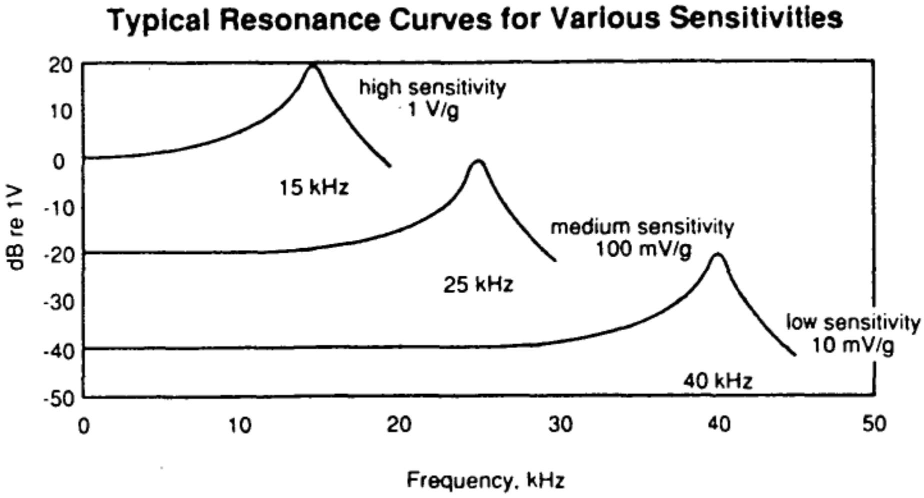


Fig. 1.10 Sensitivity Vs. frequency range for a typical accelerometer.

The raw signal data is passed from the transducer to an amplifier (see fig. 1.8) and this boosts the signal strength for further processing.

A signal conditioner is used to modify the raw data to achieve some desired result such as selection of some specific part of the signal, i.e. filtering. A low-pass filter can be used to exclude the high frequency component of the signal and a high pass filter excludes the low frequency components only. A band pass filter allows the processing of a specific frequency range of the signal and excludes above and below this band. These filtering techniques are used when the information being sought is known to occupy some specific part of the frequency range.

Once the raw signal is amplified and filtered a range of options are available that allow presentation of the data in useful forms. The signal can be stored as is for future reference or can be presented for examination using a Fast Fourier Transform (F.F.T.) which displays the data as a spectrum. A Shock Pulse Monitor (S.P.M.) presents the data in a form that gives bands of vibration level above some 'carpet' value with each band corresponding to various degrees of vibration severity.

The presentation depends to a large degree on the specific instrument being used but in general terms the F.F.T. has more information in its display than that of the S.P.M. but it is more difficult to interpret. The S.P.M. is most suited to determining defects in rolling element bearings while the spectrum analyzer can give information about gear mesh, bearings, oil whirl, rubs, unbalance, bent shafts, cracked gear teeth, etc.

Further signal processing is possible to highlight specific components of the spectrum and some of these are :

- Envelope analysis.
- Cepstrum.
- Kurtosis.

These post processing techniques are selected to suit the particular defect type being tested for or to increase the ability of the operator to interpret the spectrum.

1.2.1 <u>Time Domain</u>.

The time domain can be plotted as a graph of amplitude Vs. time and can be very useful in diagnosing cyclic defects such as modulation in gearbox signals caused by a bent shaft or eccentricity in the gear location. Similarly intermittently loaded teeth, as can arise from poor indexing of the teeth on the gear circumference, can create a once per revolution load upon which is superimposed the tooth mesh signal.

Sudden impulses are particularly noticeable in the time domain once they achieve an amplitude sufficiently large to be observable against the background signal. Unsteady signals such as those generated by reciprocating machines, are capable of exciting the natural frequencies of the machine and therefore faults can sometimes be easier to detect in the time domain than in the Spectrum.

Coast down tests can be carried out to detect transient vibrations and these can often show up in the time domain as resonances. The time domain is often characterised by the use of <u>indices</u> to convey the signal information. Some of these indices are :

(i) Average.
(ii) Peak value.
(iii) Root Mean Square (R.M.S.).
(iv) Form factor.
(v) Crest factor.

The Peak value is the peak signal amplitude reached and represents the maximum displacement, velocity, or acceleration depending on which units were used. The R.M.S. value represents the energy or power in the total signal. The Form factor is the ratio

R.M.S./Average and the Crest factor is the ratio Peak/R.M.S. Both the form factor and the crest factor give some indication of the signal shape. The crest factor is particularly useful as it indicates how peaky a particular signal is and therefore how impulsive the vibration.

Because the Spectrum averages out some of the detail in the time domain signal, it is sometimes useful to examine the time domain signal for indications of a fault that can not be positively identified in the spectrum.

With the decreasing cost of mass storage on modern computers, it is likely that historical data will be kept in time domain form rather than spectral form in future years. While time domain data takes more storage space than spectra, more information is available from the data for use at a later date.

1.2.2 Spectrum.

When the time domain signal is processed using a F.F.T. the resulting spectrum is displayed as a graph of acceleration or velocity Vs. frequency. Comparison of a spectrum taken at a given point on the machine, with the baseline spectrum of the same point, allows the detection of any change in the spectrum over time. The baseline spectra is usually taken soon after the machine is commissioned or when the machine is known to be in good condition. Comparison of spectra taken periodically over the life of the machine will show up any gradually increasing component in the spectra.

Trending of the measured vibration can be used to detect the increase in vibration that accompanies wear-out of a machine (See fig. 1.11). Examination of fig. 1.11 shows that the vibration level decreases to a 'normal' level for that machine during run-in. The machine should maintain this vibration level if operated under 'normal' conditions for most of its working life. Once the machine begins to wear out the vibration level will increase fairly rapidly until the machine either fails in service or the vibration level indicates that it is unsafe to operate the machine any longer and it is overhauled or replaced.

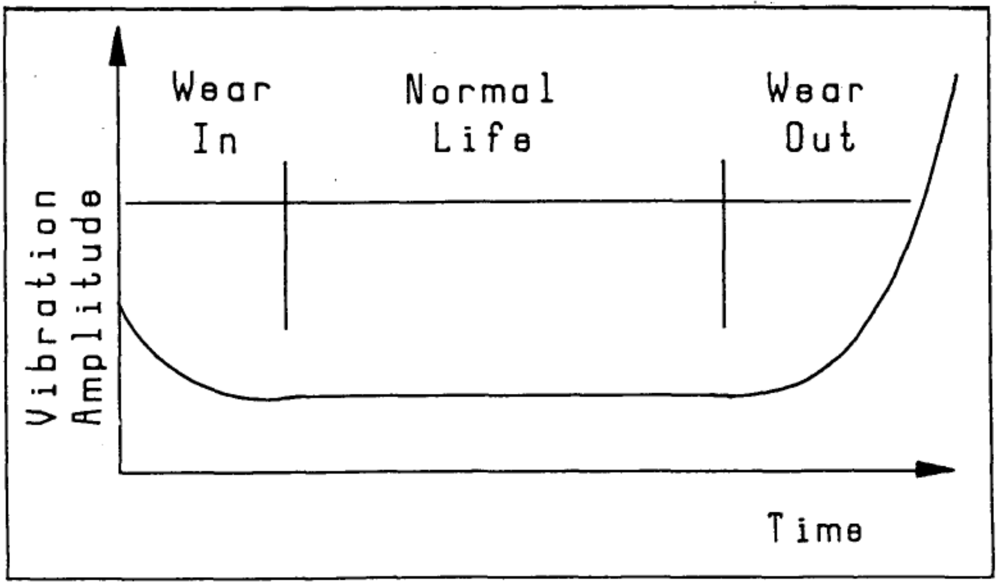


Fig. 1.11 Vibration level over the life of the machine.

The general layout of a periodic vibration monitoring system is shown in figure 1.12. The vibration signal is shown on the data-logger as the signal is collected and stored for later retrieval. This on-line display feature has the advantage that if some problem is evident while the measurement is being taken additional data may be collected for that point to assist in diagnosis.

Once all the machines being monitored are sampled the stored data is down-loaded to the host computer for further data processing and trending. The host computer is also used to archive data, the setting up of measuring points, and generating reports.

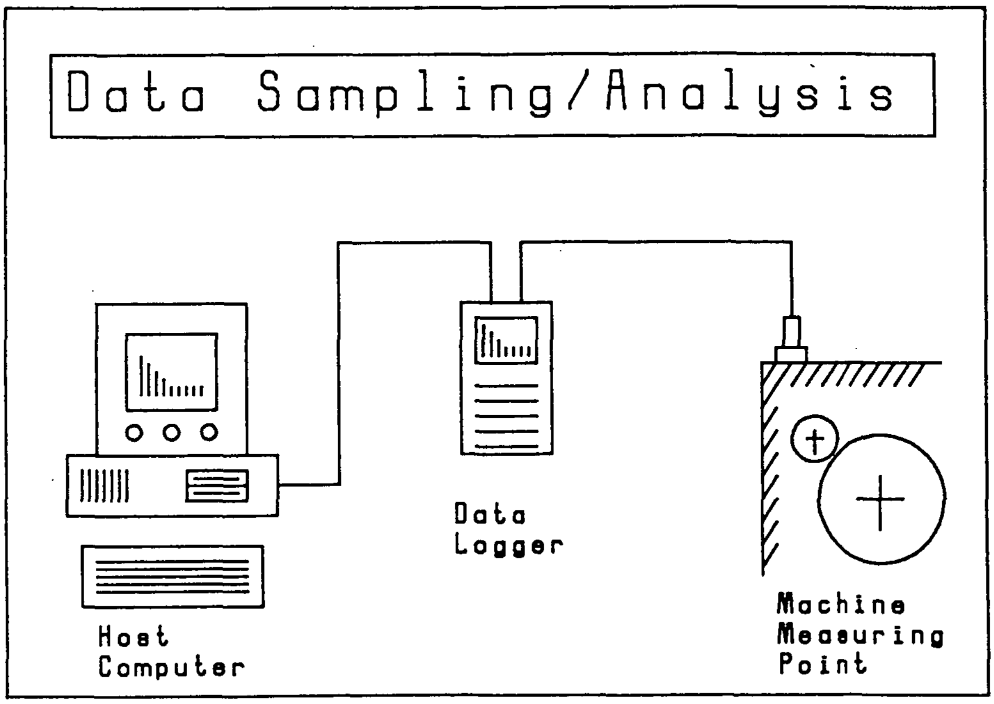


Fig. 1.12 General vibration monitoring system.

The degree of software support provided by the host computer varies between manufacturers but most provide the services mentioned here.

1.2.3 Time Synchronous Averaging.

This is a particularly useful technique for those cases where there are many sources of interference from components near the point to be measured. For example readings taken at the bearing of one shaft of a gearbox can be influenced by an adjacent shaft or shafts operating at different speeds.

Synchronous averaging allows the removal of background noise from the signal and also those signals not synchronous with the component of interest. This is achieved by monitoring the vibration with a transducer (e.g. accelerometer) while at the same time synchronising the signal with the shaft rotation with the aid of a tachometer [17].

A piece of reflective tape is attached to the shaft of interest and the light beam from the trigger is reflected from this tape once per revolution. This permits averaging of the same signal over many cycles synchronous with the running speed of the component on which the trigger is operating. Figure 1.13 shows a diagrammatic representation of a spectrum being taken using synchronous averaging.

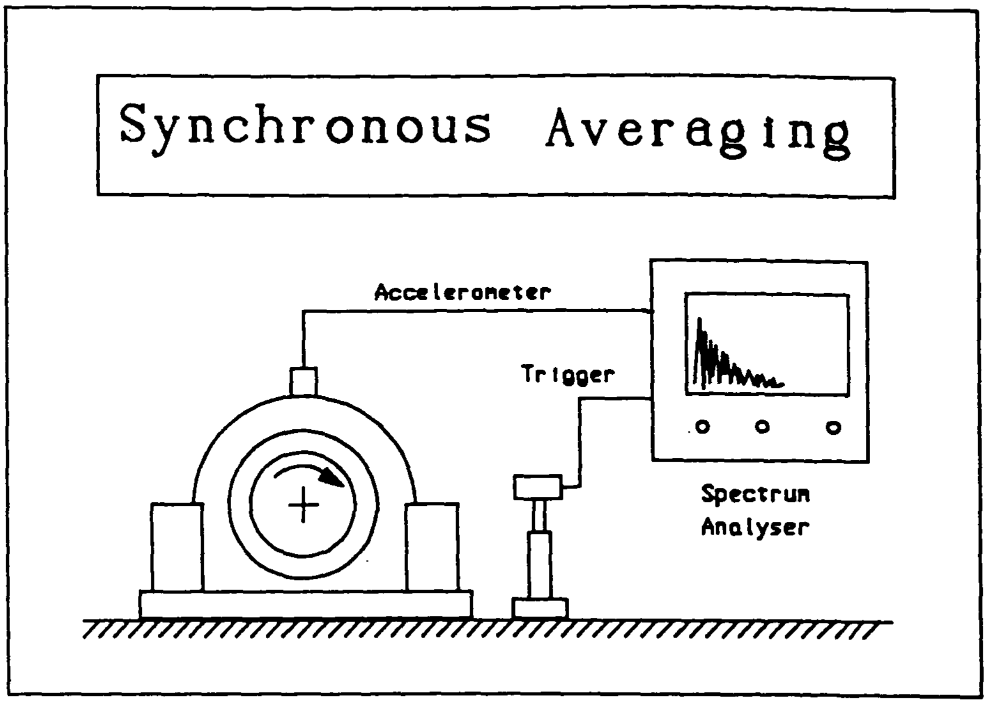


Fig. 1.13 Time synchronous averaging.

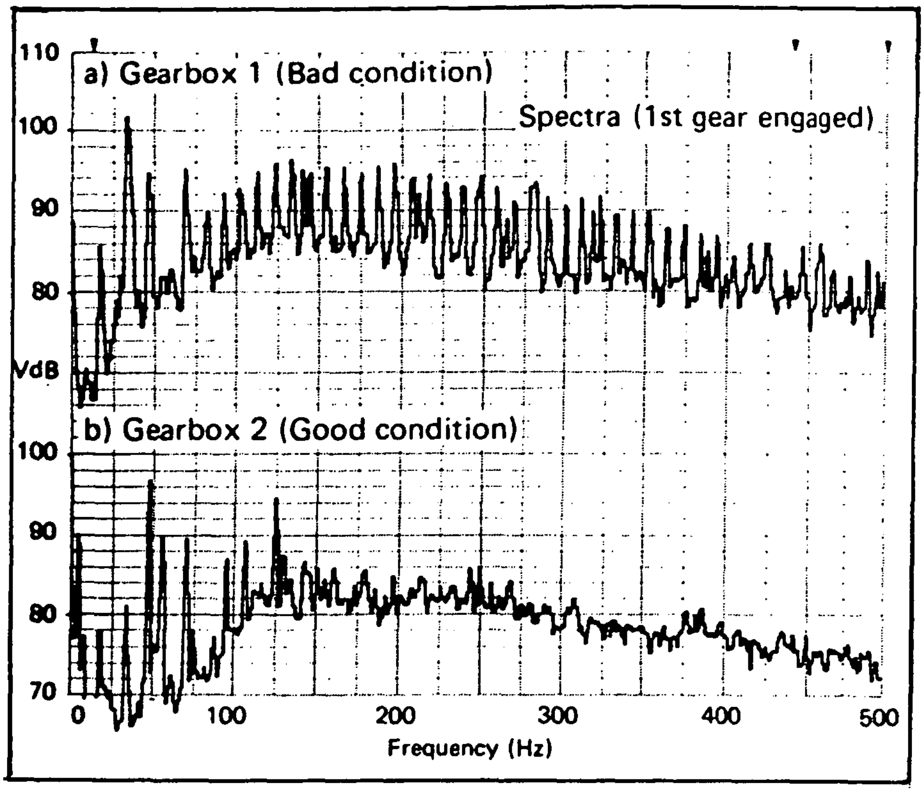
1.2.4 Cepstrum.

A Cepstrum is spectrum of a logarithmic spectrum, (i.e. a logarithmic amplitude scale and a linear frequency scale). This makes the use of Cepstrum analysis ideal for detecting periodicity in the spectrum. This periodicity can arise because of the presence of harmonics, having equal spacing, in the spectra or by sidebands commonly found in gearbox spectra. These sidebands can be generated by modulation, i.e. if a low frequency component is superimposed on the gearmesh frequency. The gearmesh frequency is relatively high with the lower frequency component being related to shaft speed. The high frequency component is referred to as the carrier frequency and the shaft frequency modulation is seen as sidebands around the carrier frequency.

Due to the fact that there are a great many lines displayed on the spectrum it can be very difficult to detect these sidebands by visual examination of the spectra. By performing Cepstrum analysis any repeditive component in the spectra will show up as a single line in the Cepstrum (See fig. 1.14).

The terminology used with Cepstrum analysis differs from that used with spectra. Some equivalent terms used when switching from spectra (frequency domain) to Cepstra (time domain) and back, are given here. The terms used in Cepstrum analysis are based on corruptions of the terms used in spectral analysis, usually by reversing the order of the first three letters of the term. Some examples of these terms are shown below.

Spectra	Cepstra
Frequency	Quefrency
Spectrum	Cepstrum
Harmonic	Rahmonic
Magnitude	Gamnitude



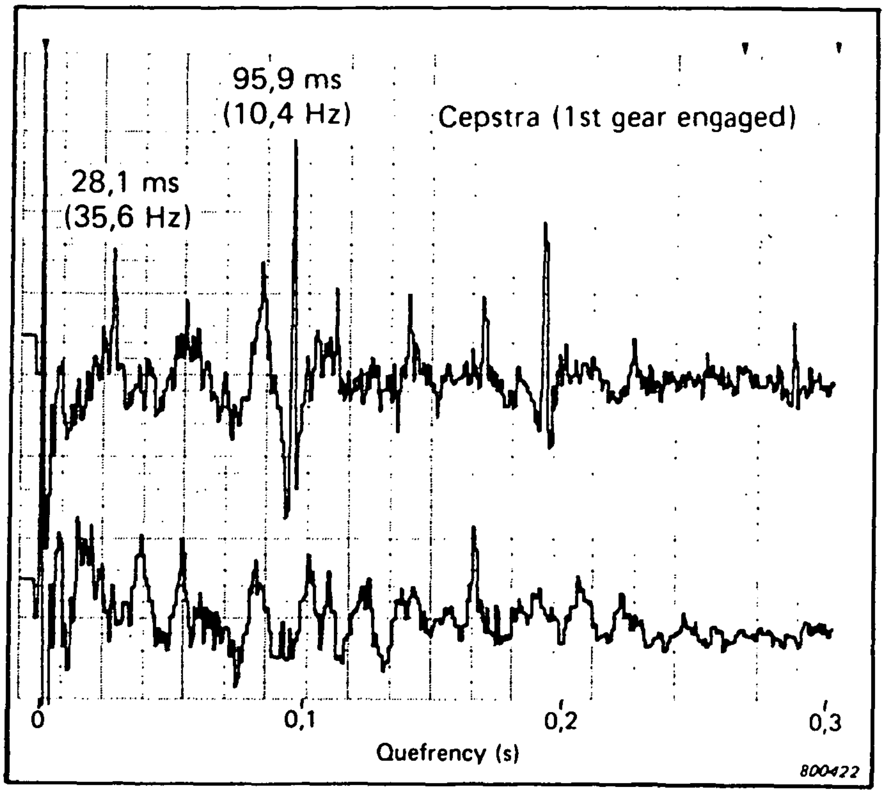


Fig. 1.14 Spectra and their corresponding Cepstra taken from a truck gearbox.

1.2.5 <u>Kurtosis</u>.

Kurtosis is used to emphasize the large peaks that extend above the general signal level when a rolling element bearing first begins to deteriorate. The amplitude characteristics of a vibration signal can generally be described by Gaussian distribution. The first four moments of the statistical data are [19] :

(i) Mean.

(ii) Variance.

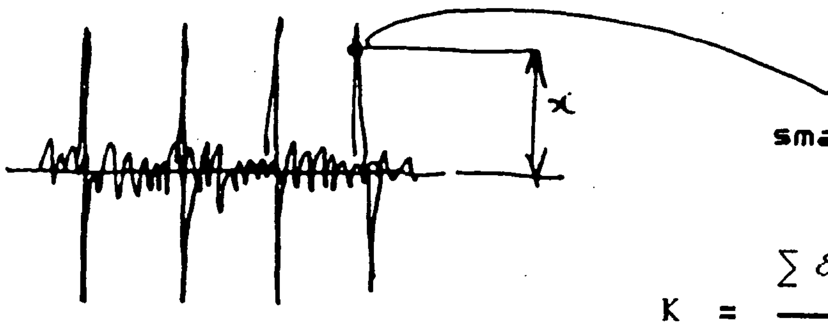
(iii) Coefficient of Skewness.

(iv) Kurtosis.

For Gaussian distribution the Kurtosis value is equal to 3 for a bearing in good condition regardless of the bearing speed or load. When the bearing shows signs of deterioration an increase in the Kurtosis value at the low frequencies is evident with an increasing Kurtosis value at high frequencies as the damage becomes more severe. As the damage to the bearing approaches that which would cause the bearing to fail in service, the Kurtosis value can start to drop again. The value can drop to a level approaching 3, especially at the lower frequencies.

In calculating the Kurtosis value, the instantaneous area under the signal is multiplied by the amplitude of this area raised to the power of 4.

After each small area under the signal is operated on in this manner over the signal width of interest, they are summed together and divided by the R.M.S. raised to the power of 4.



$$K = \frac{\sum \delta A x^4}{RMS^4}$$

Examination of this relationship shows why the Kurtosis value rises when the bearing first begins to deteriorate and drop again as the damage gets progressively worse. When the first pits develop in the bearing surface they generate large peaks in the signal. These peaks are magnified by the Kurtosis relationship and as these peaks are narrow they contribute little to the overall energy level of the signal (and therefore to the R.M.S.) with the result that the Kurtosis value rises.

As the pitting increases, the number of peaks increases along with their contribution to the overall energy of the signal. This results in an increase in the R.M.S. value until eventually its rate of increase overtakes the rate of increase due to the peaks, and the Kurtosis value again decreases towards 3.

This phenomenon makes it important to know if the bearing is good at a Kurtosis value of 3, or is it just about to fail, the Kurtosis value having risen and dropped again.

Kurtosis meters were popular in the early eighties but have decreased in popularity in recent years. One contributor to the decrease in popularity of the Kurtosis meter is that plotting data derived from the signal Crest Factor can give results comparable to those achieved from Kurtosis meters, and at considerably reduced cost.

1.2.6 Shock Pulse Monitoring. (S.P.M.)

Shock Pulse Monitoring is widely used to monitor rolling element bearings in modern machines. Unlike vibration monitoring, S.P.M. detects the compression wave that propagates ultrasonically through the structure at the moment of impact. This compression wave is detected at the machine surface using a specially tuned accelerometer, the accompanying vibration wave being filtered out electronically. This accelerometer is tuned to resonate at 32 kHz and the compression wave sets up a damped oscillation in the accelerometer at its resonance frequency. The amplitude of this resonance is directly proportional to the impact velocity [20].

In general the shock pulses from a faulty rolling element bearing can increase by up to 1000 times over those generated by a bearing in good condition [20]. This means that the amplitude scale has to be in Decibels to achieve the sensitivity at lower amplitudes while still allowing full scale display of the peaks. A baseline reading is taken when the machine is commissioned and is commonly known as a 'carpet' reading. Increases above this 'carpet' level indicates that some defect is starting to develop in the bearing and trending of the measured values over time can allow reasonable estimation of the remaining bearing life.

Shock Pulse Meters are best suited to rolling element bearing monitoring and have a good track record in being able to detect the earliest indication of a developing fault. The accelerometer mounting has to be rigid enough to transmit the high frequencies required by the instrument. These high frequencies are prone to rapid attenuation in the machine structure and therefore an uninterrupted mechanical path is required between the bearing and the transducer.

To achieve good results from S.P.M. the following points must be considered when selecting a measurement point [20].

(i) The path between the bearing and the transducer should contain no more than one mechanical interface otherwise the attenuation that occurs at each interface could reduce the signal strength to an unusable level.

(ii) The compression wave path must be solid, as straight as possible and as short as possible. The path length should not exceed 75mm if the best results are to be obtained from the monitoring equipment.

(iii) The transducer must be positioned in the loaded zone of the bearing housing to achieve as direct a path for the compression wave as possible.

(iv) The centreline of the transducer must be aligned with the loaded zone of the bearing housing otherwise considerable loss of wave energy will occur at the monitoring point interface.

1.2.7 Proximity Probes.

Proximity probes are used to sense relative displacement between two components. These probes take the form of either eddy current sensors or inductive sensors. The probe tip is placed close to the surface to be monitored (usually between 1mm and 2mm) as shown in figure 1.15. Variations in the gap between the probe tip and the surface of the shaft result in a corresponding variation in the

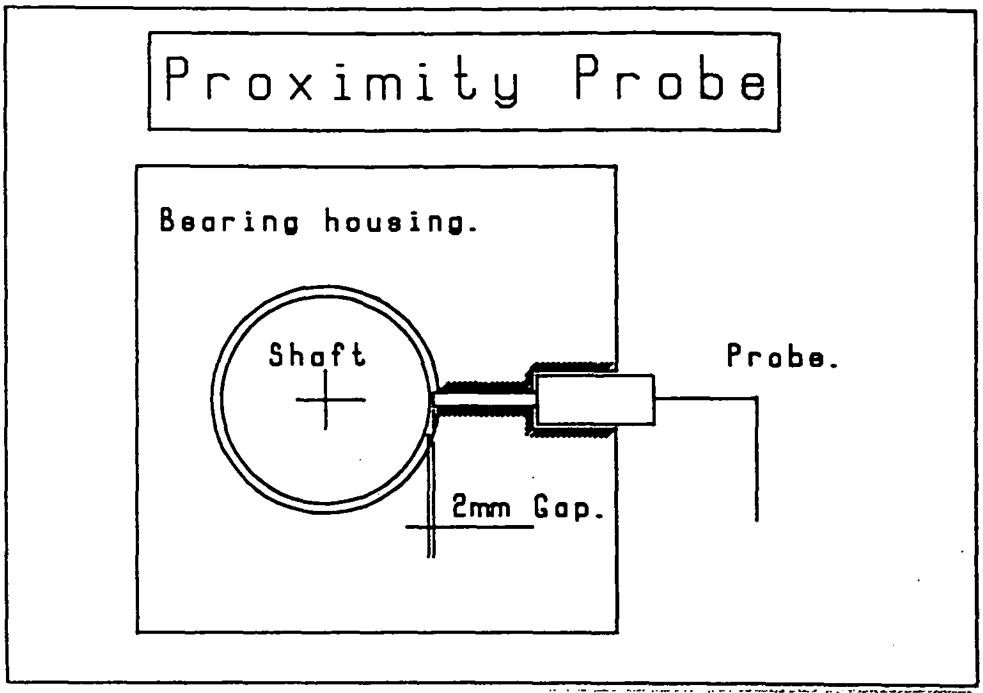


Fig. 1.15 Typical proximity probe installation.

output of the probe. When he probe is correctly positioned and calibrated, small changes in gap size can be accurately measured. This is a useful and widely used technique for measuring shaft position in journal bearings on a range of machines.

These probes are sensitive to errors in run-out of the shaft, build-up on the shaft surface and in-homogeneity of the shaft material. To overcome false readings due to the coarse grain structure of some materials, an extruded aluminium sleeve can be fitted to the shaft. This improves the probe signal because the aluminium is more homogeneous than the material with the coarse grain structure.

The gap used for the probe differs for different shaft materials, some are listed here relative to mild steel shafting.

(i)	Mild steel	1.0.
(ii)	Nickel chrome steel	0.9.
(iii)	Brass	0.5
(iv)	Aluminium	0.5
(v)	Copper	0.4

The frequency range for modern proximity probes can be from 0 Hz to 2000 Hz with higher frequency probes available for special applications.

A useful technique for monitoring shafts is the use of two proximity probes positioned at 90 degrees to each other as shown in figure 1.16. This configuration generates an orbit by connecting one probe output to the X-axis of the display and the other probe output to the Y-axis.

The images generated in this way are in the form of Lissagous figures and can be used to indicate :

(i) Journal bearing wear.

(ii) Misalignment.

(iii) Unbalance.

(iv) Lubrication instability.

(v) Shaft rubs.

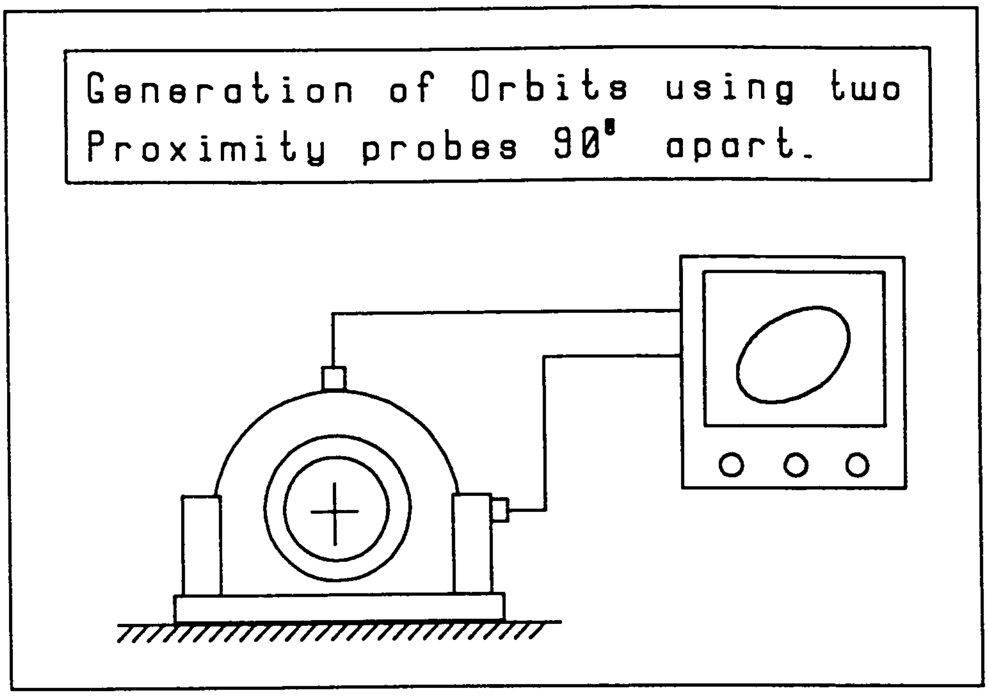


Fig. 1.16 Orbit generated by two proximity probes at 90 degrees to each other.

The major difference between using a proximity probe and an accelerometer is that the proximity probe measures the relative movement between the shaft and the bearing, while the accelerometer measures the absolute motion of the bearing housing. This is an advantage when it is necessary to exclude casing movement from the shaft vibration. This technique is commonly used in collecting vibration data from journal bearings on Turbines.

2.0 History of C.M. at the W.V. Paper Mill.

As in any modern process plant A.P.P.M.'s Wesley Vale Paper Mill maintains a wide range of machines as part of its on-going operations. While some of these machines are specific to the pulp and paper industry, many are common to industry generally. All these machines require regular maintenance to enable the twenty-four-hour-a-day, seven-day-a-week operation that exists at the Wesley Vale Mill.

Since the Mill was commissioned in the early Seventies, maintenance of this equipment has been carried out on the basis of an annual overhaul of all critical equipment (i.e. on a time basis). This has recently been extended to 18 months in a bid to reduce the cost of maintenance, however this increases the likelihood of random failures.

Replacement with a complete spare unit is sometimes possible, however it is not economically feasible to have complete spares for all machines let alone complete spare machines.

2.0.1 Needs-only Maintenance.

If this machine maintenance was performed on a needs-only basis, it would not be dismantled unless it was determined that failure was likely or a suitable opportunity to perform the repair arose. In many cases machines can be worked on during scheduled maintenance periods and/or periods when the specific machine is not required for production.

The commissioning of the Steep Bleach Plant at Wesley Vale in mid. 1989 has de-coupled the Pulp Mill from the Paper Machine to some extent and increased access to many machines for maintenance and repair. It is important to realize that some machines cannot be overhauled except when production is suspended and therefore a complete elimination of time based overhauls will not be possible. For example, access to the main boiler is possible only when production is suspended, as is access to the main air, water and steam lines under some circumstances.

The main advantages of working on a machine on a needs-only basis are :

(i) The maximum possible life is realized for that machine under the prevailing conditions.

(ii) Access to the machine can be arranged to minimize disruption to production if sufficient warning is given.

(iii) Unexpected failures can be greatly reduced.

Establishing the maintenance needs of a particular piece of machinery becomes the principal task of the Maintenance Engineer when a needs-only philosophy is pursued. It is in this area of establishing machine condition at a given time that Condition Monitoring (C.M.) is applied to a modern process plant. The single most important part of Condition Monitoring in this application is the earliest possible detection and identification of a developing fault in a machine. Only by knowing when a machine wear rate begins to increase can timely preventive maintenance be planned and carried out with the minimum possible disruption to the user.

There are many C.M. techniques available to the modern Maintenance Engineer, some of which are used more widely than others. A list of some of the more common techniques is included below.

(i) Visual Monitoring.

(ii) Vibration Monitoring.

(iii) Wear Debris Monitoring.

(iv) Radiation Testing.

(v) Temperature Monitoring.

(vi) Ultrasonic Testing.

(vii) Eddy-current Testing.

(iix) Acoustic Emission Testing.

(ix) Process Monitoring.

(x) Noise Monitoring.

There have been several applications of C.M. to equipment at the Wesley Vale Mill over the last few years with varying degrees of success. In the last couple of years however a more determined attempt has been made to introduce C.M. to the Mill particularly with the application of vibration monitoring of the main Paper Machine bearings. Some of the C.M. techniques used in the past include :

(i) <u>Dye-Penetrant testing</u>.

Dye-penetrant testing as an aid to workshop personnel in detecting cracks in shafts, rotors, castings, forgings, etc. These tests are carried out when the Engineer in charge, or the workshop foreman, considered there to be a likelihood of cracks being present in the machine component. Routine crack detection is not carried out on a regular basis at this time except in special cases, but is likely to be introduced in the near future.

A typical case in which routine crack testing would have paid for itself is in the re-building of the flights of the screws used in the 'Prex' screw-press. In one recent case a screw was built up with weld, ground smooth, the flights machined, and the mounting face squared up only to find that a crack had developed in the screw core. Dye-penetrant testing of this screw, along with several others, resulted in the built-up screw being scrapped and one other repaired because of severe cracking.

Figure 2.1 shows the extent of cracking in the screw core and even by grinding to a depth of nearly 10 mm it was not possible to grind the crack out. Over a week's work had gone into re-building this screw and this investment in time, effort and materials was ultimately lost when the screw had to be scrapped.

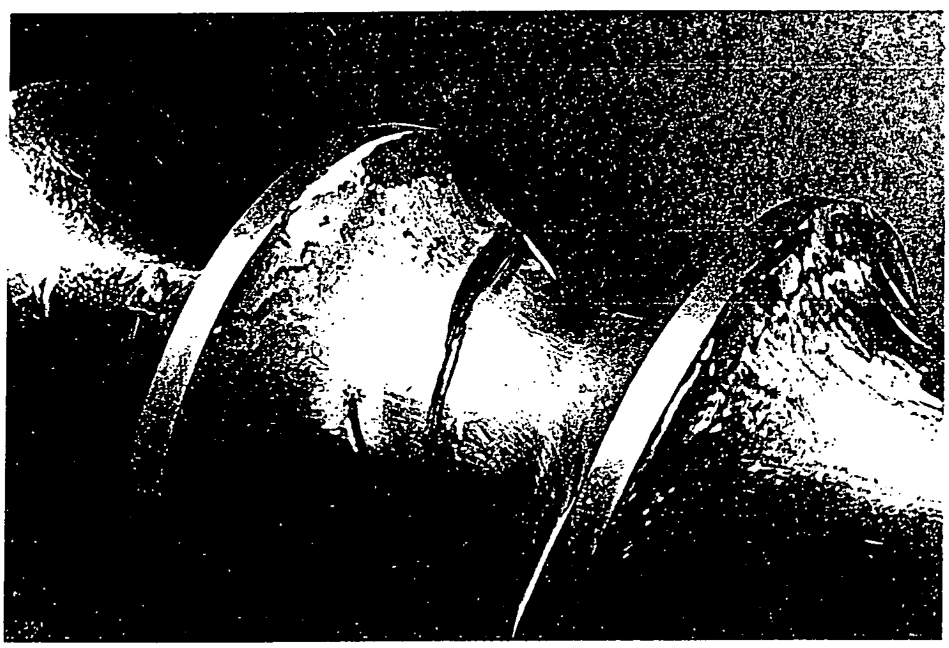


Fig. 2.1 Showing cracks in screw core. Screw had to be scrapped in this case.

Only one screw has broken in service since the plant was commissioned and cracking of these screws has not been a problem in the past, hence the lack of any crack inspection routine. Increases in production levels over the last few years (up from 70 ton/day to 100-110 ton/day, See Fig. 2.2) has increased the load on this machine and made cracking more likely. In future, screws will be crack checked prior to any work being performed on them and scrapped or repaired where necessary.

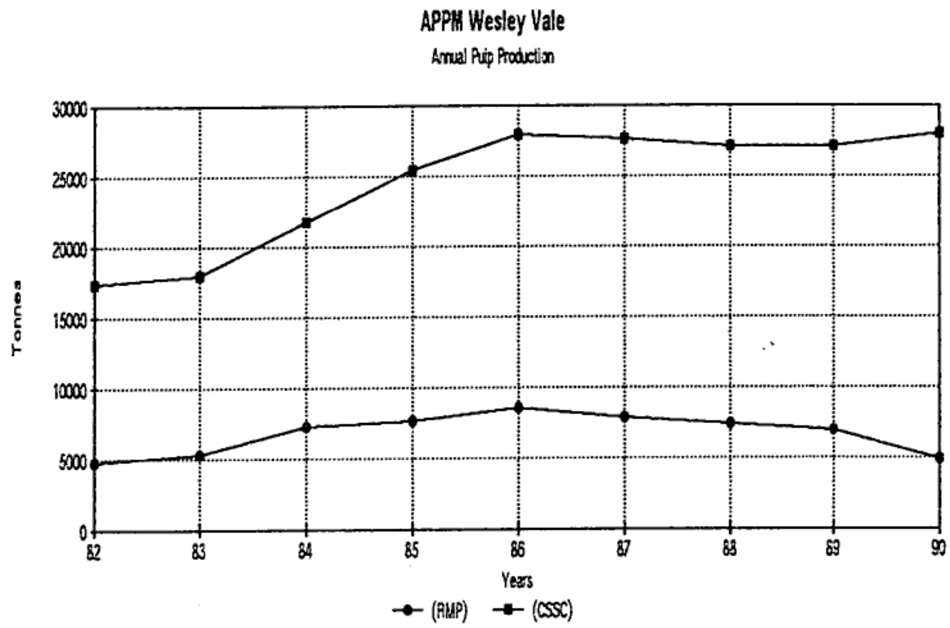


Fig. 2.2 Showing increase in tonnage through the Pulp Mill.

Other significant applications of dye-penetrant testing have been crack detection of Aluminium Compressor pistons (See Fig. 2.3), and cracking in the rim of a chipper disk (See Fig. 2.4).

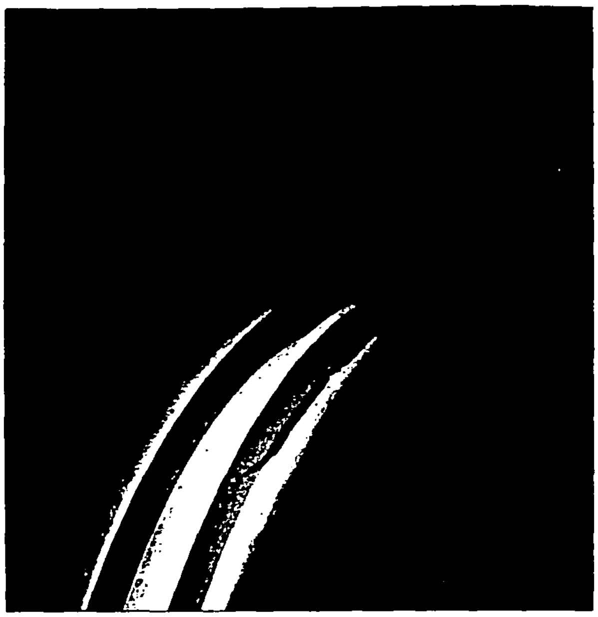


Fig. 2.3 Cracks in aluminium compressor piston as detected using dye-penetrant testing. This piston was scrapped after close inspection of the cracking highlighted by the dye-penetrant test.

The crack in the chipper disk originated in the hard weld deposit used to reduce wear in the knife pocket. The weld material used was Chrome-Carb 6000 which had developed a network of fine cracks on cooling. These cracks are thought likely to have acted as initiation sites for cracking that then extended into the disk material. The crack length was measured during a maintenance overhaul and was monitored on a regular basis to determine if the crack was growing. No growth in crack length was detected by November 1990 when the chipper was replaced by a complete new machine. The old chipper will be rebuilt and used as a spare unit and no further use will be made of hard weld facing in the area of the knife pockets.

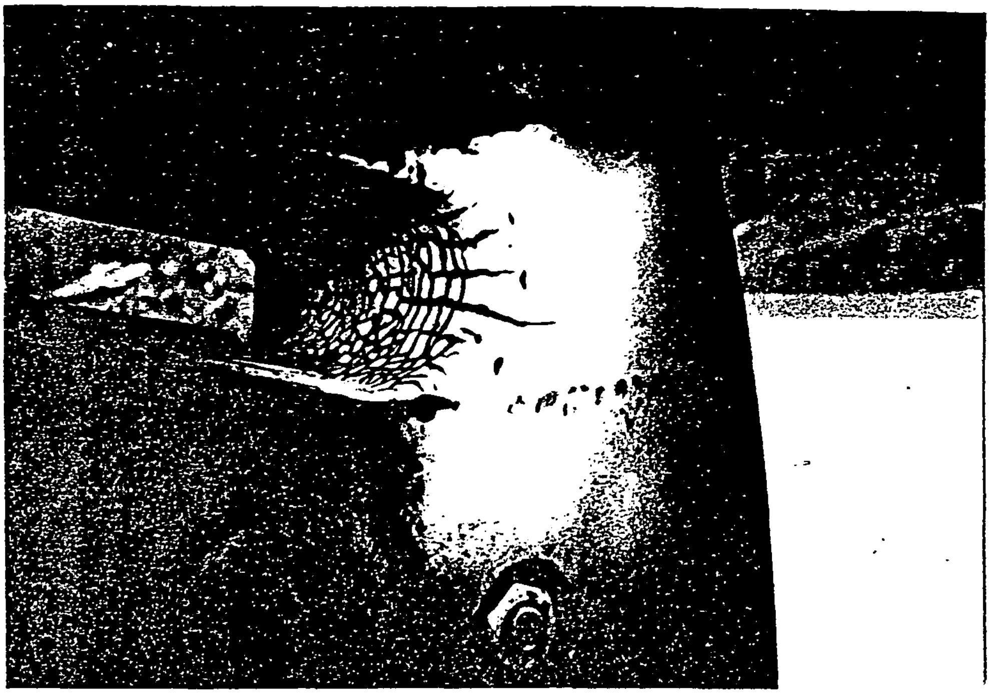


Fig. 2.4 Showing crack at weld deposit.

(ii) Thermographic Imaging.

Thermographic imaging has been used for a number of years by the Electrical Department at Wesley Vale to assess the condition of switchgear, electrical connectors, transformers, etc. Recently more extensive use has been made of this C.M. technique particularly in surveying of steam lines, steam mixers, and insulation. Additional equipment suitable for Thermographic imaging would be :

(i) Inspection of steam traps.

(ii) Inspection of steam valves.

(iii) Inspection of heat exchangers.

(iv) Inspection of heat insulation.

(v) Inspection of air pre-heater.

(vi) Inspection of boiler stack insulation.

(vii) Inspection F.R.P. piping systems for blockage.

A recent Infrared survey of selected steam system components at the pulpmill resulted in the following decisions being made :

(i) Main steam line to the Pulp Mill will require repairs to the insulation over the next year.

(ii) Bottom steam jet in press steam mixer was blocked (See fig. 2.5) and modifications were to be made to the jet design to allow clearing of this blockage without the need to strip the jet system. Routine cleaning will be established based on the rate at which the blockage develops. This blockage rate can be determined with the use of the Thermographic imager.

(iii) A hot spot was identified at the base of the main boiler stack at a point where the exhaust gas impinges on the inside of the stack wall. The refractory lining of the stack is to be repaired at the earliest available opportunity. Failure to attend to this hot spot could lead to damage to the steel outer layer of the stack. In future a routine check will be made of the condition of the stack lining on each occasion that the thermographic imager is on site.

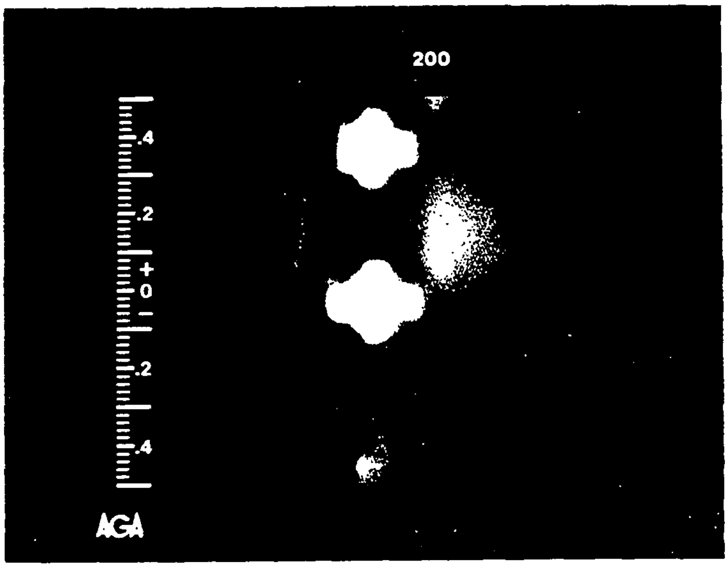


Fig. 2.5 Thermographic Image showing blocked lower steam injector. The top two injectors are operating correctly in this picture.

(iii) Vibration Monitoring.

Vibration monitoring has been a fairly recent addition to C.M. at the Wesley Vale Mill. For the past 2 to 3 years a consultant has been used to conduct a vibration monitoring survey on the paper machine on a three-monthly basis. It was found that these visits were both too infrequent for best results, and were becoming increasingly expensive. For these reasons it was decided to take over the vibration analysis in-house. This has the advantage of giving immediate access to the historical data on a specific machine, allows more regular monitoring of a suspect machine, and develops in-house expertise in vibration monitoring.

Two engineers were assigned to oversee the implementation of the vibration analysis program. One continued to extend the system already established on the paper machine, and the other, (the writer) set up a C.M. system in the Pulp Mill and Services area of the Mill where no C.M. system existed at that time.

The new system set up in the Services section included :

(i) Pulp Mill.

(ii) Filtration plant.

(iii) Wood room.

(iv) Boiler house.

(v) Clay house.

(vi) River pump station.

(vii) Clarifier.

The Pulp Mill had by far the greatest number and variety of machines outside of the paper machine house. For this reason the Pulp Mill was tackled first to give early results and to develop skills in setting up the system. Some typical machines monitored in these areas include :

Wood Room -

(i) Chipper (84" Nicholson).

(ii) Debarker pump (Multi-stage centrifical).

Pulp Mill -

(i) Refiners (Disk type, Sunds Defiberator).

(ii) Pumps (Both direct drive and magnetic drive).

(iii) Motors (0.5 kW - 4 MW).

(iv) Screw conveyers.

(v) Mixers (Andritz disk mixer).

(vi) Presses (Andritz wire press).

(vii) Agitators (For storage chests).

(iix) Fans (Extraction/induction fans).

Boiler House -

(i) Compressors (Screw/Atlas Copco).

(ii) Compressors (Reciprocating/Ingersol-Rand).

(iii) Turbine (4 MW/Stal-Laval).

(iv) Fans (Forced draught/Induced draught).

General -

(i) Gearboxes (Site wide).

(ii) Hydraulic power packs (Site wide).

River Pump Station -

(i) Pomona 5-stage centrifical.

In the Paper Machine house the general areas covered were :

(i) Paper Machine.

- approach
- first and second press
- size press
- dryer cylinders

(ii) Coater.

(iii) Supercalenders.

(iv) Winders.

(v) Colour kitchen.

(vi) Finishing area.

Some of the machines monitored included :

(i) Rolls.

(ii) Gearboxes.

(iii) Motors.

(iv) Pumps.

(v) Blowers.

(vi) Mixers.

Many of the more critical Paper Machine applications that have been monitored for some time, include :

(i) Dryer bearings.

(ii) Wire rolls.

(iii) Felt rolls.

(iv) Main rolls.

The dryer rolls, wire return rolls, and felt rolls are generally surveyed from the Tender side of the Paper Machine and measurements are taken at the drive end of a particular roll only if some defect is suspected after examination of the spectra taken at the Tender side. The main press rolls and pickup rolls are surveyed from both ends on a regular basis. Figure 2.6 shows the general layout of the paper machine at Wesley Vale with the main rolls highlighted.

Even though the vibration monitoring program has been in use for a relatively short time, quite a few faulty bearings have been detected on the paper machine in time to prevent or reduce costly down-time. A record is kept of the condition of each bearing when removed and correlated with the vibration readings taken prior to removal. This permits verification of the sensitivity of the monitoring technique and gives direct feedback to the engineer.

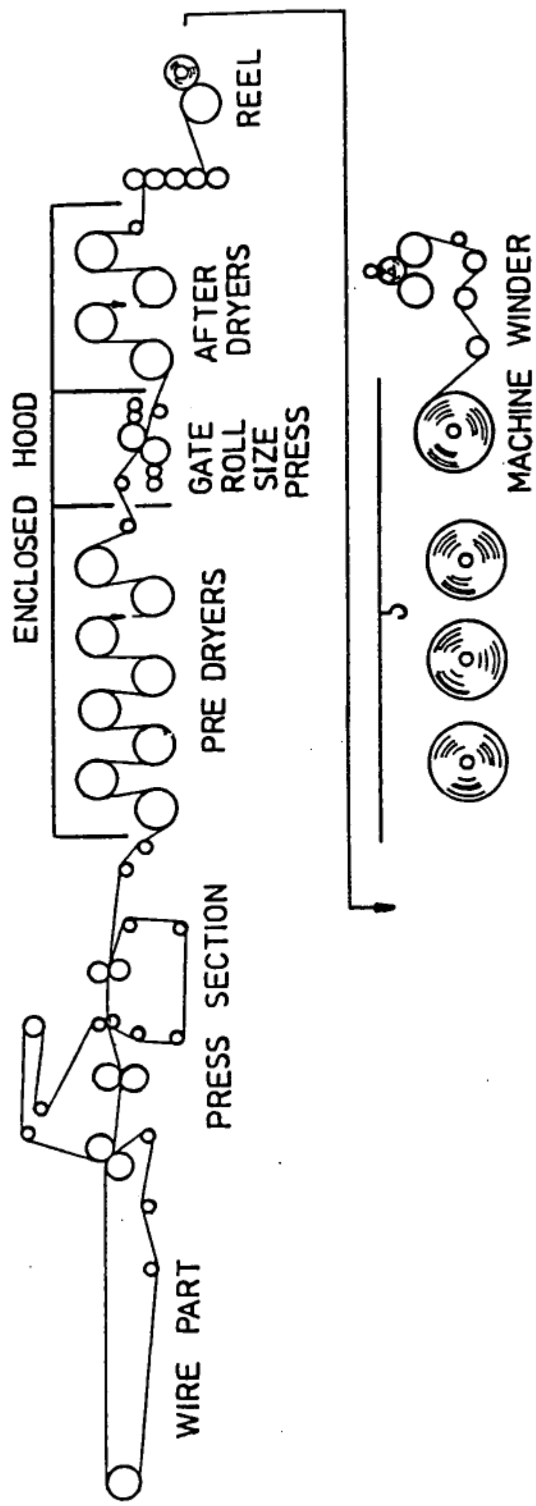


Fig. 2.6 Paper Machine layout showing main rolls

Vibration analysis in the Pulp Mill and Services area of the Mill is in its infancy, there having been no monitoring in this area until the setting up of this present monitoring program. This means that there was a considerable amount of preliminary work required before vibration measurements could be taken.

One aspect of this preliminary work involved the drawing up of A4 size floor plans that show the location and drive number of each machine on a particular floor of the Mill (See examples in Appendix 1). These plans are used by the C.M. personnel to locate each machine to be monitored and to assist in identification of any machine that does not have a drive number attached to the drive control switch panel. They are also very useful in gaining an overall view of the plant layout and greatly simplify the setting up of measurement routes.

Since the floor plans have been produced they have found an additional use in reporting problems with plant that do not show up on the vibration monitoring equipment. This is done by marking the position of the machine on the floor plan and adding a note to describe the particular problem.

3.0 Machines in use at the Wesley Vale Mill.

A brief listing of some of the machines used at the W.V. Mill was given in Chapter 2 and will be expanded upon in this section. The listing in chapter 2 mentioned only the machine types and gave no indication of the numbers of each type in use. For example, only one chipper is in use at W.V. Mill while there are hundreds of motors, pumps and gearboxes in regular use throughout the site. Most of these machines are rotating and make extensive use of rolling element bearings. With only a few exceptions, all the electric motors in use have rolling element bearing as have all gearboxes. The operating speeds of these machines vary from only a few RPM. on the wire rolls of the Andritz Press to 3000 RPM. for the 4 MW steam turbine. Some pumps operate at around 3000 RPM. with the majority operating at 1500 RPM. or less. Some of the more common machine configurations are discussed here.

(i) One of the most common drive configurations in use is a pump having a direct coupled motor on a common base (See fig. 3.1). This drive configuration is in widespread use and will figure highly in any C.M. technique used at the mill now or in the future. The widespread application of this and similar drive configurations allows a degree of standardization in setting up a C.M. program.

Fig. 3.1 Typical direct coupled pump and motor.

(ii) In the Pulp Mill, extensive use is made of screw conveyers for conveying wood chips and pulp through the various stages of the process. These machines tend to be long and light in construction, and therefore very flexible and prone to structural movement (See fig. 3.2). These conveyers are used to transport materials horizontally, vertically, and at varying angles of incline and therefore the loads experienced by the screw bearings can differ depending on the orientation of the screw. The loading experienced by the bearings and the degree of flexibility of the structure contribute in no small way to the reliability of the conveyer.

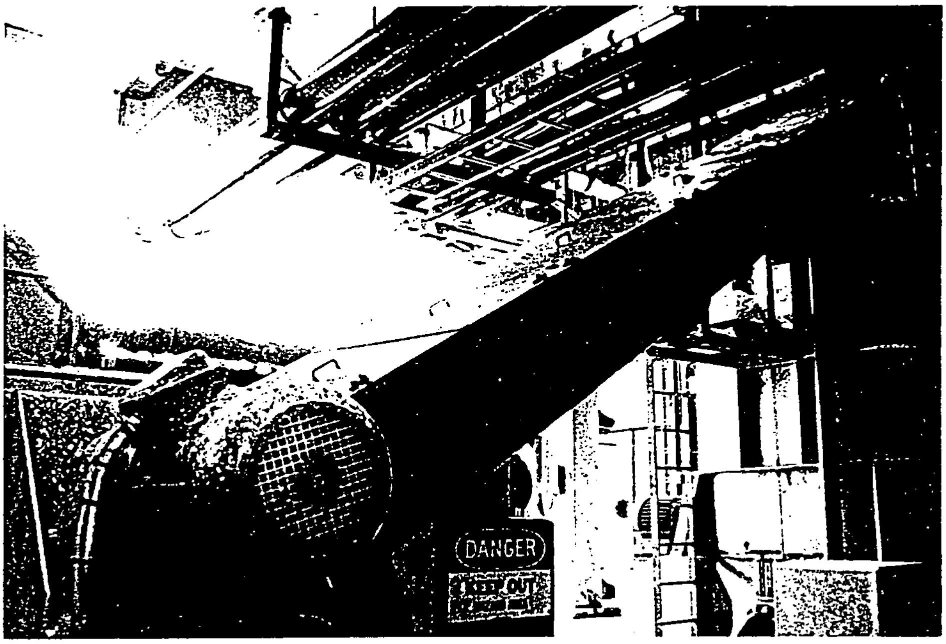


Fig. 3.2 Typical screw conveyer.

(iii) Another common machine in use at the Wesley Vale Mill is the tank/chest agitator. These machines tend to have a significant overhang beyond the outboard bearing and the whipping action of the propeller (particularly when it is partially exposed) can lead to high loads in this bearing (See fig. 3.3). This whipping action can cause damage to both the outboard bearing and to the seal in the tank/chest wall. In the past it has been almost impossible to use mechanical seals in these agitators due to the extent of flexing experienced by the shaft. For this reason the addition of an 'A' bearing or bush just behind the propeller is being considered to stabilize the shaft. At the time of writing none had been fitted.

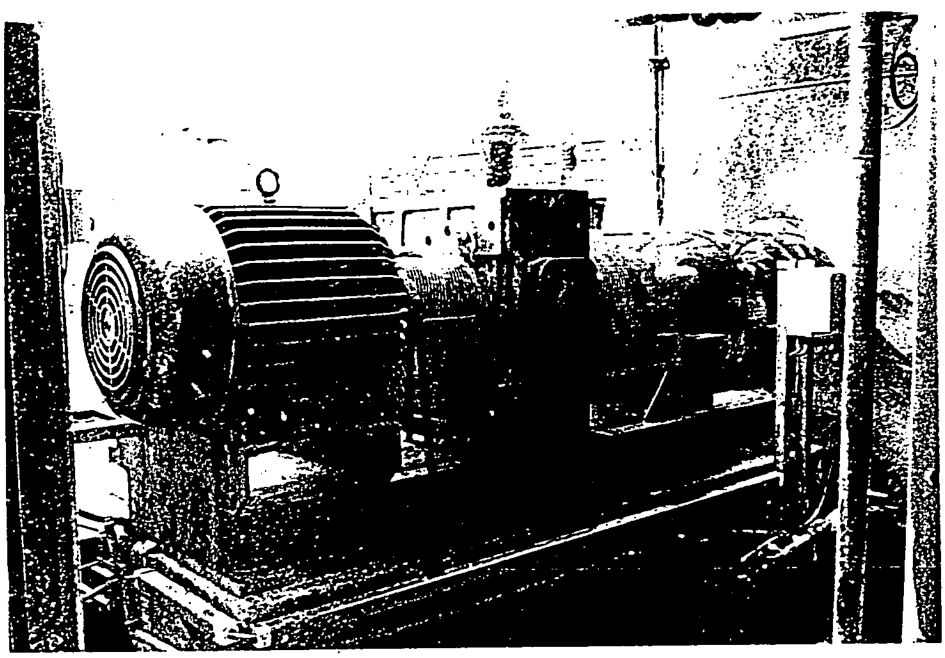


Fig. 3.3 Typical tank/chest agitator at Pulp Mill.

(iv) Some of the most important machines used in the Mill are the refiners. These machines are similar in layout to direct drive, overhung pumps except that they are driven by 800 kw motors and are much more complex in design (See fig 3.4). Due to the limited refining capacity available it is necessary to keep these machines operating at peak load and efficiency for the maximum amount of time and hence a reliable C.M. program is vital for these machines. The C.M. technique used has to be able to detect the earliest possible signs of bearing failure as the downtime to effect any repairs on the bearings of these machines runs into days rather than hours.

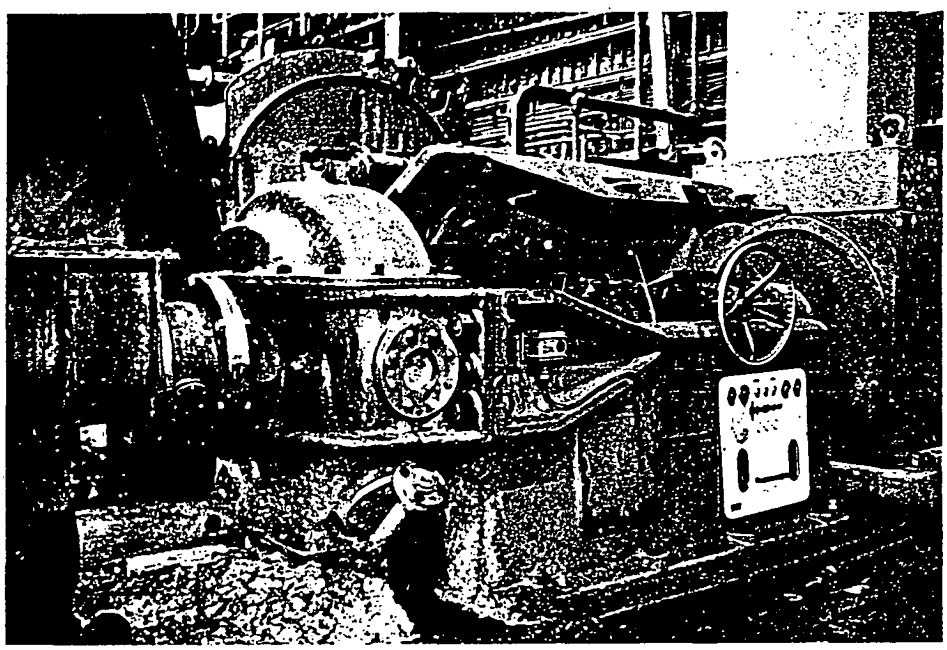


Fig. 3.4 Typical layout of 36" refiners.

As stated above, while there are very different machine types in use at the Mill some kinds are used in much greater numbers than others. For example at the time of writing the following type and number of machines are listed in the equipment records :

(i)	Motors (approx.)	2000
(ii)	Gearboxes	320
(iii)	Pumps (approx.)	450
(iv)	Chippers	1
(v)	Refiners	12
(vi)	Debarker	1
(vii)	Screw conveyers	20
(viii)	Mixers	2
(ix)	Compressors	4
(x)	Turbines	1

While this list is by no means exhaustive it gives a good idea of the numbers of each machine type in use on the site.

Only after identifying the more common types of machine in use in the mill is it possible to select a suitable monitoring technique. The monitoring technique should be selected with the machine design and configuration in mind as well as the cost of setting up and running the monitoring program.

In identifying the machine type and numbers used it is very useful if some record of previous machine failures is available. This gives historical information on the most likely types of breakdowns that can be expected and allows the C.M. program to specifically target these "weak spots". In time these weaknesses in the machines can be designed out. This is only possible if a comprehensive breakdown record-keeping system is in place. As no breakdown records were available for the machines in the Services section of the mill, the setting up of a C.M. program was an ideal time to begin such a program. This allowed future breakdowns to be recorded and correlated with information from the C.M. program.

3.1 Machine Breakdowns..

One of the most common reasons for overhauling machines at the Wesley Vale Paper Mill is because of bearing failure. The majority of these are rolling element bearings and failure can be due to a number of reasons, some of which are :

(i) Fatigue induced failure.

(ii) Damage due to water ingress.

(iii) Incorrect installation.

(iv) Insufficient lubrication.

(v) Overloading.

In the Pulp Mill the two most common causes of bearing failure can be traced to :

(i) Fatigue induced failure.

(ii) Damage due to water ingress.

Experience has shown that fatigue induced failures can usually be detected by vibration monitoring equipment. In the case of water damage however, the experience has been that these bearings can be extensively damaged by corrosion before showing any appreciable increase in the spectrum, despite having a much greater area of damage due to corrosion than is typical of fatigue failure.

Examination of typical failures of each of the above types indicates an explanation for the inability of the vibration monitoring equipment to detect the early signs of a corrosion damaged bearing. On the other hand a fatigue induced defect in the bearing is invariably in the loaded zone of the bearing, and this means that when the defect develops, the rollers/balls continue to run over the site with maximum, or near-maximum, load between the element and the ring. As the element encounters the pit while loaded, a strong pulse is generated and this shows up in the otherwise normal spectra at the frequency at which the pit encounters the elements of the bearing.

In a typical rolling element bearing this frequency is known as the <u>Outer Ball Pass Frequency</u>, if the defect has developed in the outer ring, and as the <u>Inner Ball Pass Frequency</u>, if the defect is situated on the inner ring. These ball passing frequencies can be pre-calculated for each bearing type being monitored and examination of the spectra at these frequencies can quickly show if a fault is developing.

When a bearing suffering corrosion damage is examined, the greatest corrosion is found in the non-loaded zone of the bearing. A considerable build-up of rust is often found in the non-loaded zone with widespread fine pitting in the loaded zone. In cases of severe corrosion damage it is common to find extensive wear (due to degradation of the lubricant by water) on both the rolling elements and the bearings rings, but still no large pits are visible. It is because of the lack of these relatively large, impulse generating pits that little indication of the bearing damage is to be seen in the spectra until the bearing becomes loose enough to detect.

The instances of rust damaged bearings is greatest in machines having designs where leaks from adjacent glands are directed onto the bearing (See fig. 3.5). When the gland packing leaks, the water in the pump escapes under pressure along the shaft and impinges directly on the 'V'-seal used to protect the bearing. Over time water gets past this 'V'-seal and into the bearing.

To reduce or eliminate this tendency for water impingement onto the bearing seal, plastic disks were made up that were a tight fit on the shaft and located between the gland and seal. These disks are larger than the seal and when rotating with the shaft, sling the water away from the shaft and thereby prevent water reaching the seal. The disk also acts as a physical barrier between the gland and the seal and prevents a leak from a gland being directed onto the seal and thereby getting into the bearing.

A second source of water ingress in bearings is due to the almost daily washing down of machines that occurs in a Pulp and Paper Mill. There is a very large amount of water used in a modern Pulp and Paper Mill and some of this water will inevitably find its way into machine bearings. This can be difficult to control and may require covers over exposed bearings to reduce the instances of damage from wash water.

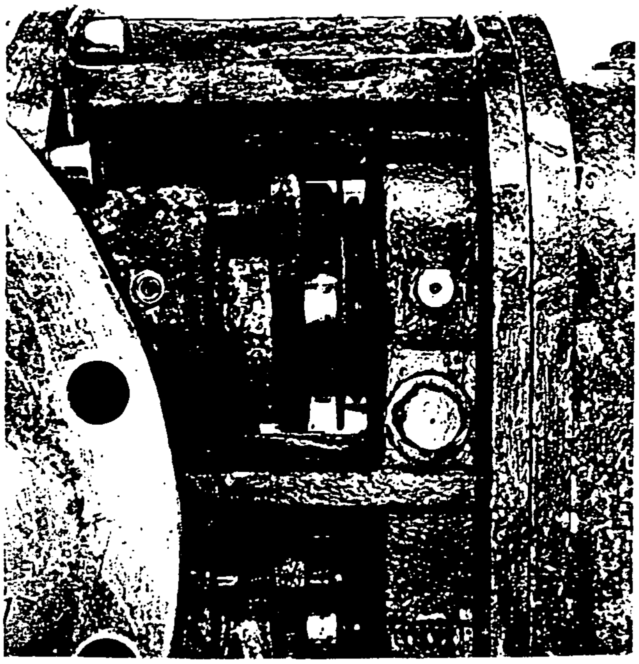


Fig. 3.5 Slinger on HD pump shaft to prevent direct impingement of water onto the bearing oil seal.

Double suction pumps (i.e. Straddle pumps) suffer from an additional design deficiency in addition to that just described. In these pumps the bearings are located on a bowl-shaped outrigger that acts as a water container whenever the drain holes become blocked (See fig. 3.6). When these drain holes becomes blocked due to dirt, pulp, etc. water leaking from the gland or wash water cannot escape and fills up the bearing support.

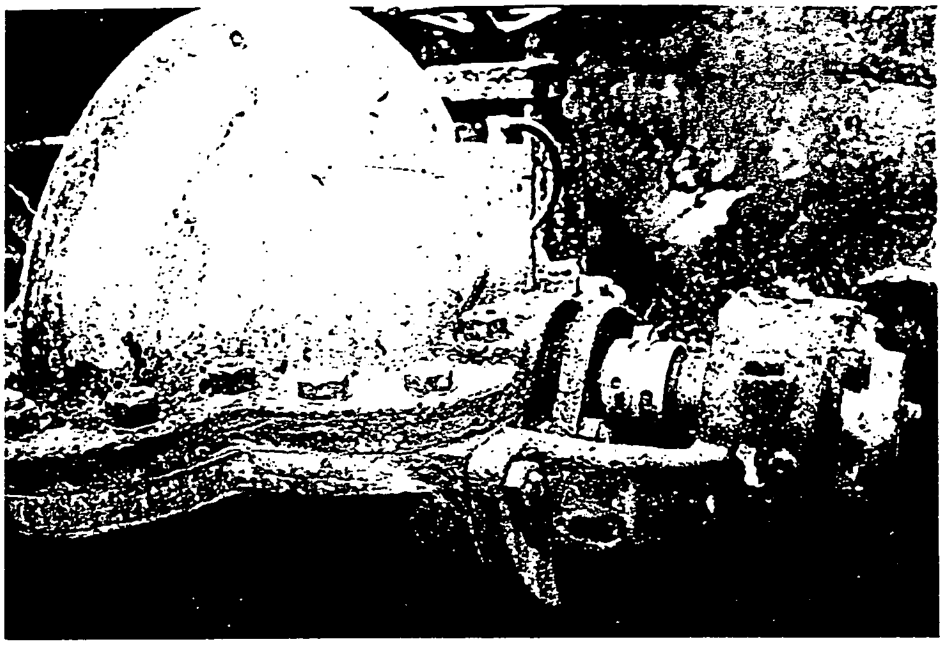


Fig. 3.6 Blockage of Outrigger bearing support drain holes on typical Straddle pump.

When this situation occurs, water works its way into the bearings and corrosive damage quickly follows. The addition of disk slingers can sometimes reduce the tendency for water damage to these bearings. However careful attention to clearing the drain holes is likely to be a better solution.

Gearbox Faults.

Gearbox failure at the Wesley Vale Mill rarely, if ever, reach the stage of total gearbox failure and manifests itself most often as increased roughness and or noise. Once the increase in roughness is noticed, either by chance or by routine monitoring, the gearbox is scheduled for overhaul at the next convenient time based on the rate at which the gearbox is deteriorating.

In the past the fault that gave rise to the need to overhaul the gearbox was not known until the gearbox was stripped for repairs. In future, as each gearbox is monitored on a regular basis, it is hoped that at least some indication of the particular fault would be known before the gearbox is taken out of service for repairs. This would be of considerable advantage in determining the spare parts required for an overhaul and enable timely ordering of specific spare parts that may not be at hand.

3.2 Selection of Appropriate C.M. Technique.

From the discussions in Sections 3.0 and 3.1 it is clear that the great majority of machines in use at Wesley Vale use rolling element bearings. Experience has shown that failure of these bearings is the most common cause of machine breakdowns. Any C.M. technique used therefore has to be able to reliably detect the early signs of bearing failure and track this fault as it gets progressively worse over time. Ideally once some trend data has been collected it should be possible to estimate how long the machine can remain in service under the existing conditions before failure occurs.

From general industry it is known that the best way to achieve the above requirements is by vibration monitoring of the machine either on a continuous basis or by regular surveys. Trending of these vibration readings can be used to indicate whether any suspected fault is getting worse or whether it is safe to let the machine continue in service. In most cases regular vibration monitoring surveys are best suited to industrial applications such as that at Wesley Vale. Continuous monitoring is required only where a very high degree of protection is necessary such as on Power Station turbines, Nuclear Power Plants, etc. and is rarely justifiable in normal industrial applications.

Other types of C.M. (e.g. Temperature Monitoring, Ultrasonics, Thermography, Ferrography, etc.) are not as suited to bearing fault detection as vibration monitoring. For example, in the case of temperature monitoring the rapid rise in temperature that accompanies bearing failure can only be detected just before the bearing actually fails and would rarely give sufficient warning of any imminent failure particularly if the bearings were being surveyed intermittently. Other applications such as compressors, motors, etc. may be more suited to temperature monitoring.

Temperature monitoring becomes more viable when used with continuous monitoring systems and indeed can provide a cost effective continuous temperature monitoring system. One example of this type of continuous temperature monitoring system is the 32 channel temperature monitor produced by Bently Nevada (See fig. 3.7).

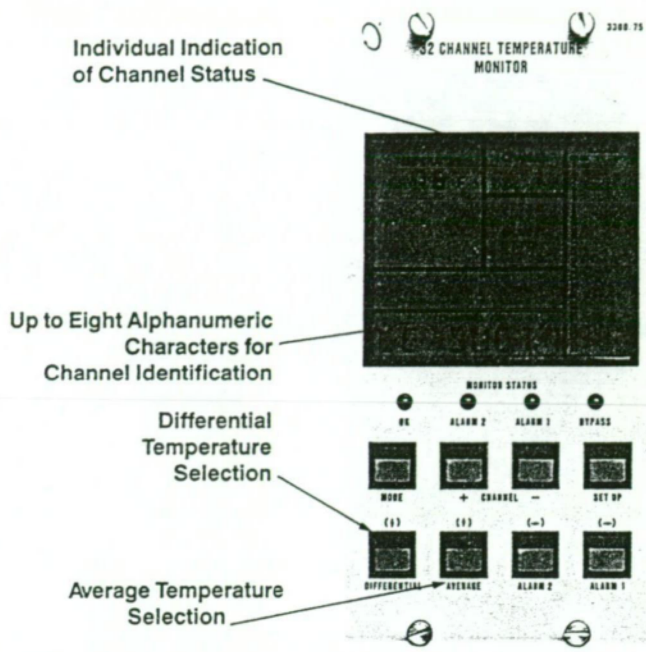


Fig. 3.7 Temperature monitoring module.

By hard-wiring each individual bearing to be monitored back to a central room it is possible to detect a temperature rise in a specific bearing hopefully in time to shut the machine down without further damage. The above shows that while temperature monitoring has its uses as a last line of defense against machine failure, it fails to give the advanced warning of say the development of a fatigue pit in a bearing, that can be achieved with a good vibration monitoring system.

Similarly with oil analysis techniques such as Ferrography or particle counting, the almost zero contribution to the wear particle count made by some small pit in a rolling element bearing race gives no indication of its presence until the generation of particles become large enough to detect. For this reason once the principal components to be monitored have been identified to be rolling element bearings, vibration monitoring becomes the natural choice as the C.M. technique.

Under the general heading of vibration monitoring several specific types of monitoring can be identified. These can be grouped under the following general headings:

(i) Wide band monitoring.

(ii) Spectrum analysis.

(iii) Shock pulse monitoring.

(i) <u>Wide Band Monitoring</u> is carried out by relatively simple hand held meters that indicate the vibration level on an analogue meter or on an array of LED's as on the Bruel and Kjaer (B&K) 2513 instrument (See fig. 3.8). The readings taken are manually recorded and graphed against time to form the trend plot. In many of these instruments both

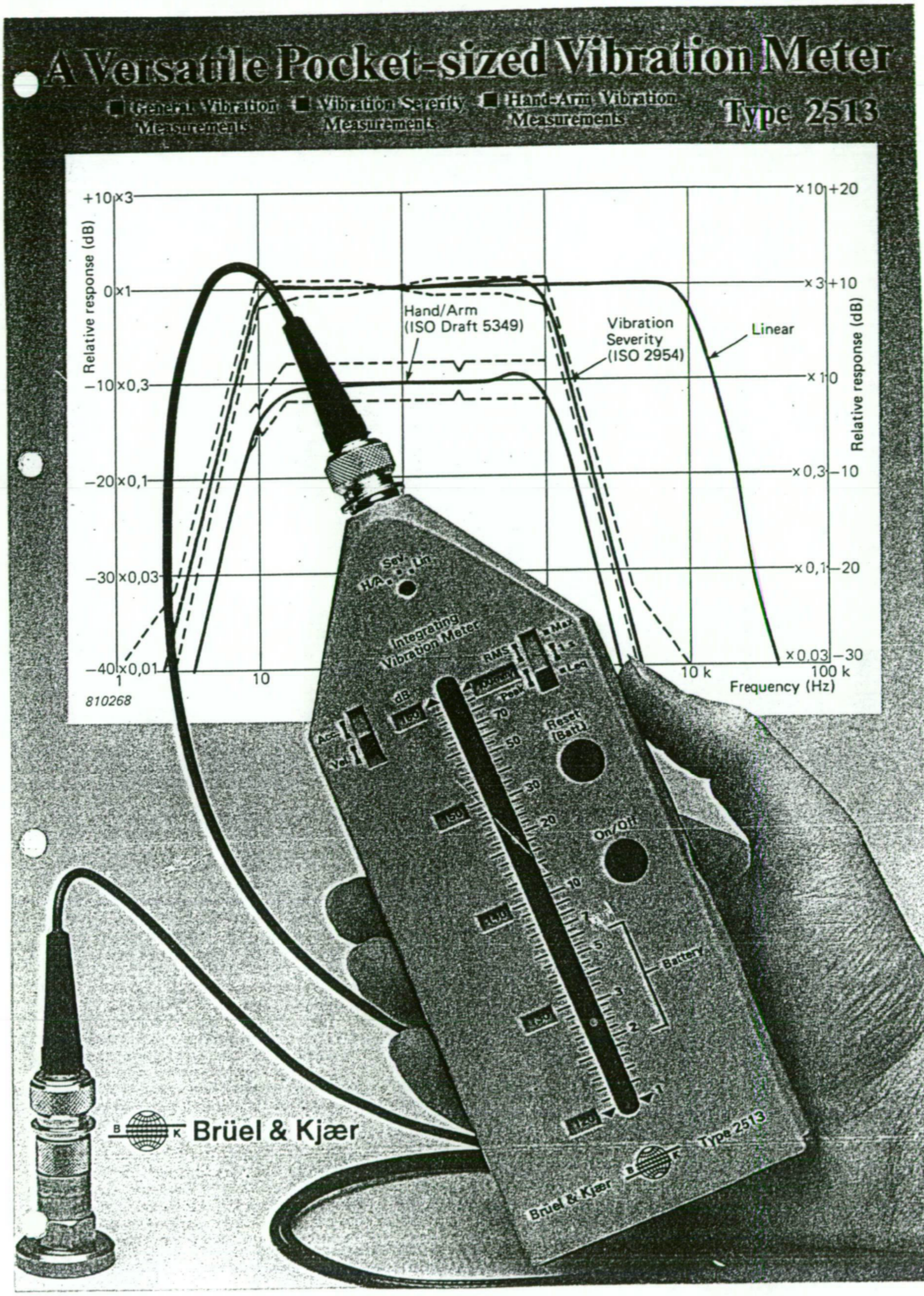


Fig. 3.8 B&K 2513 Wide Band vibration monitor.

Root Mean Square (RMS) and Peak values of velocity and acceleration can be measured. By trending both Peak and RMS values against time over a frequency range of 10Hz to 10,000Hz it is possible to detect developing faults in rolling element bearings. This is possible because a defect on the rolling contact surface will generate high frequency vibration pulses that can be detected by the Peak detector but contribute very little to the RMS reading.

Graphing the Peak values on the same time axis as the RMS values will show a noticeable increase in amplitude on the Peak curves much earlier than on the RMS curve (See fig. 3.9). Identification of specific faults in the machine is not possible using these instruments and therefore their use is restricted to trending overall vibration levels and for use in performing acceptance tests of new or rebuilt equipment.

Various standards exist that attempt to quantify acceptable levels of overall vibration for machines of different type (See fig. 3.10). These standards are only partially successful because of the interaction of the various components of a machine and any system to which it may be connected. It is important to realise that one machine may be considered to be operating correctly while having a much higher vibration reading than a similar machine operating under different conditions.

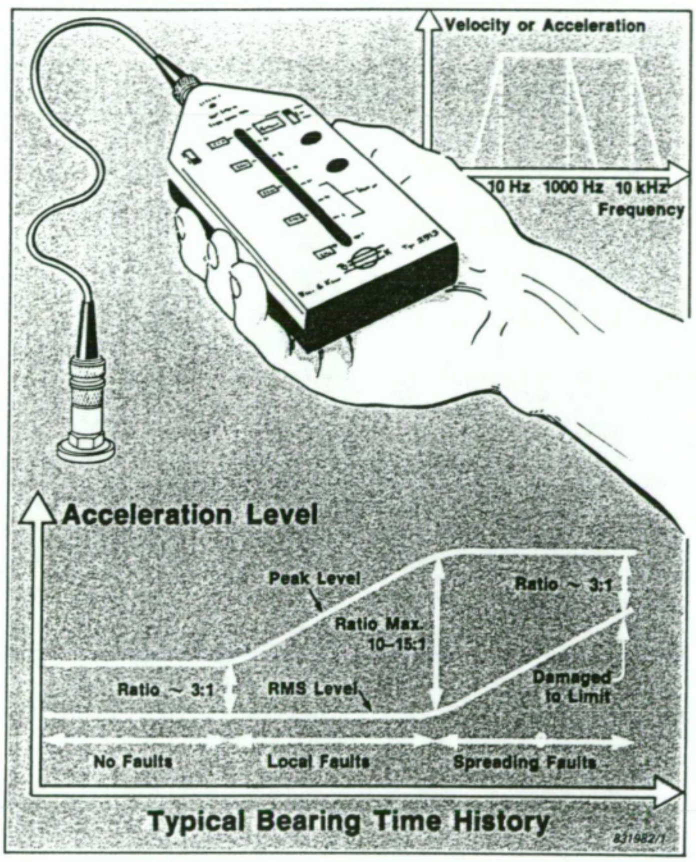


Fig. 3.9 Typical plots from wide band measurements.

A very common example of this type of problem arises when one machine is mounted on a high, relatively light structure, (such as a platform) while a identical machine can be located nearby on a solid concrete plinth. The machine on the platform will have much higher low frequency velocity readings than the machine on the plinth without there necessarily being anything wrong with the machine itself. This example highlights the interaction between a machine and its surroundings and the need to consider carefully any values stated in the standards mentioned above.

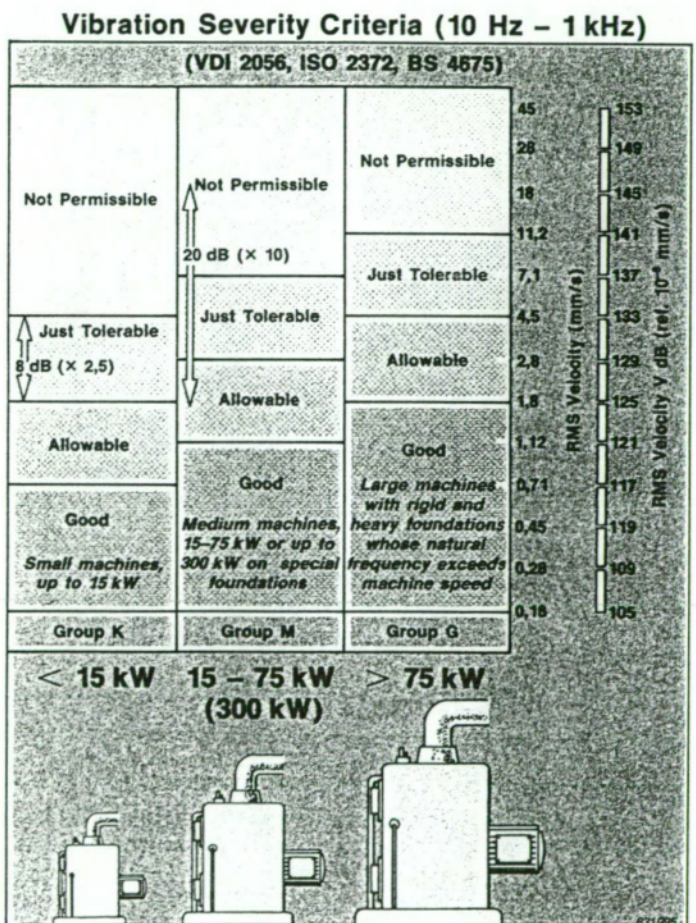


Fig. 3.10 Acceptable vibration standards.

(ii) Spectrum Analysis.

In the discussion on Wide band monitoring in section (i) above the vibrations monitored and trended over time were taken over a wide frequency range, generally 10 Hz to 10 kHz. This technique indicates a change in overall vibration levels such as Root Mean Square (R.M.S.) and gives no indication of the specific fault that has led to the increase in the vibration level.

Spectrum analysis allows the vibration signal to be divided into discreet frequencies and the amplitude of the vibration at these frequencies is displayed as a spectrum. Individual frequency lines displayed on the spectrum represent frequencies generated in the machine being monitored and therefore information on the machine condition is contained in the spectra (signature). By identifying the most important frequencies generated by the machine it is possible to detect any change in the amplitude at these frequencies. In practice the most commonly used frequencies of interest are those that correspond to the operating frequency of major components in the machine. Some typical examples of these components are listed here :

- Rolling element bearings.

- Gear meshing frequencies.
- Once-per-revolution.
- Blade passing frequency.

Changes in the amplitude (usually increasing) of the vibration signal at the operating frequency of a particular component can indicate a deterioration in the condition of the component and can give early warning of a developing fault.

When a new machine is put into service or an old machine is first monitored using vibration analysis, a vibration signature is collected to form a baseline against which future vibration measurements will be compared. This signature is referred to as a <u>reference spectrum</u> and should be taken under conditions as close as possible to those conditions under which future measurements will be taken.

Most modern vibration analyzers use this reference spectrum to generate an envelope over the spectrum that defines the shape of a normal machine signature. This envelope is used to establish statistical alarm limits that are generated automatically using the reference spectra. For this reason it is very important to use a reference signal that is as typical of normal operation as possible. An unrepresentative reference signature can lead to either a lack of alarm sensitivity or oversensitivity of the alarm limits that are based on the reference spectra.

As experience is gained with the spectrum analysis and historical data is accumulated on each machine it becomes easier to establish what the operating signature of a particular machine should resemble. This means that after the vibration monitoring program has been operating for some time it might be necessary to use a different reference spectrum to get a better comparison between the spectrum of the machine in good condition and the spectrum of the same machine as it deteriorates. This can become necessary for a number of reasons, some of which are:

(i) The signal reference spectrum was taken when the machine was not in good condition or was not operating in a standard mode.

(ii) The machine has been overhauled since the reference spectrum was taken.

(iii) The machine stiffness has been altered by modifications to base plates, mountings, etc.

For these reasons it is important to continually update and refine the alarm limits to get the best from a vibration monitoring program.

The use of spectrum analysis has an advantage over wide band vibration monitoring when it comes to defect diagnosis and is indispensable when imbalance, misalignment, bearing defects, etc. need to be identified at an early stage.

This improved sensitivity compared to wide band vibration monitoring does however have its disadvantages. While any fitter or operator can easily be trained to accept or reject a machine on the basis of a single vibration value from a wide band monitor, it is much more difficult to train these people to be able to operate a spectrum analyzer. The effect of this greater system complexity is to require the involvement of more highly trained personnel than would be required for wide band monitoring. This requirement must be taken into account when assessing the cost of setting up a regular vibration monitoring program.

(iii) Shock Pulse Monitoring (S.P.M.).

Shock Pulse Monitoring is used to detect early signs of rolling element bearing faults. While a wide band vibration monitor as discussed in section (i) can detect a damaged bearing, it is usually late in the defect life [4]. By the time the fault is detected little advanced warning is possible and clear signs of a fault may be indicated only just prior to failure. S.P.M. on the other hand is capable of detecting the early signs of bearing damage and can give useful information early enough for it to be of use to the maintenance engineer. As is the case with wide band monitors, Shock Pulse monitors are fairly simple, portable instruments that lend themselves to use by workshop staff or production personnel with a minimum of training.

Where S.P.M. differs from wide band monitoring is that the accelerometer used by S.P.M. is tuned to resonate when excited by the high frequency shock waves set up by initial bearing damage. Most commercial S.P.M. instruments modify the raw peak shock value generated by the instrument to give a more easily interpreted output and to allow for variations in bearing type and machine design.

One typical method of modifying the raw peak shock value is by the formula [4] :

$$S.P.V. = \frac{\text{Meter Reading} \times 10^8}{n^2 \times K^2}$$

where n = shaft speed.
K = geometric factor of bearing.

The output from the S.P. meter is usually given as a <u>Shock Pulse Value</u> (S.P.V.) and is related directly to bearing condition [4]. The S.P.V. is typically interpreted in the following way :

S.P.V. < 10	Good condition.
10 < S.P.V. < 40	Developing Fault.
S.P.V. > 40	Damaged.

Because the S.P.M. instrument makes use of high frequency vibrations (up to 25kHz) good contact between the instrument and the point being measured is vital. In industrial situations a mechanical connection is required to get good results from these systems. To achieve the required frequency transmission quick-connect couplings have been developed by S.P.M. manufacturers. These quick-connect couplings attach to pre-fitted studs on the machine located at each point to be measured and orientated to get the best results (See fig. 3.11).

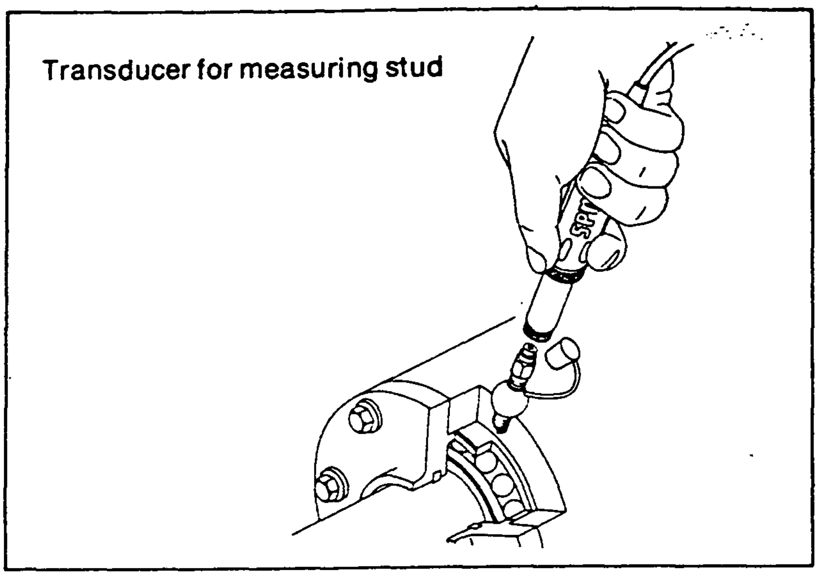


Fig. 3.11 Typical S.P.M. mechanical stud fitted to a bearing.

These pre-fitted studs should be located as close as possible to the load zone of the bearing and have as direct a path as possible to the bearing. Because the frequency of the vibrations being measured are relatively high, attenuation of the signal can be a significant problem. For this reason no more than one interface should exist between the stud and the bearing to be monitored. In practice this can be difficult to achieve on some machines and some loss of signal strength may have to be accepted.

One disadvantage with S.P.M. is that the S.P.V. can decrease as the edges of a fresh pit or spall in a bearing becomes rounded due to repeated impacts. This can lead to the conclusion that the fault has improved or the severity of a defect can be underestimated.

S.P.M. and lubrication.

In addition to detecting bearing faults, S.P.M. is often used to indicate lubrication conditions at the bearing being monitored. When lubrication conditions deteriorate and a boundary lubrication regime exists at the contacting surfaces high frequency vibrations are generated by the surface to surface contact between the rolling elements and the bearing ring. By detecting these high frequency vibrations it is possible to determine if the lubrication system is adequate and whether additional greasing or oiling is required.

The use of S.P.M. can be a viable alternative to more complex vibration monitoring techniques but as with wide band monitoring it suffers from the inability to identify the specific fault that is generating the increased vibration that accompanies a defect. Shock Pulse Monitoring can easily be implemented and used by fitters and operators in a typical industrial plant for routine condition monitoring. The relatively low cost and simplicity of use makes it a popular technique with manufacturers of machines making extensive use of rolling element bearings. Atlas-Copco include S.P.M. as part of their compressor after sales service included in the manufacturers maintenance contract with A.P.P.M. Wesley Vale.

Studies conducted by independent researchers indicate that S.P.M. is capable of giving early warning of developing faults in rolling element bearings [8] particularly when good contact is maintained between the probe and the machine. This will usually require mechanical attachment of the accelerometer to the machine point as discussed above.

Of the three general types of vibration monitoring used in industry (discussed in sections (i) through (iii)) by far the most versatile is spectrum analysis. This technique makes it possible under most industrial conditions, to not only detect that a fault is developing but also to identify the fault. In addition, a wider range of machine faults can be detected using spectrum analysis than with wide band monitoring. Defects such as imbalance, misalignment, oil whirl, etc. can be identified in the spectrum and the results of repairs or modific-ations to overcome these faults can be checked against the spectrum taken before and after the fault was repaired.

Wide Band Monitoring and Shock Pulse Monitoring are both relatively easy to implement compared to Spectrum Analysis particularly in the area of operator training. The much greater analysis power of spectrum analysis requires more highly trained personnel to achieve the best from the system and this must be considered as a cost when determining which is best for a particular situation.

Because of the much greater versatility of spectrum analysis it was selected for use as the preferred vibration monitoring technique at A.P.P.M. Wesley Vale. Some experience had been gained with a B&K 2513 as A.P.P.M. has had one of these instruments for a number of years. This instrument has been used intermittently with no notable success. This has probably been due as much to the lack of a systematic C.M. approach as to the suitability of the instrument and indeed it may have been possible to get good results with this relatively simple instrument if proper organisation and training were undertaken. This instrument will be retained and used as a quick-check instrument that is easily used and understood by the fitters.

One instance where this wide band instrument has been useful (even though the spectrum analysis program had been set up) was in monitoring the vibration level on a 'FUJI' (Roots type) blower that had a noisy N.D.E. bearing due to a cracked bearing housing. The crack in the housing had led to the bearing becoming 'pinched' at two points however replacing the housing had to wait until production could make the machine available.

This machine had to be run over a long weekend (four days) without engineering support (except on call-in) and it was decided that the machine would be monitored by the shift fitter and shut down only if the R.M.S. value exceeded a predetermined value. The results of the wide band monitoring are summarised in the graph in figure 3.12 and indicate no significant change over the monitoring period.

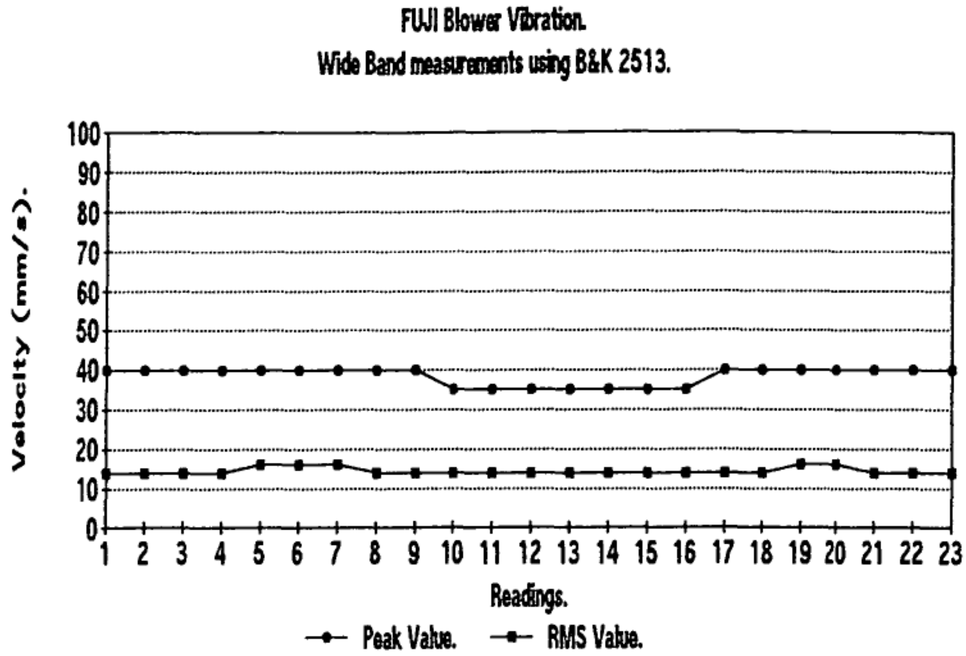


Fig. 3.12 Plot of Peak and RMS values from wide band monitoring of Blower bearing.

The costs associated with each of the vibration monitoring techniques discussed above vary widely, with spectrum analysis being by far the most expensive of the periodic monitoring systems to set-up and run. Approximate costs for the hardware and any software for each of these vibration monitoring techniques are :

(a) Wide Band Monitoring instruments such as the B&K 2513, and the IRD Mechanalysis Model 808 can be purchased for less than $5000. Additional support equipment is available to enhance the B&K unit that allows storage of readings electronically and downloading this data to a computer (See Appendix 1).

(b) Spectrum analyzers with their associated analysis software, are generally much more expensive [9].

- CSI Mastertrend - $20,950.00.
- Micrologn - $22,850.00.
- T.E.C. - $27,991.00.

(c) S.P.M. meters are available in a wide range of instruments from simple hand held meters such as the BEA-52 from SPM Instruments in Sweden for under $5,000 through the model VIB-20 used for continuous monitoring of a single machine to the BMS system for continuous monitoring of many machines. These continuous monitoring systems can cost in excess $50,000 depending on the number of channels being monitored and the amount of data that has to be handled by the support software.

As most machines to be monitored at the Wesley Vale Mill have rolling element bearings as a major component in their design, vibration analysis was selected as a major C.M. technique at this site. The basic vibration analyser would need to be a Spectrum Analyser to allow not only early detection of a fault but the identification of the specific component or bearing that was beginning to fail. As well as being suited to bearing fault detection a modern Spectrum Analyser can indicate the following faults by interrogation of its spectrum.

(i) Imbalance.

(ii) Misalignment.

(iii) Looseness.

(iv) Oil whirl.

(v) Damage to meshing gears.

A more detailed description of these faults and how they are indicated by a Spectrum Analyser is given in the vibration trouble shooting charts in Appendix 1. Additional information is available in the many texts that deal with vibration analysis as applied to Condition Monitoring [4,5,6].

4.0 Selection of Vibration Monitoring Equipment.

Routine Vibration Monitoring of the Number 11 Paper Machine at Wesley Vale has been carried out by Tensor Systems (a Melbourne based vibration consultancy) for about four years. These vibration surveys were performed every three months and repairs or alterations were made on the basis of these surveys. It was felt that in light of the fact that unpredicted failures were occurring between surveys that these surveys should be carried out more frequently. As Tensor Systems would not be available at short notice, it was decided that as much of the monitoring as possible should be performed in-house.

Taking over the vibration monitoring in-house had advantages and disadvantages and both were considered when making the decision to commit resources to vibration monitoring.

(i) Advantages of in-house C.M.

- Allows more frequent monitoring.
- More immediate feedback.
- Development of in-house expertise.
- Can be extended to include other machines at will.

- Allows on-condition maintenance rather than the traditional time based system commonly used.
- Reduced cost to the company.

(ii) Disadvantages.

- Cost of equipment required.
- Requires skilled personnel particularly when setting up.
- Requires an approximately two year learning period.
- Requires good follow up procedures to get the best from the equipment and personnel.
- Requires support at upper management level.

Once the decision had been made to develop an in-house vibration monitoring program it was then necessary to determine which combination of hard-ware and software best suited the needs of the company. As a regular vibration survey had been conducted by Tensor Systems over a couple of years quite a deal of historical data was available and the new equipment would need to be compatible with this data. This, and the fact that it was known from the consultant's experience which type of equipment would be suitable, made the selection of the type of vibration analyzer fairly simple.

To maintain compatibility with the existing database and to permit the greatest flexibility in extending the range of the vibration monitoring, a Digital Data Analyzer rather than a Shock Pulse Monitoring system or a wide band monitor, was considered most desirable. Three different brands of analyzer were assessed before a final decision was made and a summary of the features of the different machines, as prepared by Tensor Systems is included in Appendix 1 along with specifications sheets for each machine.

The machine finally selected was a C.S.I. Mastertrend 2110 Data Analyzer. This unit was selected for a number of reasons:

(i) A slice of the database could be extracted and down-loaded by modem to the consultant in Melbourne. This was preferred over the need to download the complete database as would be required by the T.E.C. unit.

(ii) The cost of the C.S.I. Mastertrend 2110 was the lowest of the three units considered [9].

(iii) The proposed future software upgrades of each machine was investigated and the C.S.I. unit was considered to have the more flexible applications.

It is important to realise that any of these three machines (and probably several others) would be suitable for setting up an effective Vibration Monitoring program. The final selection from this steadily expanding range of equipment was made in light of the specific advantages identified in items (i) to (iii) on page 4.3.

The data collector from C.S.I., and the Mastertrend software package for the host computer, cost approximately $21,000 not including the computer to run the software.

As well as the basic C.S.I. data analyzer and software, additional items were purchased to be used in association with the data logger and are listed here with their approximate prices at the time of purchase [9].

(i)	B&K 4391 Accelerometer	-	$450
(ii)	High quality cable	-	$390
(iii)	Charge amplifier	-	$750
(iv)	S.P.M. quick-connect coupling	-	$600
(v)	Demodulator (manufactured by Tensor Systems)	-	$750
(vi)	Personal computer	-	$7,000
(vii)	Modem (Nettcom 1234 SA)	-	$950

The costs listed here do not take into account the cost of training or the cost incurred in fitting the studs to the machines to be monitored. Initially these studs, made from brass, were purchased from Tensor Systems at a cost of approximately $2.50 each. Several hundred of these studs were fitted to various machines both in the Pulp Mill and the Paper machine.

In practice it was found that some of these studs corroded badly when used in the Pulp Mill requiring replacement after about six months. To overcome this corrosion new studs were made from stainless steel and fitted to those machines that required stud replacement. These studs have been in service for over eighteen months and show no signs of deteriorating. The cost of producing the stainless steel studs was comparable with the cost of the brass studs.

The cost of training directly attributable to condition monitoring has been mainly for attendance at training seminars. Some of these courses have been given by the equipment suppliers while others have been courses arranged by third parties such as Monash University in Melbourne.

Costs additional to training have been several visits by the consultant from Tensor Systems to assist in setting up some of he machines to be monitored and to ensure that the in-house program could cope with the workload. In all, this direct and indirect training would not have exceeded $12,000 to this time.

In addition to the training outlined above a considerable amount of study was undertaken in the field of condition monitoring by the writer while preparing this thesis. This study directly contributed to the setting up the vibration monitoring program as it is today. While this work was not charged against A.P.P.M. it would have to be allowed for in any new system that did not operate under similar circumstances.

5.0 Setting up of Vibration Monitoring Program.

Setting up a Vibration Monitoring program required a considerable amount of groundwork to be performed before meaningful results could be obtained. As the Paper Machine had been surveyed for some time by a consultant, much of the groundwork had already been done in this area. This made the transition to in-house monitoring of the Paper Machine relatively straightforward. Most of the Paper Machine rolls are surveyed on a monthly basis from the 'tender' side only, the drive side being monitored only if some fault is indicated in the tender side spectra.

In the case of the Pulp Mill and Services area of the Mill, no Vibration Monitoring had been performed in the past and so it was necessary to establish a monitoring program from the beginning rather than build on an existing system as had been the case at the Paper Machine. This required the following initial steps to be taken :

(i) Identification of all machines in the area of interest.

(ii) Floor plans to identify machine location (See Appendix 1).

(iii) Technical data for each machine to be monitored had to be gathered such as:

(a) Speed.

(b) Drive ratios (belt, gears, chain, etc.).

(c) Bearing numbers (to be entered in database).

(d) Number of gear teeth.

(iv) Fitting of quick-connect studs to all points to be measured.

(v) Setting up measurement routes (It is in this step that the floor plans are of greatest use).

By far the two most difficult and drawn-out steps in setting up the vibration monitoring program was in collecting the huge amount of information required to get the best from the software package, and getting the quick-connect studs attached to the individual machines. The C.S.I. Mastertrend software is capable of highlighting up to seven individual frequencies for each measurement point. These frequencies can be identified by a vertical marker on the computer screen overlaying the spectra. In this way frequencies of interest can be quickly identified thus ensuring more rapid interrogation of the spectra. Some of the typical frequencies that are set up in the W.V. database are :

- Gear mesh frequencies (gear boxes, gear motors, etc.)
- Outer ball pass frequencies (all bearings.)

- Inner ball pass frequencies (all bearings.)
- Cage frequencies (all bearings.)
- Blade passing frequencies (pumps, fans)
- 1 x RPM (for imbalance, etc.).
- 2 x RPM (alignment, etc.).

Not all of these frequencies will need to be set for each machine however, and it is necessary to identify which frequencies are of interest to the operator to enable identification of major, known frequencies in the spectra. Setting up this information is simplified to some extent if it is possible to identify common bearings etc. in a range of machines. This is possible particularly with motors and gearboxes because manufacturers tend to use the same bearings within a particular frame or case design. For example all motor bearing within a specific frame size tend to be the same provided the motors are from the same manufacturer (See Appendix 1).

The opposite however is the case when it comes to finding out how many teeth are in a gear set in a gearbox. Most gearbox manufacturers supply catalogues that give bearing numbers etc., but rarely give gear teeth numbers. In this case it is necessary to either physically count the gear teeth, estimate the gear ratio, or approach the manufacturer for specific gear teeth numbers.

Fitting the quick-connect studs to the machines was a considerable undertaking and was made all the more frustrating by the fact that it was considered a low priority by all but those trying to set up the system. Most of the studs were eventually fitted by a couple of apprentices who concentrated on fitting the studs one or two days a week until they were all attached. In the case of the W.V. Pulp Mill over 400 studs were installed, some of which had to be altered slightly soon after for various minor reasons. In hindsight it would have been better to have hired in someone to do nothing but fit these studs as the job tended to drag on and only constant follow-up ensured it was not left as jobs of more immediate importance came up. Since the surveys have begun to show results it has been easier to get occasional studs that required relocation or replacement attended to.

Once all of the studs were fitted to the machines on the ground floor of the Pulp Mill, regular monitoring began. This area was selected as the first place for monitoring as it contained a large number of important machines in a relatively small area, and because some of these machines were fairly old. The first two to three surveys were carried out on a monthly basis to establish some baseline readings and to iron out any problems with the software setup and stud locations. Even after the first of these surveys immediate feedback was available and some repairs were instigated on the basis of the report from this survey. Some of the problems detected were :

- loose footing on agitator drive (base plate was found to be badly corroded and required extensive repair).
- high vibration in stock pump (pump was overhauled, and while the vibration was still relatively high it was markedly reduced.)
- gearbox noisy and rough (spare gearbox overhauled and fitted.)
- noisy and rough motor NDE bearing (motor overhauled.)
- agitator coupling noisy and rough (coupling replaced.)

5.1 Setting up the Vibration Database.

The initial database used was the one that had been set up by Tensor Systems. This database was maintained and extended for use by the in-house monitoring program on the paper machine. The Pulp Mill and Services area uses a separate database file to prevent having one file becoming too large as this would slow down access and increase the time needed when the file is backed-up at regular intervals (approximately once a month). Each database follows the structure shown in fig. 5.1 [7].

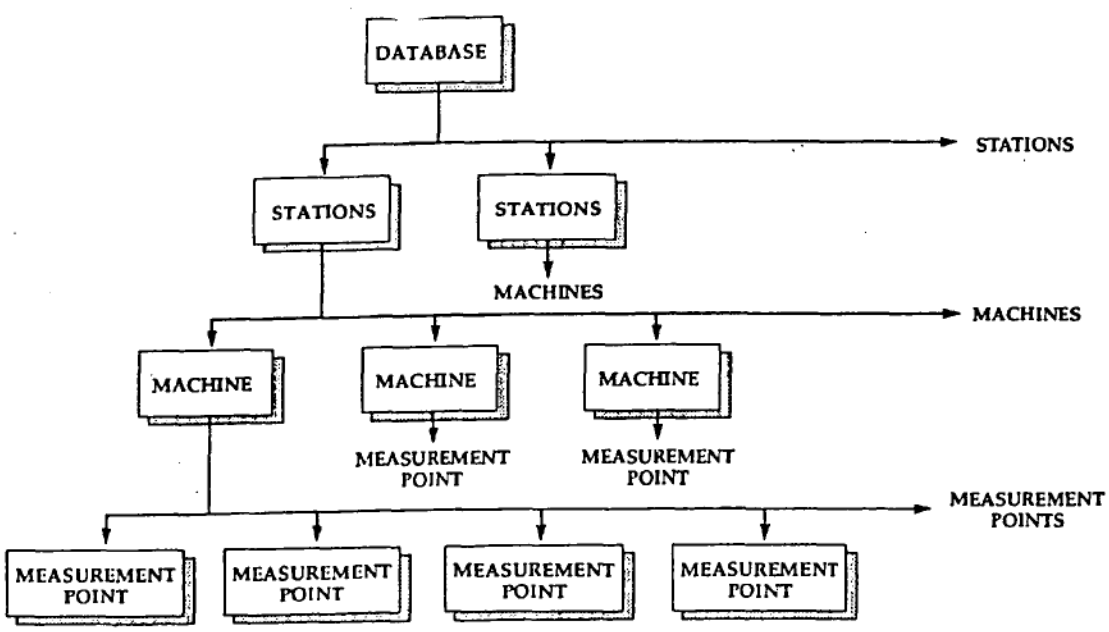


Fig. 5.1. Layout of database showing hierarchy.

(1) The Database Manager Program organizes and manipulates the database and includes Stations, Machines, Measuring points, Analysis Parameter sets, Alarm Limit sets and Fault Frequency sets. Each of these sections of the database have to be set up to suit the machines to be monitored and to enable rapid identification of a particular peak on the spectrum.

(2) Station are the highest level in the database hierarchy and make up a collection of machines that have some common feature. In the database for the Pulp Mill and Services section of the mill the stations are structured to accommodate machines from a specific area of the mill. At present the machines are grouped in the following stations :

- Pump Station.
- Filtration Plant.
- Woodroom.
- Pulp Mill.
- Boiler-house.
- Chemical House.

(3) Machines are the next level down in the database hierarchy and are usually complete machines such as drives, compressors, turbines, pumps, blowers, etc. At A.P.P.M. machines were established

on the basis of existing drive numbers used on site to identify specific pieces of plant. This simplified the collection of information for inclusion in the database to some extent by allowing direct reference to existing information on the basis of drive number. One example of these drive numbers is Ka 123 where the letters Ka identify the plant area as being Semi-Chemical Pulp Mill and the numbers uniquely identify a specific machine in this area. It is these identification numbers that appear on the floor plans made up to locate machines for the C.M. operator. They also appear on labels attached to the switch panel for each drive out on the site, thus making identification of each machine relatively simple.

(4) Measuring Points are the lowest level in the database hierarchy and describe the specific point on a particular machine at which a vibration reading is to be taken. The convention used at Wesley Vale is to start at the non-drive end of the drive motor and number each bearing progressively through the particular machine. When not all of the bearings are monitored on a particular machine the identification numbers reflect the fact that some were skipped by skipping these numbers in the list.

A typical measuring point sequence is shown in fig. 5.2 for simple motor driven pump.

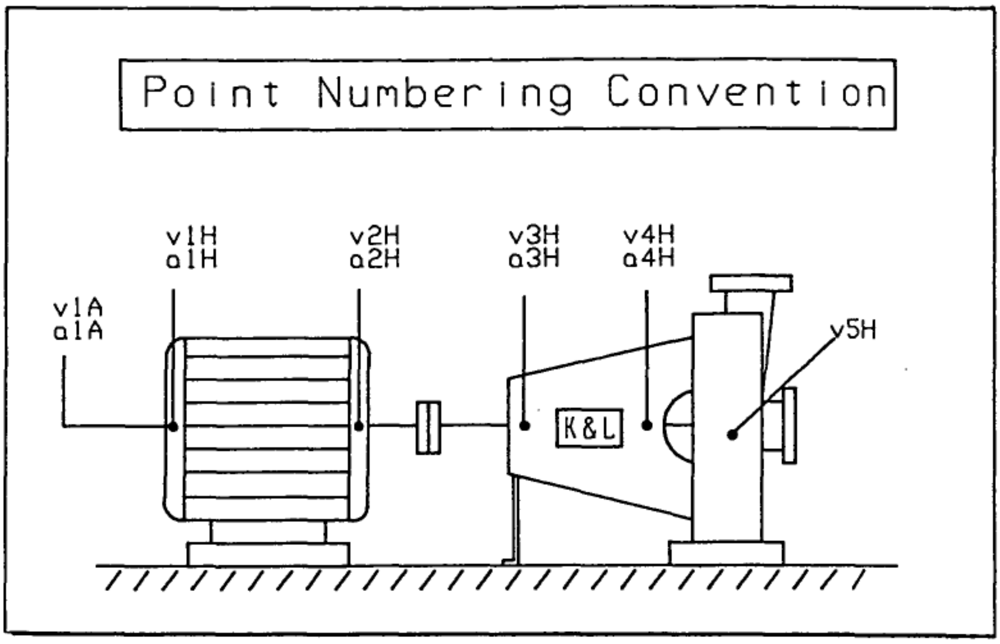


Fig. 5.2. Typical measurement point labelling system.

(5) Analysis Parameter Sets are used to divide the range of the frequency spectrum into a group of up to six analysis parameters that are individually analyzed. Each analysis parameter is selected to contain a segment of the spectrum where particular machine frequencies exist. Typical parameter segments would include:

(i) Subharmonics, i.e. less than one order.

(ii) One order.

(iii) Two orders.

(iv) Three to four orders.

(v) Five to twelve orders.

(vi) High frequency domain.

These parameters are selected to capture frequencies of interest such as gear mesh frequencies, bearing fault frequencies, blade passing frequencies, etc. In addition each analysis parameter set contains information that allows the analyzer to collect and store the data for each measurement points [7].

Once a particular analysis parameter set is set up it can be used for many different machines and measurement points simply by identifying it by its unique set identification number. Up to 255 analysis parameter sets can be created in the C.S.I. software however it is unlikely that all of these will be required since each set can be used many times.

(6) <u>Alarm Limit Sets</u> are used to set the level above which, under normal circumstances, the amplitude of the vibration would be considered to be unacceptable. The alarm limit set contains an alarm for the overall signal and a separate alarm level for each of the parameters configured in the

analysis parameter set. Once one of these alarm limits is reached it gives an alarm on the data analyzer at the time the data is recorded and lists the alarm on the reporting sheet for that survey.

Some pre-configured alarm limit sets are available with the C.S.I. software and can be used as a starting point for a C.M. program. These sets are configured to suit the following general machine conditions [7] :

- Very smooth.
- Smooth.
- Typical vibration.
- High vibration levels.
- Very high vibration levels.

As well as the pre-set alarm levels there is also an early warning alarm that is statistical in nature and is used to detect if a particular value has changed significantly from an earlier baseline value. This alarm can be triggered even if a specific alarm level has not been reached. One way of calculating the early warning levels is by what is known in the C.S.I. software as 'Baseline Ratio'. This is calculated by comparing the measured signal with some multiple of the expected signal. For example if the amplitude is not expected to increase by more than say 20% under normal conditions setting the baseline ratio to 1.2 will ensure that if the signal should increase by more than 20%, but still not reach the lower pre-set alarm level, the change will be flagged by the early warning alarm.

An alternative method of calculating the early alarm level [7] :

"...establishes a level equal to the calculated mean plus (or minus) the number of Maximum Deviations (specified in the alarm limit set) times the standard deviation. These two levels are then compared, and the most restrictive level is used for the early warning."

(7) <u>Fault Frequency Sets</u> are used to identify specific frequencies within the spectrum that correspond to faults that may develop in the machine over time. These faults can be ball passing frequencies of rolling element bearings, gearmeshing frequencies, blade passing frequencies or any other frequency that may be of interest to the C.M. operator. Once a fault frequency set is set up it can be used in many machines and for many measurement points where applicable.

Fault frequency sets are a very useful aid in the interrogation of spectra but take a lot of effort to set up correctly. It is necessary to know the bearing make and number for each measurement point along with the number of vanes on a pump impeller blades on a fan, etc. that apply to the specific point. For this reason it is best to identify any common units in the plant that are to be monitored and make one fault frequency set that can be used over all or most of these machines.

At A.P.P.M. Wesley Vale there are seven, 36" Sunds disk refiners each having an 800 kW motor and for these machines one fault frequency set was made up for the drive motors and a separate set for the refiners. While it is possible to use the C.S.I. database without setting up fault frequency sets it is well worth the effort especially for those machines that are high priority items in the C.M. program.

5.2 Setting up the Vibration Survey Routes.

Once the machines to be monitored in a particular Station have been set up in the database and have been assigned Analysis Parameter Sets, Alarm Limit Sets, and where applicable Fault Frequency sets, it is necessary to group them in a logical order to simplify routine measurements. In small stations having only a few machines it is possible to group all the machines into one measurement route without disadvantage. In the Pump Station, Woodroom and Chemical House one route each is considered sufficient for these stations.

In the case of lot of machines being in one station, it is often best to divide them up into separate routes on the basis of location, monitoring frequency, machine type, size, etc. This is very convenient because it allows monitoring of specific routes on different days and by different people if necessary. The Pulp Mill station is divided up into the following routes to reduce the work and to simplify organization of the surveys (See Appendix 1).

(i) Ground floor North side, East end.

(ii) Ground floor North side, West end.

(iii) Ground floor, South side, East end.

(iv) Ground floor South side, West end.

(v) Upper floor North side.

(vi) Upper floor South side.

(vii) Semi-Chemical Refiners.

(iix) Refined Wood Refiners.

(ix) Stock Washers.

(x) Andritz Presses and Mixers.

(xi) High Density Pumps.

(xii) Prexing Unit.

It is in the setting up of the measuring routes that the floor plans (See Appendix 1) are of most use. These floor plans show adjacent machines and allow a logical progression from one machine to the next without having to backtrack. It is important when setting up the measurement routes to consider the operating times and production sequence of particular machines to ensure that the machine to be monitored is operating at the time of the survey. This can be a problem when some machines are operated only intermittently or outside normal business hours.

Another point to be considered at this and earlier stages is whether the vibration readings will be taken with the machine loaded or idling. When monitoring the chipper in the Woodroom it is possible only to take readings with the chipper idling as the vibration generated by the cutting action of the chipper creates widely varying data depending on the type of wood being chipped and the time taken to completely chip the log. An additional problem is caused by the fact that the chipper motor overload trip takes seven seconds to activate and the log has to be chipped in this period followed by a second or two of no load. This time is generally too short to collect the eight averages that we prefer when taking readings and therefore the conditions under which the readings are taken change. This could be overcome by reducing the number of averages taken but it would not overcome the variability due to the chipping action.

In this particular case monitoring the chipper while idling presents no problem as the weight of the chipper disk is several tonnes and this alone generates a sufficiently useful vibration signal for trending.

The C.S.I. software currently being used is limited to 25 routes per station. This is usually adequate so long as the machines are distributed throughout different stations in a logical manner. Over time changes have been made to the routes with a view to reducing the size of particular routes and to generate specific routes for like machines. From the monitoring schedule chart in Appendix 1 it can been seen that the refiners are tied together in a separate route as are the stock washers. Compressors and pumps in the Boiler House station are also given separate routes.

When setting up a new route the program asks for some global settings to be defined. Both the spectra and waveform storage parameters can be set separately from the following list of options :

1. No data stored.
2. Store data on HI status.
3. Store all data.

At present the setting being used are No. 3 for the spectra (i.e. store all spectra) and No. 2 for the waveforms (i.e. store waveforms only when a HI alarm is indicated). If both spectra and waveform were stored for all measurements the analyzer would very quickly fill up with data and would have to be downloaded much more frequently than if using the settings mentioned above.

6.0 Turbine Monitoring Program.

The A.P.P.M. Paper Mill at Wesley Vale operates a 4MW steam turbine to supplement the electrical supply from the state grid. This is a Stal-Laval DSM 1244 Back Pressure turbine that runs on a 24 hour-a-day basis at 3000 RPM. Power output from this turbine is usually in the range, 1.5 - 3.5 MW.

Routine overhauls are carried out about once every four years by the maintenance staff of ABB Stal operating from South Australia. Between overhauls the only condition monitoring carried out (besides performance monitoring) has been two lubricating oil analysis tests performed by Shell each year. By early 1990 the turbine was overdue for a major overhaul especially since it was known that some of the turbine blades had surface pitting when last inspected in 1986.

At this point in time no specific problem was known to exist except for some high vibration levels at the exciter. However as the maintenance was overdue it was decided to increase the monitoring of the turbine. This increased monitoring would be continued after the turbine was overhauled and would consist of three complimentary techniques.

(i) Wear debris analysis of lubricating oil (to detect increased wear in journal bearings).

(ii) Vibration analysis using an accelerometer.

(iii) Vibration analysis using proximity probes (to detect rubs, etc.).

6.1 Wear Debris Analysis of Turbine oil.

Wear debris monitoring is possible using a wide range of techniques, and when correctly applied, can be used to detect developing faults in many kinds of machine [4,6,15]. One or more of these techniques would be suitable for use in monitoring the oil quality in the A.P.P.M. turbine. The tests performed every six months by Shell included both manual tests and Spectrometric Oil Analysis (SOAP). A sample SOAP sheet is included in Appendix 2 and shows results from the following tests:

(a) Alkalinity.

(b) Viscosity.

(c) Water content.

(d) Total acid number (T.A.N.).

(e) Appearance.

(f) Oxidization.

(g) Spectrometric analysis.

(i) Iron. (v) Lead.

(ii) Chromium. (vi) Sodium.

(iii) Silicon. (vii) Tin.

(iv) Copper.

Because the increased monitoring of the turbine was undertaken to give early warning of a developing problem with the machine rather than the oil, the wear debris analysis was of major interest. Examination of the oil analysis procedures and test results since 1987 (just after the last overhaul) showed a number of problems that would have to be overcome if useful trending was to be possible.

Two samples were normally taken for each six monthly oil test. The oil samples used for these tests were taken from the drain line at the lubricating oil filter and from a drain line on the governing oil filter (No. 7 and No. 12 in figure 6.1 respectively). These sampling points are not ideal as they do not give a sample that is representative of the particle concentration in the main body of the oil.

In a typical lubrication or hydraulic system there are several different places from which the oil sample can be obtained. Some of these sampling sites are more suitable than others for obtaining representative samples of the oil.

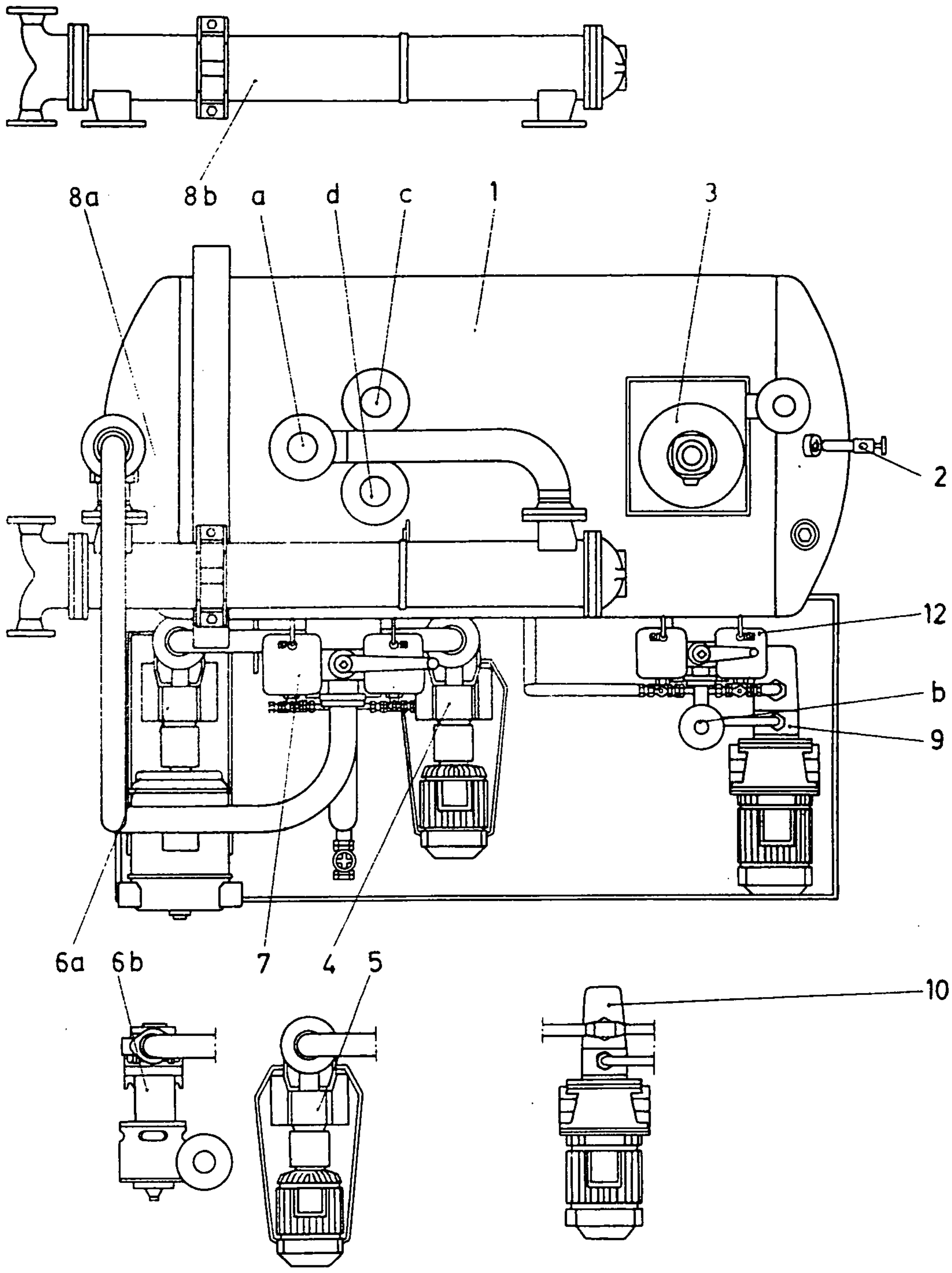


Fig. 6.1 Layout of lubrication system on the 4MW turbine at A.P.P.M. Mill at W.V. (See Appendix 2 for KEY to this figure).

Some of the commonly available sampling points are shown in fig. 6.2 and include :

(a) From the reservoir drain valve.

(b) Through the reservoir filler neck.

(c) Before the filter.

(d) After the filter.

(e) From drains on pumps and lines.

(f) From points on the machine.

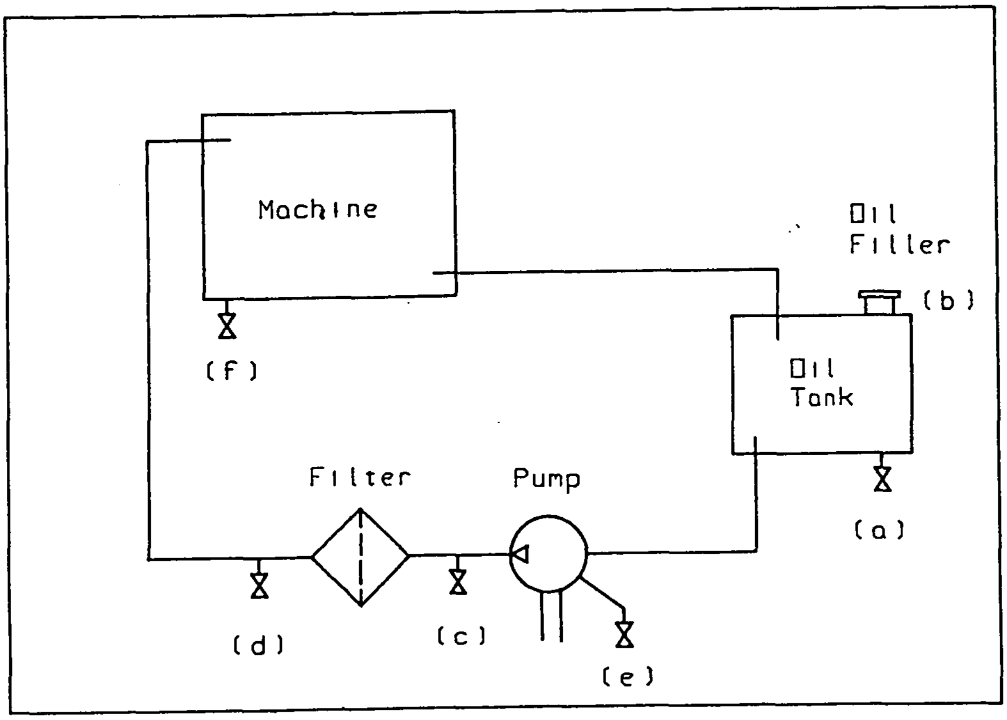


Fig. 6.2 Typical sampling points available in a lubricating or hydraulic circuit.

6.1.1 <u>System Equilibrium</u>.

Before considering the most appropriate sampling location for a lubrication or hydraulic system the concept of system equilibrium needs to be discussed.

After a disturbance to the machine that influences the particle concentration or distribution in the lubricating or hydraulic fluid, a period of normal running is required after the disturbance for the system to again reach equilibrium. When a system is operating for some time and has reached equilibrium, the same number of particles are generated at the wear surfaces as are removed by the filter, settle out from slow moving oil columns, adhere to machine surfaces, or are lost due to oil leaks. Except for particles too small to be trapped by the oil filter, the filter is the chief means of particle removal.

If the particle concentration is higher than at equilibrium as a result of the system disturbance, the filter action, settling etc. will have the effect of reducing this concentration to the equilibrium level. This is because the rate of particle removal is greater than the rate of particle generation. This cleaning of the lubricating oil can take several hours or days after start-up depending on the cycling rate of the lubricant.

If the particle concentration is lower than at equilibrium after the disturbance, the particle concentration in the oil will increase to the equilibrium level because the rate of particle generation is greater than the rate of particle removal.

The time required to reach equilibrium will depend on several factors, some of which are [2] :

(i) Filter efficiency for a particular particle size.

(ii) The number of times a particle passes through the filter.

(iii) The lubricant cycling rate (i.e. how often the total volume of oil is cycled through the system per unit time).

(iv) The dispersive properties of the oil. If the oil has strong dispersant additives present, these will prevent small particles combining to form large clumps that would be more easily removed by the filter. These dispersant additives also reduce particle settling thereby keeping them in the lubricant stream longer.

In normal industrial applications the disturbances to lubricating or hydraulic system equilibrium can be due to one or more of the following :

(i) Major machine rebuild.

(ii) Significant oil leaks.

(iii) Ingress of foreign particles.

(iv) Total oil change.

(v) Oil level top up.

In the case of a major machine rebuild, new oil will be added and the particle concentration in the oil will start to increase as soon as the machine begins to operate. Figure 6.3 shows the change in concentration for particles typically greater than 1 micron over the life of the machine. Particles generally less than 1 micron follow the curve in figure 6.4 rising rapidly during run-in and rising more slowly during normal machine operation. The reason that the curves on figure 6.3 and figure 6.4 are different is that particles normally too small to be removed by the filter tend to stay suspended in the oil and are not generally removed by the filter to any great extent, while larger particles are eventually removed by the filter after repeated passages through the filter medium. The particle size that remains in suspension in the oil and is not removed by the filter, will depend on the filtering efficiency of the filter at that particle size and may be greater than the 1 micron mentioned here.

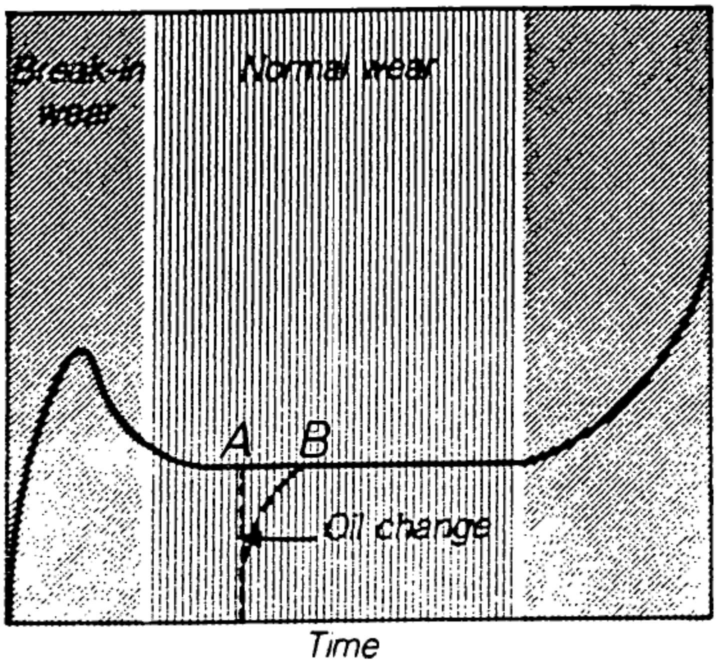


Fig. 6.3 Particles concentration Vs. time for large particles.

Oil leaks that remove particles as well as oil from the system, ingress of foreign particles, and oil level top-up, all upset the system equilibrium. The equilibrium will be re-established after sufficient operating time by the balancing forces of particle generation and particle removal.

When total oil changes are carried out as part of routine maintenance on lubricating or hydraulic systems, the particle concentration equilibrium is drastically upset. In figure 6.3 the oil is drained and replaced with clean oil at point 'A'. Upon start-up the particle concentration again begins to rise until equilibrium is re-established at point 'B'. From this it can be seen that any oil samples taken for analysis must be taken after equilibrium is established. It is also obvious from this graph that there is a need to change the filter fairly soon after the machine has been commissioned as the filter could be overwhelmed by the large number of particles being generated by the running-in process.

Figure 6.4 shows the effect of an oil change on particle concentration for those particles small enough not to be trapped by the filter. The oil is drained and replaced with new oil at point 'A' and the particle concentration begins to increase immediately after start-up. The increase in concentration in this case being a mirror image of the original concentration change. Examination of figure 6.3 and figure 6.4 shows that the smaller particles generated by the machine are removed by changing the oil, while the larger particles are removed only by changing the oil filter.

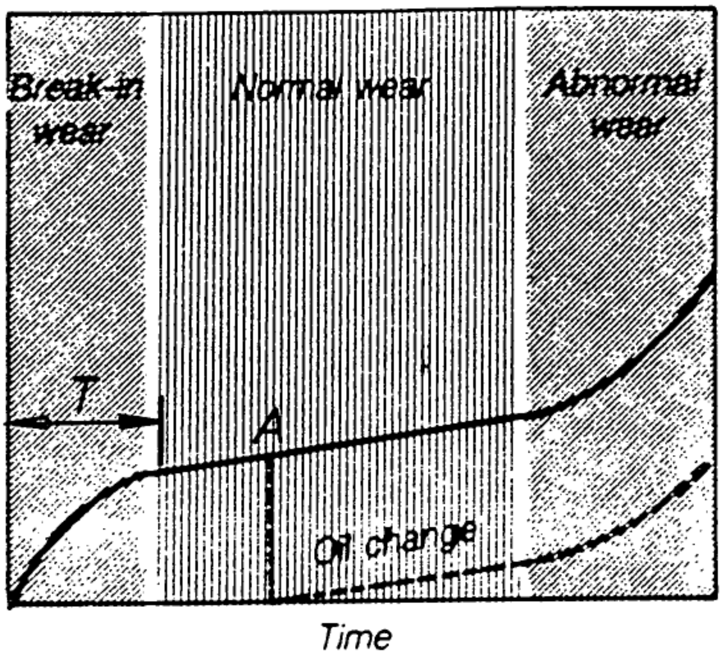


Fig. 6.4 Change in average particle concentration due to effect of an oil change.

In this case the particle concentration is approximately zero in the new clean oil and rises to equilibrium in time 'T'. An oil sample collected for analysis <u>within</u> time 'T' would not be representative of the oil body condition after equilibrium.

When the machine begins to wear out the particle concentration in the oil sample increases because the rate of wear particle generation increases above the rate of particle removal. It is this reasonably sudden and drastic increase in particle concentration and particle size that has to be detected by wear debris analysis to give sufficient early warning of impending machine failure.

6.1.2 Samples from reservoir drain valve.

Samples taken from the reservoir will only be useful for wear debris analysis and trending if they are taken from the oil body. Samples taken from the reservoir drain valve will not give a representative sample as there will be a natural tendency for particles to accumulate at the bottom of the reservoir under the influence of gravity. The particles settled on the bottom of the reservoir will tend to accumulate in drains and lines and any samples taken from these lines will have a high proportion of wear particles (See fig. 6.5).

Figure 6.5(a) shows the natural build-up of particles at the bottom of the reservoir and how some of these particles can build-up in the pipe stub connecting the valve to the reservoir. Figure 6.5(b) shows one way to reduce the influence of this sediment on the sample taken from the bottom of the reservoir. The stand-pipe extends above the layer of settled material at the bottom of the reservoir and prevents this material being carried over into the sample.

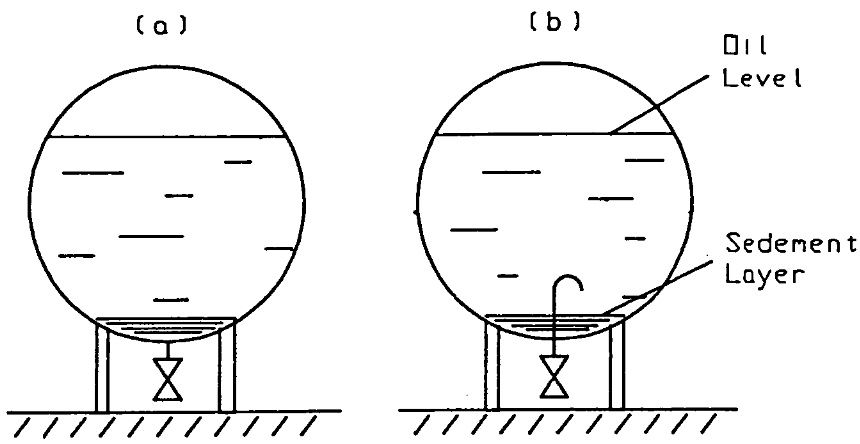


Fig. 6.5 Effect of sediment on readings taken from the bottom of a reservoir.

The hooked end of the stand-pipe prevents particles settling in the connection between the reservoir and the valve and thus any samples taken are representative of solids suspended in the oil and do not contain carry-over that had already settled out from the lubricant. It is necessary for this stand-pipe to be tall enough to extend well above the sediment layer while always remaining covered in oil. These requirements can reduce the suitability of this point as a drain by leaving an excessive amount of oil in the reservoir after draining. For this reason the stand-pipe cannot be used as a drain.

6.1.3 Samples from reservoir filler neck.

Samples taken through the normal filler neck of the reservoir are generally to be preferred when it is desired to get a sample representative of the system as a whole. In most applications it is possible to collect a sample of the lubricant when the machine is running. This generally gives the best sample as it ensures that the particles in the lubricant have not begun to settle out. By taking the oil sample when the machine is running, it is possible to get a sample that represents the oil body provided system equilibrium has been reached. It also has the advantage that the machine does not have to be stopped to obtain the sample.

In some lubricating or hydraulic systems the reservoir is sealed to allow pressurization or partial de-pressurization and this can make it impossible to obtain a sample from the reservoir while the machine is running. To overcome this problem it is necessary to stop the machine and take the sample in a sufficiently short period of time to ensure that the wear particles have not settled out of the lubricant at the sampling point to any appreciable extent. The time available to collect a representative sample after stopping the machine depends on several factors. Some of these influencing factors are listed here :

(i) Viscosity of oil (High viscosity oil will increase settling times).

(ii) Size of particle (Larger particles will settle fastest).

(iii) Shape of particle (Spherical particles will settle faster than irregular particles).

(iv) Particle density (Heavy particles will settle quickly).

(v) Strength of convective currents present. Particles can be held higher in the tank due to up-currents in the oil. These convective currents are set up by the fact that the lubricant is generally hotter than ambient.

(vi) The presence of a gel coating on the particle. This gel coating is created by the oil and has a density similar to that of the oil. This effectively reduces the density of the particle/gel volume falling in the oil.

Figure 6.6 shows a graph indicating the sinking rate of particles of various size [1]. This graph is based on calculations using Stokes Law and ignores the effect of convective currents on the settling times of small particles. For this reason this diagram will tend to underestimate the settling time for small particles (e.g. particles < 5 microns). This graph shows the settling rates of spherical particles in oil of 5 centistoke viscosity and at a temperature of 210^{o}F. The oil specific gravity = 0.90 (This graph was taken from a reference paper by Mr. Alan Beerbower of ESSO Research laboratories).

Figure 6.6 can be useful as a general guide however, but it must be appreciated that as larger particles are indicative of severe wear in a machine (i.e. > 50 microns), the time to obtain a representative sample is quite short.

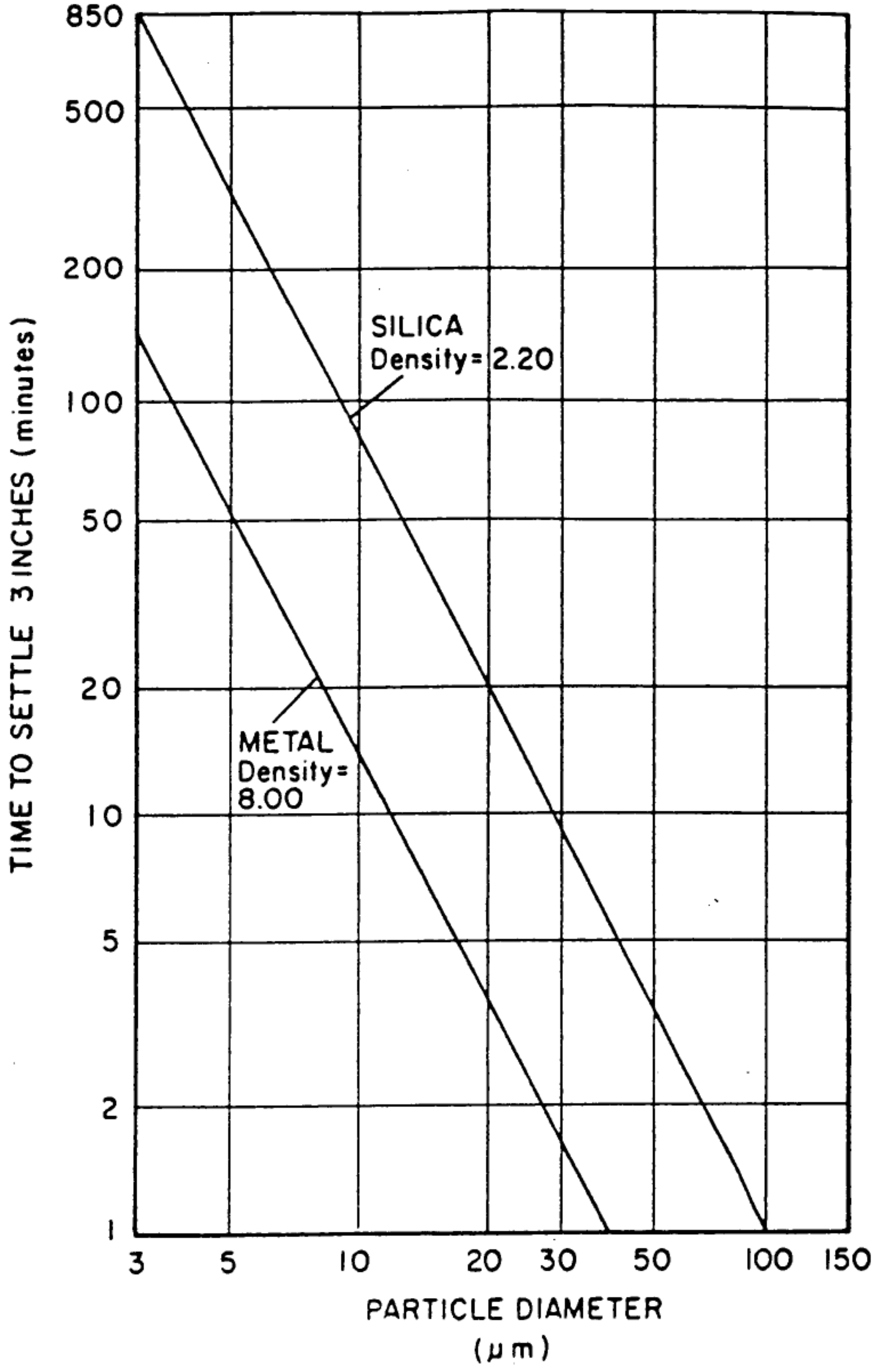


Fig. 6.6 Settling times for a range of particle sizes.

6.1.4 Samples taken at or before the filter.

As previously mentioned the oil analysis program used on the A.P.P.M. Turbine used samples taken from the lubricating oil filter and at the governing oil filter. Examination of these sampling sites indicates that there are two main problems associated with this sampling technique.

Firstly, the samples were taken just before the filter element and therefore will tend to have a higher than average number of large particles in the sample. This is because large particles generated in the system are stopped by the filter resulting in an increase in particle concentration at this point.

Secondly, as seen in figure 6.7, the drain (8) from which the sample was obtained is situated at the lowest point on the oil filter housing and therefore will have a higher than average proportion of particles. These particles accumulate at this point and settle on the bottom of the filter housing. Some of these particles can be swept into the sample bottle even if the customary two times the oil volume is flushed from the drain line before the sample is taken.

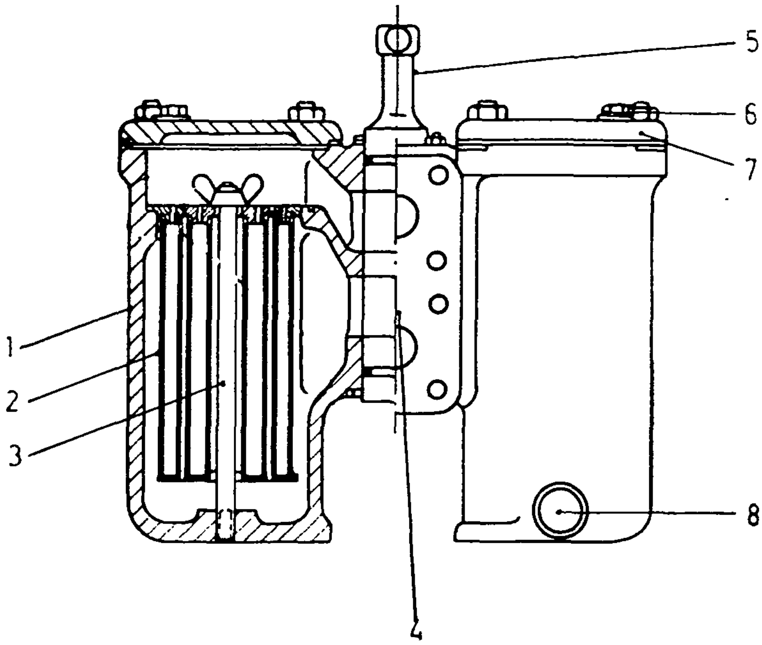


Fig. 6.7 Duplex Oil Filter system (See Appendix 2 for KEY to this figure).

6.1.5 <u>Samples taken after the oil filter</u>.

A sample taken after the oil filter is not representative of the oil body because both the total particle concentration in the sample, and the particle size distribution has been altered by the filter. The particle concentration after the filter depends on the filtering efficiency of the filter in the system and it is important to realize that this efficiency varies with particle size. Figure 6.8 shows filtration curves for typical filters and from these it is clear that the filtration efficiency is particle size dependent.

The value of Beta in figure 6.8 is defined as :

$$\text{Beta} = \frac{\text{No. of particles > 'X' microns before the filter.}}{\text{No. of particles > 'X' microns after the filter.}}$$

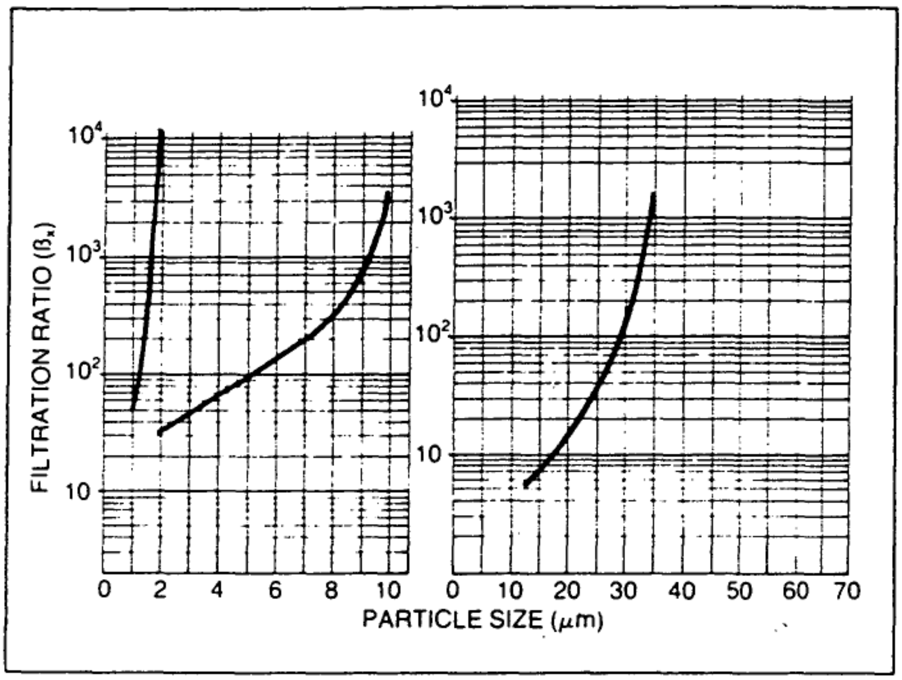


Fig. 6.8 Graph of Beta Vs. Particle size from Pall oil filter catalogue.

The higher the Beta value, the more particles are trapped by the filter.

The removal efficiency of the filter can be calculated using the Beta value.

$$\text{Removal efficiency} = \frac{(\text{Beta} - 1)}{\text{Beta}} \times 100\%$$

From this it can be seen that the removal efficiency of the filter greatly influences the particle concentration in any oil sample taken after the filter.

Referring again to figure 6.8 it is clear that the Beta value increases with increasing particle size. This means that a filter having a particular pore size will remove large particles more efficiently than small particles. Thus an oil sample taken after the filter will have a disproportionate number of small particles and larger particles will be under-represented in the sample. While this is intuitive and desirable when designing filters it is undesirable when sampling a lubricant for wear debris analysis.

Figure 6.9 shows the increase in particle size and concentration through the life of the machine from mild wear through to possible catastrophic failure. Because the filter removes the large particles more efficiently than smaller particles the increase in large particles can be missed if the sample is taken after the filter.

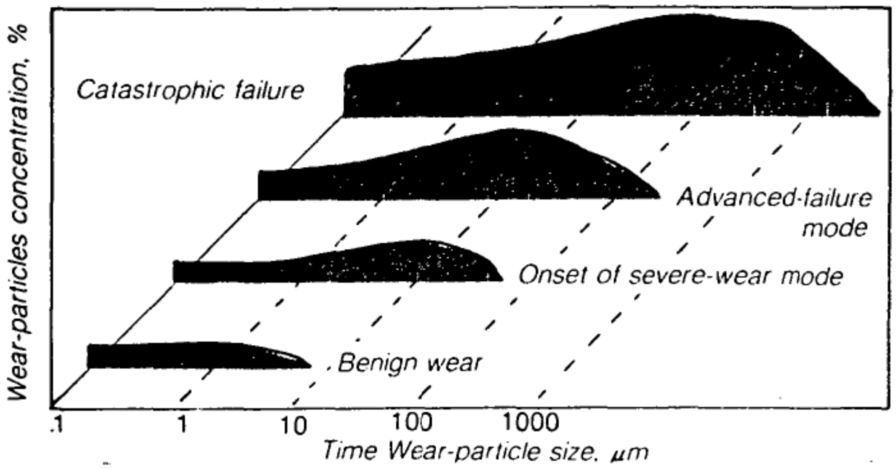


Fig. 6.9 Change in particle size and concentration with time.

6.1.6 Samples from drains on pumps and lines.

As for the samples collected at reservoir drains, samples collected from bleeds or drains on pumps suffer from an accumulation of particles at the necessarily low points at which these drains are located. For this reason it is advisable not to take samples from these points.

6.1.7 Modified Wear Debris Analysis technique.

Future wear debris monitoring of the turbine oil at Wesley Vale will be based on the following parameters :

(i) A single oil sample will be collected from the reservoir filler cap after the machine has been running at normal load for several hours. These samples will be taken at two-monthly intervals initially, however this sampling interval may be modified as more experience is gained.

(ii) Initially the six-monthly oil sample presently sent to Shell will be continued. However a single sample taken from the reservoir, under standard conditions, will be used instead of the two samples taken from the filter housings as in previous cases. Information on water content, viscosity, T.A.N., etc. is more easily determined by a well set up testing laboratory. In future these tests may also be undertaken at Wesley Vale.

(iii) <u>Different oil analysis techniques</u> will be investigated to determine their usefulness for C.M. and to determine their suitability for in-house Oil analysis at Wesley Vale. The effective range of some of the more common oil analysis techniques are shown in figure 6.10.

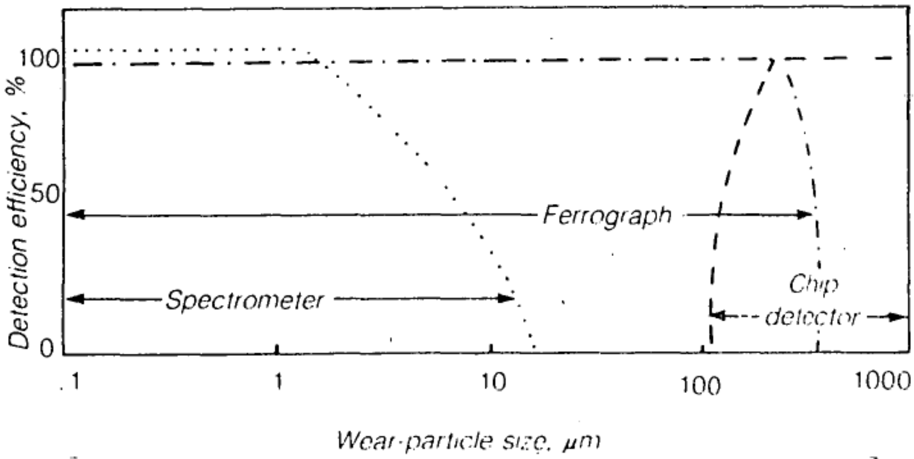


Fig. 6.10 Effective detection ranges for some common oil analysis techniques.

6.2 Turbine Vibration Monitoring.

As outlined in Section 6.0 the vibration monitoring program set up to monitor the Stal-Laval steam turbine at A.P.P.M. consists of :

(i) Vibration analysis using an accelerometer.

This involves taking both horizontal and vertical vibration readings on the turbine casing at specific points along the machine in the plane of each journal bearing and at the exciter outrigger bearing. In addition, two measurements are taken in the axial direction at each end of the turbine. Each measurement point is fitted with a vibration stud identical to those used on machines elsewhere in the mill (See Appendix 1).

The general layout of the turbine is shown in Appendix 2 and consists of a central steam chest with contra-rotating alternators, one at each end. One of the alternators has an exciter mounted on the non-drive end. Axial thrust is taken by a tilting pad bearing at the non-drive end of each rotor and forms part of the non-drive end journal bearing assembly.

(ii) Vibration analysis using proximity probes.

Two proximity probes were set up on each journal bearing to measure the relative motion between the rotor shaft and the journal bearing housing of the machine. These probes are positioned at 90° to each other and the data from both probes can be combined using specialised software to generate orbital plots at each journal. This software can also combine the data from several journals to calculate the dominant vibration mode. One such software package has been designed by Tensor Systems and it is envisaged that the data collected will be analysed by the consultant using this software, there being no intention to purchase this advanced software in the immediate future.

This form of analysis can be used to detect cracked shafts, imbalance, shaft rubs, and misalignment much more accurately than a casing mounted accelerometer measuring absolute vibration on journal bearing machines. This is partly due to the fact that journal bearing machines have a much thicker oil film (3 - 10 micron) compared to rolling element bearings (0.1 - 1.5 micron) during operation and this greater film thickness results in greater damping of the vibration. This, combined with the reduced vibration transmission in a journal bearing, compared to a rolling element bearing, results in a reduced ability to detect rotating faults with casing mounted accelerometers. Proximity probes located close to the shaft and measuring relative displacement between the journal and the bearing give a much better indication of journal bearing machine faults.

The proximity probes used on the A.P.P.M. turbine are Eddy current probes made by Karman Measuring Systems of the U.S.A., Model KD-2400. Ten probes are fitted to the turbine including two axial probes, and have a claimed 10 kHz frequency response and 10 microinch resolution. Technical sheets for these probes are included in Appendix 3.

In addition to the probes, a signal conditioning module is used to provide an analog signal from the probe that is proportional to displacement. Calibration of the signal conditioning module was carried out by adjusting the sensitivity control on the module to achieve a linear variation with changes in the gap between a steel test piece and a probe. This relationship was plotted to show the slope of the line and is shown in figure 6.11.

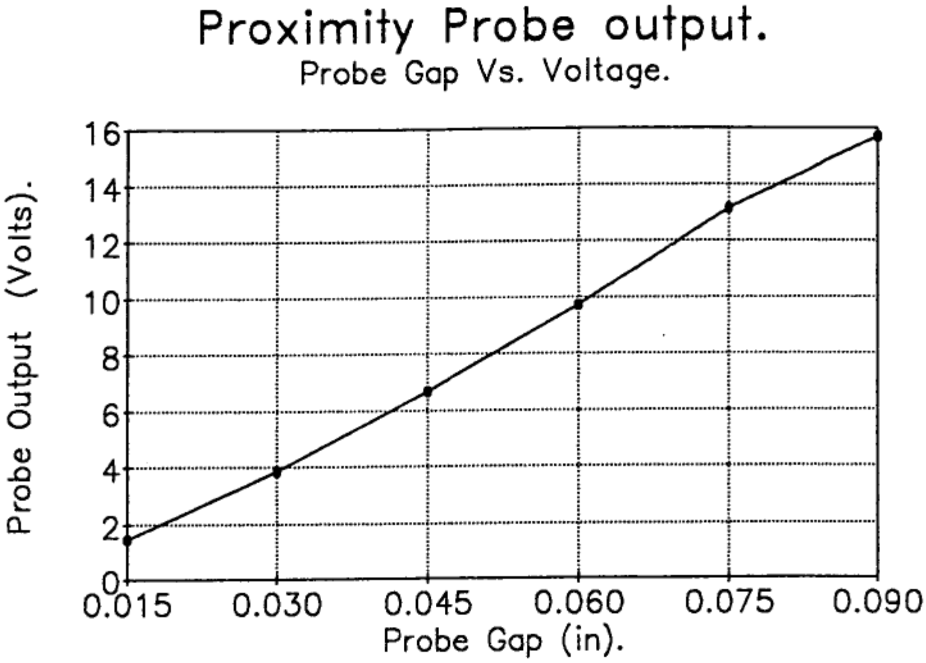


Fig. 6.11. Calibration graph for Signal Conditioning Module.

From this graph the installed probe gap was selected to be 0.060" and was set with the use of feeler gauges. When more experience has been gained with this system it may be necessary to adjust this gap setting or to increase the accuracy of setting.

The proximity probes require a power supply in the range of 12V - 24V with minimum ripple and a repeatability such that recordings taken at different times are not affected by slight variations in power supply voltage. The necessary power supply for this system was made up by the instrument shop at the mill and was built to the following specifications :

- Voltage supply 19V to two decimal places.
- Supply ripple < 1mV.

Bench tests on this power supply indicate that it can perform satisfactorily and its simplicity makes operating it in the field very easy (See figure 6.12). Just prior to taking each reading the output voltage from the power supply is checked to ensure that it has not drifted from the 19V set point and is re-adjusted if necessary.

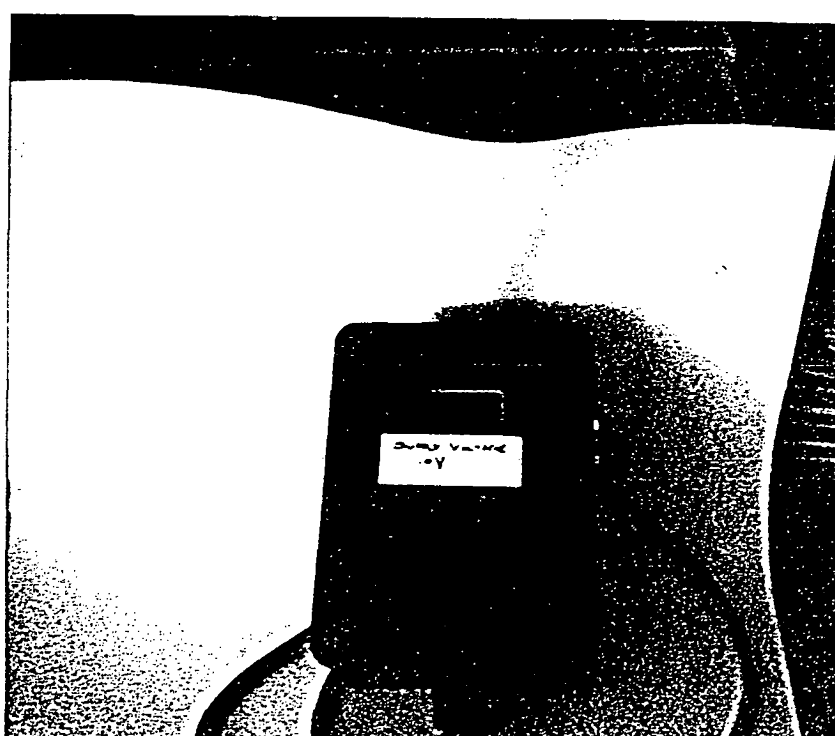


Fig. 6.12 Power supply unit for proximity probes used on Turbine.

Routine vibration monitoring is carried out on the turbine once every second month using this equipment and the CSI 2110 analyser and the data is trended in the normal manner. All readings are taken with the turbine loaded to 3.2MW in an attempt to standardise the monitoring conditions.

6.2.1 Turbine Balancing.

Some of the first vibration measurements taken of the turbine using a casing mounted accelerometer indicated a very high one-order vibration consistent with imbalance (See figure 6.13). These high vibration levels could eventually result in damage to the adjacent journal bearing and would have to be reduced to ensure the continued reliability of the turbine.

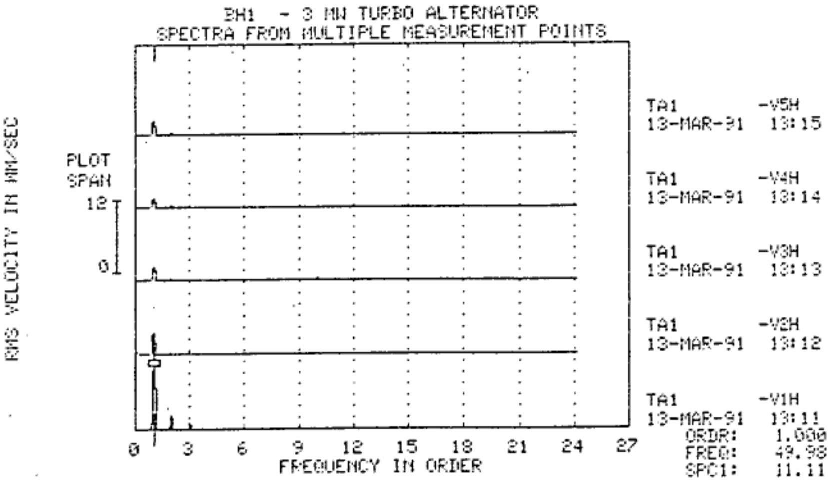


Fig. 6.13 Plot of horizontal vibration levels along the turbine showing the very high one-order vibration at the exciter end.

The position of each of the measuring points is shown in the drawing of the turbine in figure 6.14. The fact that demand on the turbine was expected to increase over the following twelve months made it all the more important to reduce the imbalance.

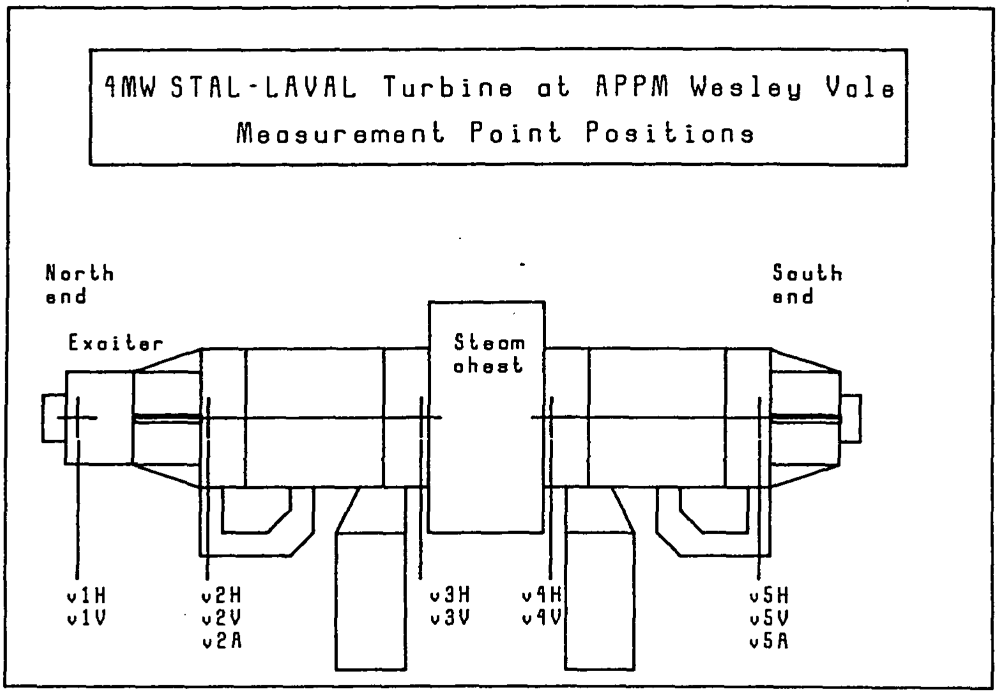


Fig. 6.14 Drawing of turbine showing the location of each measuring point.

The highest vibration readings were found at the outboard end of the exciter in the horizontal direction and consistently exceeded 14 mm/s. The design of this machine is such that any imbalance in the rotating assembly will lead to high casing movement due to the canterlever nature of the exciter mounting and the tall, spindly nature of the structure (See layout of turbine in Appendix 2).

The turbine rotating assembly can be considered as four identifiable components any one of which could be the cause of the imbalance.

(i) The exciter mounted on the non-drive-end (NDE) of the northern rotor.

(ii) The northern rotor.

(iii) The Steam Chest.

(iv) The southern rotor.

Because the exciter displayed the highest vibration levels it was logical (and easier due to restricted access to the machine) to consider this first. Any work done on the exciter would be aimed at achieving either :

(i) Improve (ie. reduce) the vibration level.

(ii) Eliminate the exciter as the source of the imbalance.

The first step was to check the existing exciter for alignment and to check the outboard bush for wear. After inspection both the alignment and the bush were found to be within specifications so it was decided to replace the exciter with the spare unit that had been overhauled in the workshop and balanced on A.P.M.'S soft bed roll balancing machine. Careful installation and alignment was carried out and the clearance in the outboard bush checked. On startup no noticeable improvement could be detected in vibration levels and it was considered that the exciter could be ruled out as the source of the imbalance.

After the machine had continued in service with the replacement exciter for some time however doubts were raised about the suitability of the roll balancer for balancing something as small as this exciter. Considering the exciter weighed less than 100 kg. and the rolls balanced in this machine can weigh in excess of 3000 kg. it was likely that the quality of the balance job using this machine would be less than required for an exciter running at 3000 R.P.M. To eliminate these doubts the exciter that had been removed was sent to Paul England Pty. Ltd. in Essendon in Victoria to check the existing balance and to improve it if necessary.

On testing the exciter the balance was found to be poor and not equal on each of the two correction planes. The exciter was re-balanced to reduce the overall values and to give the same readings on each of the correction planes.

The readings before and after the balancing job by Paul England were :

Before balancing -

- Fan end 1510 g/mil.
- Commutator end 1280 g/mil.

After balancing -

- Fan end 100 g/mil.
- Commutator end 100 g/mil.

When this exciter was returned to the Mill it was installed at the next opportunity and considerable attention given to alignment and setup. On starting the turbine, no significant reduction in imbalance was seen. This for all practical purposes eliminated the exciter as the source of the imbalance and further work on the turbine rotors and steam chest would be required to reduce the high vibration levels.

Consultations held with Tensor Systems led to the decision to trim balance the turbine to within the G 2.5 standard (using the proximity probes previously installed for vibration monitoring) at the first opportunity (See the table of balance grades in Appendix 2). Approximately three to four days would be required for the balancing to run the turbine up to speed, take the necessary readings, shut the turbine and fit the correcting weights. This would have to be repeated several times to get the best results and uninterrupted access to the turbine would be necessary. As access to the turbine for any maintenance was severely restricted it would be necessary to wait for a paper machine shutdown that extended into at least three days. The only likelihood of this occurring was if market forces dictated a reduction in production levels and this was considered unlikely at that time.

Startup after the Christmas break '90 gave rise to a situation that made access to the machine possible. When the Mill was shutdown over Christmas moisture had damaged the turbine windings causing an electrical failure on startup that necessitated stripping the turbine to repair the field windings. Once it was realised that the turbine rotors would be available for about four days it was decided to check, and if possible, improve the rotor balance during this time.

By January 4th the rotors were removed from the turbine and the consultant from Tensor Systems had arrived on site to carry out the balancing using A.P.P.M.'s roll balancer. As the rotors were several tonnes in weight they approximated the rolls normally balanced in this machine both in weight and configuration (See figure 6.15).

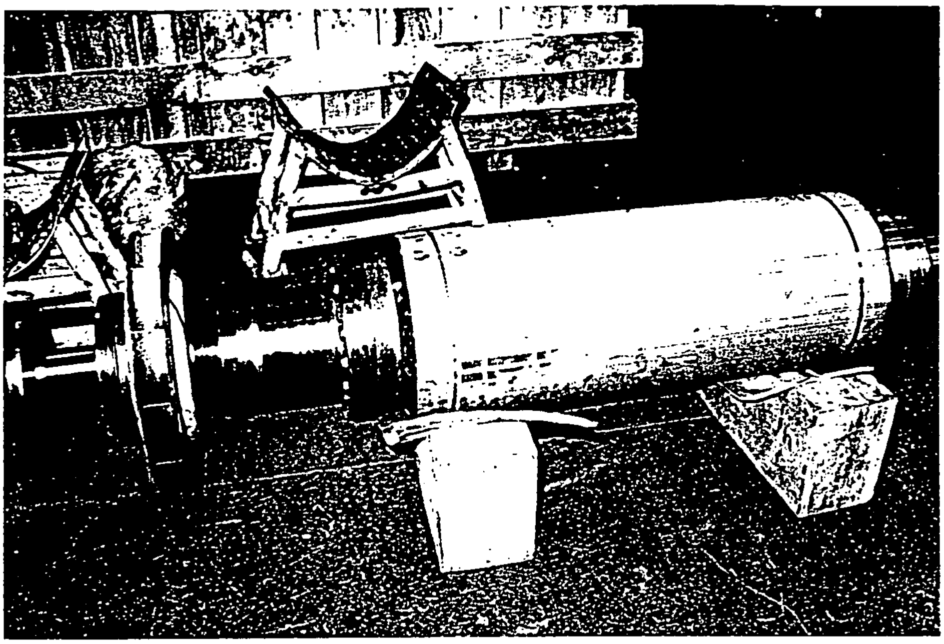


Fig. 6.15 One of the rotors checked and balanced.

Setting up the rotors in the balancing machine involved some minor modifications to the roller support plates before the first balancing runs could be made. Because the balancing machine did not have self aligning rollers, and because the journal size on the rotor did not suit the roller size, it was impossible to run the rotors on their journal bearing surfaces when carrying out the balancing. It was suggested by the consultant that it may be possible to run the rotors on the machined surfaces adjacent to the journals provided displacement readings were taken at the journal surfaces. Due to eccentricity between the machined surfaces of the rotors and the journals it was impossible to balance the rotors over the machined surfaces only. Because the balancing machine was a soft bed design, the readings at the journals would be zero when the rotor was balanced irrespective of any movement at the support rollers [10]. Based on this premise the balancing trials got underway.

The <u>south rotor</u> was tested and gave the following readings [10] when adjusted to running speed :

Hot end - 2.44 mm/s 0-Peak at 3000 R.P.M.

Cold end - 4.88 mm/s 0-Peak at 3000 R.P.M.

While the hot end of the rotor (ie. the steam chest end) was within specifications (ie. < G 2.5) the cold end was almost twice the recommended value. As the south end of the turbine was not showing significantly high vibration readings in operation compared to the north end it was decided to leave this rotor until the north rotor had been checked. As time ran short towards the end of the job this rotor was not worked on again and was reassembled with the above values unchanged.

The north rotor was tested and gave the following readings [10] when adjusted to running speed :

Hot end - 2.97 mm/s 0-Peak at 3000 R.P.M.

Cold end - 11.67 mm/s 0-Peak at 3000 R.P.M.

The hot end of the north rotor was only slightly above the G2.5 specification and would probably have been left as it was, however the cold end was approximately four times the recommended standard. This rotor was concentrated on as the measured imbalance was high at the cold end which coincided with the mounting flange of the exciter. As this was the end of the machine that gave the very high one-order vibration readings in operation it was evident that this cold end imbalance was the major source of the high readings at the exciter.

Because of the importance of good alignment between the exciter and the cold end of the rotor it was decided to check the mounting faces of the attachment flanges for flatness and squareness with the rotor centreline. While these faces proved to be fairly square with the centreline there was a hollow between two of the attachment bolts requiring slight machining of the faces to ensure a good fit on assembly. After machining it was possible to fit the exciter to the rotor to better than 0.003" peak-peak.

Considerable difficulty was experienced in getting repeatable readings while performing the balancing runs and several attempts were made using accelerometers and displacement probes (SCAPA gauge) in various arrangements before two proximity probes were set up using the power supply described in Section 6.2, fig. 6.12 and the CSI 2110 data analyzer. The proximity probes gave good results despite the unknown permeability errors inherent in their use on a steel journal.

From the data collected with the proximity probes, a final correction weight was calculated for each of the two balance planes on the north rotor. These weights were added to the existing weight present in the balance holes and an equivalent lead weight cast up for each plane. Pressure from the turbine assembly crew, who were waiting to assemble the north rotor, prevented a proof run to double check the accuracy of these weight calculations and the rotor was handed over for installation.

After installation and startup it was quickly apparent that there was a noticeable reduction in vibration levels even without taking vibration readings. In the past the vibration was very noticeable through the steel plate floor around the turbine and this had been noticeably reduced. Vibration readings taken with the casing mounted accelerometer (as previously used) indicated a significant reduction particularly in the plane of the exciter outboard end in the vertical direction.

Figure 6.16 shows the velocity spectrum of the exciter after balancing (25 Jan. '91) in the horizontal direction and indicates a reduction in the one-order amplitude compared to earlier readings. Noticeable also is a reduction in the second and third order peaks compared to earlier readings.

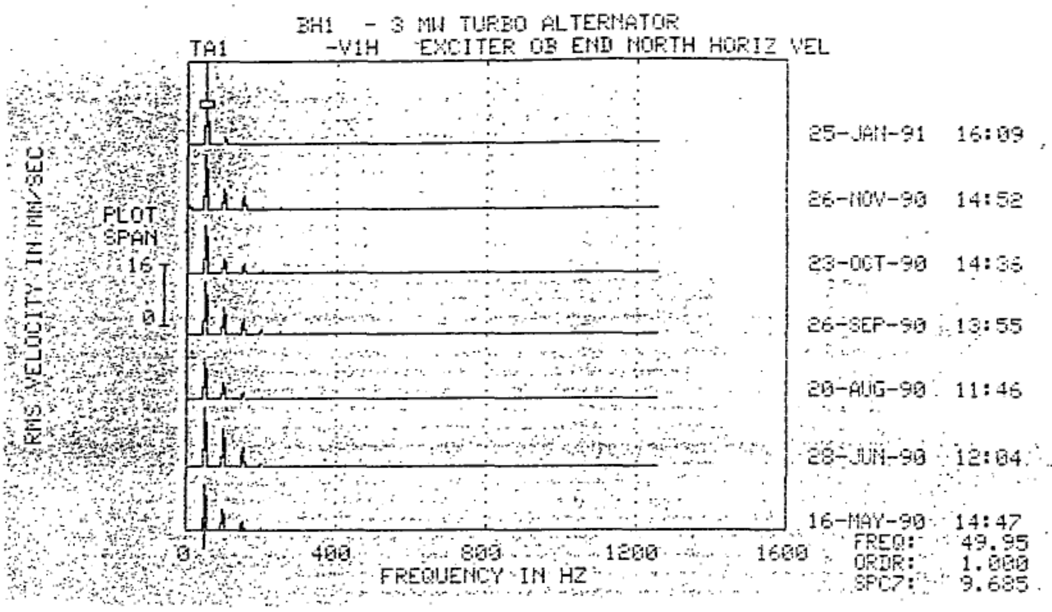


Fig. 6.16 Velocity spectra over time showing reduced one-order horizontal peak after balancing.

A similar plot is shown in figure 6.17 for the exciter in the vertical direction and shows a noticeable reduction in one-order amplitude compared to previous measurements.

Trend plots for each of the measurement points are shown in Appendix 2 and clearly indicate a reduction in one-order vibration levels for the northern end of the turbine particularly in the vertical direction. As would be expected there is little or no change at the south end of the turbine there having been no change made to the balance quality of the south rotor.

Future work will involve trim balancing of the rotating assembly as originally intended and a further significant improvement can be expected from this. Reducing the imbalance of this turbine is not likely to show any improvement in performance but if it contributes to improved reliability it will more than pay for the work involved.

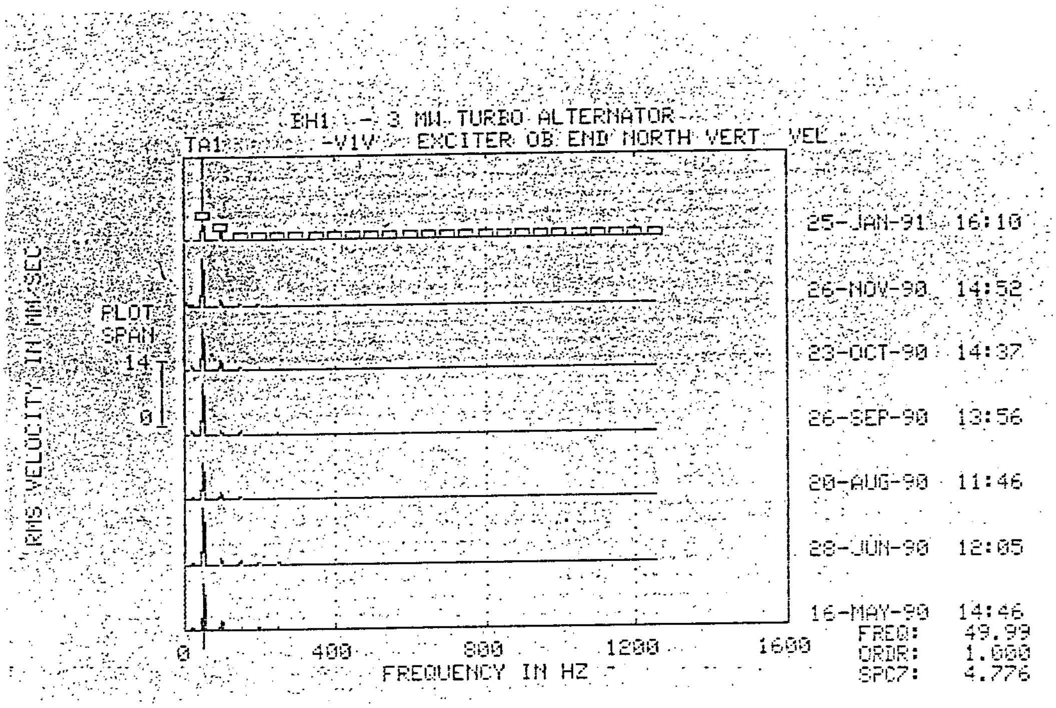


Fig. 6.17 Velocity spectra over time showing reduced one-order vertical peak after balancing.

7.0 Vibration Monitoring Results and Follow-up.

Since first gaining access to vibration monitoring equipment at Wesley Vale it has been possible to detect faults in machine bearings, alignment, balance, etc. The success rate of this monitoring has improved markedly as more experience has been gained and as the support procedures have been put in place. Increased acceptance by the maintenance staff has led to regular requests for vibration tests to be performed as an aid in diagnosing developing faults. Typical of these requests are :

- Vibration checks on paper machine roll bearings.
- Checks on electric motors due to high noise levels.
- Vibration tests on gearboxes due to roughness or noise.
- Test on disk refiners because of high vibration levels which are usually due to imbalance of the refiner plates.

These and similar tests are in addition to the regular vibration monitoring carried out to schedules like the one in Appendix 1 for the Pulp Mill and Services area of the mill. The ability to carry out spot vibration tests like this is one of the greatest advantages that in-house monitoring has over monitoring by a consultant. Having the equipment and expertise available at short notice allows a machine to be run longer than would be the case if one were relying on readings taken every two or three months. In the last six months or so it has become quite common for decisions on when to strip a machine to be based largely on how the machine vibration signature has changed over the last few days or hours.

Scheduled maintenance planning now includes the need to attend to faults detected by the vibration monitoring program and giving feedback to the area Engineer overseeing the vibration monitoring program. A photographic record is kept of the bearing damage detected by the vibration monitoring equipment to allow the operators of the program to develop a 'feel' for how sensitive the equipment is to defects.

One of the modules available with the Mastertrend software package used to store and trend vibration survey data is called COMPILE and is used to generate standardised reports and to maintain a history of each drive. This allows historical data for each drive to be used to identify repeated failures and to generate a cost analysis based on parts and labor costs for repairing each machine. At this time all reports generated from vibration surveys are processed using COMPILE in a bid to get as much information as possible into the historical record. As more and more work is done with the vibration monitoring program at Wesley Vale increased experience and historical data will enable the system to be refined further.

7.1 <u>Training for Fitters in Data Collecting</u>.

Once the vibration monitoring program was up and running attention was turned to training the maintenance fitters to collect the vibration data in their area. This has the advantage of making them part of the vibration monitoring program and not just users of the information generated by the program. An additional benefit has been that it frees up a substantial amount of the area Engineer's time for more productive work such as diagnosis and system maintenance.

It is a fact that when a vibration monitoring program is set up properly the actual data collecting can be carried out by anyone with only a limited amount of training. This means that data collecting can be carried out by apprentices or trades assistants (T/A's) and does not require a fitter or

Engineer who could be more gainfully employed. It will be necessary for engineering support to be available to assist in setting up new machines and to diagnose problems indicated by the spectra.

The aims of the training program at Wesley Vale were :

(i) To make all maintenance personnel familiar with the vibration monitoring program, in particular :

- program philosophy.
- program aims.
- program limitations.
- hardware.
- software.
- data collecting techniques.
- use of equipment for diagnosis.
- use of equipment for acceptance testing.

(ii) To include the maintenance staff in the program in a practical and meaningful way. This ensures the cooperation of the maintenance staff in maintaining and replacing the vibration studs on the machines as required (See Appendix 1). This also ensures prompt follow-up on fault reports generated by the vibration monitoring program.

(iii) To develop in the maintenance staff and supervisors an appreciation of Predictive Maintenance and to point out the advantages of this approach to maintenance over Preventative Maintenance and/or Breakdown Maintenance.

Since the very first months of use of the vibration monitoring equipment at the mill the mechanical fitters in the Pulp Mill and Services group have had close involvement in the vibration monitoring program. This has allowed them the opportunity to be involved in the setting up phase such as fitting the studs to the machines and to see the credibility increase as more experience was gained. This early involvement has made the introduction of data collecting by the group members much easier to implement.

Before the training scheme got underway a number of requests had been received from group members for more information on the vibration monitoring program and at least one request for training in using the equipment if the opportunity arose.

The first steps in setting up this training program were taken in February 1990 with agreement being reached between the two area engineers (the writer and the Coater and Finishing area Engineer) involved in the vibration monitoring program to standardise the training approach in each of the areas involved. The first step was to produce a booklet that would be given to each fitter put through the training sessions as a reference for future use and as a means of passing on additional useful information to each participant.

In the first instance all members of the maintenance group would be put through the training program as this would allow any one of the group to conduct a survey. In practice however it was expected that not everyone would be interested in taking these readings on a regular basis and that some would show more liking for the job than others. Where possible it was intended to make use of this greater enthusiasm by having these people carry out the bulk of the readings.

While everyone in the group would be trained in taking the vibration readings the quality of the data collected would be more easily maintained by having a limited number of people collecting the data. For this reason great importance was placed on collecting good data and follow-up checks would have to be made by the area Engineer's until such time as sufficient confidence had developed in the data being collected by the maintenance personnel.

The training program was designed to get all the maintenance personnel to the stage of being able to carry out the following steps :

(i) Switch on the host computer and access the CSI Mastertrend software package.

(ii) Select the appropriate database.

(iii) Check the data analyser battery and cables.

(iv) Charge the battery.

(v) Download the routes to be measured to the analyser.

(vi) Take the vibration measurements from the machines on the route. Use the notepad feature to record any related information on the analyser (e.g. leaks, loose structures, damaged guards, etc.).

(vii) Download the collected data from the analyser to the host computer.

(viii) Print the exception report for the measured route.

The exception report is then given to the area Engineer for analysis and fault identification. It is intended that the maintenance staff member who collected the data would be involved in at least part of this analysis stage. It is not intended to train the maintenance personnel to the stage of being able to interpret the vibration spectra at this time as it is considered to be both outside their area of expertise and not the best use of their time.

In time, as Expert System diagnostic aids are developed by the software manufacturer it may be possible to have the maintenance personnel take over an increasing role in this analysis stage.

7.2 Some Case Studies from the V.M. program.

The discussion in Chapter 6, Section 6.2 on vibration monitoring of the steam turbine included details on a specific imbalance problem encountered with this machine and how vibration monitoring figured in this case. Many other examples exist from the monitoring program that involved detection of a fault and follow up repairs. Some of these cases are discussed here.

(i) Filtered Water Pump - This large, double suction pump showed a large number of one-order harmonics at the drive end (DE) bearing cap from the very first vibration reading taken of this machine (See fig. 7.1). When the pump was dismantled it was found that one of the sealing rings was incorrectly fitted and was rubbing against the impeller. The pump was otherwise in good condition and on reassembly the harmonics were no longer evident.

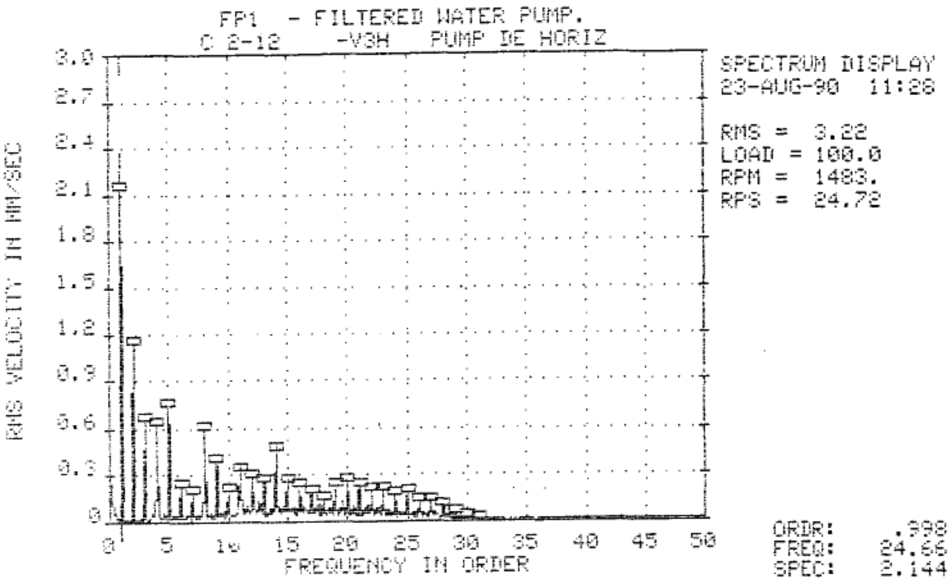


Fig. 7.1. Filtered water pump DE bearing spectra showing harmonics due to rubbing sealing ring.

(ii) <u>Retention Tank Extraction Pump</u> - This double suction pump began to display an increasing number of harmonics and a raised energy level (See fig. 7.2) over time. Despite this, the velocity readings were quite low.

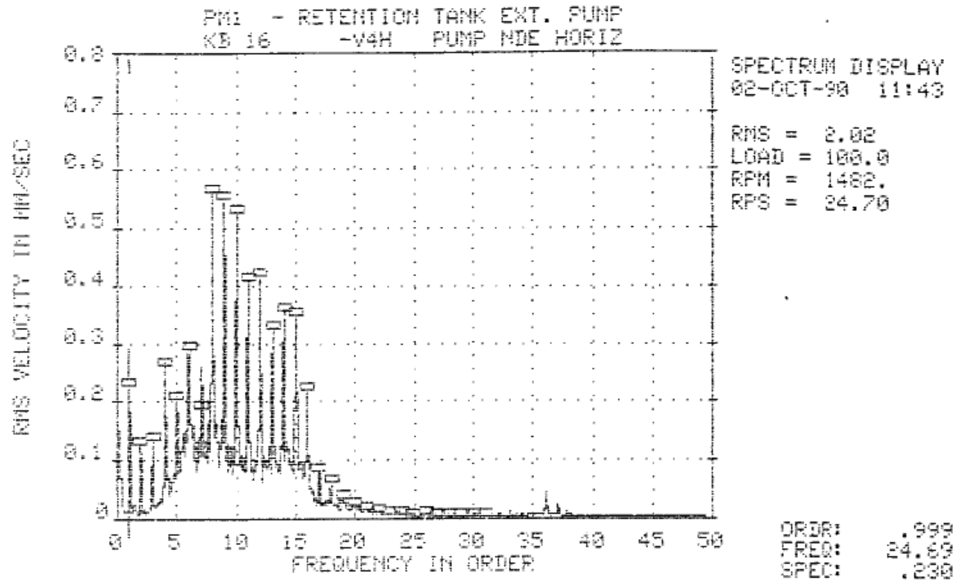


Fig. 7.2. Retention tank pump NDE bearing showing looseness.

The time waveform was quite random and showed no impulsiveness or repeatability indicating that the problem was looseness in the bearing or the mounting (See fig. 7.3).

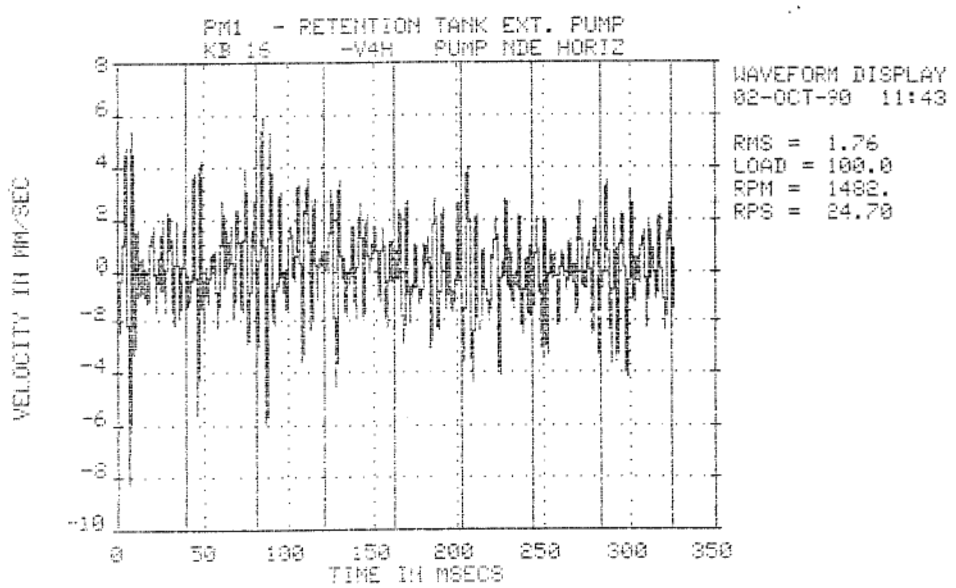


Fig. 7.3. Time waveform for the bearing shown in figure 7.2.

When the pump bearing was removed at a subsequent overhaul it was found to be quite loose on the shaft. The shaft was replaced and the pump rebuilt with new bearings eliminating this problem.

(iii) Centricleaner Feed Pump - This pump is similar to the one discussed in (ii) above but displayed a strong second-order vibration and one-order harmonics in the DE bearing of the pump. The second-order peak was over twice that of the one-order peak as shown in figure 7.4. Examination of

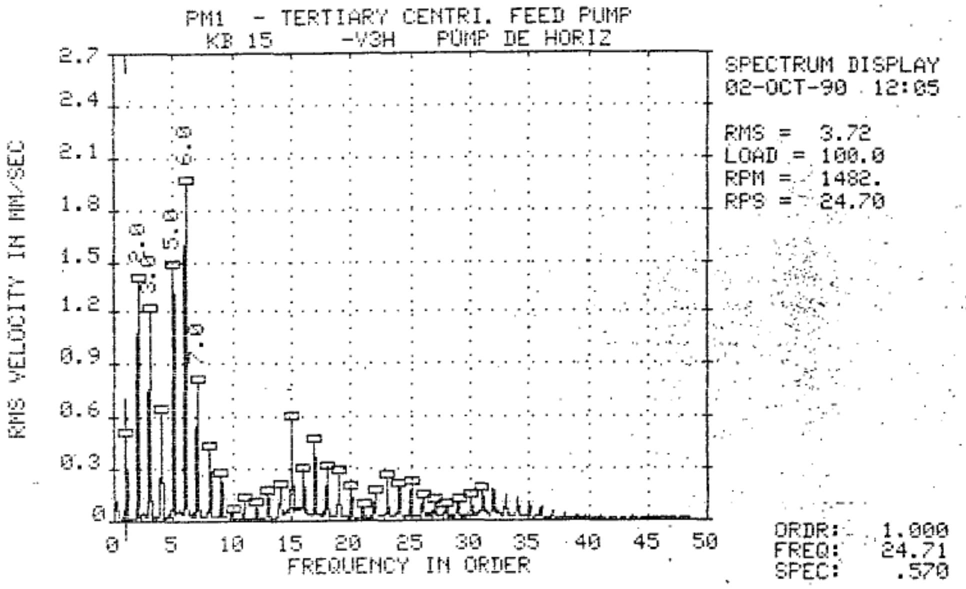


Fig. 7.4. Spectra of DE bearing of Centricleaner feed pump.

the time waveform showed a strong repeatable signal that, when taken with the spectra, indicated a misalignment problem (See fig. 7.5).

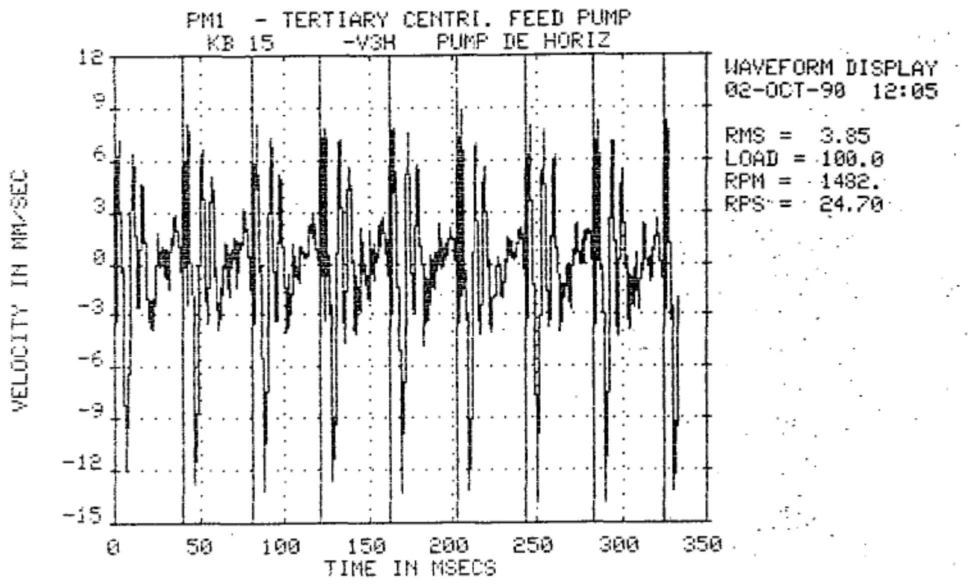


Fig. 7.5. Time waveform for DE bearing.

The alignment of the motor/pump assembly was checked and the motor found to be considerably lower than the pump centreline. Realignment reduced the spectra in figure 7.4 to negligible levels.

(iv) Wire Press Shredder - Two wire presses are operated in the Pulp Mill, one on continuous duty in the Semi. Chemical (S.C.) pulp line and the other on intermittent duty in the Refined Wood (R.W.) line. Both presses are slow moving except for the Shredder rolls that are used to break up the pulp cake as it comes off the presses. This Shredder roll runs at approximately 950 R.P.M. and has 16 rows of pegs along its length to aid in breaking up the pulp cake.

A minor bearing fault became evident in the R.W. press Shredder NDE bearing in January 1991 (see fig. 7.6) with a similar fault being indicated in the S.C. press Shredder towards the end of February.

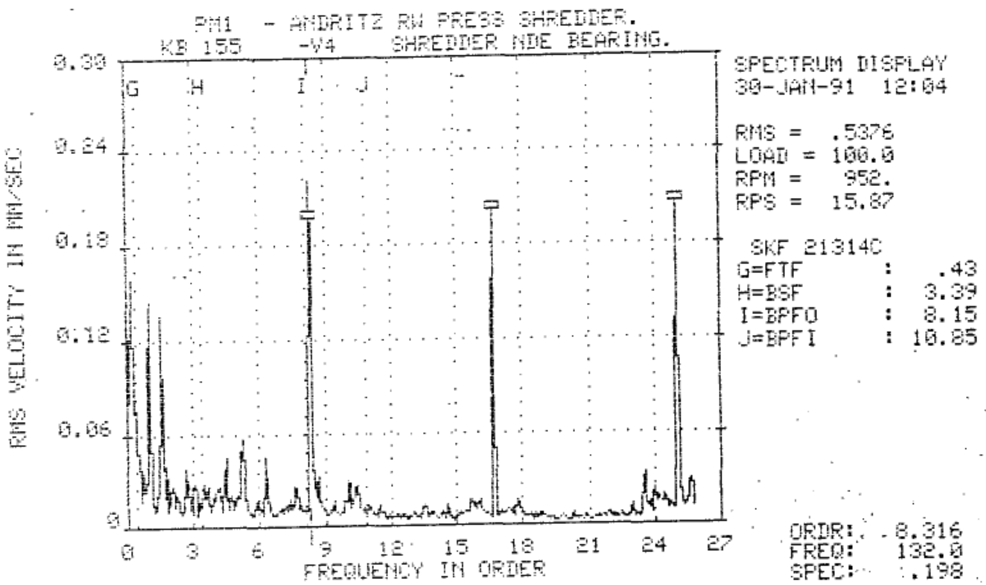


Fig. 7.6. Spectra of R.W. Shredder NDE bearing.

While both faults were thought to be fairly minor it was decided to strip the R.W. Shredder bearing to gain some indication of how bad a fault was required to give the indication on the spectra. As there was no restrictions on access to the R.W. press Shredder it was stripped and the NDE bearing replaced. Examination of the bearing showed a small mark across the path of the roller on the outer race (See fig. 7.7).

Fig. 7.7. Mark on the R.W. Shredder bearing that generated the bearing fault shown in fig. 7.6.

As this fault looked minor it was decided to leave the S.C. press Shredder bearing for some time and continue to monitor it on a more regular basis. This eliminated the need to interrupt production and the bearing will be replaced at the next scheduled shut.

(v) R.W. Bleached Pulp Supply Pump - This pump is used to supply R.W. pulp to the paper machine once the pulp has been reclaimed from the stockpiles. There is approximately 15 minutes of buffer storage at the paper machine so any failure of this pump that takes longer than about 15 minutes to repair either shuts down the paper machine or forces it to switch to a different grade. Either of these cases would result in financial loss to the company.

In early March 1991 this pump was showing a very definite <u>outer ball pass frequency</u> fault (BPFO) at the DE bearing of the pump (See figure 7.8). This was within a day or so of the paper machine going onto a four to five day run of telephone directory that would have required this pump to run continuously for this period.

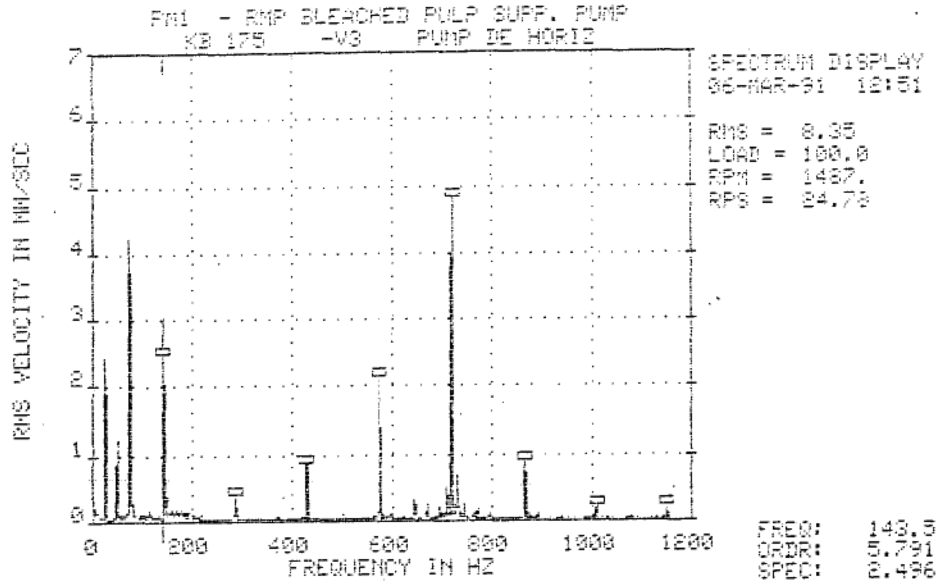


Fig. 7.8 Spectra of the pump DE bearing showing the BPFO fault.

If this pump had failed in service it would have taken approximately four hours to fit the spare pump and get underway again. This would have resulted in a loss of approximately $20,000.00 in down-time, there having being no alternative grade to switch to, and an additional loss due to spoilt product at shutdown and startup. The pump was re-placed with the spare unit when it was not being used and the old bearings removed for examination. Figure 7.9 shows the extent of the damage to the bearing outer ring. It is clear from the extent of the damage to the bearing that this pump was very likely to have failed when subjected to the heavy draw required for the telephone directory run.

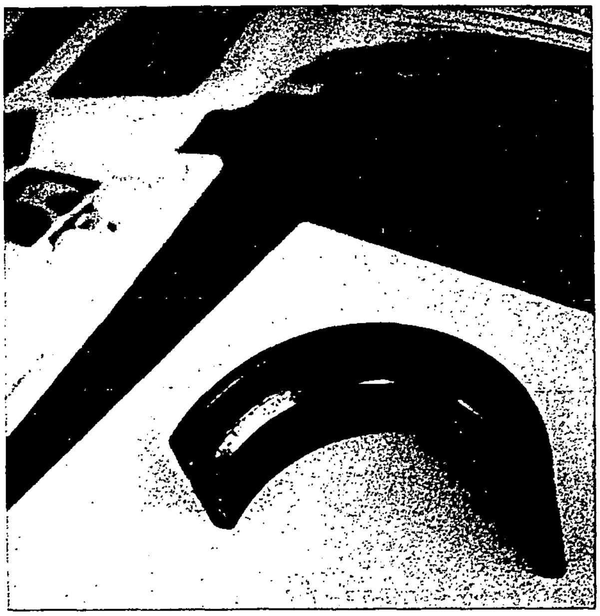


Fig. 7.9 Damage to the outer bearing ring that generated the spectra in fig. 7.8.

8.0 Computer Maintenance Management Systems.

A natural parallel to Condition Monitoring in a modern Process Plant is the use of Computerised Maintenance Management Packages. These computer packages are available with varying degrees of sophistication extending from the most basic of computer aids used to track a specific item, to the more expensive packages that interface with stores, accounts, job control, and Condition Monitoring site wide.

Regardless of the degree of sophistication of the computer package in use, it is of the utmost importance to achieve the best results with the minimum of complexity. This is particularly important when the users of the system are not skilled at modifying or updating the computer package in use.

It is often forgotten in the initial rush to computerise record keeping and maintenance planning, that the very system designed to ease the workload of the maintenance personnel, can itself be a hindrance if it breaks down. For this reason it is worth considering at the outset what the ramifications would be of a system failure. It is of little use to the end-user of a computerised maintenance package if access to data is restricted due to repeated system failures or poor design. Some basic guidelines in selecting a suitable package from among the many now available are :

(i) Ease of use (e.g. Menu Selection).

(ii) Robust code (i.e. does not 'crash' because of incorrect entry such as entering a letter when a number is required or vice-versa).

(iii) Availability of help screens to assist the user.

(iv) Access to information even if the system is down. This is often difficult to achieve but can be approached by making regular printouts of the relevant data. Personal Computer (P.C.) based systems can be particularly flexible in that transferring a recent backup copy of the data to an alternative computer can allow access to the data while repairs are carried out on the original P.C. This would obviously be impossible with main frame based software.

Over the last few years there has been a steady increase in the number of P.C. based maintenance packages available. Some of these packages are aimed at specific tasks and where a limited range of tasks only are required they can be very effective. In the more demanding applications a more comprehensive maintenance management package will be required, particularly when integration of the different functions is necessary such as :

(i) Vibration Analysis (See Appendix 1).

- Computational Systems Incorporated (C.S.I.)
- Palomar Technology International (Microlog)
- Technology for Energy Corporation (T.E.C.)
- Diagnostic Instruments (D.I.)
- Bruel & Kjaer (B&K)

(ii) Lubrication Management (See appendix 2)

- Applied Chemical (Mod-lube).
- Mobil Oil Co. (MI/DAC II).

The more elaborate maintenance management packages are aimed at integrating many of the record keeping and control activities in a large scale business and can be used by people outside the maintenance field. Some of the typical activities carried out by one of these computer packages (TRIDENT) are shown in fig. 8.1 :

- Plant Register.
- Job control.
- Inventory Management.

- Condition Monitoring.
- Shutdown planning.

Some of the better known integrated maintenance packages in use in Australia are:

- Computer Assisted Maintenance Management System (C.A.M.M.S.).
- Maintenance Planning and Control (Mainpac).
- Trident Maintenance Management System (Trident).

Both 'Mainpac' and 'Trident' are P.C. based as well as mainframe based systems and as such lend themselves to use by small and medium companies as well as large. Each of the above systems are designed in modular form and therefore additional subsystems can be added as the need arises.

Within the context of this thesis on Condition Monitoring, it is the ability of the maintenance management package to compliment the condition monitoring program that makes it so important to the Condition Monitoring specialist.

A well established and maintained maintenance management system can supply much of the necessary historical information required to make meaningful diagnosis of plant and machine condition.

TRIDENT MAINTENANCE SYSTEM STRUCTURE

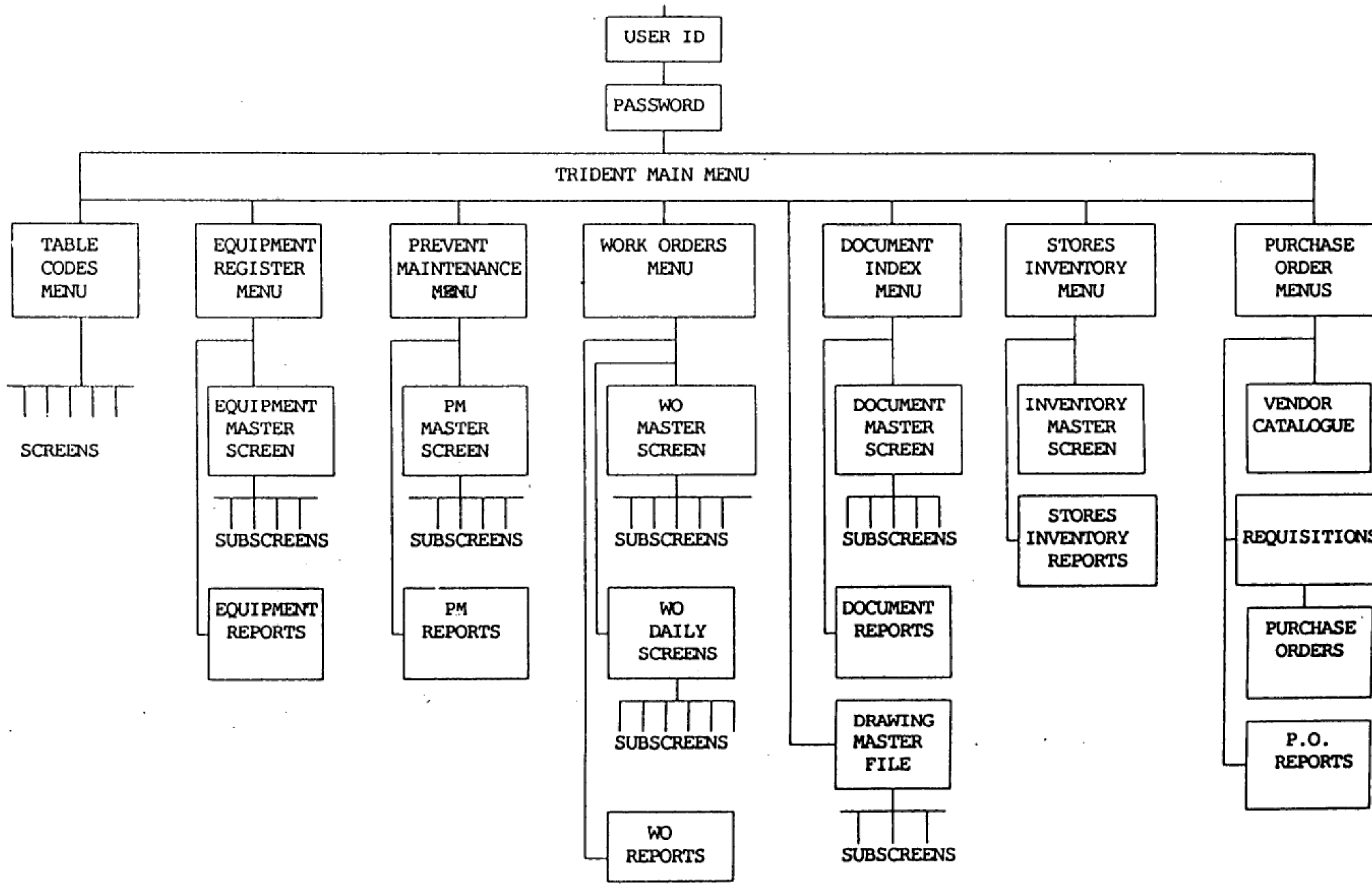


Fig. 8.1 TRIDENT integrated maintenance management package.

The availability of the maintenance history of specific machines from well kept records has many uses in C.M. some of which are :

(i) Identify repeat failures.

(ii) Identify weakness in design.

(iii) Provide supportive evidence for a diagnosis.

(iv) Allow targeting of suspect machines.

(v) Allow better utilisation of scarce resources.

(vi) When combined with information from the C.M. program allows informed selection of new machines based on previous (documented) experience.

(vii) Allows selection of suitable monitoring techniques to use for C.M. or to extend the range of C.M.

Without this database of information on plant and equipment it is almost impossible in medium to large companies to accurately determine the best use of scarce maintenance resources, both human and capital. An added advantage of a well kept record system is that it makes it possible to assess any new machine or maintenance procedure introduced and to determine its effectiveness by examination of the machine history. For example if a vibration monitoring program is introduced by maintenance personnel its effectiveness can only be gauged by determining the number of un-predicted machine breakdowns before and after introduction of the C.M. program.

8.1 Computerised Maintenance Systems at A.P.P.M.

At A.P.P.M. Wesley Vale a relatively comprehensive stores stock, purchasing, and order tracking system is in place using a C.A.M.M.S. system, however this did not begin to extend into the maintenance area until about 1990. When vibration analysis was introduced in 1986-87 there was no systematic recording of machine breakdowns that would have allowed before and after breakdown analysis thereby permitting a quantifiable assessment of the effectiveness of the vibration analysis program.

When the research for this paper was begun in mid 1989 a review of machine breakdowns in the Pulp Mill was undertaken and any available information collected. By June 1990 it was possible to put together a bar graph of bearing replacements versus time for the ten years 1980-1990. This data was suspect from the outset and it was quickly realised that improvements in machine record keeping would be required.

This bearing replacement history was based largely on record cards maintained by the area maintenance foreman and was organised such that there was a separate card for each drive. On this card was entered maintenance carried out, date of repair and a lot of commonly used spare parts. The entries on these cards however were not detailed enough to determine the cause of the failure or to allow any breakdown of machine history beyond what was entered. It was also known that the entry of information varied from time to time and that it was quite common for the cards not to be filled in at all. The effect of preventative maintenance and annual shuts were not known and this reduced the reliability of the information used to generate the bar charts of bearing failures and as such only highlighted the need for an effective breakdown recording system. The introduction of a C.A.M.M.S. Plant and Unit Record control system made these cards less important and it was felt that this was an appropriate time to re-design the record system.

8.1.1 First attempts at recording machine history.

As a consequence of the lack of documented breakdown information for machines in the Mill a systematic recording system that would bring together the breakdown reports from the maintenance areas and record them in a central database for future analysis and trending was designed. In the first instance this database would be P.C. based using dBase IV but would eventually be taken over by the mainframe based C.A.M.M.S. system when it was fully implemented (not expected to be before the end of 1992).

In determining what information should be recorded it was thought best to look at previous instances where breakdowns had occurred and ask what information would have been of most use in assessing these problems. It was also desirable to include some measure of the cost of the breakdowns both in material cost and lost time. Similarly it would be necessary to set up a system that would allow interaction with the C.M. program in use at the Mill by allowing correlation between the breakdowns and any previous monitoring that may have failed to detect the developing fault. Given these and other requirements a preliminary list of user requirements was made and included the following points:

(i) Individual drive history - this would permit recalling all breakdowns since recording began and the type and frequency of these breakdowns.

(ii) Lost time analysis - this would be possible for a specific machine or for a group of machine in an area.

(iii) Breakdown analysis - this would permit extraction of all breakdowns of a particular type, e.g. bearings, drive belts, oil related, etc.

(iv) Effectiveness of C.M. - required to quantify any improvements due to applying C.M. to a machine or group of machines.

(v) Effectiveness of change - required to determine how effective some change was e.g. use of a different lubricant, component type, or procedure.

(vi) C.M. requirements - enable selection of C.M. technique to detect specific types of failure, e.g. vibration analysis for rolling element bearings, Thermography for switch gear, insulation etc.

(vii) <u>Machine hours run</u> - this would allow calculation of expected machine life and be used to target machines that fail to give good reliability.

(iix) <u>Breakdown times</u> - this could be used to improve allocation of resources such as access to maintenance staff on dayshift or on a 24 hour-a-day basis.

(ix) <u>Job completion time</u> - this can be used to identify those machines that take an unreasonable amount of time to repair and allow improvements to machine access etc. where identified.

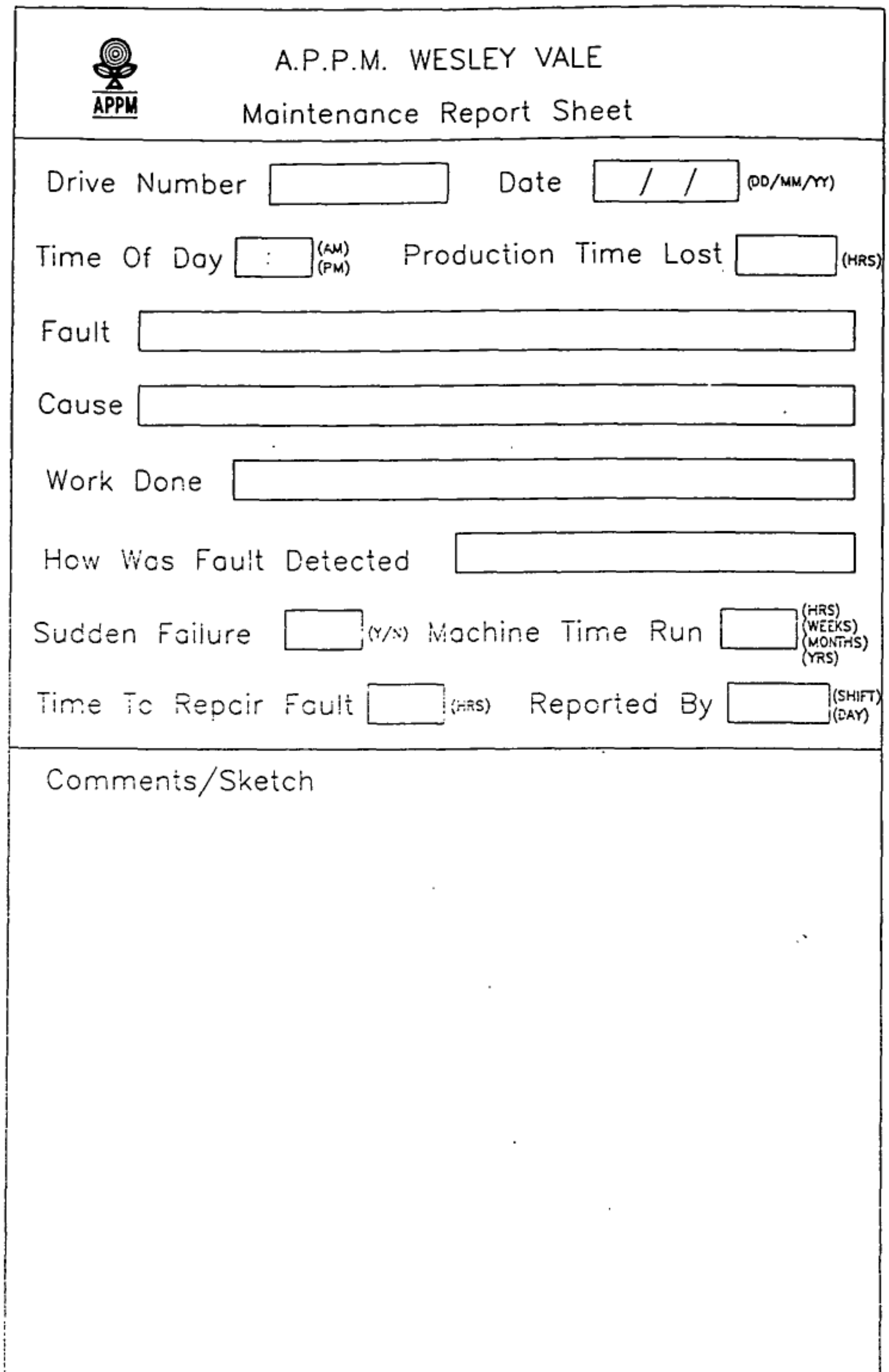
(x) <u>Profile of machine type</u> - when considering purchase of a particular machine (e.g. pump, gearbox, etc.) the history of similar machines can be a useful guide to reliability, ease of maintenance, cost of spares etc.

(xi) <u>Graphical presentation of trends</u> - this feature would make it much easier to present information to maintenance personnel and to detect changes in trend data.

Based on these output requirements a P.C. based database was designed using dBase IV to assess the suitability of such a system for use at the Wesley Vale Mill. The initial database would be used to record and process the raw data collected on each job and breakdown as it became available. It was recognised from the outset that this would be a long term project becoming more useful as the database built up.

As a means of standardising the information to be fed into the database, a reporting form was designed for use by those carrying out the repairs. This report form was kept as simple as possible while still ensuring that the desired information was recorded (See fig. 8.2). This reporting form was intended to bring together all the relevant information for inclusion in the database. It was also intended that this form would be used to follow up on incomplete reports of breakdowns that may have been made either verbally or on this or other reporting forms.

An advantage of this recording procedure is that when new personnel join the maintenance team the information available in the database can be used to get a quick overview of machines in the area and help to identify the most troublesome machines for closer attention.



A.P.P.M. WESLEY VALE

Maintenance Report Sheet

APPM

Drive Number [ ] Date [/ /] (DD/MM/YY)

Time Of Day [:] (AM) (PM) Production Time Lost [ ] (HRS)

Fault [ ]

Cause [ ]

Work Done [ ]

How Was Fault Detected [ ]

Sudden Failure [ ] (Y/N) Machine Time Run [ ] (HRS) (WEEKS) (MONTHS) (YRS)

Time To Repair Fault [ ] (HRS) Reported By [ ] (SHIFT) (DAY)

Comments/Sketch

Fig. 8.2 Proposed work report sheet.

It is important to maintain any type of recording procedure to get the best results when the information is required. If the correct information is not fed into the database in the first instance, it will not be much use examining the machine history at a later date. The old adage 'garbage in - garbage out' is particularly applicable in this application. For this reason it can be argued that the people who will use the information stored in the database should have some responsibility for collecting and maintaining that database. It is very important to instill in the maintenance personnel that the information that they have entered into the database is of the highest quality as poor or incomplete information will hamper diagnosis or fault finding at a later date.

The best way to get good information and regular reporting from the maintenance personnel is to convince them of the benefits of having this information in a readily accessible database. This can be achieved by giving regular feedback on how the database acquisition is progressing (e.g. % of data supplied on the forms) to those who fill in the breakdown reports and do the repair work and demonstrate some instances where the database was recently used to advantage. As the database is developed it will have an increasing amount of useful information available and therefore it will be easier to demonstrate its usefulness to maintenance planning.

As this database was designed to provide historical information on each drive in use in the Mill it will be of particular use to the C.M. program in allowing an overview of the breakdown history of the machine and in pin-pointing the most common causes of breakdown. If this or a similar record system was implemented the database would be refined over time and specific reports generated and circulated to all concerned as the need arose. This would be in addition to specific searches done on particular machines and the format of these reports would be determined by the demand.

8.1.2 Extension of C.A.M.M.S. system to include the machine history.

At the end of 1990 investigations were being carried out by the writer into suitable lubrication scheduling systems for use at the pulp mill. These investigations led to the conclusion that early implementation of the C.A.M.M.S. 'Preventative Maintenance' (P.M.) module would satisfy not only the lubrication scheduling requirements but also the machine history requirements mentioned earlier. With this in mind the available information on the P.M. module was collected and contact made with the C.A.M.M.S. control group at the A.P.P.M. Burnie mill. The P.M. module had been in use at the Burnie mill for about three years and a considerable amount of experience had been gained by the system developers. These experienced personnel were available to assist in implementing the P.M. module at Wesley Vale and their experience and assistance would allow implementation in a much shorter time than would otherwise be the case.

The recently completed implementation of the Plant and Unit Record module provided the basic information required by the P.M. module. This along with the Works Requests module allows tracking of individual machine history.

Development of this extension to the existing C.A.M.M.S. system at Wesley Vale was under way at the time of writing this thesis and is expected to be operational by early 1992.

9.0 Expert Systems and Condition Monitoring.

It is a characteristic of many Condition Monitoring techniques that a considerable amount of skill and experience is required by the operator of any program based on one of these techniques. The inability on the part of the C.M. program operator to extract all the useful information from C.M. technique in use can greatly reduce both its consistency and its effectiveness. The skills required can be partly gained by a well structured training course aimed at training the operator in fault recognition. Experience on the other hand, can only be gained by repeated exposure to machine fault diagnosis, and good follow-up to determine if the diagnosis was correctly made. This can best be achieved by personal investigation on the part of the C.M. operator to correlate the findings of the repair team with the problem indicated by the C.M. program. If a diagnosis is poorly made it is important to determine if this was because of the limitations of the technique being used or inexperience on the part of the C.M. operator.

Once a C.M. program is set up the operator should begin to develop experience quite quickly. It is commonly cited in general literature on C.M. that it can take approximately two years to get a C.M. operator to the skill and experience level required to be reliable in his diagnosis. This is consistent with the experience at Wesley Vale. The need to split ones time between C.M. and routine maintenance work can increase this time scale.

Some of the techniques that are particularly demanding of skill and expertise are :

(i) Ferrography.

(ii) Spectrometric Oil analysis.

(iii) Infrared Spectroscopy.

(iv) Radiography.

(v) Ultrasonic testing.

(vi) Acoustic emission.

(vii) Vibration monitoring.

The vibration monitoring program at Wesley Vale is one of the techniques that requires both skill and experience to optimize the results. This restricts the involvement of the maintenance fitters in the C.M. program to some extent as it is not practical to train them to the point where they can interpret the vibration spectra with sufficient reliability to achieve the results being sought from the system as it is presently set up. Overcoming this restriction on delegation is likely to develop into a high priority in industry over the next few years as the closer the vibration monitoring program is to the maintenance function (i.e. a part of the maintenance fitters tools of trade) the better able will be the maintenance team to adopt a predictive approach to maintenance.

The development of industrial Expert Systems (E.S.) over the last five years or so has meant that software packages are now available to perform at least some of the tasks previously performed by the highly skilled and experienced C.M. operator. These packages can be either '<u>Stand-alone</u>' or '<u>On-line</u>' systems that assist the relatively inexperienced C.M. operator to extract the maximum amount of information from the C.M. technique in use.

'<u>Stand-alone</u>' expert systems are add on packages that are operated separately to the main C.M. system and request specific input data from the C.M. operator. The E.S. software package then uses this information to suggest a possible interpretation of this input data. The use of this kind of expert system can be considered only a partial substitute for an experienced operator but can be of particular value when a C.M. program is relatively new and operator experience is at a minimum.

'On-line' expert systems collect some or all of the input data they require automatically via. software links to the main C.M. system and perform fault diagnosis on this data. These packages are becoming increasingly sophisticated and perform a vital role in continuous monitoring systems where high risk is associated with machine failure. These systems are likely to become increasingly used in the continuous monitoring of nuclear power plant, aircraft, large turbines, and anywhere that critical plant and equipment is operated.

Expert Systems can be considered as being made up of three main parts :

(i) A front-end or user interface - this is the part of the E.S. that the operator interacts with and provides the following main functions.

- Data input.
- Displays current status of consultation.
- Outputs results of consultation.
- Graphical presentation (if any).

(ii) A knowledge or facts base - this part of the expert system contains the rules and/or facts that relate the different pieces of input data to one another in such a way as to allow a conclusion to be reached. Collecting the information needed to formulate these rules and relationships is probably the most demanding part of writing an E.S. package.

The information required for the formulation of these rules has to be gleaned from a recognised expert (i.e. the Domain Expert) in the field that the E.S. will address when completed. Currently, extracting this information from Domain Experts can be very difficult to achieve as in many cases the experts themselves do not completely understand the method used to arrive at a conclusion.

The person developing the E.S. (i.e. the Knowledge Engineer) is rarely the person possessing the expertise in the target field of the E.S. application and good interaction between the Knowledge Engineer and the Domain Expert is vital if a useful system is to be developed. The interaction between the Knowledge Engineer and the Domain Expert proceeds in a iterative fashion until the knowledge base has developed to a satisfactory level. This interaction can be represented by the flow chart in fig. 9.1 [21].

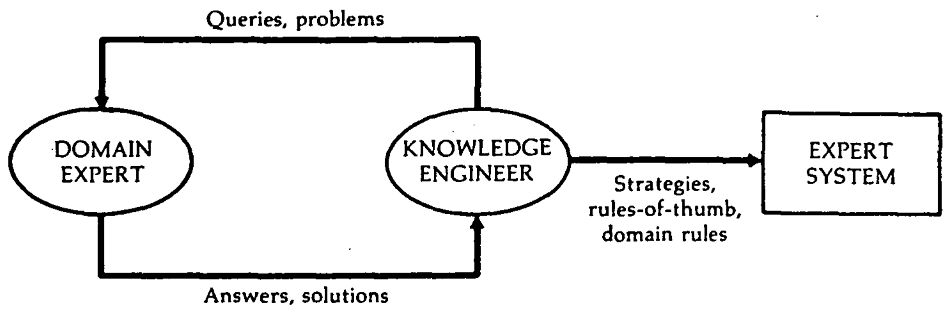


Fig. 9.1. Interaction between the Knowledge Engineer and the Domain Expert leads to a useful Expert System.

(iii) The Inference Engine - this can be considered to be the 'Smart' part of an E.S. in that it is used to control the reasoning process behind the E.S. and to interpret the rules in the knowledge base. The inference engine decides how to apply the rules and available facts to infer new knowledge and contains a schedule to determine the order of execution of the rules [21]. The most common method used to decide which rule to use is the 'first encountered', 'first fired' method. Other techniques based on priority rules or probability can also be used.

A well designed E.S. can be used to great effect when it is well understood by the user and is targeted to a narrow field of application. It is impossible to get an E.S. that can be all things to all users and this is often the failing of commercially available E.S.'s that are promoted as being complete systems.

In the field of Condition Monitoring the use of an E.S. in fault diagnosis using vibration analysis has been addressed by Computational Systems Incorporated (C.S.I.), among others, over the last few years. One of the first commercially available E.S.'s produced by C.S.I. for machinery diagnosis was a stand alone system called DEXPERT and required considerable input by the system user. The system interface could be run in either Novice or Expert mode. The Novice mode requiring less decisions by the operator while the Expert mode gave greater control over the consultation.

The latest E.S. available from C.S.I. is called NSPECTR and can be run on the same computer used to operate the Mastertrend software. Unlike DEXPERT, NSPECTR can extract much of the information it requires for a consultation from the vibration spectra being analysed. Over 50 pieces of information are extracted from the spectra and the inference engine uses this data along with the facts and rules stored in the knowledge base to make a diagnosis. NSPECTR can be used as an automated E.S. that examines all the spectra in a machine, a route, a station, or a complete database and generates a list of machine faults and possible causes.

The on-line analysis of data is, generally speaking, in its infancy and it's likely to be quite a few years before an E.S. is available that can eliminate the need for a highly skilled operator from the vibration monitoring program. The use of E.S. in Condition Monitoring has to be considered in light of both the advantages and disadvantages of any such system. In general terms the advantages of using an E.S. can be considered to include the following points.

(i) Fast data analysis, particularly when automated data acquisition is used.

(ii) Can be configured to request additional tests to refine the accuracy of the solution.

(iii) Reduces or eliminates the need for highly skilled and experienced personnel to spend large amounts of time on data reduction and analysis.

(iv) Maintains an impartial approach to problem solving.

(v) Considers all possible options.

(vi) Does not tire or take breaks.

(vii) Can be used as a training aid for less experienced personnel.

(iix) Allows automated fault history to be built up for each machine.

(ix) Permits a level of expertise to be reached as soon as the system is implemented that might take months or years to reach if individual experience had to be developed.

(x) Allows duplication of the expertise. This is useful if more than operator uses the E.S., particularly at different locations.

(xi) Provides a means of capturing expert knowledge that would otherwise be lost due to retirement, death, or the loss of an experienced person from the company.

(xii) Can be built up from a pool of expertise generated by several experts.

(xiii) Can deal with a large amount of input data often better than a human expert.

(xiv) Can grow with the addition of new rules and facts.

As well as the advantages listed above there are problems associated with the use of E.S.'s as they are designed today. Some of these problems will have more impact than others on any individual company and care must be exercised when deciding to buy or develop an E.S. Some of the problems associated with the use of E.S.'s are listed here.

(i) Expert Systems are usually expensive to purchase or develop. A considerable amount of time is required to build up the knowledge base and as this knowledge has to come from highly skilled and experienced personnel this time will tend to be expensive.

(ii) Access to suitable experts can be greatly restricted in some areas, particularly if experts in the area are scarce.

(iii) Expert Systems are never really completed as they require the addition of new information when it becomes available and this upkeep requires access to a knowledge engineer as well as a Domain expert to service the software.

(iv) Expert Systems have no way of knowing what they don't know and using them outside their design area can lead to unpredictable results.

(v) Even the best E.S. has no ability to exercise 'common' sense and they are quite capable of generating meaningless results that a human expert would instinctively know were not correct.

(vi) Perhaps one of the most disturbing side effects of using an E.S. is that its very ability can reduce the likelihood of a human expert developing in that particular field as it tends to reduce the demand for such experts. In time this can result in the E.S. becoming more and more out of date and no human expert having been developed to maintain a desired skill level.

Despite the disadvantages listed above there are many advantages in using E.S.'s and the disadvantages can be reduced or eliminated by good management practices. If an E.S. is being considered for an industrial application such as Condition Monitoring the following features should be considered as mandatory.

- Be able to justify any conclusion reached.
- Be as human as possible in its reasoning.
- Have the ability to cope with uncertain or incomplete data.
- Use natural language as much as possible.

- Have good interface features to make use of the system more pleasant for the user. This makes the system more likely to be used.

As E.S.'s are developed further over the next few years it is likely that they will be increasingly used as an aid to Condition Monitoring, particularly in diagnosing faults from vibration spectra. The present relatively high cost of these systems (approx. $10,000 for NSPECTR from C.S.I.) and their relatively poor success rate (80% success rate is the aim point for NSPECTR II) makes them a useful but not totally reliable tool for the C.M. operator.

It is not intended at this time to purchase an E.S. for use in vibration spectrum analysis at Wesley Vale but this is likely to change as the systems become more sophisticated. In the first half of '91 the writer attended a 16 week night course at the Devonport Technical College in E.S.'s as a first step in determining their usefulness to A.P.P.M. and to develop some introductory skills in their design. As part of this 16 week course a knowledge based E.S. was designed and developed for identifying faults in electric motors. This is a stand-alone system and uses data from vibration spectra, fed in by the operator, to reach a conclusion about any possible faults. It is not intended that this become a commercial E.S. package but it is hoped that it will provide a vehicle by which a more informed decision on the future use of E.S.'s can be based.

10.0 Conclusions.

Condition Monitoring as a philosophy is gaining considerable ground in industrial maintenance and the development of equipment, procedures, and practices over the last few years has made it easier to implement.

Condition monitoring makes it possible to quantify machine condition indicators such as vibration, noise levels, temperature, and wear in such a way that different people can relate to the machine condition in a uniform way. Previously these indicators were accessed on a qualitative basis making it very difficult to get uniform accessments of machine condition. Similarly it was very difficult to communicate this information to others. Plant maintenance based on condition monitoring allows early detection of faults and reduced downtime where appropriate preventative measures are taken.

Routine crack testing using dye-penetrant testing has been successfully used in accessing the condition of screw press components at Wesley Vale (W.V.) before refurbishing. This has largely eliminated the problem of components being partly rebuilt only to be scrapped at a later stage due to cracks becoming evident.

Thermographic imaging has proven useful in detecting blockages of steam injection nozzles, and heat loss from steam lines.

The major cause of downtime on machines at W.V.is due to bearing related failures that can be traced to *fatigue, water damage, incorrect installation,* and *poor lubrication.* Routine vibration monitoring of critical machines has proven successful in detecting these faults at an early stage. Continuous monitoring was considered unnecessary at this time but would be reviewed as appropriate.

Selection of the hardware and software for the vibration monitoring program at W.V. was based on recommendations from a consultant from *Tensor Systems* in Melbourne who had experience with the machines at W.V. The hardware purchased was a CSI 2110 analyser and the associated Mastertrend software by the same supplier. Both the hardware and software have performed well with no significant problems being encountered.

The papermachine monitoring was taken over in-house by the plant maintenence department as set up by the consultant and the pulp mill and services area set up from the beginning by the author, there being no program existing at that time.

Collection of the large amount of data required to set up the vibration database took several months as did the fitting of the measuring studs to each measurement position on each machine to be monitored. Survey routes were set up by the author taking into account the proximity of one machine to the next and whether or not the next machine was running as part of the same process line. Once the routes were established they were listed in a schedule to show when each was due. This schedule has remained virtually unchanged except for some minor refinements.

The oil analysis previously being carried out on the turbine oil was considered to be poorly organised and some changes were made by the author to improve the sample collection. The oil analysis program will eventually be taken over in-house at W.V. and possibly extended to include a range of additional machines best suited to monitoring by this technique. Vibration monitoring is limited to casing readings at present but will include proximity probe readings as soon as these are set up. Balancing of the northern turbine rotor resulted in a significant reduction in one-order vibration. Future work required on the turbine to replace the blading in the steam chest will provide an opportunity to further improve the rotor balance.

The mechanical maintenance fitters trained to take the routine vibration readings have adapted well to the task showing enthusiasm and a willingness to learn. This has greatly increased their receptiveness to the general Condition Monitoring approach to maintenance. It is fair to say that assisting the change from a Preventative Maintenance philosophy to one of Predictive Maintenance is one of Condition Monitoring's greatest strengths.

Computer maintenance management packages can be a significant aid in maintenance management particularly when designed to include or complement a C.M. program. The Preventative maintenance module of the *Computer Aided Maintenance Management System* (C.A.M.M.S.) used at W.V. is currently being implemented and should improve maintenance effectiveness by giving better control of maintenance activities. This will complement the C.M. program and contribute significantly to reduced plant downtime.

The development of expert systems over the next few years should enable faster and more reliable analysis of the data collected by the vibration monitoring program and therefore give more timely indication of any developing faults. The use of continuous monitoring systems coupled to expert systems will eventually allow a machine to perform self-test routines and detect any faults within and recommend the most appropriate corrective action to be taken by the maintenance personnel.

Implementation of the vibration monitoring program at the A.P.P.M. paper mill at Wesley Vale has been quite successful. The lack of adequate breakdown records prior to setting up the vibration monitoring program has made a quantifiable comparison of the programs effectiveness impossible. It can be said however that from the experience gained by the author and the maintenance staff involved in the vibration monitoring program, that the ability to monitor a machine has resulted in some machines being left in service longer without overhaul than would have been the case previously.

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Appendix 1

(i) Vibration survey chart.

(ii) Plant layout.

(iii) Pulp Mill ground floor layout.

(iv) Pulp Mill first floor layout.

(v) Comparison of digital analysers.

(vi) Specification sheet for SD Microlog.

(vii) Specification sheets for CSI 2110.

(iix) Information sheet for TEC Card Memory.

(ix) Information on Reid Technology Datalog.

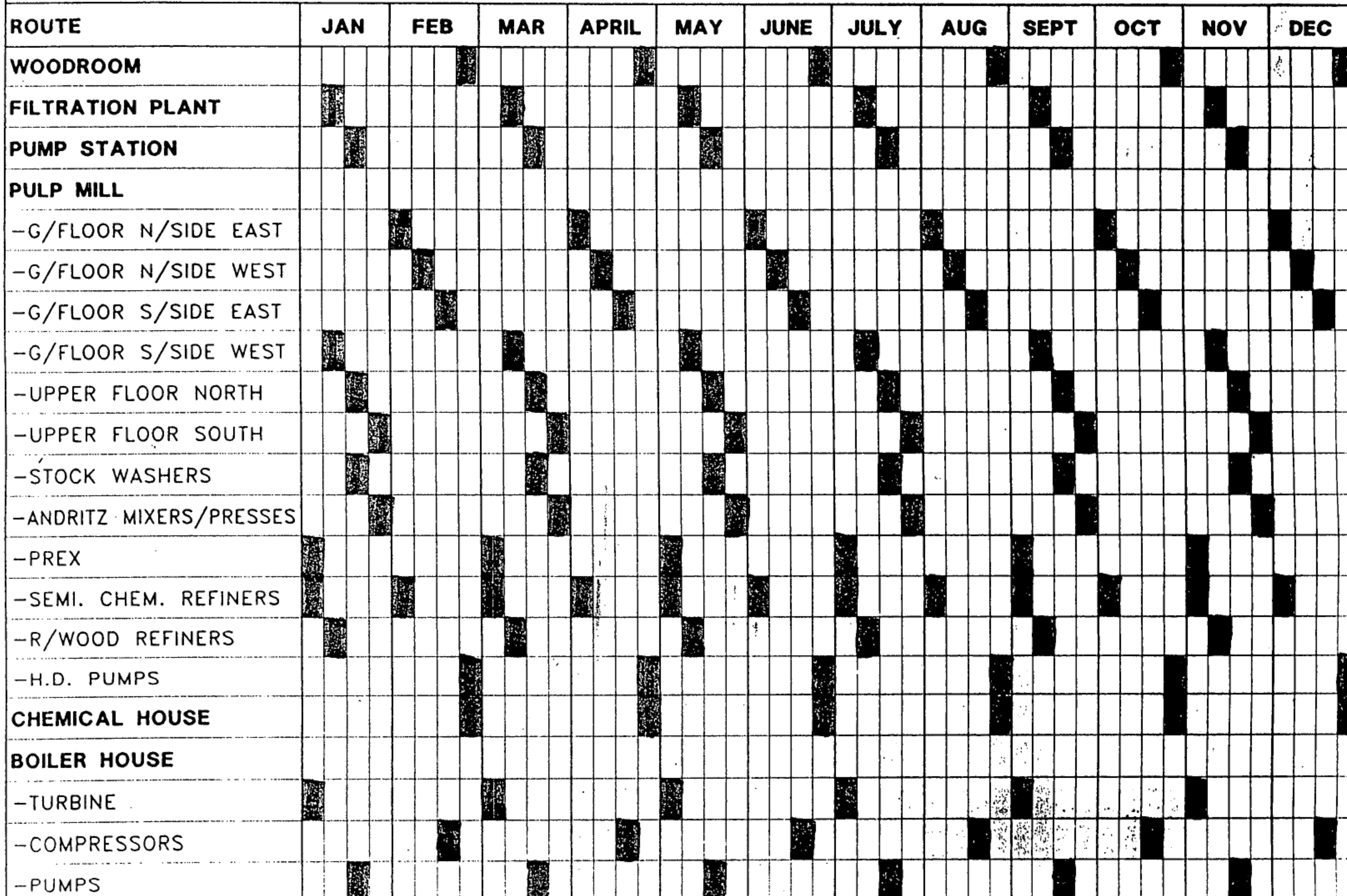
(x) Machine classification used at Wesley Vale.

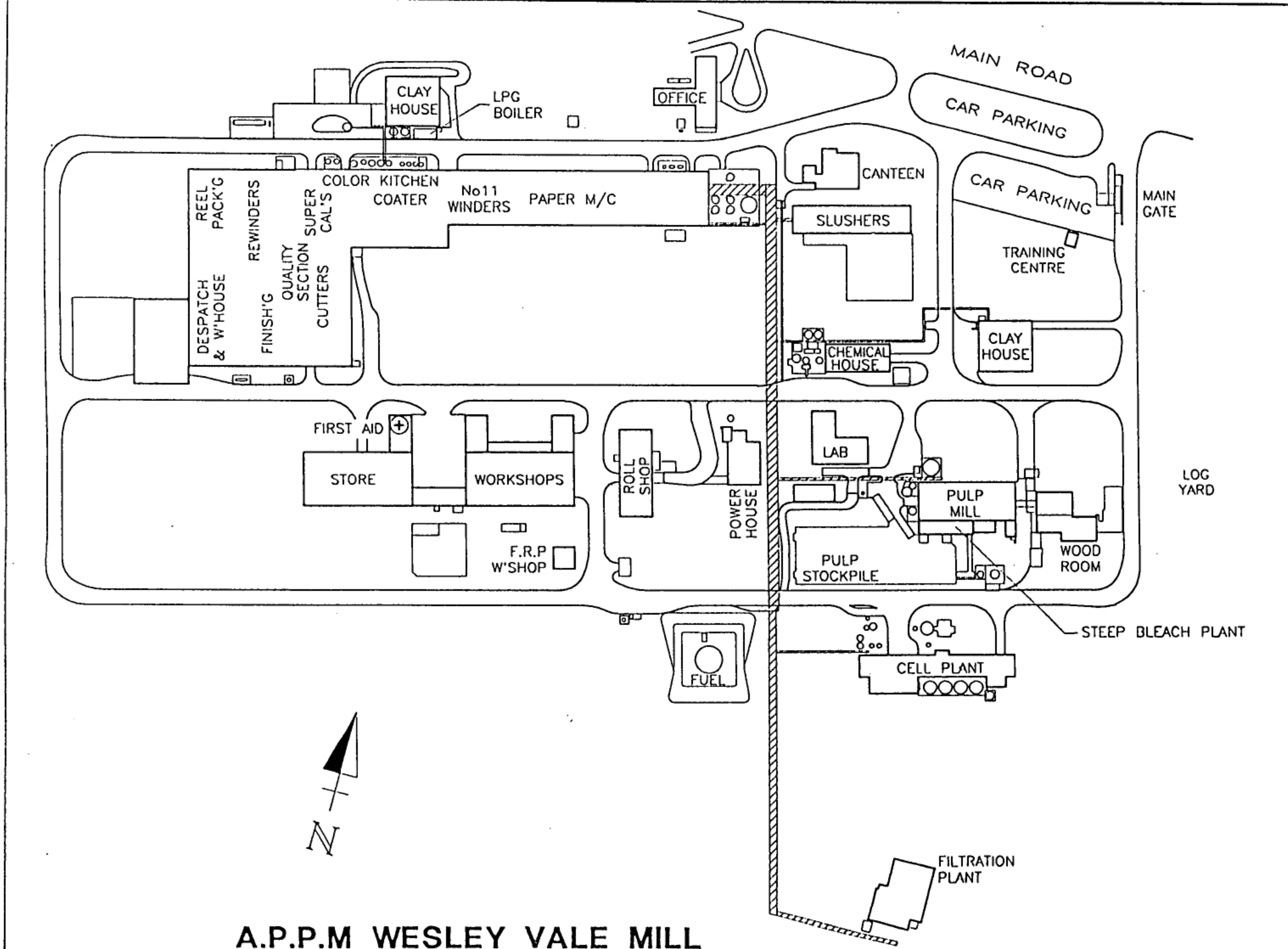
(xi) Vibration studs and mounting block details.

(xii) Vibration troubleshooting charts.

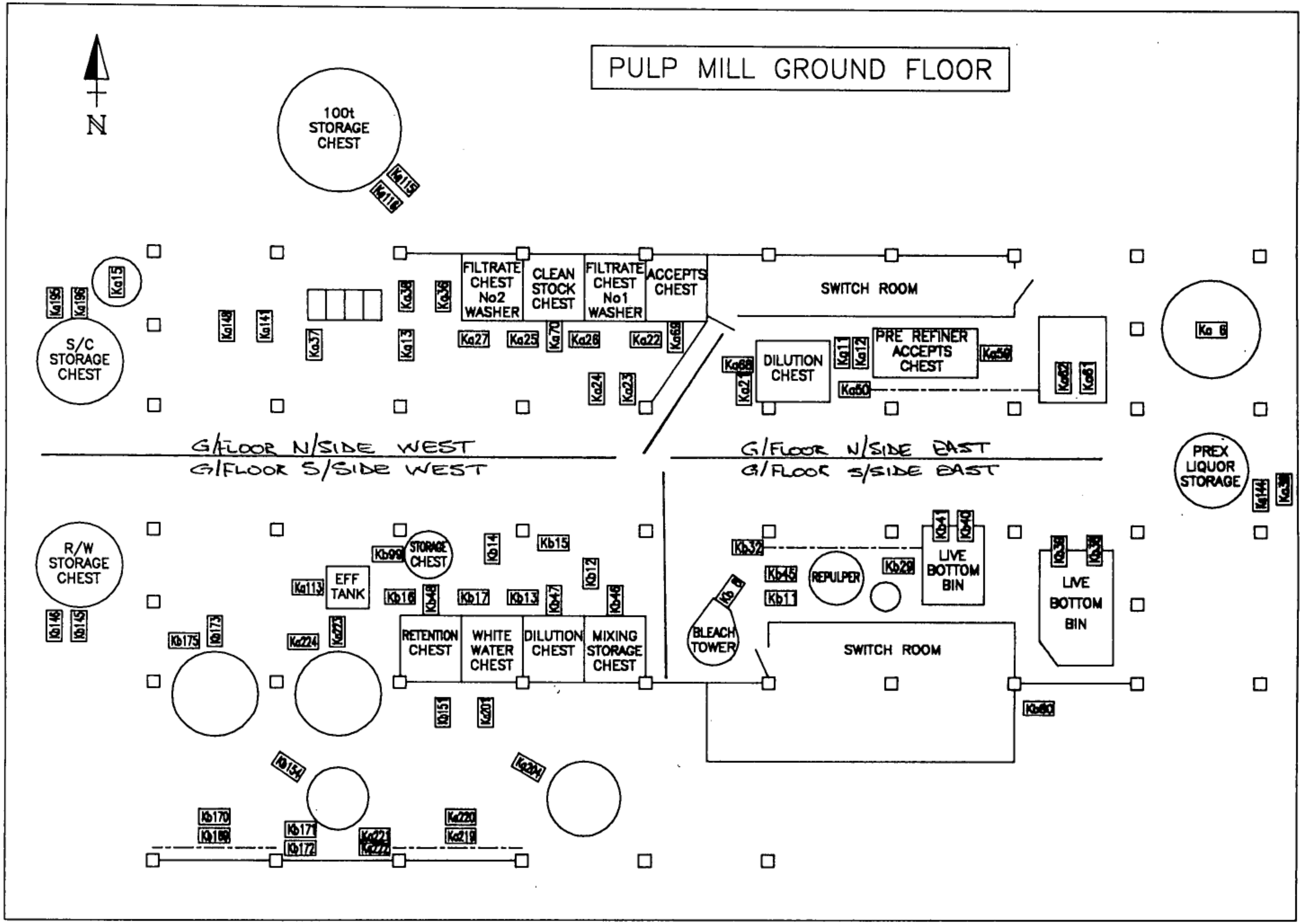
(xiii) Table of criteria for bearing vibration measurement.

SERVICES AREA VIBRATION SHEDULE JAN - DEC 1991





A.P.P.M WESLEY VALE MILL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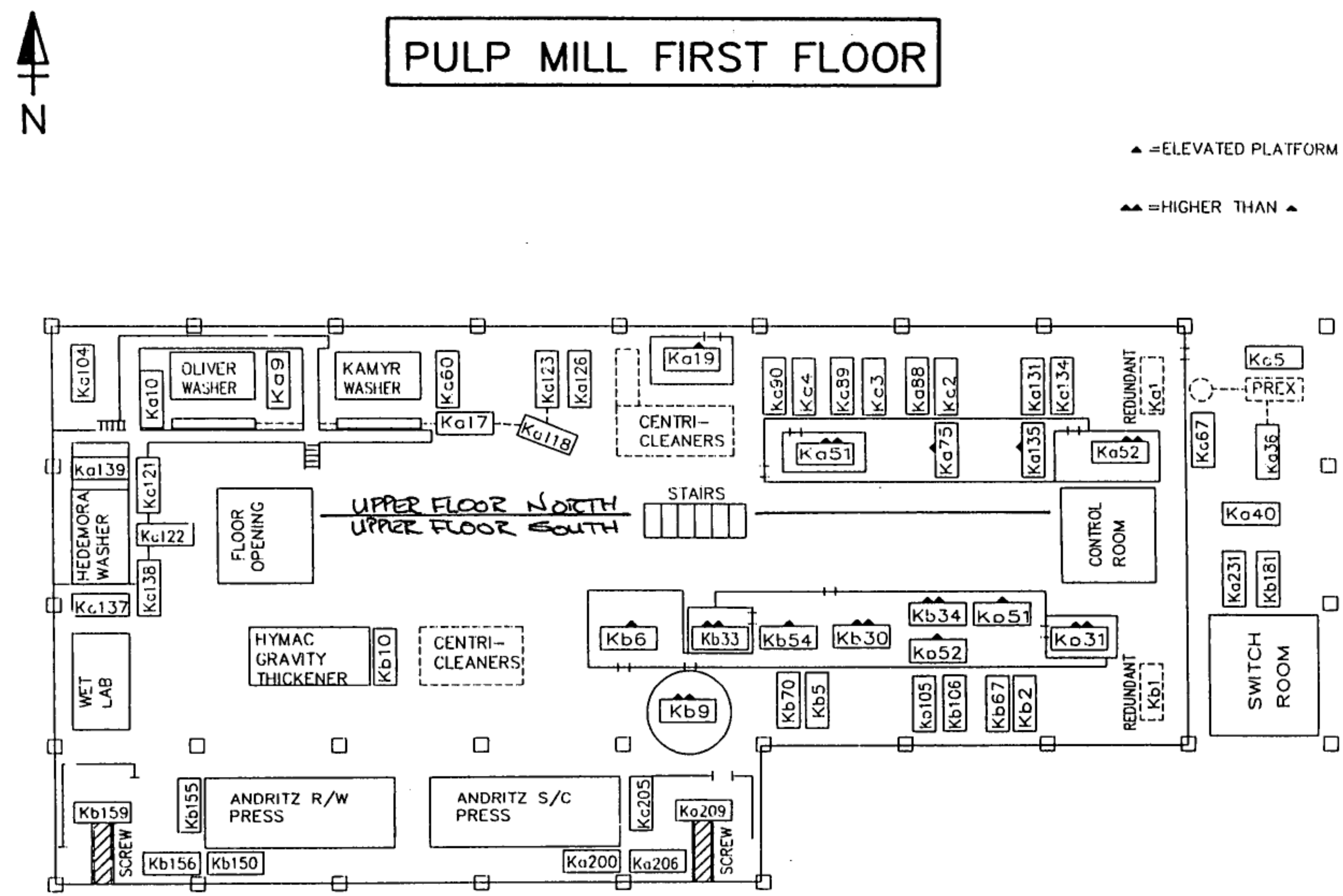
N
100t STORAGE CHEST
S/C STORAGE CHEST
FILTRATE CHEST No2 WASHER
CLEAN STOCK CHEST
FILTRATE CHEST No1 WASHER
ACCEPTS CHEST
SWITCH ROOM
DILUTION CHEST
PRE REFINER ACCEPTS CHEST
G/FLOOR N/SIDE WEST
G/FLOOR S/SIDE WEST
G/FLOOR N/SIDE EAST
G/FLOOR S/SIDE EAST
PREX LIQUOR STORAGE
R/W STORAGE CHEST
STORAGE CHEST
EFF TANK
RETENTION CHEST
WHITE WATER CHEST
DILUTION CHEST
MIXING STORAGE CHEST
BLEACH TOWER
REPULPER
LIVE BOTTOM BIN
LIVE BOTTOM BIN
SWITCH ROOM

PULP MILL FIRST FLOOR



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As requested, our product comparison of three forthcoming PDC's as of 18/04/88 is presented.

PDC Features	Microlog	CSI(std mem)	TEC(card mem)
Dynamic Range	72 dB	72 dB	72 dB
Max Lines	3200	3200	1600
Zoom	no	yes	no
Stored 800 line Spectra	440	280	unlimited
Stored max line Spectra	110	80	unlimited
Store/view real time wave forms	yes	yes	yes
" " " " spectra	yes	yes	yes
Time Sync. Average spectra	yes	yes	yes
" " " wave forms	?	?	?
Triggering delay	?	yes	?
Display size	2.75x5.0	2.75x5.0	2.5x5.0
PDC screen spectrum scrolling	yes	yes	yes
PDC cursor controls- spect. line	yes	yes	yes
" " " - exact freq.	no	yes	no
" " " - harmonics	no	yes	no
Overwrite a bad measurement	yes	yes	yes
Low freq. tacho limit	.5 Hz	.5 Hz	.5 Hz
Portability - size length	10.5	10.5	10.75
width	8.5	6.75	8.5
depth	2.75	1.6	3.5
" - weight	5 lb	4 lb	5.5 lb
Software Features			
Color	yes	yes	yes
Windows	yes	no	no
Speed/load trending compensation	yes	yes	yes
Balancing, multi-plane in situ.	yes	yes	yes
Transmitting a slice of database	3 months	yes	"Carbon Copy" (terminal emulator)
System Upgrades			
Software	yes	yes	yes
Firmware	yes	yes	yes
Hardware	yes	yes	yes
Product Support			
PDC repairs	contractor repairs OK	contractor untested	in-house repairs OK

D MICROLOG

FEATURES AND SPECIFICATIONS

CE
- ation Pickups—Acceleration or velocity, hand- l or attached with magnet or quick connect. ninal 2.2 mA current source available from it. Compatible with integral electronic piezoe- ic accelerometers. Open circuit voltage is +24 s nominal.
- perature Pickups—Contact thermocouple or (with adapter) non-contact infrared (direct it). Range -250 to 1,000°F (-150 to 550°C).
- n Installed Monitoring System—Acceleration, city, and non-contact shaft displacement and l position pickups.
- board Entry—Measurements read from indi- ors or installed instruments entered in engi- ring units. Maximum of 8 places including sign r -) and decimal point.
- se Reference—Non-contact optical with TTL c output. Non TTL inputs with Model 6155 se reference adapter.
- and DC Volts—From any source. See Input age Range.
- Measurement Observations—Added to mea- ement as coded notes or in plain language to a l of 42 characters per measurement point.

PARAMETERS
- t Impedance—1M Ohm.
- t Coupling—Low frequency 3dB roll off at 0.2
- t Voltage Range—AC ±25 V peak, DC ±50 V.
- amic Range—80 dB (14 bit signal conversion) 60 dB of gain ranging for a total signal input ge of 140 dB.
- plitude Accuracy—Within 1% of input at one cified frequency.
- plitude Ranging—Automatic or manual from board.
- imum Measurable Signal—.00025 volts at the it.

PROCESSING and STORAGE
- roprocessor—Full 16 bit microprocessor tech- gy (16 bit data bus).
- mory—1 Mbtye (768K RAM, 256K EPROM) 2 overall measurements.

UREMENT POINT PARAMETERS
- ntification—Unrestricted alphanumeric ID. grammable to a maximum of 20 characters per isurement record.
- cription—Plain language name and/or cription/location of measurement. Program- ble to a maximum of 32 characters per mea- ement record.
- e—Recorded with measurement; month, day, , hour, minute, second.
- te (Sequence of Measurements)—Transferred n host microcomputer in List (Route) or Hier- ny (outline) form.
- kup Sensitivity—Programmed individually for h measurement point. 0 to 99,999 MV/engi- ring unit.
- lish or Metric—Programmed globally.
- quency—Hz or CPM programmed globally.
- plitude Ranges—User specified, fully grammable.
- egration—None, single or double, grammable.
- ation Amplitude Units—

cceleration	G's
elocity	in/sec (mm/sec)
isplacement	mils (micrometers)
FD (bearing cond.)	G's

- rm Type—Level, in window, out of window.
- rm Limits—Two (2) independent, program- ble values for each overall measurement to call ntion to abnormal conditions and initiate FFT ection when so programmed.
- asurement Display—Current and previous rall value displayed numerically. Gauge or bar- ph with alarm markers for visual observation of amic characteristics and physical relationship larm setpoints. Alarm status displayed in plain uage.

NG ELEMENT - ING CONDITION - HFD
- quency Range—5 Hz to 60 KHz
- ection—True Peak or RMS

MIC ANALYSIS
- e—Narrowband magnitude spectrum, phase ctrum, time domain.

- **Display**—Single or dual split screen displays of magnitude spectrum, phase spectrum or time domain.
- **Display Mode**—
  Normal—programmed start and end frequency
  Zoom—increased frequency/time resolution
  Expand—change frequency and amplitude display span
- **Measurement**—Amplitude, frequency, order, phase and/or time displayed numerically at the position of the display cursor
- **Averaging**—Off, Average, Peak Hold, or Time Synchronous. Completion determined by **Averaging Mode.**

  Off—No averaging performed on the data.

  Average—Ensamble average of n averages where n is programmable from 1 to 9,999.

  Peak Hold—Highest value attained for each FFT line.

  Time Sync—Synchronously (from the trigger pulse) averaged in the time domain. The FFT is performed on the averaged time domain signal.
- **Averaging Mode**—Continuous, Finite, Repeat

  Continuous—Continuous running average of most recent n averages where n is programmable from 1 to 9,999.

  Finite—Stops averaging and holds the display when n averages have been completed.

  Repeat—Resets n to 0 and repeats averaging when n averages have been completed.
- **Markers**—Harmonic, Relative, Sideband, indexed to the location specified in **Marker Mode.**

  Harmonic—Marker displayed at each integer multiple of a specified location, 2x, 3x, 4x, etc.

  Relative—Marks a location on the display referenced to a specified location.

  Sideband—Marks 2 sidebands at a programmed sideband frequency on either side of a specified location.
- **Marker Mode**—Fixed frequency, cursor lock.

  Fixed Frequency—Markers permanently positioned relative to a programmable reference frequency.

  Cursor Lock—Markers indexed to and follow position of the controllable cursor.
- **Trigger Modes**—Free Run, External, and Input. Input amplitude trigger thresholds, trigger slope, and pre- and post-trigger time delays are fully programmable.

  Free Run—A new measurement is initiated by completion of the previous measurement.

  External—A new measurement is initiated by a TTL pulse applied to the external trigger input.

  Input—A new measurement is initiated when the input signal meets the defined trigger level conditions. Triggering can be set to occur when the input reaches a user definable input level. Definable from 0 to ±100% of full scale range setting. Positive and negative levels and slopes can be set.
- **Trigger Delays**—
  Pre-Trigger—Up to 24,000 times the time resolution

  Post-Trigger—Up to 99,999,999 mS

NARROWBAND MAGNITUDE SPECTRUM (FFT) ANALYSIS
- **Start Frequency**—Preprogrammed between 0 and the maximum frequency.
- **Maximum Frequency**—Selected between 1 Hz (60 CPM) and 20 KHz (1200 KCPM).
- **Resolution**—Programmable 100, 200, 400, 800, 1600, 3200, and 6400 lines.
- **Frequency Accuracy**—0.01% of the frequency measured at the position of the display cursor.
- **Measurement Windows**—Hanning, Uniform, Flat Top.

  Hanning—Provides an amplitude accuracy/frequency resolution compromise. Useful for machine vibration measurements, general purpose and measurements using random noise.

  Uniform—Equal weighting of the time record for measuring transients, or mechanical response measurements.

  Flat Top—Provides optimum amplitude accuracy. Useful for calibration or machine vibration measurements using displacement probes in fluid-film bearings.

- **Window Flatness**—(scallop loss)

Flat Top	Hanning	Uniform
+0, -0.01 dB	+0, -1.5 dB	+0, -4.0 dB

- **Real Time Bandwidth**—

Operating Mode	Real Time Bandwidth	400-Line Spectra/sec
Single Display	400 Hz	1.0
Fast Averaging	520 Hz	1.3

- **Spectrum Functions**—Actuated by dedicated keys without departing analysis display.

  Markers ON/OFF; Freeze Display; Zoom IN/OUT; Save Data; Display Expand; Set 1xRPM (running frequency index for orders); Reset Measurement; Lin/Log; Shift Cursor

TIME WAVEFORM ANALYSIS
- **Time Domain Resolution**—

FFT Lines	Time Samples
100	256
200	512
400	1024
800	2048
1600	4096
3200	8192
6400	16384

VISUAL OBSERVATIONS
- **Type**—
  Coded Notes—Selected from list of up to 40 observed conditions.

  Plain Language—Entered through keypad, up to 42 characters per measurement record.

OUTPUT
- **Communications to Host Computer**—1200 to 38,400 baud, programmable.
- **Printer**—Direct printout of report lists and graphic spectra.

VIBRATION PICKUP
- **Model 6151 Handheld Pickup**—Frequency response (±5%) 2 Hz (120 CPM) to 5,000 Hz (300 KCPM).
- **Model 793 Accelerometer**—Frequency response (±5%) 2 Hz (120 cpm) to 5,000 Hz (300 KCPM); (±3dB) 1 Hz (60 CPM) to 15,000 Hz (900 KCPM).

PHYSICAL DATA
- **Size**—7.88 in. (20 cm) wide, 10.5 in. (26.7 cm) high, 2.5 in. (6.35 cm) deep.
- **Weight**—4.5 pounds (2.04 kg).
- **Temperature Range**—
  Operating—14 to +122°F (-10 to +50°C)
  Storage—14 to +140°F (-10 to +60°C)
- **Display**—
  Type—Supertwist Liquid Crystal (LCD) 256 by 128 pixels

  Viewable Area—4.84 inches (12.3cm) wide by 2.42 inches (6.1cm).

  Text—High contrast character set, 32 characters by 16 lines.

  Backlight—Turned on and off manually from keyboard.

  Contrast—Adjustable from keyboard.

  Overload and battery charge status displayed on screen.
- **Keyboard**—
  Thirteen (13) .55 inch (14.0mm) by .5 inch (16.5mm). ON/OFF, ENTER, MENU, ESCAPE, ARROW and CONTROL.

  Twenty-Four (24) .75 inch (19.1mm) by .65 inch (16.5mm) Alphanumeric.

  All keys are raised embossed with tactile feedback.
- **Power Supply**—
  1.5 amp hour rechargeable NiCad batteries in a removable cartridge.

  Onboard back-up power source to preserve memory, data and clock during battery change.

  Recharged automatically by the support module.

  Time between charges—8 hours of normal operation.

  Time to recharge from full discharge—5 hours.

5421-J AVENIDA ENCINAS
CARLSBAD, CA 92008 USA
619/438-6891
TELEX 910-997-3980
FAX 619-438-6895

Key Functions of the Model 2110 Analyzer

RPM/PHASE INPUT
Provides entry for once-per-rev pulse (TTL) signals to measure RPM.

OFF ROUTE
Allows measurements to be taken on machines, or at positions, that are not part of the preprogrammed route.

RS232 PORT
Provides entry for data communications between the 2110 and the host computer for all vibration or process signals.

ANALYZE
Enables the 2110 to function as a general-purpose signal analyzer for acquiring FFT spectra, time waveforms, overall signal amplitude, DC, or RPM measurements.

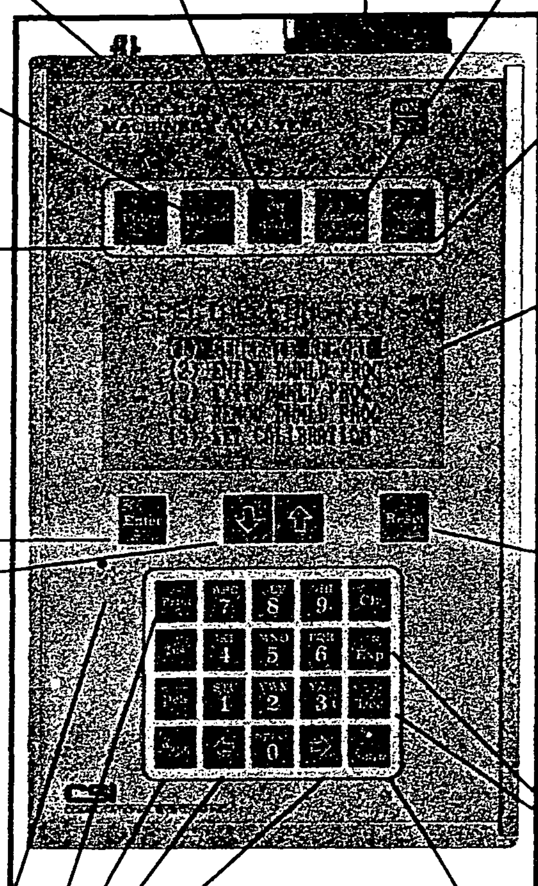
KEYPAD
Provides the user with the alphanumeric capability needed for the Off-Route mode, for entering data during route collection, and for making field notes.

UTILITY
Provides access to six functions that allow the user to set up operation parameters, indicate communications parameters, download routes into the 2110, select the measurement route, transfer data into the host computer, and enter the 2110 calibration mode.

ENTER
When in the data acquisition mode, initiates all data collection for the measurement point. In other operational modes, this button executes the selected menu choice.

JP/DOWN ARROWS
Allows the user to quickly move to any point on the measurement route. When depressed with graphics on the display, the full scale amplitude (vertical) is increased or decreased, as desired, to enhance the presentation.

ED
igh-intensity LED flashes, and ounds a beep to provide the user ith confirmation of keyboard entries.



NOTES
Provides a list of preprogrammed observations on the status of monitored equipment from which the user can choose. It is also used with the Keypad function to record personalized, free-form notations.

LCD DISPLAY
Wide-angle, backlit screen using "super-twist" graphics technology. Adjustable contrast. Resolution of 128 by 256 pixels. Viewable area is 2.31 by 4.69 inches.

RESET
Provides immediate return to Route Collection mode from any other mode, or aborts any measurements or keypad entries in progress.

EXPAND/DECREASE
Allows the user to expand or contract the scale of the horizontal axis to obtain a more detailed view of the peaks and baseline features on a curve.

CURSOR CONTROLS
(1) Arrows. Activate a graphical cursor that, when positioned on a spectrum or time waveform, read out the specific amplitudes or frequencies. (2) Print. Pressing this key provides an instant hardcopy when the 2110 is cabled to a dot matrix printer. (3) Page. Moves user within multiple pages of the same function.

MARK
Pressing the decimal key once provides a more accurate readout of frequency and amplitude at the current cursor position. Pressing the key a second time activates the harmonic cursors.

nstrument Shown at 45% of Actual Size

echnical Specifications

PUT SIGNALS

2 milliamp ICP-type power supply is provided inside the trument for powering sensors such as accelerometers, lometers and others. The power supply provides 2 mil-mperes constant current at 20 volts. Depending upon the be of input adapter used to connect the sensor, the ICP wer supply can be used or bypassed.

LL SCALE INPUT LEVEL

P used +/- 9 volts
e full scale vibration level depends upon the type of nsor used. Full scale vibration level is +/- 90 G's when using 100 millivolt per g accelerometer.

P bypassed +/- 18 volts
r small signals, full-scale range is lowered in binary steps m 1 to 512 for improved signal-to-noise ratio. Selection of oper full-scale range occurs automatically at the begin-ng of every analysis and is called autoranging.

out Impedance	200 KOhms

PUT SIGNAL TYPES

namic Signal	Single Channel
C Signals	Single Channel
M/Tach Signal	TTL Pulse
ypad Entry	Full alphanumeric capability
mperature Input	CSI infrared sensor or thermocouple

WER SUPPLY

e analyzer is powered by a 24-volt rechargeable nickel dmium battery pack with a capacity of 0.75 amphours. A charging module to support a spare battery pack is pro-ded with each Model 2110. The analyzer can be com-etely recharged in 12 to 14 hours and will operate from 7.5 10 hours on a full charge, depending on the operations ing performed. Data in the analyzer's memory is pre-ved for at least one week after the data collection is ibited due to a low battery.

ttery capacity	750 milliampere hours
ttery voltage	24 volts
charger current	50 milliamperes
charge time	12-14 hours

CHOMETER INPUT

tachometer input is provided for the purpose of meas-ng a once-per-rev pulse, thereby allowing the analyzer measure RPM and synchronous vibration and phase.

M Range	30 to 30,000 RPM
ch Input Level	TTL compatible (0 to +5 volt pulse)

FREQUENCY ANALYSIS

The frequency analysis range is adjustable from 0-10 Hz (lower limit) to 0-20,000 Hz (upper limit), and is variable in steps of 1, 2, 3, 4, 5, 6, 7, 8, 9, X10, X100, X1000, and X10,000. The number of spectral lines in the FFT can be selected as 100, 200, 400, 800, 1600, or 3200. A high-rolloff, seven-pole elliptical, anti-aliasing filter is used with a Bergland FFT algorithm to transform data to the frequency domain. The low frequency response is flat to DC. The number of FFT averages can be varied from 1 to 999.

DATA ANALYSIS TIME

Autoranging signal	1.0 to 3.0 seconds
100-line spectrum	0.2 seconds per average
200-line spectrum	0.3 seconds per average
400-line spectrum	0.7 seconds per average
800-line spectrum	1.5 seconds per average
1600-line spectrum	3.2 seconds per average
3200-line spectrum	7.1 seconds per average

DATA STORAGE CAPACITY

Data is stored in nonvolatile Random Access Memory (RAM). Depending on the mix selected, many more spectra than the maximums listed can be recorded.

Standard Memory	320 K bytes
Expanded Memory	832 K bytes

	Number of Spectra Stored	
Data Type	Standard Memory	Expanded Memory
Overall levels plus selected bands	3100	8200
100-line spectra	1200	3200
200-line spectra	820	2100
400-line spectra	500	1300
800-line spectra	280	730
1600-line spectra	150	400
3200-line spectra	80	200

ENVIRONMENTAL CONDITIONS

Temperature	15 to 120 degrees Fahrenheit -10 to 50 degrees Centigrade
Relative Humidity	0 to 95 percent non-condensing

AUTORANGING

The M2110 automatically scans the input signal for each measurement and sets the input range to maximize the dynamic resolution. The dynamic range is maintained at 72 decibels (12 bits).

CSi™

THE NEW MODEL 1325 SMART METER.

The Model 1325 Smart Meter— A new concept in portable data collectors.

TEC continues its leadership in providing machinery monitoring tools for predictive maintenance. Our new Model 1325 Smart Meter is both a portable data collector and a powerful diagnostic instrument that will satisfy your machine monitoring needs now and in the future. The innovative new Option Port* offers the user unlimited memory capacity and special programs on plug-in, credit card-sized Intelli-Cards. You add only the additional memory or new features that you need.

A third generation instrument, the Model 1325 Smart Meter is extremely easy to use and has a number of outstanding features. Vibration data acquired with the Model 1325 is compatible with data acquired using TEC's Model 1310 and 1320 Smart Meters. This upward compatibility allows you to use the Model 1325 in preventive maintenance programs that already use either of these TEC products. And TEC continues to offer its popular Model 1320 Smart Meter for users who do not require all the features of the Model 1325.

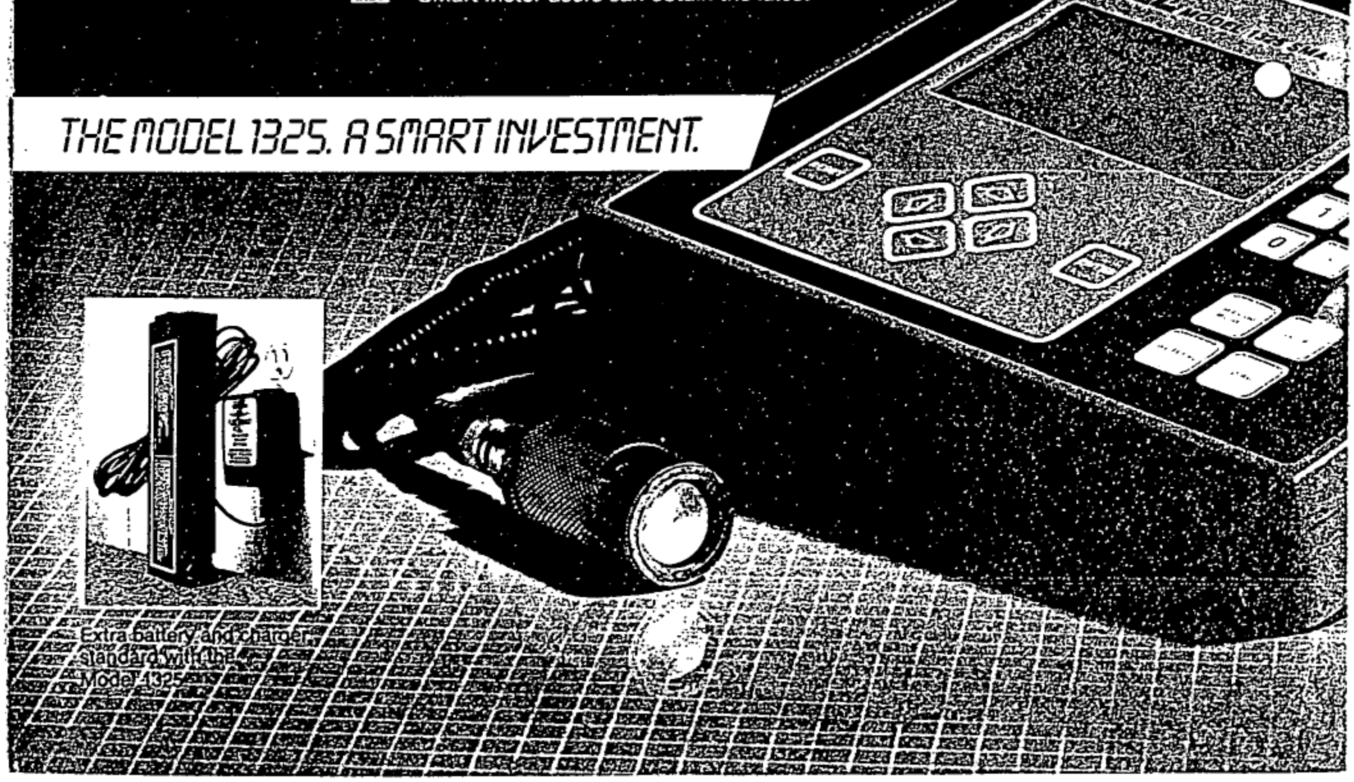
*patent pending

The fourth generation of Intelli-Trend software maximizes Model 1325 features.

The Model 1325 Smart Meter uses TEC's powerful, user-friendly Intelli-Trend software for machine condition reporting and accurate data and trend analysis. Our unique software gives you maximum benefits from the powerful Model 1325 Smart Meter.

Newest version of Intelli-Trend provided free to current users.

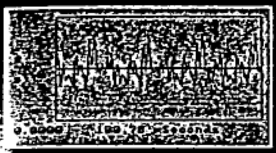
Current Model 1310 and Model 1320 Smart Meter users can obtain the latest version of Intelli-Trend at no additional cost with the purchase of the Model 1325. When you purchase products from TEC, you are assured of upward compatibility and protection from obsolescence.



Extra battery and charger standard with the Model 1325.

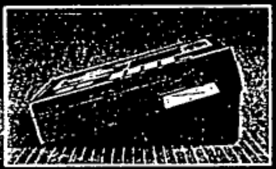
High-performance features of the Model 1325 Smart Meter.

- **Unlimited memory capacity** with unique Option Port and Intelli-Cards.
- **Easy-to-read display in all lighting conditions** with the large 2.4" x 5.0" high-contrast, supertwist, backlit LCD display.
- **Lightweight (5.5 lbs.) and handy** size for easy use in the factory.
- **Field-replaceable battery without memory loss** with battery-backed memory chips.
- **Accurate low-frequency data** obtained through low-noise analog electronics and user-selected, low-frequency cut off.
- **1600-line resolution** for more in-depth analysis capability.
- **High-performance 16-bit microprocessor** provides a 72 dB dynamic range and fast data acquisition and analysis.
- **Six user-selected narrow bands** to detect problems with specific machine elements.
- **Time trace capability** permits you to view, label and store time traces.
- **Time synchronous averaging** improves diagnostic capability.
- **Display of previous overall RMS** value along with current value to provide instant recognition of changes in vibration levels.
- **High-capacity rechargeable battery** provides for 24-hours of use under typical conditions.



Time waveform data can be viewed in the diagnostic mode.

Frequency domain data can be viewed as log, linear or dB spectrum plots in the diagnostic mode.



The Smart Meter is designed for both easy handling in the factory and easy viewing on the desktop.

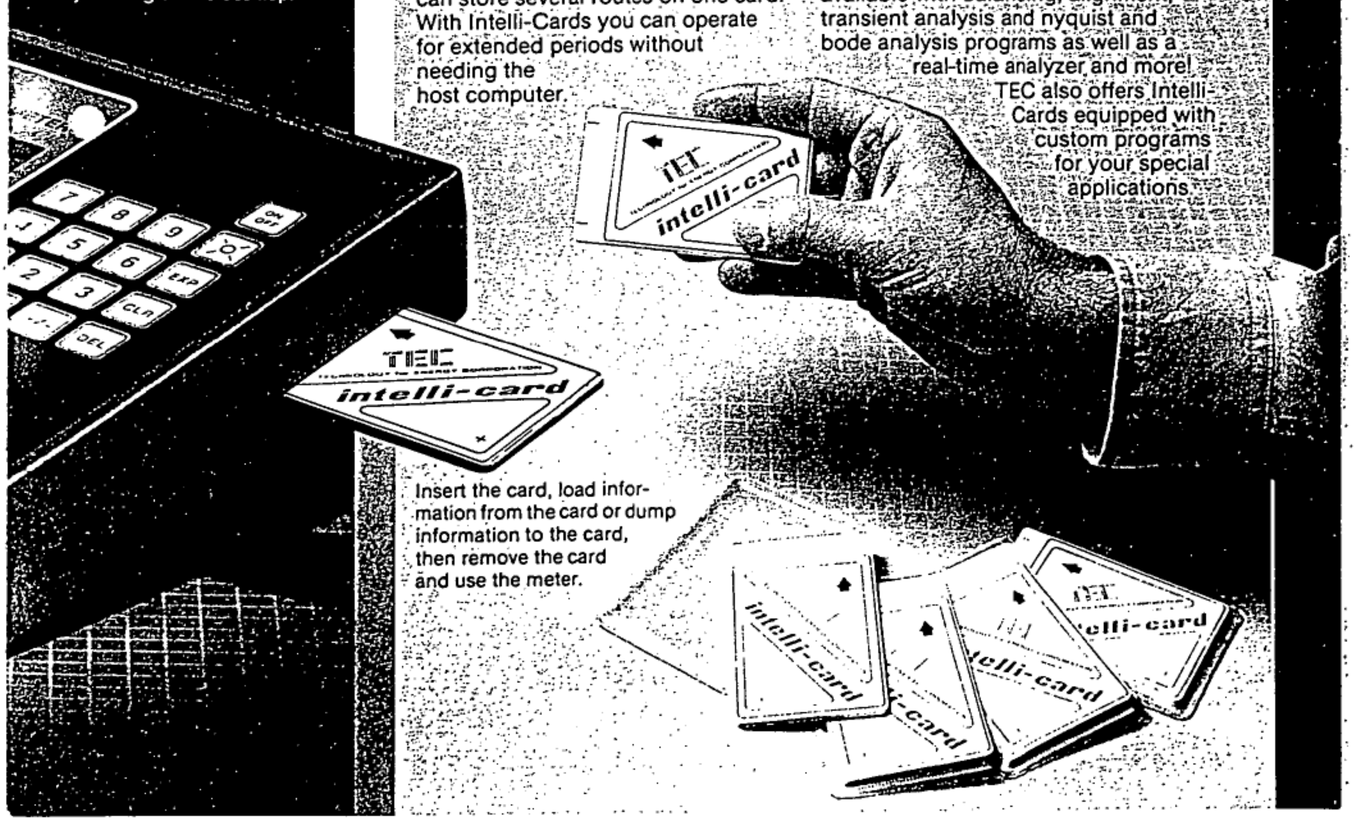
Intelli-Cards—
A new concept to expand the capability of the Smart Meter.

Unlimited memory capacity.

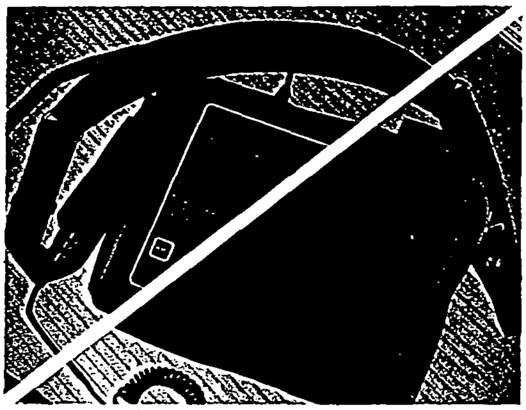
Memory Intelli-Cards allow you to acquire unlimited amounts of vibration data and full signatures. You can store several routes on one card. With Intelli-Cards you can operate for extended periods without needing the host computer.

Add optional In-Meter Programs.

Program Intelli-Cards let you accomplish special tasks with your 1325 Smart Meter. Intelli-Cards are available with balancing, alignment, transient analysis and nyquist and bode analysis programs as well as a real-time analyzer and more! TEC also offers Intelli-Cards equipped with custom programs for your special applications.



Insert the card, load information from the card or dump information to the card, then remove the card and use the meter.



A padded carrying case is standard with TEC Smart Meter. When the padded cover is removed, the meter can be operated through a transparent, plastic shield.

TEC's Technical Support Team.

Protect your investment with our experience.

At TEC, our number one priority is making sure you're able to get the most out of your machinery monitoring system. And the good thing about working with TEC is the fact that when you have a problem, you only make one call. We are committed to training you on how to use our products.

Our full-service support programs include:

- Pilot programs that let you experience the benefits of TEC's Smart Meter and Intelli-Trend software.
- Start-up support to assist you in getting your machinery monitoring program on the right track. This typically includes assistance in selecting which machines to monitor and in setting up your database.
- Training programs and seminars for your plant personnel. Choose from such topics as Basic Predictive Maintenance, Dynamics of Machine Train Operation, Basic Vibration Analysis Techniques, Advanced Vibration Analysis or Process Machinery Troubleshooting.
- Machinery Diagnostics Service at your plant to help you diagnose and cure your problem machines quickly.
- Machinery Monitoring services where TEC collects and analyzes your data and provides timely reports on the health of your machinery.

Join the growing list of satisfied companies who monitor their machinery the Smart way.

ECOTECH PTY LTD

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NEW SOUTH WALES
2/73 Albert Avenue, Chatswood 2067, Australia
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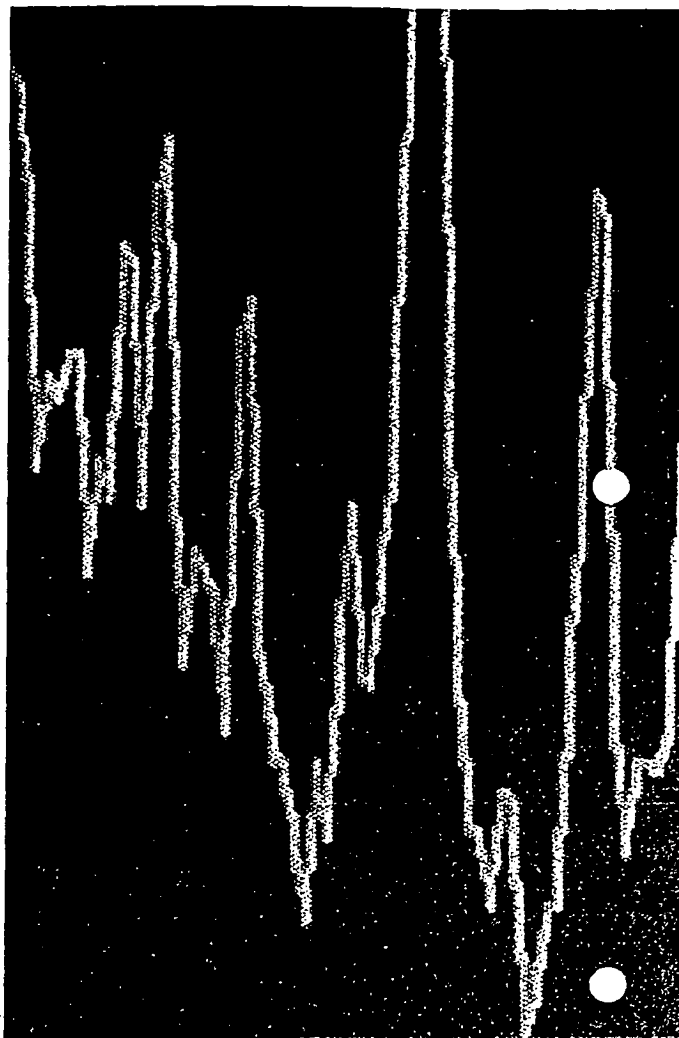


"Technology of the Future...Today."

TEC *Technology for Energy Corporation*

One Energy Center • P.O. Box 22996
10737 Lexington Drive • Knoxville, TN 37933-0996 USA

DATALOG

For use in conjunction with Brüel & Kjær Type 2513 Vibration Meter.

REID TECHNOLOGY

2513 Electronic DataLog

The DSIR 2513 Electronic DataLog is a purpose-designed instrument to be used in conjunction with the Brüel & Kjær Type 2513 hand-held vibration meter.
Interfaced to the vibration meter, the Electronic DataLog allows communication to and from a personal computer.
Pre-determined measurement routes may be set up on file and transferred to the Electronic DataLog by means of the software and interface supplied with the system.
The system prompts the operator with the measurement location. When the operator is satisfied with the value displayed on the vibration meter, he/she stores the value with a single key stroke and is prompted for the next measurement location.
On completion of a route the Electronic DataLog is connected to a personal computer and the collected vibration levels are transferred to a data base for trending and reporting.
For maintenance engineering staff already using the Brüel & Kjær 2513 Vibration Meter, major savings can be made in the time taken to collect data.
Errors in transferring field-recorded values onto the maintenance history files have virtually been eliminated.
Increase in trend level reports can be generated automatically by the system.
The time saving achieved by the use of the Electronic DataLog can allow maintenance staff to increase the frequency or number of measurements, or expand their measurement program into other areas of their plant.
For the engineer using vibration measurement for the first time, the system allows him/her to set up a program directly on a personal computer without the need for a costly, time-consuming manual system being implemented.

Software Specifications

The communication software is purpose-made for communicating with the 2513 Electronic DataLog and IBM XT or AT personal computers or compatible systems.
A special interface and software are available for the IBM PS2 system as an optional extra.
The communication software will only operate when the interface cable is connected to the PC serial communication port ONE or TWO.

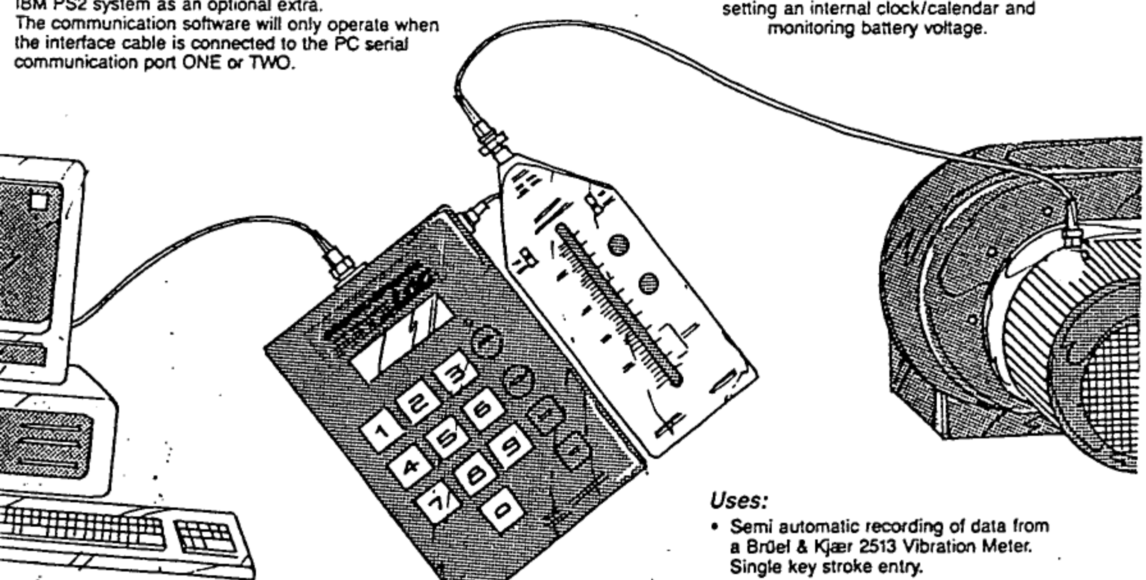
The software allows collected data to be transferred from the PC screen, then printed or stored as a file. It allows pre-determined route directories to be transferred from a PC to the 2513 Electronic DataLog.
Data acquired by the system can be further processed and displayed using a number of proprietory data base systems usually supplied with PC's.

Specifications

Data Storage	Up to 3000 sites
Power Supply	9V, 6xAA cells
Power Consumption	Log/Download 24mA Power down 60 microAmps 'LOW' battery indication at 6V Minimum operating voltage 5.5V
Rechargeable Batteries	NiCads may be used, but require external charger
Overall Dimensions	Height: 180mm (7in) Width: 130mm (5¹/₈in) Depth: 25mm (1in)
Weight	2kg, complete as illustrated (4.4lbs)
Display	16 characters x 2 lines
Keyboard	10-key telephone-type pad 0-9, plus ON, OFF, ENTER, EXIT
Interface	RS232 port at 1200 baud

Batteries must be removed while the Electronic DataLo is in storage!

Site information is entered via the keypad or downloaded from a terminal. The output of the B&K Vibration Meter is directly connected to an analog input and is displayed and logged accordingly. Stored data may be dumped via a 9-pin RS232 port at 1200 baud.
The Electronic DataLog 'learns' the route on the first walk through. On subsequent passes, the monitors will prompt the user with the previously learnt route.
There is provision for recalling and amending data, setting an internal clock/calendar and monitoring battery voltage.



Uses:

- Semi automatic recording of data from a Brüel & Kjær 2513 Vibration Meter. Single key stroke entry.
- Automatic prompting of pre-determined routes.
- Field entry of site data.

Features:

- Unique compatibility with Brüel & Kjær Type 2513.
- Matching robust slim line construction.
- Low energy consumption for long battery life.
- AT/XT compatibility.
- Complete with leather case, software and interface cable.
- Storage for up to 3000 measurement points.
- Non volatile memory.

REID TECHNOLOGY

Reid Technology Limited
Top Floor, 9c Union Street,
PO Box 1898, Auckland, New Zealand.
Fax: +64 9 392-285. Telephone: +64 9 796-011.

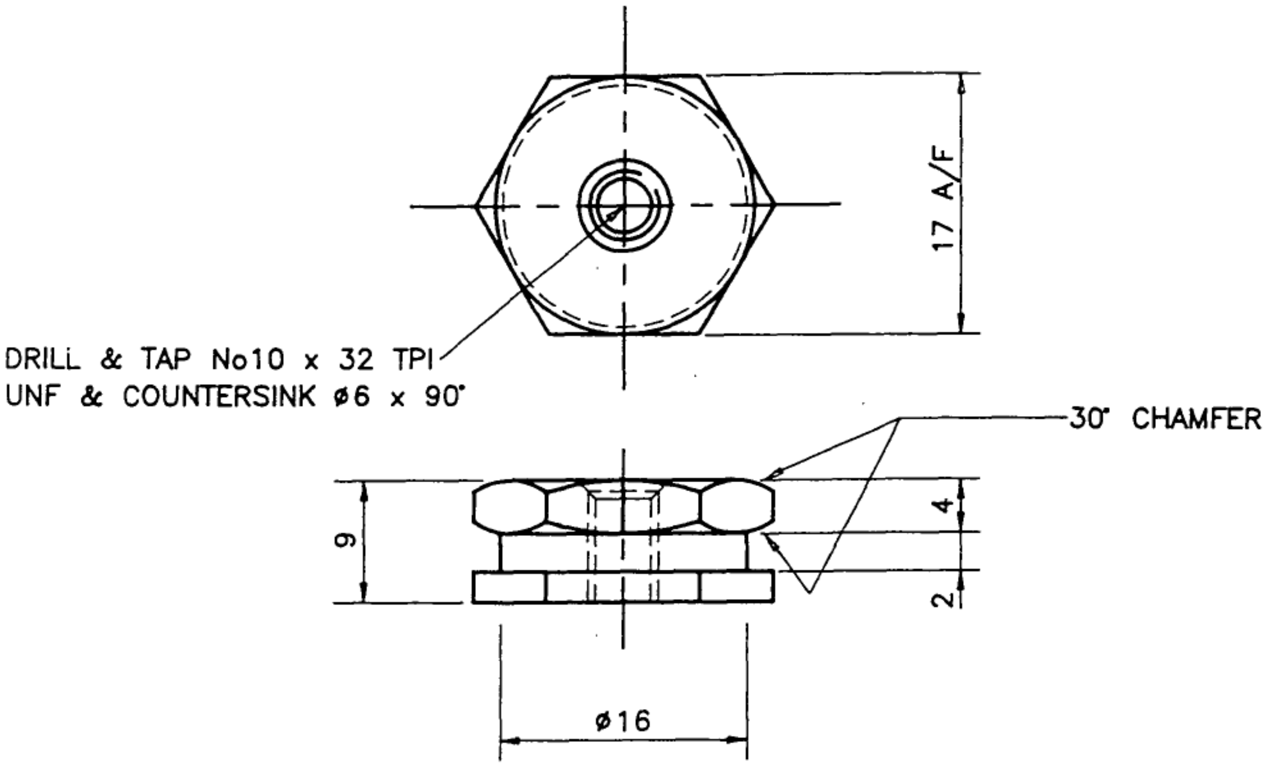
Machine Classifications   Date Jan. '90

Code	Meaning
Machine Type	
M	Motor
GB	Gearbox
Agi	Agitator
P	Pump (Any Type)
Mx	Mixer
Cs	Screw Compressor
Cr	Reciprocating Compressor
Bl	Blower (Vacuum or Pressure)
F	Fan
R	Refiner
W	Washer
Ch	Chipper
Sc	Screw (Feeder or Press)
Configuration	
D	Direct Drive
F	Fluid Coupling
B	Belt Drive
C	Chain drive
S	Straddle
O	Overhung
V	Vertical
H	Horizontal
I	Inclined
Size/Stiffness	
L.S	Large Stiff
L.F	Large Flexible
M.S	Medium Stiff
M.F	Medium Flexible
S.S	Small Stiff
S.F	Small Flexible

Example of code

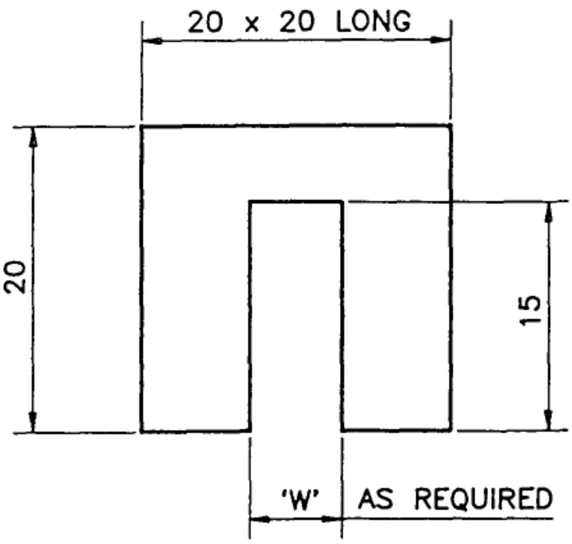
Machine Type/Configuration/Size and Stiffness

Eg. M,GB,Agi/D,O/L.S



STUD — BRASS OR ST.STL.

(2:1)



MOUNTING BLOCK — BRASS OR ST.STL.

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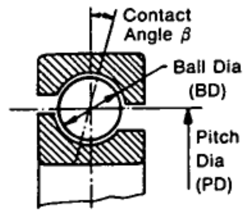
REVISION ① DIMS CHANGED & MTG BLOCK ADDED DDK 16/5/90 J.A.H

APPM	ASSOCIATED PULP & PAPER MILLS PAPER DIVISION WESLEY VALE, TAS. 7310 A DIVISION OF NORTH BROKEN HILL LTD.			MISCELLANEOUS DIVISION VIBRATION MONITORING QUICK CONNECT STUD & MOUNTING BLOCK DETAILS	(v)Y-C-15
	DRAWN	DDK	CHECKED		REV 1
	DATE	3/1/90	APPROVED ALP		SHEET — CONT

Vibration Trouble-Shooting Chart

Nature of Fault	Frequency of Dominant Vibration (Hz=rpm/60)	Direction	Remarks
Rotating Members out of Balance	1 × rpm	Radial	A common cause of excess vibration in machinery
Misalignment & Bent Shaft	Usually 1 × rpm Often 2 × rpm Sometimes 3&4 × rpm	Radial & Axial	A common fault
Damaged Rolling Element Bearings (Ball, Roller, etc.)	Impact rates for the individual bearing component* Also vibrations at high frequencies (2 to 60 kHz) often related to radial resonances in bearings	Radial & Axial	Uneven vibration levels, often with shocks. * Impact-Rates:  **Impact Rates f (Hz)** For Outer Race Defect $f(Hz) = \frac{n}{2} f_r \left(1 - \frac{BD}{PD} \cos\beta\right)$ For Inner Race Defect $f(Hz) = \frac{n}{2} f_r \left(1 + \frac{BD}{PD} \cos\beta\right)$ For Ball Defect $f(Hz) = \frac{PD}{BD} f_r \left[1 - \left(\frac{BD}{PD} \cos\beta\right)^2\right]$ n = number of balls or rollers f_r = relative rev./s between inner & outer races
Journal Bearings Loose in Housing	Sub-harmonics of shaft rpm, exactly 1/2 or 1/3 × rpm	Primarily Radial	Looseness may only develop at operating speed and temperature (e.g. turbomachines).
Oil Film Whirl or Whip in Journal Bearings	Slightly less than half shaft speed (42% to 48%)	Primarily Radial	Applicable to high-speed (e.g. turbo) machines.
Hysteresis Whirl	Shaft critical speed	Primarily Radial	Vibrations excited when passing through critical shaft speed are maintained at higher shaft speeds. Can sometimes be cured by checking tightness of rotor components.
Damaged or Worn gears	Tooth meshing frequencies (shaft rpm × number of teeth) and harmonics	Radial & Axial	Sidebands around tooth meshing frequencies indicate modulation (e.g. eccentricity) at frequency corresponding to sideband spacings. Normally only detectable with very narrow-band analysis and cepstrum
Mechanical Looseness	2 × rpm		Also sub- and interharmonics, as for loose Journal bearings
Faulty Belt Drive	1, 2, 3 & 4 × rpm of belt	Radial	The precise problem can usually be identified visually with the help of a stroboscope
Unbalanced Reciprocating Forces and Couples	1 × rpm and/or multiples for higher order unbalance	Primarily Radial	
Increased Turbulence	Blade & Vane passing frequencies and harmonics	Radial & Axial	Increasing levels indicate increasing turbulence
Electrically Induced Vibrations	1 × rpm or 1 or 2 times synchronous frequency	Radial & Axial	Should disappear when turning off the power

Vibration trouble-shooting chart.

Table of Criteria for Bearing Vibration Measurements (10-10 000 Hz)

Extracted from Canadian Government Specification CDA/MS/NVSH 107: "Vibration Limits For Maintenance".

Measure overall velocity RMS and allow for the following machine types:	FOR NEW MACHINES				FOR WORN MACHINES (full speed & power)			
	Long life[1]		Short life[2]		Check (recondition) level[3]		Recondition to new (Oct. analysis)[4]	
	VdB*	mm/s	VdB*	mm/s	VdB*	mm/s	VdB*	mm/s
Gas Turbines								
(over 20,000 HP)	138	7,9	145	18	145	18	150	32
(6 to 20,000 HP)	128	2,5	135	5,6	140	10	145	18
(up to 5,000 HP)	118	0,79	130	3,2	135	5,6	140	10
Steam Turbines								
(over 20,000 HP)	125	1,8	145	18	145	18	150	32
(6 to 20,000 HP)	120	1,0	135	5,6	145	18	150	32
(up to 5,000 HP)	115	0,56	130	3,2	140	10	145	18
Compressors								
(free piston)	140	10	150	32	150	32	155	56
(HP air, air cond.)	133	4,5	140	10	140	10	145	18
(LP air)	123	1,4	135	5,6	140	10	145	18
(refridge)	115	0,56	135	5,6	140	10	145	18
Diesel Generators	123	1,4	140	10	145	18	150	32
Centrifuges, Oil Separators	123	1,4	140	10	145	18	150	32
Gear Boxes								
(over 10,000 HP)	120	1,0	140	10	145	18	150	32
(10 to 10,000 HP)	115	0,56	135	5,6	145	18	150	32
(up to 10 HP)	110	0,32	130	3,2	140	10	145	18

Measure overall velocity RMS and allow for the following machine types:	FOR NEW MACHINES				FOR WORN MACHINES (full speed & power)			
	Long life[1]		Short life[2]		Check (recondition) level[3]		Recondition to new (Oct. analysis)[4]	
	VdB*	mm/s	VdB*	mm/s	VdB*	mm/s	VdB*	mm/s
Boilers (Aux.)	120	1,0	130	3,2	135	5,6	140	10
Motor Generator Sets	120	1,0	130	3,2	135	5,6	140	10
Pumps								
(over 5 HP)	123	1,4	135	5,6	140	10	145	18
(up to 5 HP)	118	0,79	130	3,2	135	5,6	140	10
Fans								
(below 1800 rpm)	120	1,0	130	3,2	135	5,6	140	10
(above 1800 rpm)	115	0,56	130	3,2	135	5,6	140	10
Electric Motors								
(over 5 HP or below 1200 rpm)	108	0,25	125	1,8	130	3,2	135	5,6
(upto 5 HP or above 1200 rpm)	103	0,14	125	1,8	130	3,2	135	5,6
Transformers								
(over 1 kVA)	103	0,14	–	–	115	0,56	120	1,0
(1 kVA or below)	100	0,10	–	–	110	0,32	115	0,56

* Ref. 10^{-6} mm/s. Originally an older specification for VdB gave values 20 dB smaller than those found here. (Due to a different dB reference level used.)

1) Long life is approximately 1000 to 10000 hours.

2) Short life is approximately 100 to 1000 hours.

3) When this level is reached, service is called for. Alternatively perform frequent octave analysis and refer to next column.

4) When this level is exceeded in any octave band repair immediately.

Table of generally acceptable vibration levels for both new and worn machines.

These values are for use when setting initial Alarm Limits and should be refined to suit each individual machine.

<u>Appendix 2</u>

(i) Cutaway of Stal-Laval 4 MW Steam Turbine at Wesley Vale.

(ii) Turbine Oil and Water system schematic.

(iii) Key to figures 6.1 and 6.7.

(iv) Typical Shellcheck oil analysis report.

(v) Turbine vibration standards.

(vi) Balance grades as per ISO 1940 (1973).

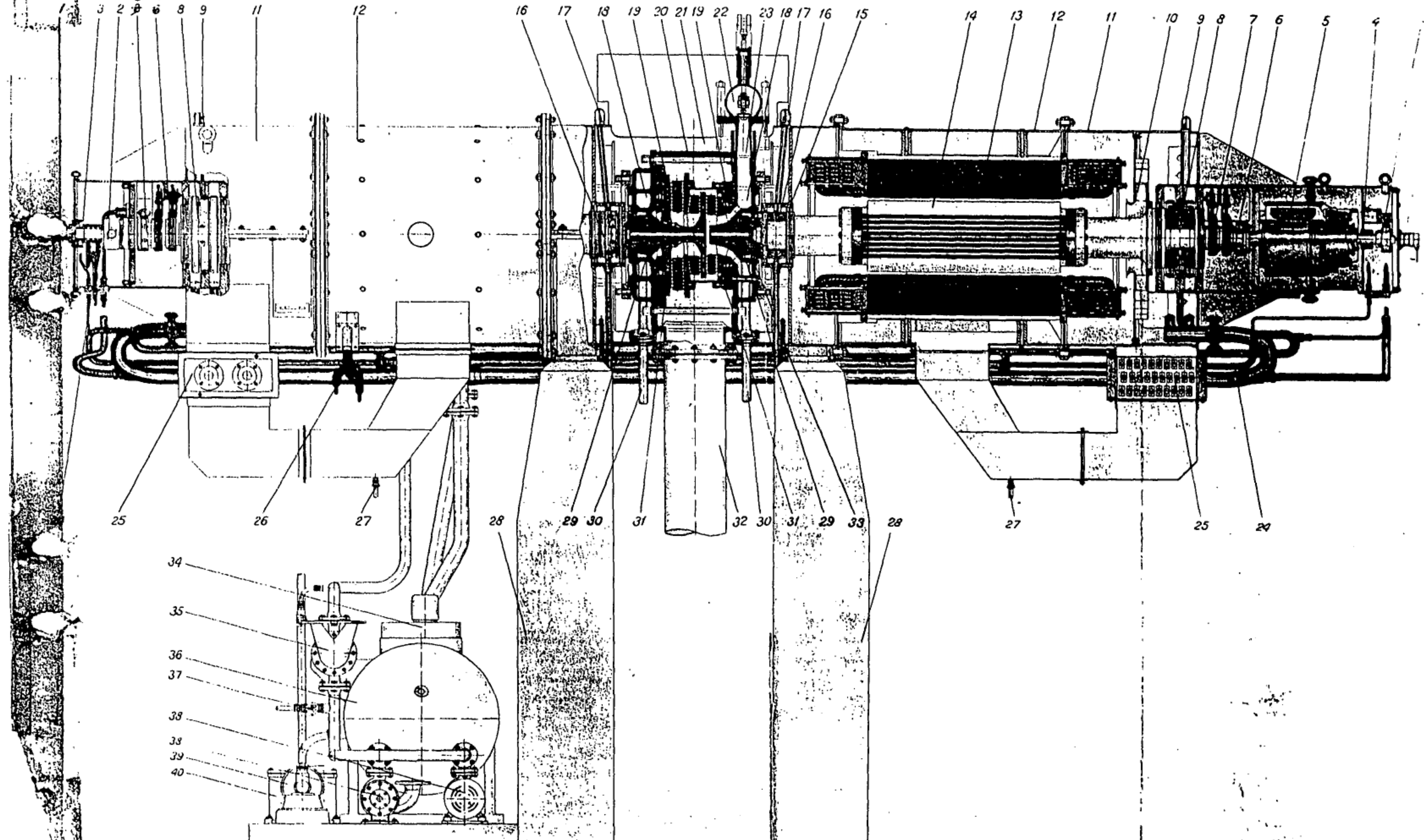
(vii) One-order vibration trend plots for the turbine after balancing.

Key to figure 6.1.

a. Oil to bearings.
b. Oil to governing equipment.
c. Drain oil from governing equipment and bearings.
d. Air from bearings.
1. Oil tank.
2. Oil level sight glass.
3. Oil vapor fan. Used to maintain a slight vacuum in the oil tank.
4. A.C. motor driven lubricating oil pump.
5. Stand-by pump (Not used at W.V.).
6. Emergency lubricating oil pump.
   a. Electric motor (Not used at W.V.).
   b. Steam turbine.
7. Duplex lubricating oil filter.
8. a. Oil cooler
   b. Optional cooler (Not used at W.V.).
9. A.C. motor driven governing oil pump.
10. Stand-by pump for 9 (Not used at W.V.).
11. Emergency governing oil pump.
    a. Electric motor (Not used at W.V.).
    b. Steam turbine.
12. Duplex governing oil filter.

Key to figure 6.7.

1. Filter body.
2. Filter element, comprising items 9 and 10.
3. Centrebolt.
4. Changeover valve.
5. Changeover valve handle.
6. Air bleed valve.
7. Top cover.
8. Drain plug.
9. Support tube.
10. Filter cloth.


1 3 2 6 7 8 9 11 12 16 17 18 19 20 21 19 22 23 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4
25 26 27 28 29 30 31 32 30 31 29 33 28 27 25 24
34
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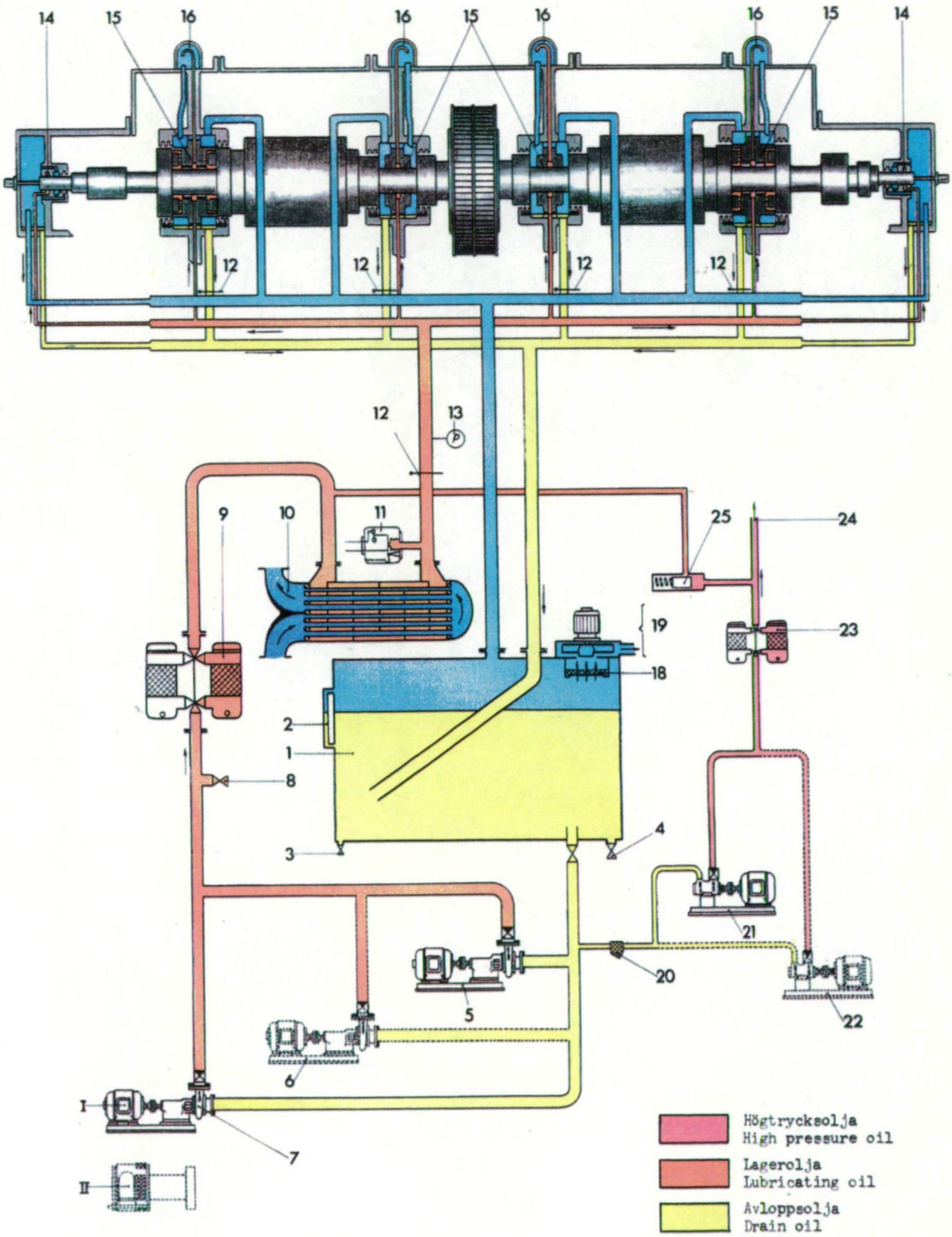


	Högtrycksolja High pressure oil
	Lagerolja Lubricating oil
	Avloppsolja Drain oil
	Vatten Water
	Luft Air

L CIRCUIT (for type 12, 15 and
7 turbines)

.) Oil tank. The drain line is located a relatively long distance away from the suction line. By this means the oil is effectively dearated and impurities are allowed to settle out before the oil is pumped back into the circuit.

2) Oil level sight glass.

3) Sampling valve.

4) Valve for draining remaining oil and for connecting an oil separator or other form of purifier. (See point 8).

5) A.C. motor driven main lubricating oil pump.

6) Optional extra: Provision of second pump identical to that specified in point 5. The pumps are normally connected to separate power supply sources. Only one of the pumps is normally in operation whilst the other is on standby duty.

7) Emergency lubricating oil pump. When the plant is in operation, the emergency pump is started and stopped automatically by pressure switch 11a. By this means the supply of oil to the bearings is assured. The emergency oil pump may be driven by:

☐ I) a D.C. motor or

☒ II) a steam turbine

8) Drain valve. To drain the oil tank, this valve should be opened and the lubricating oil pump 5 should be started. The remaining oil can be drained through valve 4.

9) Duplex lubricating oil filter.

10a) Oil cooler.

10b) Optional extra: Provision of an additional oil cooler. Changing over from one cooler to the other may be carried out by means of interconnected change-over valves.

11) Pressure switches.

a) When the oil pressure rises to the preset value (the main lubricating oil pump supplies the oil demand) this pressure switch will stop the emergency oil pump. If the oil pressure should fall to the preset value (below the level at which (b) operates) another pressure switch trips the turbine. Simultaneously the emergency oil pump 7 is started.

b) If the oil pressure should fall to the preset value, this pressure switch will start the main lubricating oil pump (5 or 6) which is on standby duty.

☐ c) Pressure switch for H.P. oil (not shown on the figure). If the H.P. oil pressure should fall to the preset value, this pressure switch will start the governing oil pump (20 or 21) which is on standby duty.

12) Capillary tube thermometers for oil before and after the bearings.

13) Pressure gauge.

14) Journal bearings for governor and exciter shafts.

15) Generator bearing. This is a combined thrust and journal bearing.

16) Oil sight glass.

17) Turbine bearing. This is a journal bearing of the three-lobe type.

18) Filter which separates the oil from the vapour extracted by fan 19.

19) Oil vapour extractor fan. This maintains a slight vacuum in the oil tank, bearing housings and the governing compartment of the turbine control desk. By this means the risk of oil leakage is eliminated. The fan is connected in such a manner that it will be in operation whenever one of the oil pumps is operative.

20) Suction strainer for governing oil pumps.

21) A.C. motor driven governing oil pump which delivers oil at a higher pressure than the lubricating oil. Under steady conditions the pump delivers an sppreciable excess flow which is discharged into the lubricating oil circuit through the overflow valve 25.

22) Optional extra equipment in accordance with one of the following alternatives:

☐ a) Provision of a second A.C. motor driven pump identical to that specified in point 20. The pumps are generally connected to separate power supply sources. Only one pump is normally in operation whilst the other is on standby duty.

☒ b) Provision of a D.C. motor steam driven governing oil pump as a standby for the pump specified in point 21.

23) Duplex governing oil filter.

24) H.P. oil to governing and tripping circuits.

25) Overflow valve.

SHELLCHECK OIL ANALYSIS - SHELL NEWPORT LABORATORIES

ROM SHELLCHECK NEWPORT LABORATORY
O A.P.P.M. BURNIE. TAS. ATTN. DAVID BURT. FAX NO. 004 3[redacted]2 237202

EF NPT0020010 17/11/88

TTENTION DA[redacted]RT Power House

SHELLCHECK OIL ANALYSIS

ESCRIPTION		TURBO ALT. T-40				TURBO ALT T-41				
AKE		S.LAV				S.LAV				
ODEL		DSM 1244				DSM 1244				
ERIAL NO		T 40				T 41				
OMPARTMENT		TURBO				TURBO				
IL TYPE		TURBO T 46				TURBO T 46				
OOLANT										
IL ADDED		200				200				
RS/KM ON OIL		5050 HRS				5050 HRS				
OTAL HRS/KM		25700 HRS				25700 HRS				
EAR METALS (P.P.M)										
		CURRENT	(PREVIOUS)			CURRENT	(PREVIOUS)			
ATE SAMPLED		03/11 1988	08/10 1987	10/04 1987	00/00 1900	03/11 1988	08/10 1987	10/04 1987	00/00 1900	
RON	FE	7	(3	L1	)	9	(4	L1	)	
HROMIUM	CR	5	(1	L1	)	5	(2	1	)	
ILICON	SI	5	(1	L1	)	5	(1	L1	)	
OPPER	CU	6	(2	1	)	4	(4	1	)	
EAD	PB	L1	(1	2	)	L1	(L1	L1	)	
ODIUM	NA	L1	(L1	L1	)	L1	(L1	L1	)	
IN	SN	L1	(L1	1	)	L1	(L1	2	)	
ISC AT 40		47.2	(46.5	45.4	)	47.2	(46.2	45.2	)	
ATER PCT		L.02	(L.02	L.02	)	L.02	(L.02	L.02	)	
AN MGKOH/G		.09	(.04	.14	)	.11	(.04	.13	)	
PPEARANCE		NORM.	(NORM.	NORM.	)	NORM.	(NORM.	NORM.	)	
DOUR		NORM.	(NORM.	NORM.	)	NORM.	(NORM.	NORM.	)	

OMMENTS

URBO T 40
ESULTS NORMAL.

URBO T 41
ESULTS NORMAL.

VIBRATION CHECKING of STAL-LAVAL turbines

Replaces DO 3216-4 and KM 20E

1. General

Continuous vibration checking on a turbine affords the possibility of detecting serious disturbances at an early stage. Thus to-day it has become a normal routine in all power plants. The measurements may be made with panel instruments or with portable service instruments. Reliable supervision requires a continuous record of the vibration, which should be filed together with other operating data.

Special steps need only be taken when abnormal changes occur whereas changes in amplitude related to starting up or to changes in load need not necessarily be a cause for concern once the normal behaviour of the turbine is known.

2. Causes of vibration

Vibration in stationary and rotating parts is usually caused by out-of-balance.

If during normal operating conditions the vibrations have increased slowly over a long period of time, the reason is usually increased out-of-balance due to deposits or irregular wear (water erosion).

This type of vibration increase is not so serious, and comparatively large vibrations may be permitted over a short period. However they should not exceed the values stipulated by VDI, see page 2.

Faults resulting in rapid changes in the vibration amplitude and deviations from the normal behaviour of the turbine indicate a serious deterioration in the operational conditions of the unit, even though the amplitude may be still within the permissible range.

The reason for this can be a serious fault in the turbine, such as heavy deposits in the blade system, blade failure, mechanical or electrical rotor faults etc. An investigation should be started immediately.

Increased vibration after overhauls may depend on changes in the alignment of the couplings. Alignment and balancing as outlined in K-2095-1 should be made.

As a basis for the investigation of the cause of the disturbance and what steps to be taken, the vibration measurements and a continuous operational record should comprise the following information:

a. During what length of time has the rise in vibration above normal level been observed?

b. Can the rise in vibration be located to a certain part of the turbine? Are there measurable vibrations in fundamental parts such as bearings and turbine casing?

c. Does the vibration vary with the operating conditions e.g. between no-load and load, with the steam temperature or with the generator temperature (field current)?

d. Is the vibration exceptionally high at rated speed?

e. Does a peak in vibration occur immediately after start-up and when load is applied?

f. Is it possible that the increase in vibration results from a short-circuit, slugs of water, high oil temperature etc. Erectors and service personnel should always carry a vibrometer. Vibrometers are available from our representatives or in Finspång.

3. Record of vibrations

For normal operating conditions the stipulations laid down in VDI 2056 of Oct. 1964 are to be followed.

For turbines operating at constant speed the magnitude of the vibration should be expressed in vibrational amplitude, whereas for turbines operating at variable speed it is more convenient to use vibrational speed, V mm/s, which will give the same borderline values in the diagrams on page 2 irrespective of the speed of the turbine.

The vibrational speed is the effective value of the speed of the vibration

$$V_{eff} = \frac{\omega \cdot A}{\sqrt{2}} \approx 0{,}074 \cdot n \cdot A$$

It should be noted that these recommendations refer to measuring points located at functionally important points such as the generator bearings, and not at the outer ends.

Thus rapid changes in the vibrational amplitude are more decisive than the absolute magnitude of the amplitude when determining a suitable operating level.

4. Measuring points to be referred to in reports

Abnormal vibrations should be reported immediately to STAL-LAVAL who decide what steps are to be taken. In order to obtain uniform reference points in reports the measuring points should be located and numbered according to form F 592 in the case of STAL-turbines, F 595 for gas turbines and F 596 for de LAVAL-turbines.

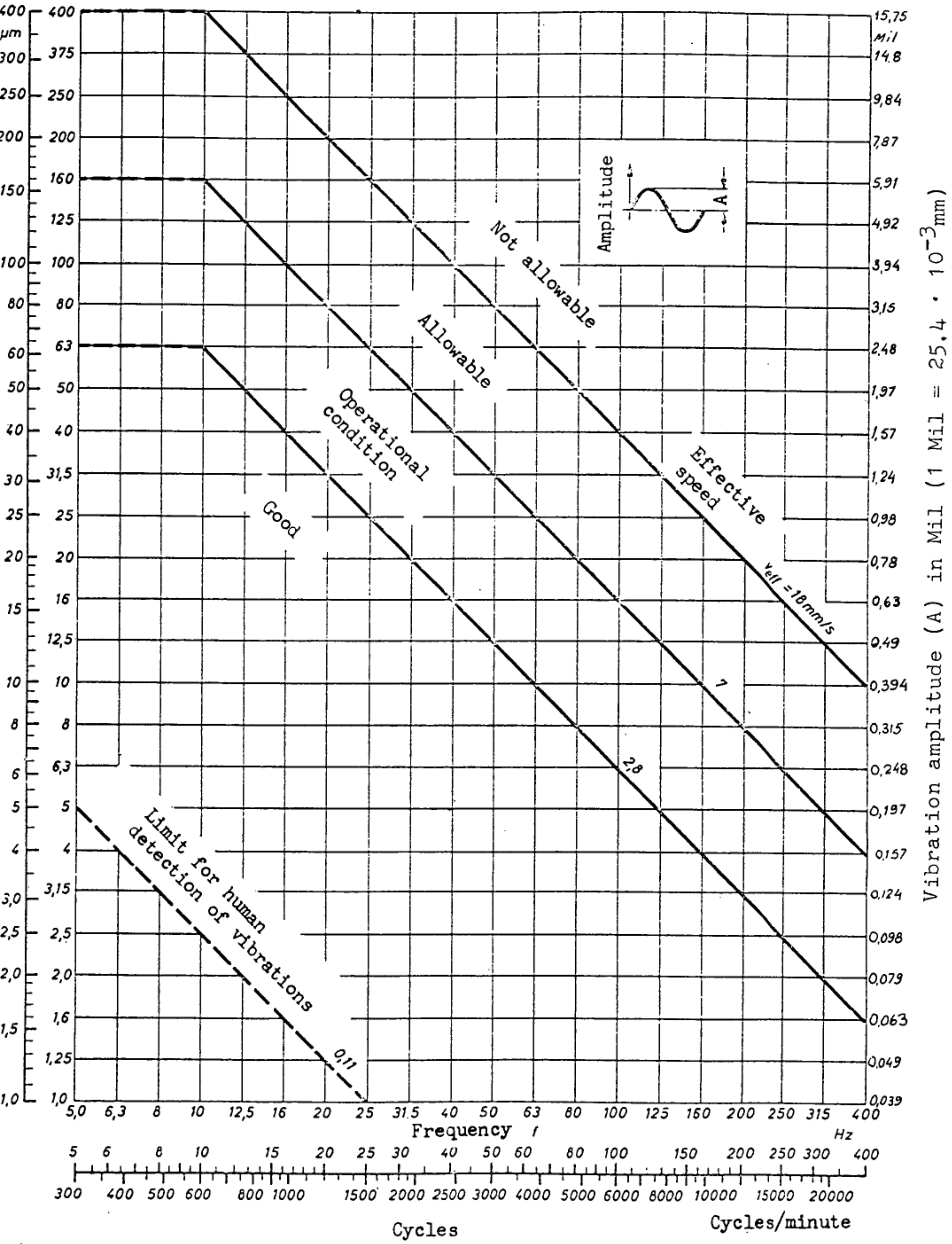
For the purpose of studying the changes of the vibrations measurements at certain important points are sufficient.

All the vibration readings reported to STAL-LAVAL have to be half peak to peak values.

Besides the recorded values this report should also contain information as to when the turbine was started as well as other special operating data as outlined in paragraph 2.

Number and direction of measurement may be stated in cables e.g. for STAL-turbines 1H, 3V etc., for de LAVAL and Gas turbines 1X, 3Y or 4Z.

VIBRATION CHECKING of STAL-LAVAL turbines



Balancing Grades for Various Groups of Representative Rigid Rotors

Quality grade G	e_{ω} (1) (2) mm/sec	Rotor types – General examples
G 4000	4000	Chrankshaft-drives (3) of rigidly mounted slow marine diesel engines with uneven number of cylinders (4).
G 1600	1600	Crankshaft-drives of rigidly mounted large two-cycle engines.
G 630	630	Crankshaft-drives of rigidly mounted large four-cycle engines. Crankshaft-drives of elastically mounted marine diesel engines.
G 250	250	Crankshaft-drives of rigidly mounted fast four-cylinder diesel engines (4).
G 100	100	Crankshaft-drives of fast diesel engines with six and more cylinders (4). Complete engines (gasoline or diesel) for cars, trucks and locomotives (5).
G 40	40	Car wheels, wheel rims, wheel sets, drive shafts. Crankshaft-drives of elastically mounted fast four-cycle engines (gasoline or diesel) with six and more cylinders(4). Crankshaft-drives for engines of cars, trucks and locomotives.
G 16	16	Drive shafts (propeller shafts, cardan shafts) with special requirements. Parts of crushing machinery. Parts of agricultural machinery. Individual components of engines (gasoline or diesel, for cars, trucks and locomotives. Crankshaft-drives of engines with six and more cylinders under special requirements.
G 6.3	6.3	Parts of process plant machines. Marine main turbine gears (merchant service). Centrifuge drums. Fans. Assembled aircraft gas turbine rotors. Fly wheels. Pump impellers. Machine-tool and general machinery parts. Normal electrical armatures. Individual components of engines under special requirements.
G 2.5	2.5	Gas and steam turbines, including marine main turbines (merchant service). Rigid turbo-generator rotors. Rotors. Turbo-compressors. Machine-tool drives. Medium and large electrical armatures with special requirements. Small electrical armatures. Turbine-driven punps.
G 1	1	Tape recorder and phonograph (gramophone) drives. Grinding-machine drives. Small electrical armatures with special requirements.
G 0.4	0.4	Spindles, discs, and armatures of precision grinders. Gyroscopes.

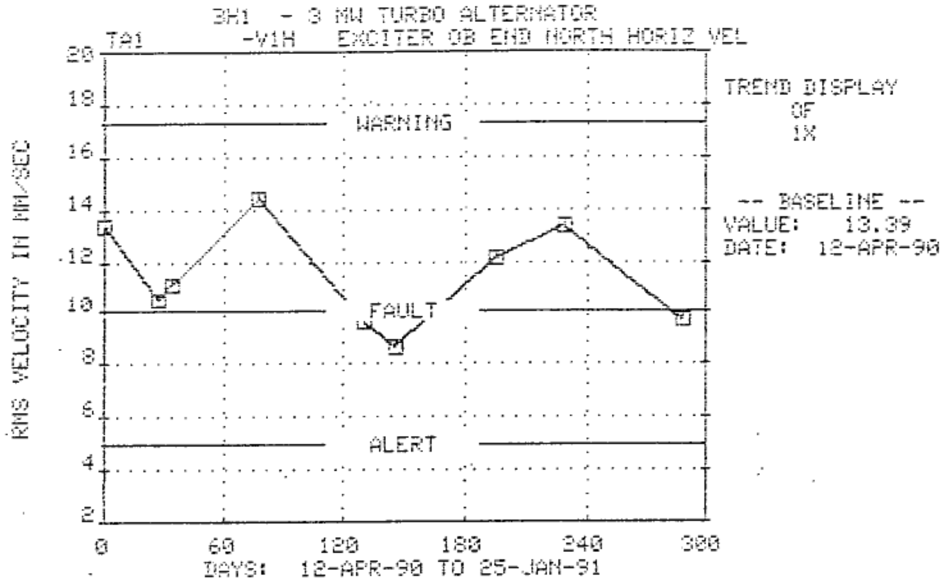
Notes:

1. $\omega = 2\pi n/60 \approx n/10$, if n is measured in revolutions per minute and ω in radians per second.
2. In general, for rigid rotors with two correction planes, one half of the recommended residual unbalance is to be taken for each plane; these values apply usually for any two arbitrarily chosen planes, but the state of unbalance may be improved upon at the bearings. For disc-shaped rotors the full recommended value holds for one plane.
3. A crankshaft-drive is an assembly which includes the crankshaft, a flywheel, clutch, pulley, vibration damper, rotating portion of connecting rod, etc.
4. For the present purposes, slow diesel engines are those with a piston velocity of less than 9 m/s; fast diesel engines are those with a piston velocity of greater than 9 m/s.
5. In complete engines the rotor mass comprises the sum of all masses belonging to the crankshaft-drive described in footnote 3 above.

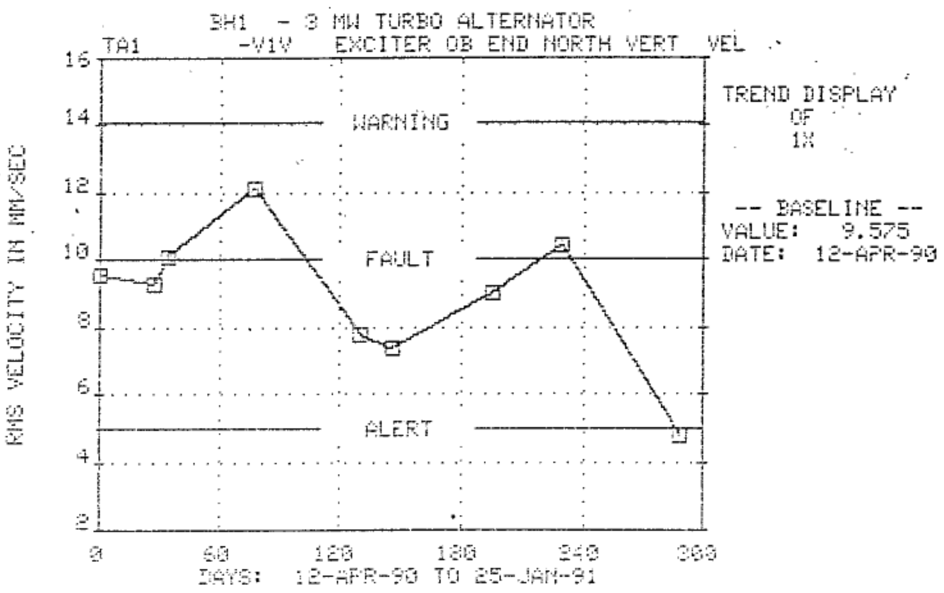
800624

Maximum residual unbalance corresponding to recommended Balance Quality Grades, G, as laid down in ISO 1940 (1973)

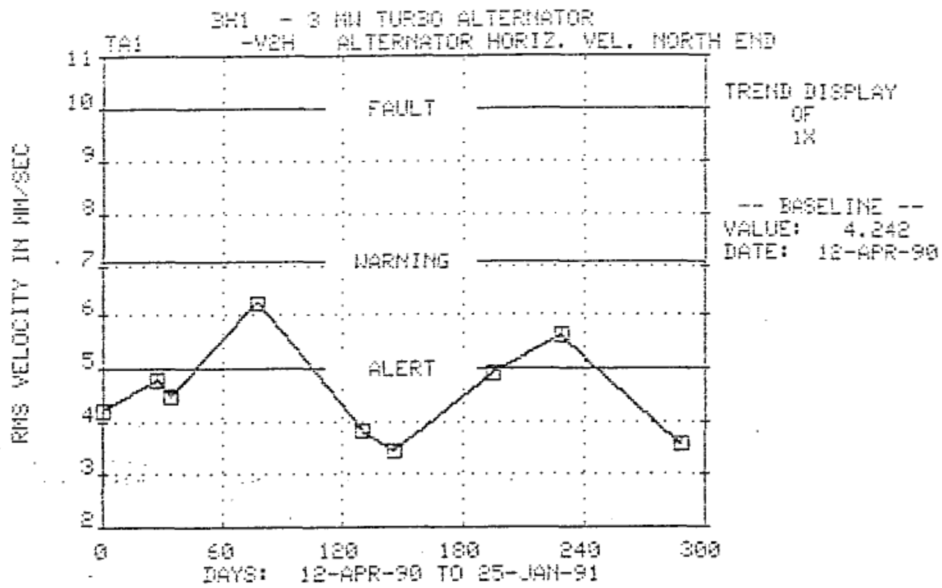
Balance grades for rigid rotors.



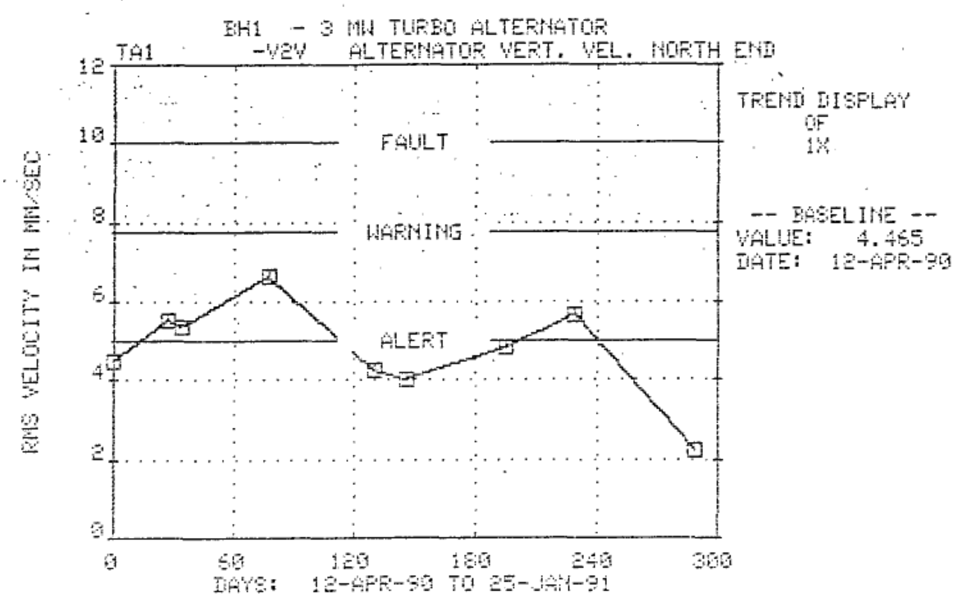
A2-1 Trend plot of the horizontal velocity vibration readings on the outboard end of the exciter.



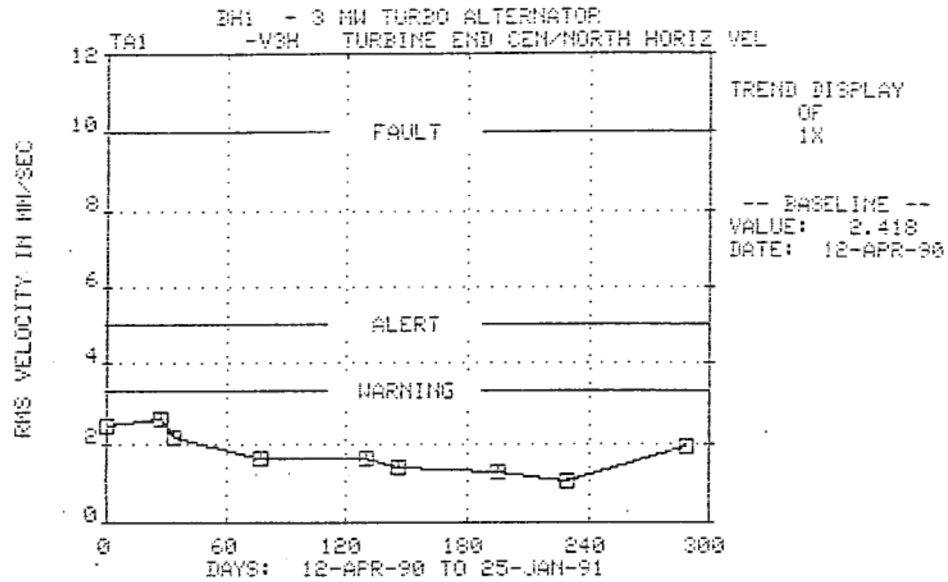
A2-2 Trend plot of the vertical velocity vibration readings on the outboard end of the exciter.



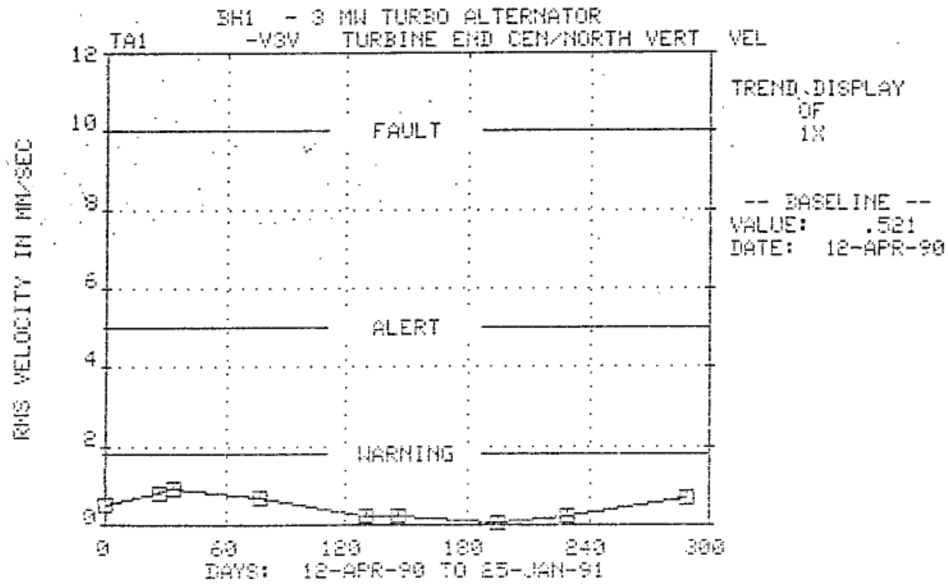
A2-3 Trend plot of the horizontal velocity vibration readings at the outboard bearing of the Northern alternator. This is the closest journal bearing to the exciter.



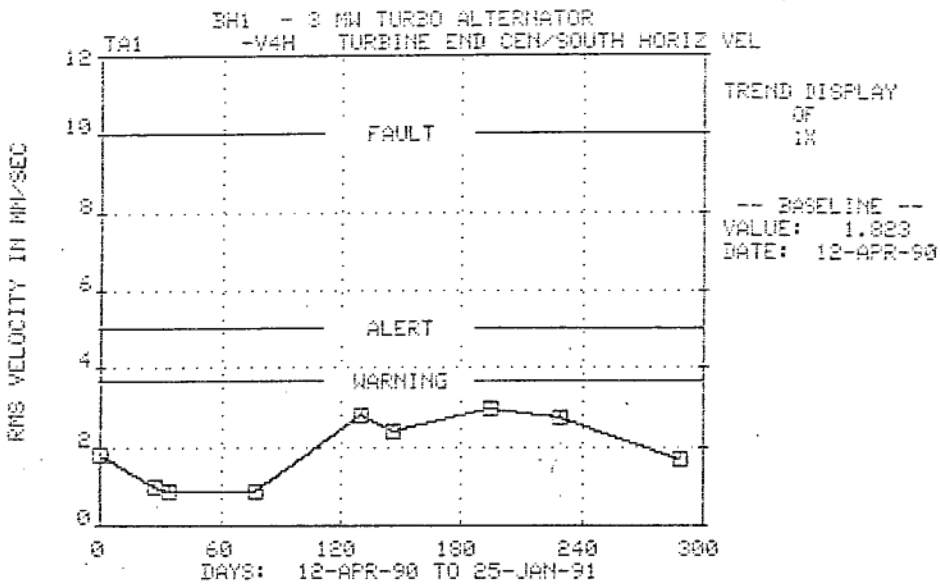
A2-4 Trend plot of the vertical velocity vibration readings at the outboard bearing of the Northern alternator. This is the closest journal bearing to the exciter.



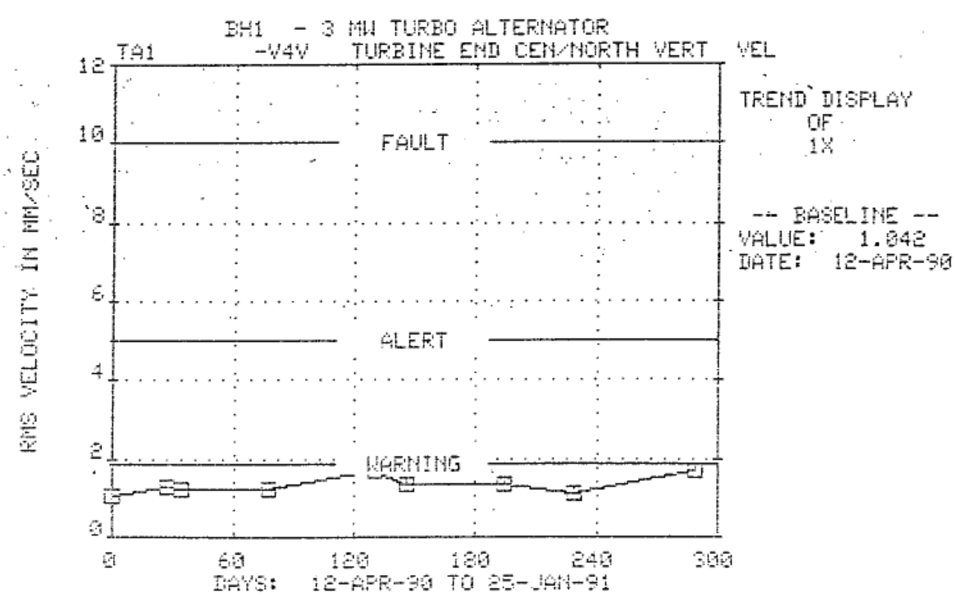
A2-5 Trend plot of the horizontal velocity vibration readings at the inboard bearing of the Northern alternator. This is the closest journal bearing to the steam chest.



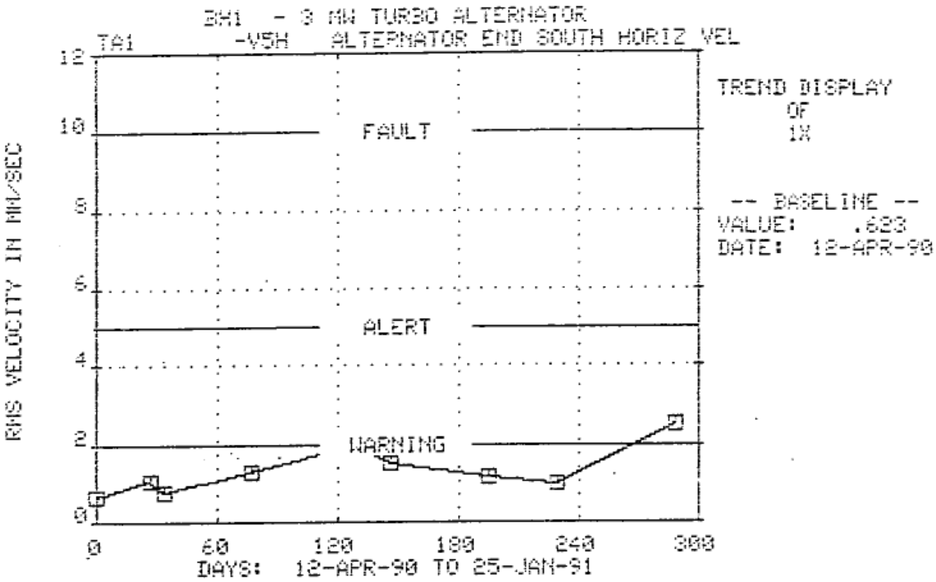
A2-6 Trend plot of the vertical velocity vibration readings at the inboard bearing of the Northern alternator. This is the closest journal bearing to the steam chest.



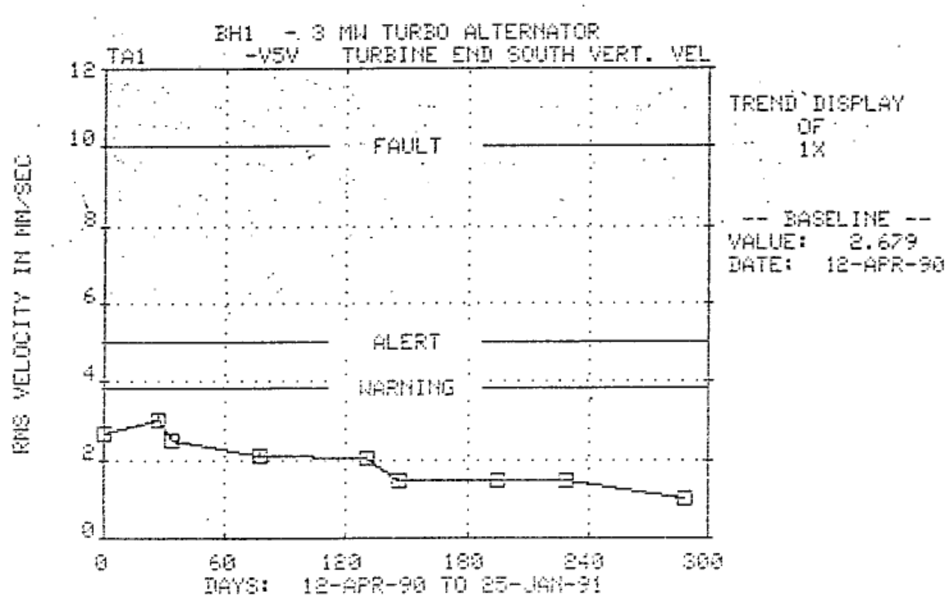
A2-7 Trend plot of the horizontal velocity vibration readings at the inboard bearing of the Southern alternator. This is the closest journal bearing to the steam chest.



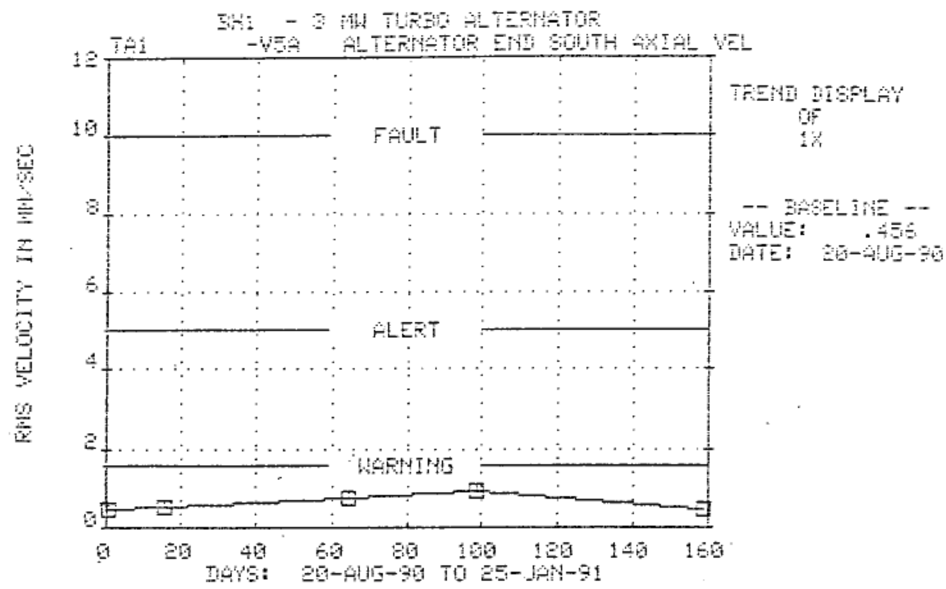
A2-8 Trend plot of the vertical velocity vibration readings at the inboard bearing of the Southern alternator. This is the closest journal bearing to the steam chest.



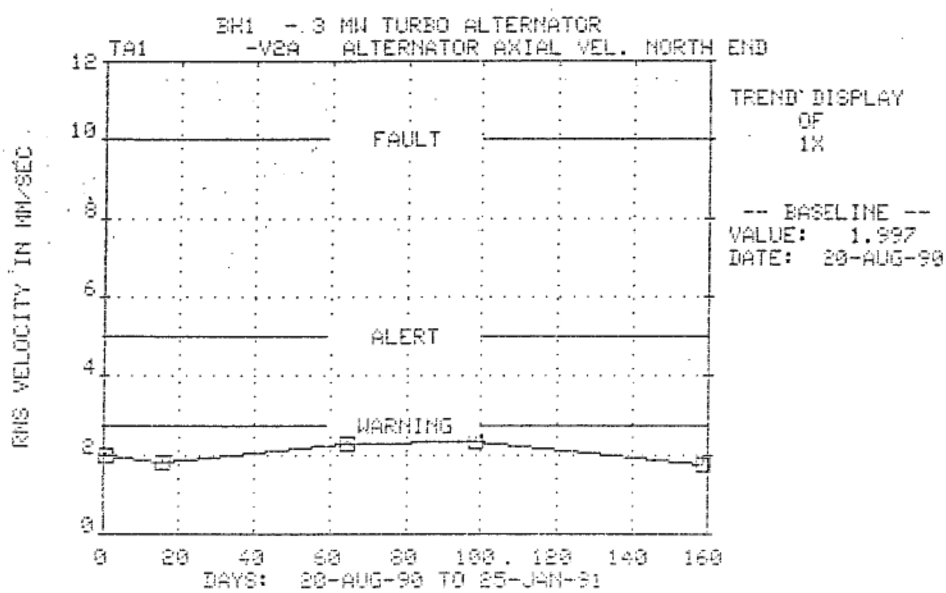
A2-9 Trend plot of the horizontal velocity vibration readings at the outboard bearing of the Southern alternator.



A2-10 Trend plot of the vertical velocity vibration readings at the outboard bearing of the Southern alternator.



A2-11 Trend plot of axial velocity vibration readings for the Southern alternator.



A2-12 Trend plot of axial velocity vibration readings for the Northern alternator.

Appendix 3

(i) Proximity probe information sheets.

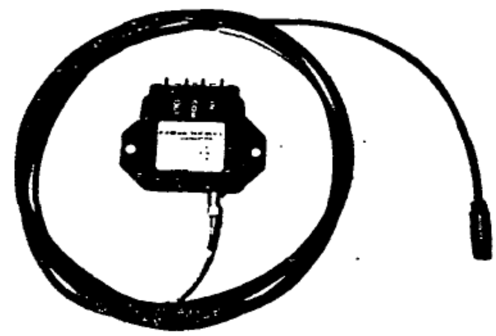
+24V ± 0.1% (GREATER)
1 mV RIPPLE (MAX)

KAMAN *Measuring Systems*

PROXIMITY MEASURING SYSTEM

MODEL KD-2400

FEATURES



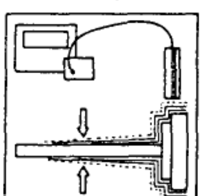
- LOW COST
- NON-CONTACTING
- EDDY CURRENT OPERATING PRINCIPLE
- 10 KHz FREQUENCY RESPONSE
- ADJUSTABLE GAGE FACTOR
- 10 MICROINCH RESOLUTION

KAMAN'S PROXIMITY MEASURING SYSTEM is a new, low cost device which enables the engineer to use innovative ideas in systems which require position measurements of metallic objects. Because this is a non-contacting system, it offers excellent resolution and repeatability, enabling static, as well as high frequency motions, to be monitored with great accuracies.

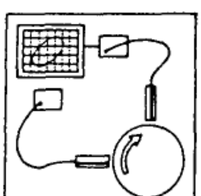
This measuring device uses an inductive operating principle to measure the distance between a coil (sensor) and any metallic object (target). The proximity of the sensor to the target controls an oscillator's amplitude, which is detected and conditioned to provide an analog signal proportional to displacement. The gage factor (ratio of output voltage to displacement) is adjustable by setting the sensitivity control potentiometer on the signal conditioning module. Additionally, the magnitude of the output voltage can be increased by utilizing a higher voltage power supply.

This flexible device monitors radial and axial motion, as well as vibration of shafts, can be used for positioning and control, or can simply measure distance. Applications include position measurements of shafts, disks, plates, foils, or other ferrous and nonferrous metallic objects. Because the KD-2400 operates using inductive proximity principles it is unaffected by oily, dirty, or humid industrial environments.

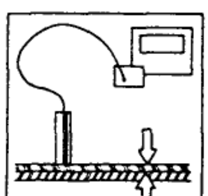
TYPICAL APPLICATIONS



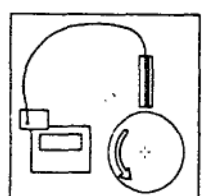
VIBRATION FREQUENCY AND AMPLITUDE



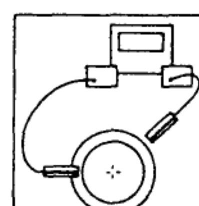
ORBIT TRACING



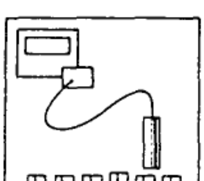
NON-CONDUCTIVE MATERIAL THICKNESS



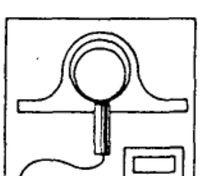
SHAFT RUNOUT



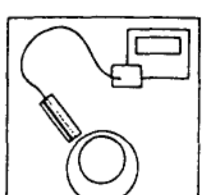
CONCENTRICITY



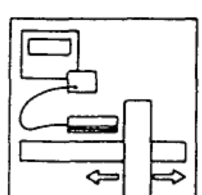
METALLIC PARTS GAUGING



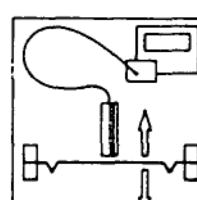
OIL FILM THICKNESS



ECCENTRICITY



AXIAL MOTION



PROXIMITY AND DYNAMIC CHANGES

SPECIFICATIONS

ELECTRICAL

INPUT
Voltage: Regulated 12 Vdc to 24 Vdc
Current: Full load 35 mA maximum

OUTPUT
Current (full load): 10 mA maximum
Impedance: 600Ω
Voltage: 0–18 Vdc minimum with 24 Vdc input
0–8 Vdc minimum with 12 Vdc input
(See FIG. 2)

FREQUENCY RESPONSE
0–10 KHz (± 3db)

NOISE FLOOR
18 Vdc output with 24 Vdc battery power
Less than 50 mV P-P unfiltered
Less than 0.1 mV P-P filtered above 20 KHz

ENVIRONMENTAL

OPERATING TEMPERATURE RANGE
Sensor and cable: 0°F to 200°F (–18°C to 93°C)
Electronics: 32°F to 150°F (0°C to 65°C)

STORAGE TEMPERATURE RANGE
Sensor and cable: –60°F to 250°F (–51°C to 120°C)
Electronics: –58°F to 212°F (–50°C to 100°C)

THERMAL DRIFT
Less than 0.1%/°F of full scale for sensor, electronics or system.

OPTIONS

Metric thread on sensor: M10 x 1

NOTE: Specifications are based on systems with standard 8 foot cables which have been calibrated for aluminum targets.

TYPICAL MEASUREMENT RANGES

Target Material	12 Vdc Power Supply		24 Vdc Power Supply	
	Min. G.F. (1)	Max. G.F. (2)	Min. G.F. (1)	Max. G.F. (2)
Non-Ferrous	0–.090 in. (0–2.3 mm)	0–.020 in. (0–.5 mm)	0–.110 in. (0–2.78 mm)	0–.015 in. (0–.38 mm)
Non-Magnetic Steels	.015–.115 in. (.38–2.9 mm)	.005–.040 in. (.13–1.0 mm)	.010–.150 in. (.25–3.81 mm)	.005–.030 in. (.13–.76 mm)
Magnetic	.020–.100 in. (.5–2.54 mm)	.017–.075 in. (.45–1.9 mm)	.020–.175 in. (.5–4.4 mm)	.018–.060 in. (.45–1.5 mm)

(1) Minimum Gage Factor (G.F.) is defined as the sensitivity control setting that adjusts the output voltage to be zero volts at the recommended minimum target sensor spacing.

(2) Maximum Gage Factor (G.F.) is obtained when the sensitivity control is adjusted fully clockwise.

ORDERING INFORMATION

Specify by model number and desired option. Standard unit will be supplied with 3/8 – 24 UNF – 2A thread. If metric thread is required, add "Metric thread M10 x 1 required" after model number.

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TYPICAL OUTPUT VS GAP CHARACTERISTICS

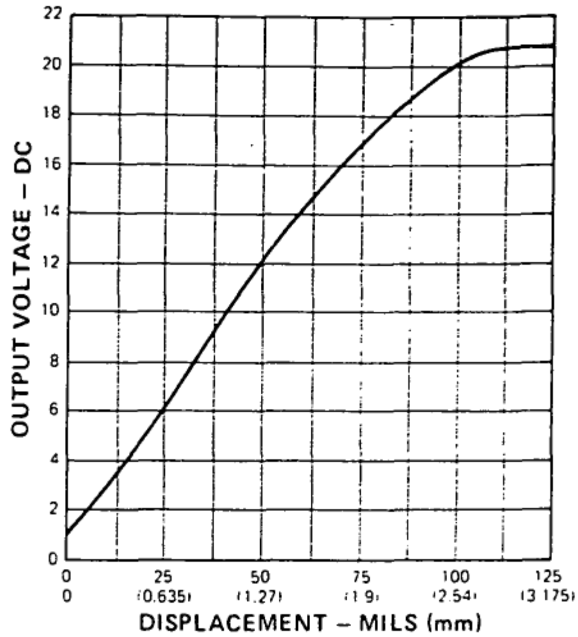


FIG. 1
Graph for aluminum target, median gage factor, and 24 volt power supply.

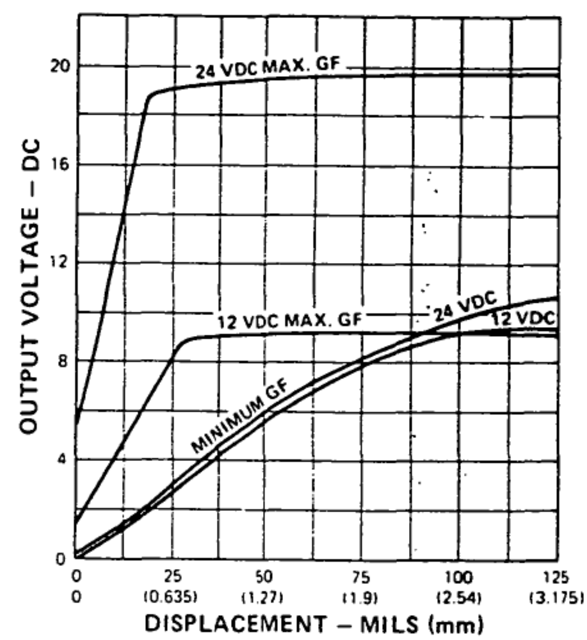


FIG. 2
Graph showing limits as a function of gage factor and input voltage for aluminum target.

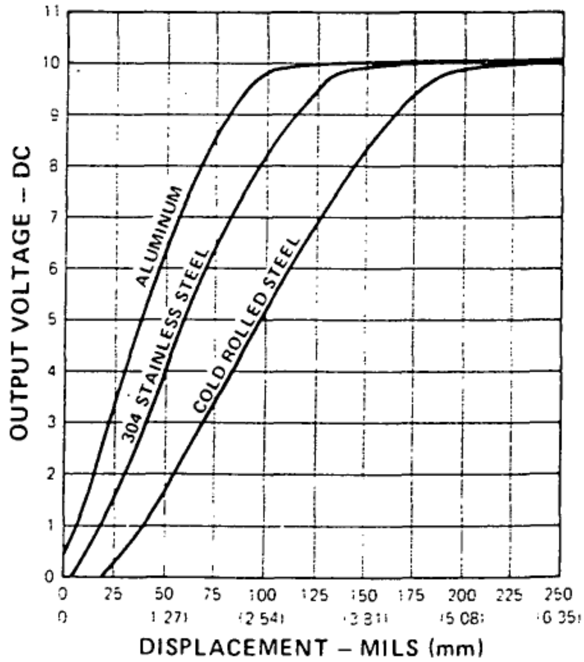


FIG. 3
Graph of different target materials with 12 Vdc input voltage and constant gage factor.

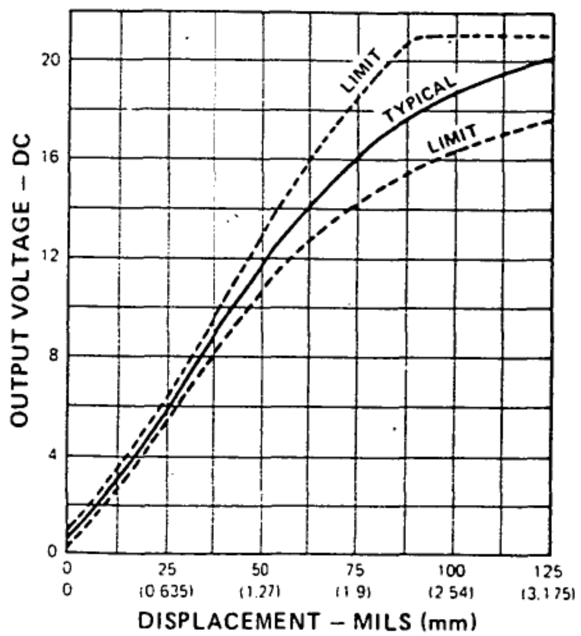


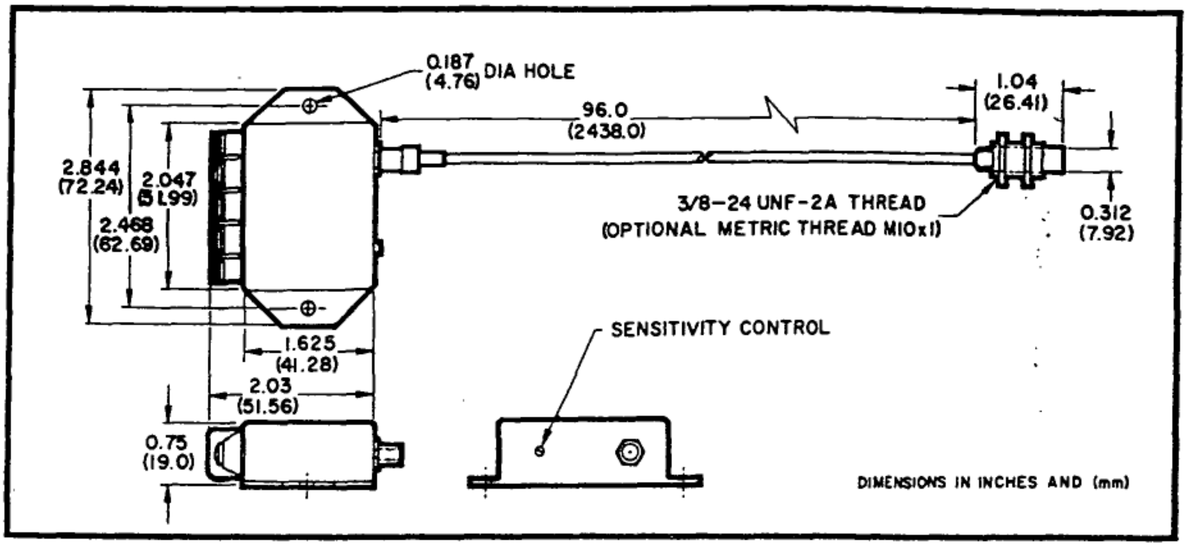
FIG. 4
Graph of typical limits for replacement sensor without recalibration.

KAMAN Measuring Systems

PROXIMITY MEASURING SYSTEM

MODEL KD-2400

DIMENSIONS



OPERATING INSTRUCTIONS

The KD–2400 system consists of two sub-assemblies; the sensor with an interconnecting cable and a solid state signal conditioning module. The proximity of the sensor to the target controls a variable gain oscillator section within the electronic sub-assembly. The oscillator's amplitude is detected and conditioned to provide an analog signal proportional to displacement.

The KD–2400 will operate with an input power supply voltage from 12 to 24 Vdc. However, it must be regulated at the selected operating voltage because any input ripple will be apparent in the output. Located on the electronic module is a terminal strip. The power supply voltage must be connected between the IN terminal and the COM terminal. The analog output signal is taken from the OUT and COM terminals.

The gage factor (ratio of output voltage to sensor displacement) is adjustable by setting the sensitivity control potentiometer on the signal conditioning module. Counterclockwise adjustment of this control decreases the gage factor. A clockwise adjustment increases the gage factor.

When changing types of target materials or power supply voltages, it will be necessary to readjust the sensitivity control for the desired gage factor.

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