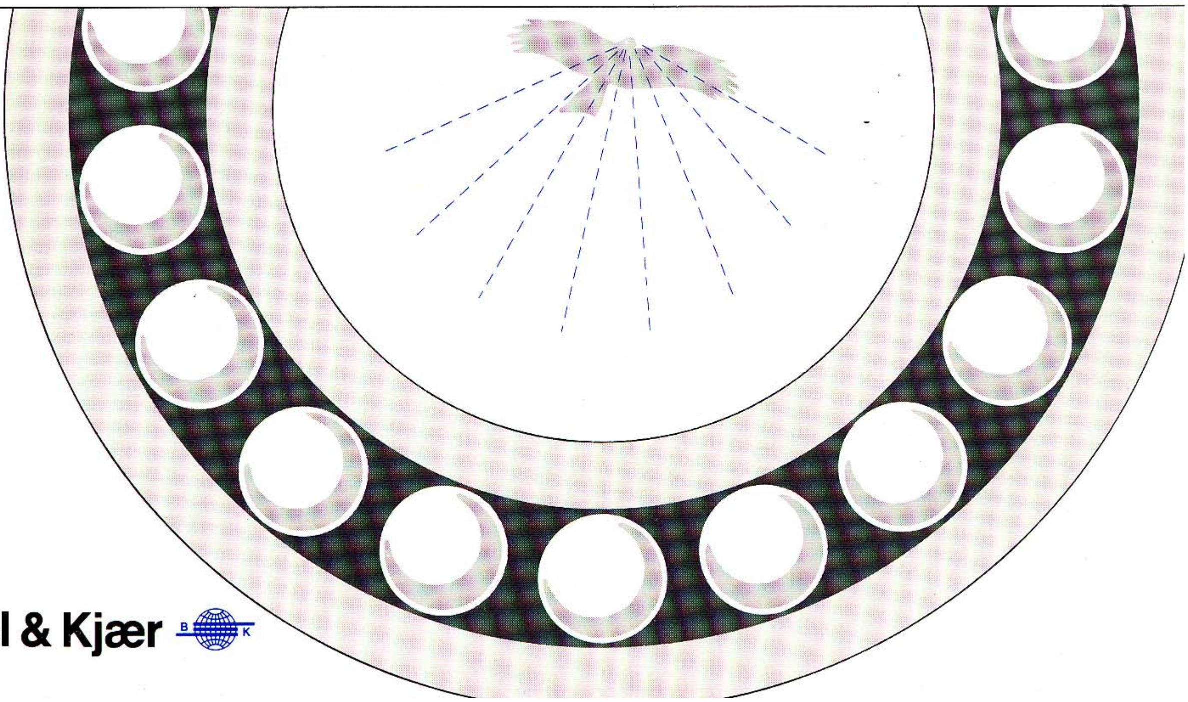
Machine Condition Monitoring



Brüel & Kjær

Introduction

This booklet aims to illustrate the important role that vibration measurement and analysis can play in plant maintenance and protection. Although it is intended as a basic introduction to the subject, it assumes that the reader is familiar with the fundamental techniques of vibration measurement which are covered by the companion booklet "Measuring Vibration". Topics covered here are as follows:

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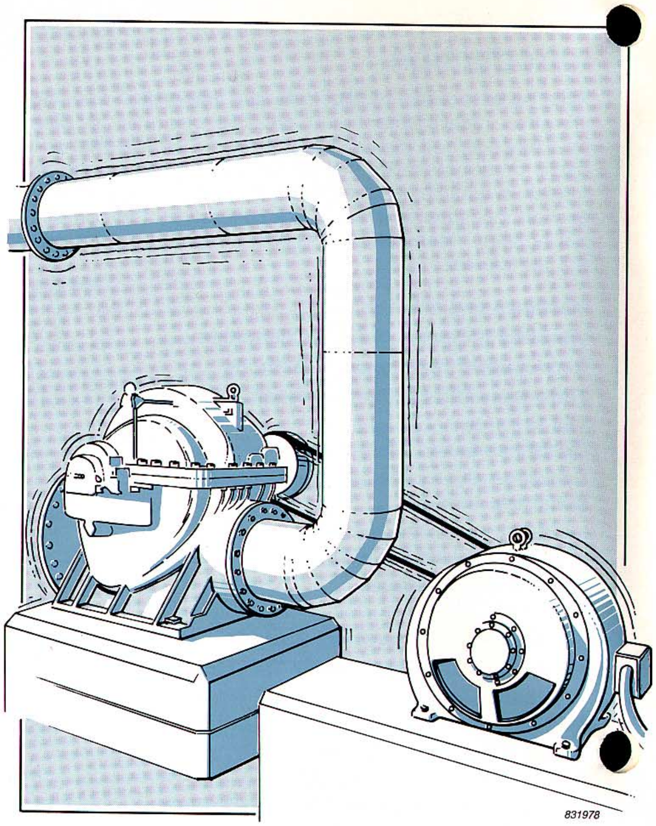
Machines and Vibration

An ideal machine would produce no vibration at all because all energy would be channelled into the job of work to be done. In practice, vibration occurs as a by–product of the normal transmission of cyclic forces through the mechanism. Machine elements react against each other and energy is dissipated through the structure in the form of vibration.

A good design will produce low levels of inherent vibration. As the machine wears, however, foundations settle, and parts deform, subtle changes in the dynamic properties of the machine begin to occur. Shafts become misaligned, parts begin to wear, rotors become unbalanced, and clearances increase. All of these factors are reflected in an increase in vibration energy, which, as it is dissipated throughout the machine, excites resonances and puts considerable extra dynamic loads on bearings. Cause and effect reinforce each other, and the machine progresses towards ultimate breakdown.

In the past, experienced plant engineers have been able to recognise by touch and hearing whether a machine was running smoothly or whether a fault was developing. This cannot be relied upon any longer for at least two reasons: The days of plant attendants with an oily rag and a grease gun at hand who tend "their" machines are gone. The "personal" relationship between man and machine is not economically feasible and not even required because machines are expected to run automatically with only occasional attention from service personnel. Secondly, most modern machinery runs so fast that many tell–tale vibrations occur at such a high frequency that instruments are needed to detect and measure them.



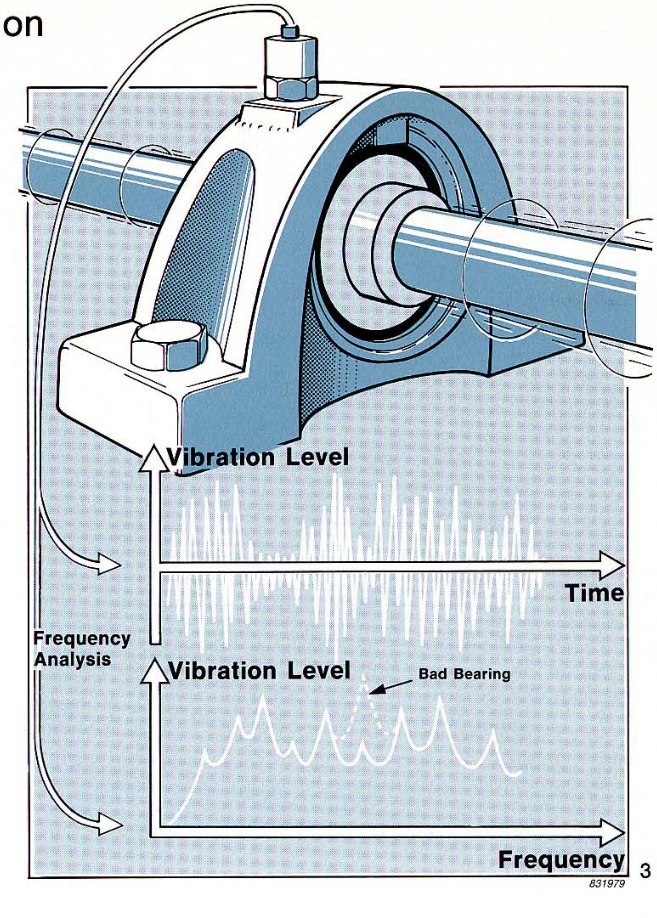
Vibration Indicates Machine Condition

[illegible] we have seen, vibration is normally a destructive by–product of the force transmission through a machine which provokes wear and accelerates breakdown. Machine elements which constrain these forces, for example bearing housings, are usually accessible from the outside of the machine so that vibration resulting from the excitation forces can be measured at these points.

As long as the excitation forces are constant, or vary within certain limits, the vibration level measured will also be constant and vary within similar limits. Furthermore, for most machines, the vibration has a *typical* level and its frequency spectrum has a *characteristic* shape when the machine is in good condition. This frequency spectrum, a plot of vibration amplitude against frequency, is known as the vibration signature of the machine, and is obtained by frequency–analyzing the machine vibration–signal.

When faults begin to develop, the dynamic processes in the machine change and some of the forces acting on machine parts are also changed — thereby influencing the vibration level and the shape of the vibration spectrum.

The fact that vibration signals carry much information relating to running condition of machines is the basis for using regular vibration measurement and analysis as an indicator of machine health trends and the need for maintenance.



Conventional Maintenance Methods

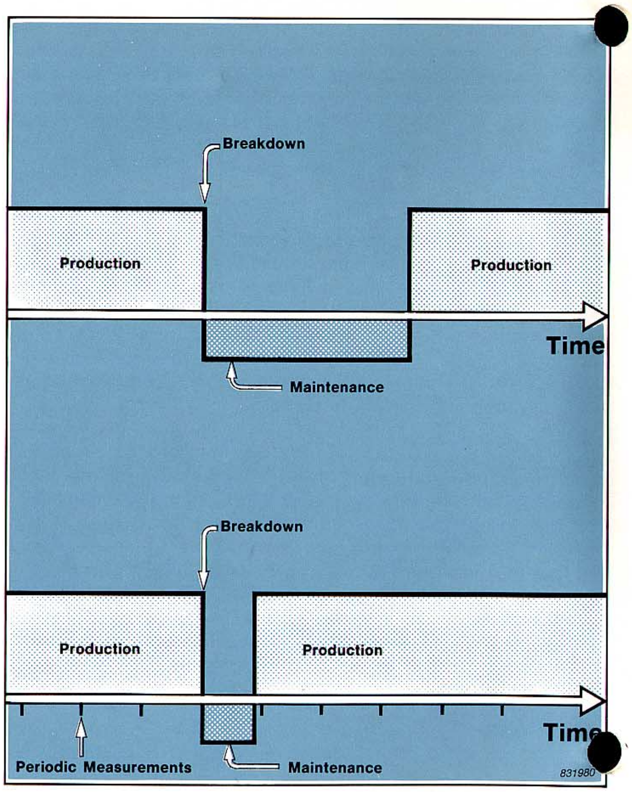
Traditional machinery maintenance practice in industry can broadly be categorized into two methods, **Run–to–Breakdown** and **Time–based Preventive Maintenance.**

Run–to–Breakdown

In industries running many inexpensive machines and having each important process duplicated, machines are usually run until they break down. Loss of production is not significant as spare machines can usually take over.

In this situation, vibration measurements will not be of help as there is usually no economic or safety advantage in knowing when breakdowns will occur, and for most simple machines the cause will be obvious.

In a few cases, large unduplicated process–machines are still run to breakdown. In this case it is of *vital* importance to know *what* is going wrong and *when* breakdown is likely to occur. This information can be obtained by studying vibration spectra trends built up from regular measurements. Knowing what is going wrong will allow the plant engineer to order the necessary spare parts ahead of expected breakdown and thereby avoid a large standing stock of spare parts. Furthermore, maintenance personnel are better prepared and can be expected to effect a more reliable repair in a shorter time.

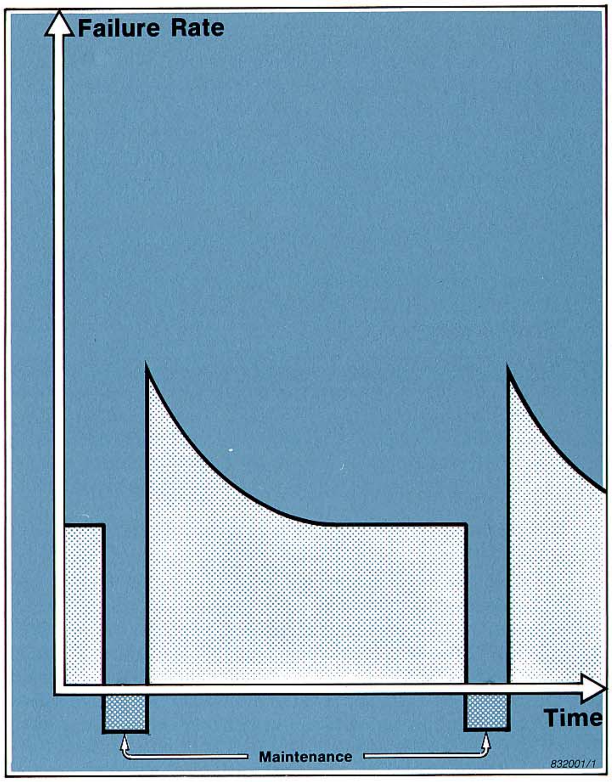


Time–based Preventive Maintenance

Where important machines are not fully duplicated or where unscheduled production stops can result in large losses, maintenance operations are often performed at fixed intervals such as every 3000 operating hours or once per year. This system is therefore called *Preventive Maintenance,* or more correctly, *Time–based Preventive Maintenance.*

The service intervals are often determined statistically as the period, measured from the time when the machines are in a new or fully serviced condition, to when the manufacturer expects no more than 2% of the machine population to have failed. By servicing at these intervals it is generally believed that, as 98% of the machines should survive the running period, failure should be a rare occurrence.

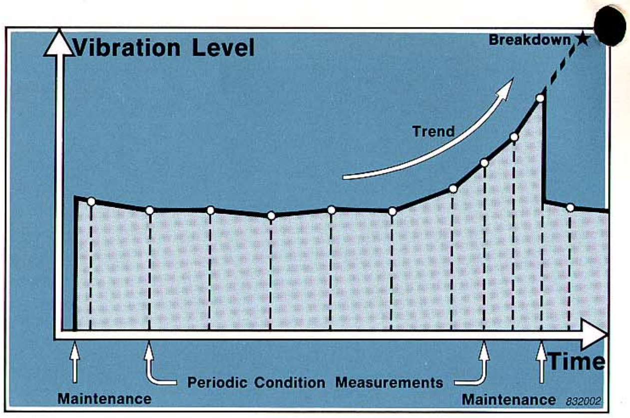
Experience has shown that in the vast majority of cases, time–based preventive maintenance is uneconomical. A significant fact is that the failure rate of many machines is *not* improved by replacing wearing parts regularly. On the contrary, the reliability of newly–serviced machines is often *reduced* temporarily by human interference. As the actual failure pattern for each individual machine cannot be predicted, time–based preventive maintenance cannot be efficiently applied. An individual approach is needed, and this is the axiom of *Condition–Based Maintenance.*



The Individual Approach — Condition–Based Maintenance

This method considers each machine individually. By replacing fixed–interval overhauls by fixed–interval measurements, developments in the running condition of each individual machine can be followed closely. As previously seen, mechanical vibration is a very good indicator of a machine's running condition and this is the reason why the most common form of machine *Condition Monitoring* uses vibration measurements as an indicator. **The axiom of Condition–Based Maintenance is that servicing is permitted only when measurements show it to be necessary.** This is also in agreement with most engineers' instincts that it is unwise to interfere with a smoothly running machine.

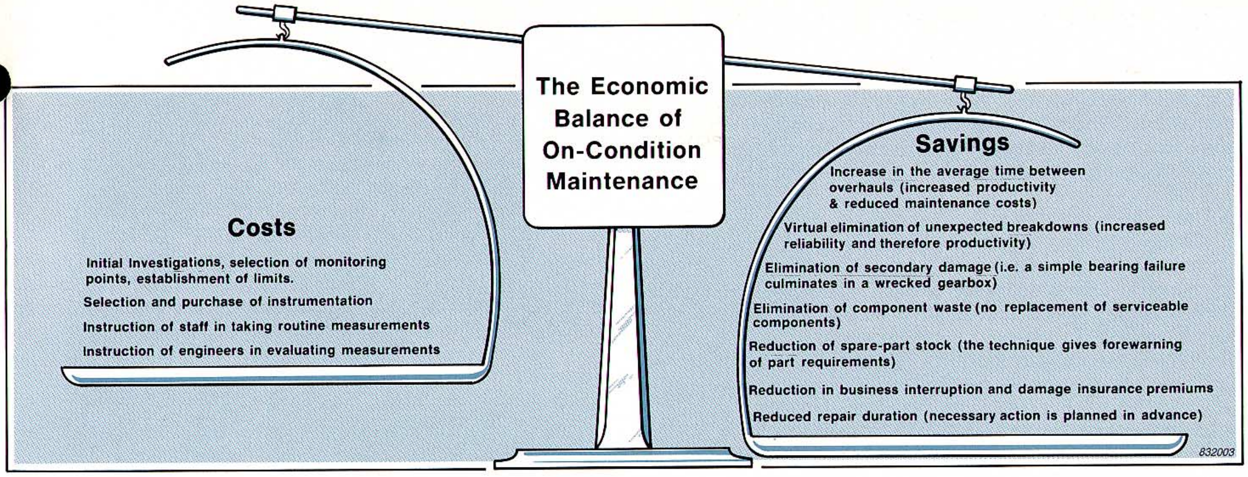
By means of regular vibration measurements, the onset of fault conditions can be detected and their development followed. Measurements can be extrapolated in order to predict when unacceptable vibration levels will be reached and when the machine must be serviced. This is called *Trend Monitoring* and it allows the engineer to plan for repairs well in advance.



Condition–Based Maintenance Gives Economic Benefits

Condition–based maintenance based on vibration monitoring has been employed successfully in the continuous–process industries since the early 1970s. Oil and chemical plants quickly adopted the technique and achieved great savings owing to the higher availability of production machinery and the corresponding increase in productivity.

Condition monitoring has since spread rapidly through most industries employing rotating machinery. Success stories are numerous. A chemical plant reduced the number of annual maintenance/repair operations from 247 to 14 using condition–based maintenance, and these are virtually all planned as the time and cause of breakdown can be predicted. Likewise, an oil refinery has reduced maintenance costs of its electric motors by 75%. With a first–year savings of at least $250 000, a paper mill was able to cover the cost of their vibration monitoring instrumentation more than ten–fold. A nuclear power plant realized savings of more than $3 mil. in maintenance costs in a single year with the additional bonus of an increase of $19 mil. in generating revenue.



Such drastic savings in maintenance work do not necessarily mean that maintenance personnel are thrown out of work. They are employed in performing the condition measurements and probably have time to do a more thorough overhaul and test job on any machine that is taken down for repair, thus contributing even more to the long-term reliability of the machine. The many rush–jobs which could only be patched up in a temporary fashion become a thing of the past.

The maintenance engineer will be faced with the task of evaluating the costs/benefits of vibration measurements for condition–based maintenance with respect to his plant. The figure (above) highlights some of the more important factors to consider.

The success of such a maintenance program does not necessarily depend on a large initial investment in sophisticated computer–based analysis equipment. Many successful schemes start with relatively inexpensive analogue vibration meters on a representative group of machines. As experience is gained and the scheme is extended, the use of faster and more powerful instrumentation becomes a natural progression. However, it is wise to buy high–quality equipment from the beginning. Inaccurate and inconsistent results, especially in the introductory phase, can severely limit the credibility of a condition–based maintenance programme.

Instrumentation Systems for Condition–Based Maintenance

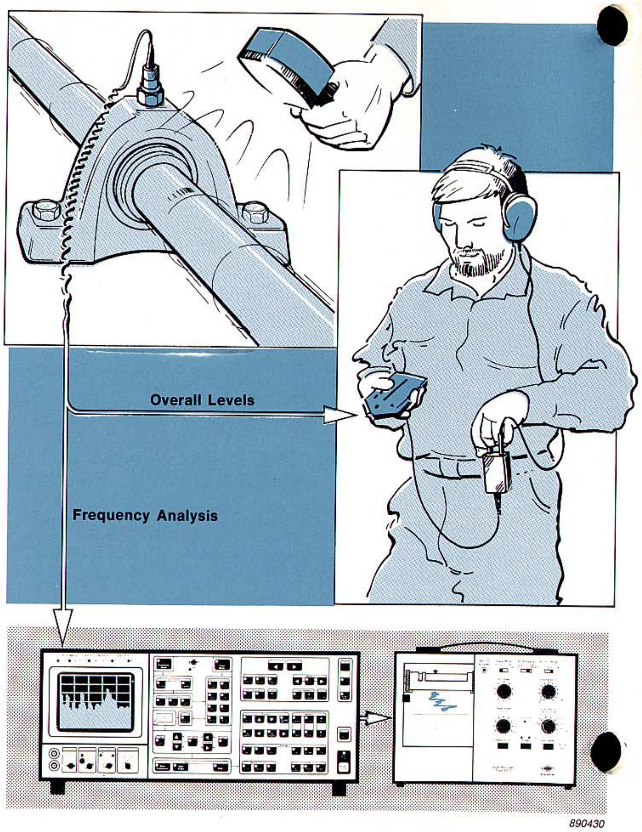
Instrumentation systems for vibration monitoring can be broadly classified into three levels of sophistication. This classification reflects their speed of operation, how early they can detect faults and how accurately the time of ultimate failure can be predicted.

A Basic System

A simple vibration monitoring scheme can be obtained by combining a straightforward pocket–sized vibration meter to measure overall vibration levels, a stroboscope to measure machine speed and relative motion of machine parts and a headset to listen to machine vibration. Overall vibration levels can be compared with general standards or established reference values for each machine. A stroboscope "freezes" reciprocating or rotating machine elements, allowing the human eye to observe their motion. A headset connected to the vibration meter links the operator directly with the internal workings of his machine. These simple techniques are discussed further on page 10.

A Portable Fault Detection/Diagnostics System

Earlier fault detection, combined with diagnosis and breakdown prediction, is possible with a system which performs frequency analysis. Ideally, the system should be portable, capable of withstanding adverse environmental conditions and have the ability to store all measured data. It should also possess the diagnostic capabilities to perform on–the–spot frequency analysis and spectrum plot–out at each monitoring point. Currently recorded spectra can then be automatically compared with stored reference spectra to reveal increases in individual frequency components. Inbuilt diagnostics allow further analysis of any suspected fault, leading to an earlier solution to the problem. Such a portable system is discussed further on pages 14 and 15.



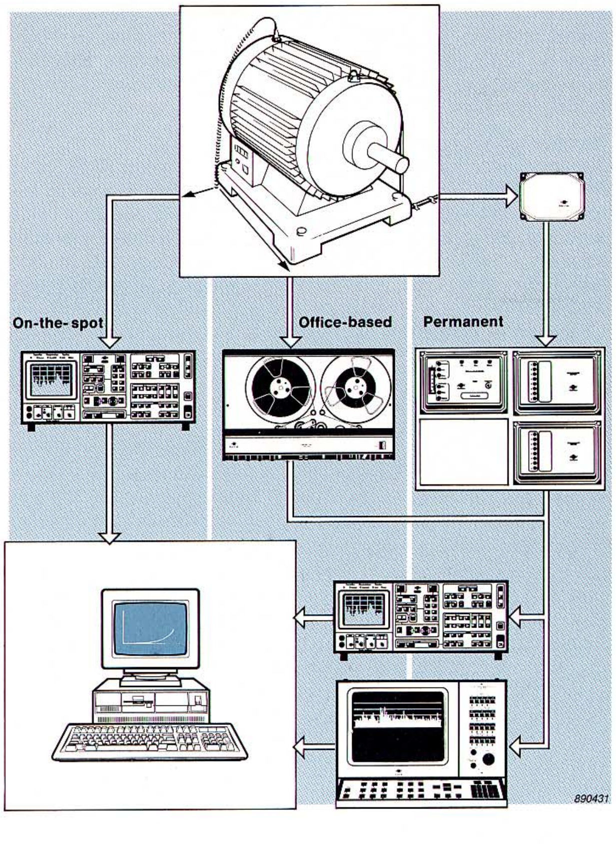
Computer–Based Systems

As the number of monitoring points and complexity of fault detection increases, a computer–based system will be the most economic solution. A typical system will combine the on–the–spot analysis and detection capabilities allied to a portable system with the centralized data–base and diagnostic capabilities of a computer. Collection of vibration samples from each machine can be organised by the computer on the basis of a measurement route. The route system ensures that each machine is monitored frequently, and in the manner most appropriate to early detection of faults.

A complementary computer–based system uses a tape–recorder (analogue or DAT) to record vibration signals from each machine on the measurement route. The measurements are then played back into the computer for post–processing and storage in a central data–base. Once again, the computer may serve as both a diagnostic tool and a measurement organizer. A major benefit of this method of data collection is that the entire vibration signal is permanently preserved on tape, allowing the signals to be subjected to a wide range of analysis techniques. These systems are covered more fully from pages 16 to 19.

Permanent Monitoring

Where the monitored machine is critical to production (and therefore to profit) or where a complete failure of the machine can lead to expensive repairs, permanent monitoring should be considered. Dedicated vibration monitors connected to permanently mounted accelerometers yield instant feedback on changing machine condition. The monitors can activate alarms on detection of excessive vibration levels and if necessary, shut the machine down. Permanent monitoring is discussed further in pages 20 and 21.

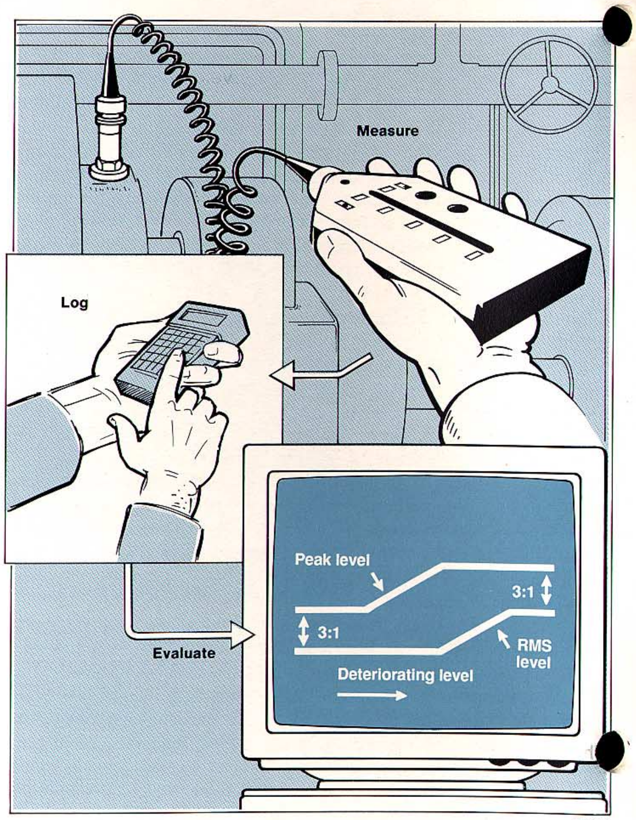


The Simple Approach: One, Two, Three

For those who wish to make a cautious start with vibration measurements for machine condition monitoring, a high-quality, hand-held vibration meter, measuring overall vibration levels, can provide a sound basis for initializing a monitoring program.

Measuring Vibration Levels
A hand-held vibration meter gives a single-digit RMS, max. RMS or Peak level reading of vibratory acceleration or velocity, over selectable frequency ranges. RMS velocity readings can be compared directly with standardised vibration severity criteria values, such as those on page 28, to indicate the need for maintenance. Plotting overall levels against time in a trend plot reveals how rapidly machine condition is changing. When the meter is used in conjunction with a pocket computer (Psion Organizer®), the collection and storage of measurements is greatly simplified. Connecting a tape-recorder (analogue or DAT) to the meter, stores the vibration signal for use with a more advanced system at a later date. The wideband meter though is rather limited with respect to early fault detection, diagnosis, and breakdown prediction, when compared to systems using frequency analysis. This is discussed further on pages 12 and 13.

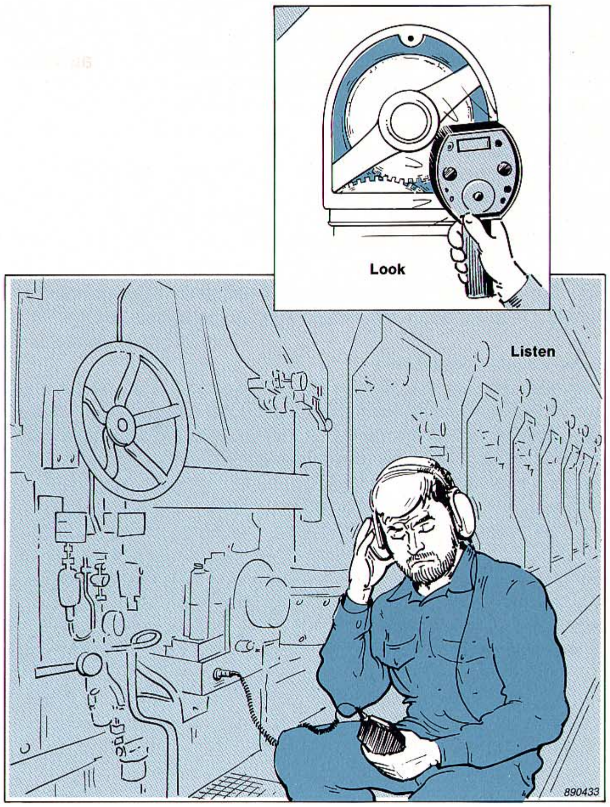
In the specific case of rolling element bearings and where vibrations from other sources do not dominate, early warning of bearing deterioration *can* be obtained using the "crest factor" technique. The meter is switched to *simultaneously* measure both the Peak and RMS vibration levels. When small defects on the balls/rollers and outer and inner races begin to form, they issue high frequency vibration pulses which are measured by the peak detector in the vibration meter. In the early stages, very little change in the RMS level is noted although the peak level increases significantly. This Peak/RMS ratio is called the crest factor, and by monitoring it, many rolling element bearing faults can be detected at an early stage of their development.



Listening to Vibration
The machine operator listening to a bearing with a screwdriver may seem a totally antiquated method of fault detection, yet the human ear is a perfectly constructed signal analyzer, albeit somewhat lacking in dynamic range. A headset with an integral amplifier connected to the vibration transducer allows the operator to hear how the machine is running. Comparing how a machine sounds over a period of time is analogous to comparing frequency spectra, and in the hands of an experienced operator, can be almost as effective.

Looking at Vibration
Finally, there is the question of what we can learn about a machine from visual inspection of its operation? If faults such as misalignment, unbalance and looseness are allowed to progress, they become visually obvious – no instrumentation is required to detect them. But they could have been detected earlier, if the quality of the visual information was enhanced. A portable stroboscope can "freeze" a rotating component, allowing not alone the speed of rotation to be measured, but also the nature of the rotation. Misaligned shafts may describe non-symmetrical orbits. Looseness may show up as relative movement between the bearing and the housing, an unbalanced rotor can manifest itself in a rocking motion along the length of the rotor.

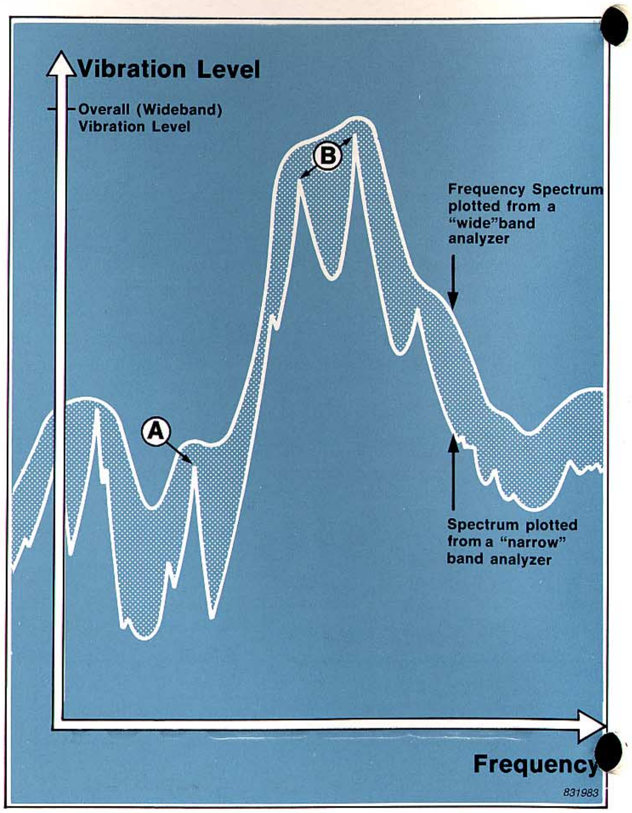
These and many other faults can be detected by the simple methods outlined here. It should be remembered though, that the more complex the nature of the fault, the more powerful the detection techniques required to locate it.



The Benefits of Frequency Analysis — Early Fault Detection, Diagnosis and Breakdown Prediction

A simple vibration meter, such as the one mentioned in the previous section, measures the overall level of vibration over a wide frequency range. The measured level reflects the vibration amplitude of the dominating frequency component. This is normally the machine rotation speed, and is of course, important to monitor. But when the same vibration signal is frequency–analysed and the spectrum plotted in graphical form, the level of many more, possibly equally important, frequency components is revealed. These frequency components, which are usually lower in level than that for the rotation speed, *can* result from high excitation forces. This topic is discussed further on page 29.

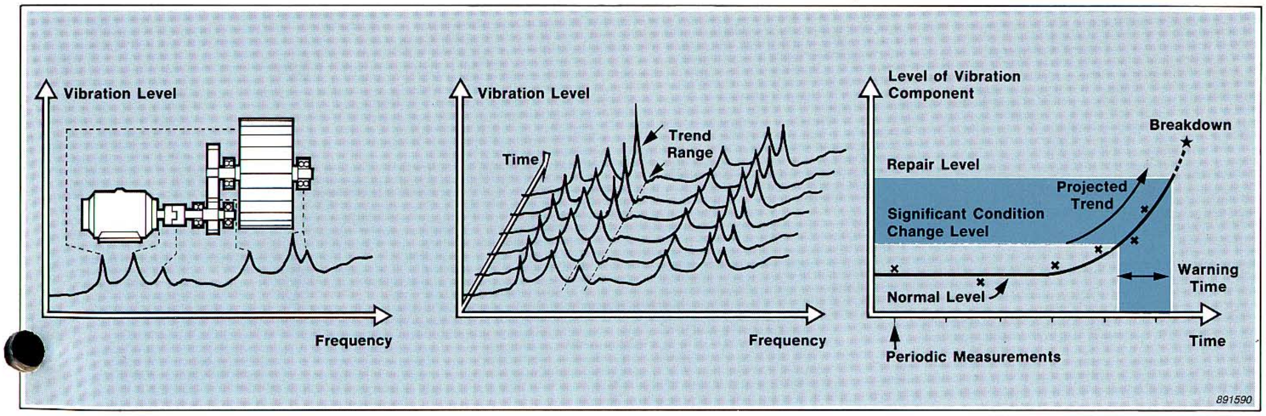
Early Fault–Detection
The adjacent sketch illustrates this point. Since the level of the frequency component Ⓑ largely determines the overall vibration level, an increase in the possibly important component Ⓐ can only be detected at an early stage by frequency analysis. Note also that as the analysis bandwidth is reduced, a more detailed spectrum which separates individual peaks is obtained. In general, the narrower the analysis bandwidth, the earlier developing faults can be detected. But on the other hand, the narrower the bandwidth, the longer the analysis takes unless more sophisticated instrumentation is used.



ult Diagnosis
Not only do level–increases in frequency components give an early indication of faults, but also the frequency at which they occur indicates which machine parts are deteriorating. For each monitoring point, unbalance, misalignment, bearing erosion, gear tooth damage etc. will all have their characteristic frequencies which can be revealed with the help of frequency analysis. The trouble–shooting charts on pages 32 and 33 illustrate this relationship.

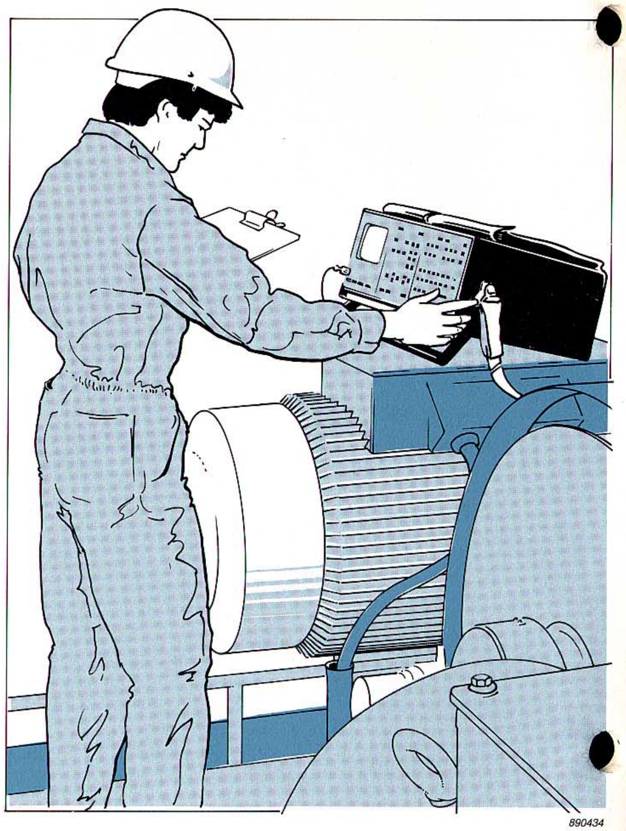
3D–Plots
A complete overview of the changing nature of a machine's vibration can be obtained by plotting a series of spectra, recorded at fixed time intervals, in a 3–dimensional format. The 3D–plot is essentially a trend–graph across the entire frequency spectrum. Analysis of the plot will highlight frequencies where amplitude increases are occurring, and allow direct visual comparison of increases in different areas of the spectrum. Once a potential problem is identified, the measurement interval is decreased to obtain a more quantitative assessment of the specific increases occurring.

Trend Prediction
Plotting the level increase of one or more individual frequency components over a number of periodic measurements, enables level–time trends in the development of faults to be followed. The resulting curves can be extrapolated forward in time to indicate when the condition will reach a danger limit so that maintenance can be scheduled for a convenient date.



Applying Frequency Analysis Techniques

Instruments which apply frequency analysis techniques to machine condition monitoring should be accurate, portable, capable of operating in harsh environments, and built to last. They should also be capable of recording and storing a variety of different types of data with the minimum operator effort. Ideally, these criteria should be combined with a powerful on–the–spot detection and diagnostics capability, and the ability to integrate the instrument with larger computer–based monitoring systems. Such an instrument is available in the form of a portable FFT vibration analyzer. Being battery–powered, it can be used throughout the plant or facility – anywhere maintenance is required.

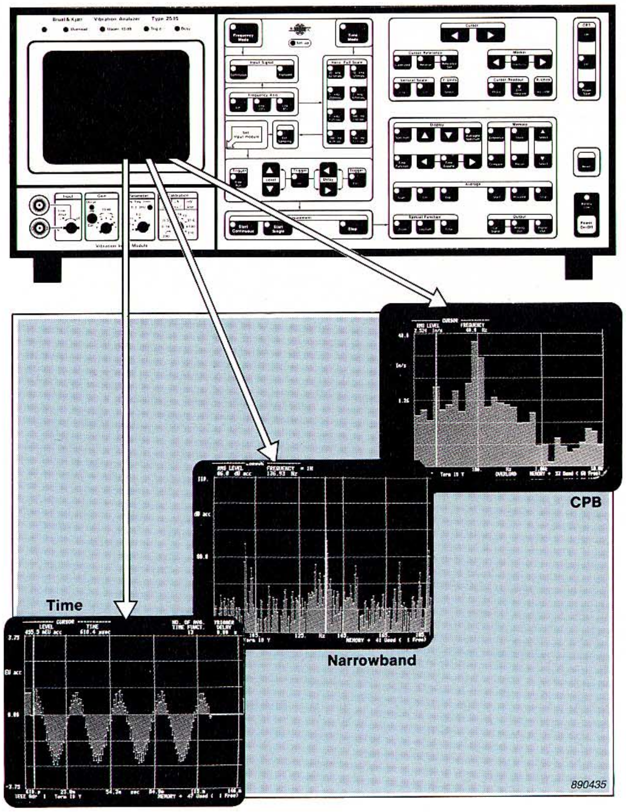


For Fault Detection:
When used as part of a regular vibration monitoring route, the analyzer's main function is to record and store vibration spectra from each of the route's measurement points. Each newly recorded spectrum can be electronically compared with a "Reference Spectrum". The reference spectrum being a spectrum recorded at that measurement point when the machine was in a known "good condition". The comparison of the two spectra reveals if any of the frequency components are increasing in amplitude – significant increases being indicative of propagating faults and therefore requiring further investigation.

For Fault Diagnosis:
Such further investigation is facilitated by the analyzer's diagnostic capability. Suspected faults such as loose journal bearings, faulty belt drives and certain electrically induced vibrations can be examined using Harmonic Cursors. Cepstrum Analysis may be used to diagnose gearbox faults. Envelope Analysis is an invaluable tool in the diagnosis of faulty rolling element bearings. These and other diagnostic tools; Phase Analysis; Scan Analysis; Time Averaging; External Sampling etc. allow the machine operator to make qualitative assessments of machine condition on–the–spot.

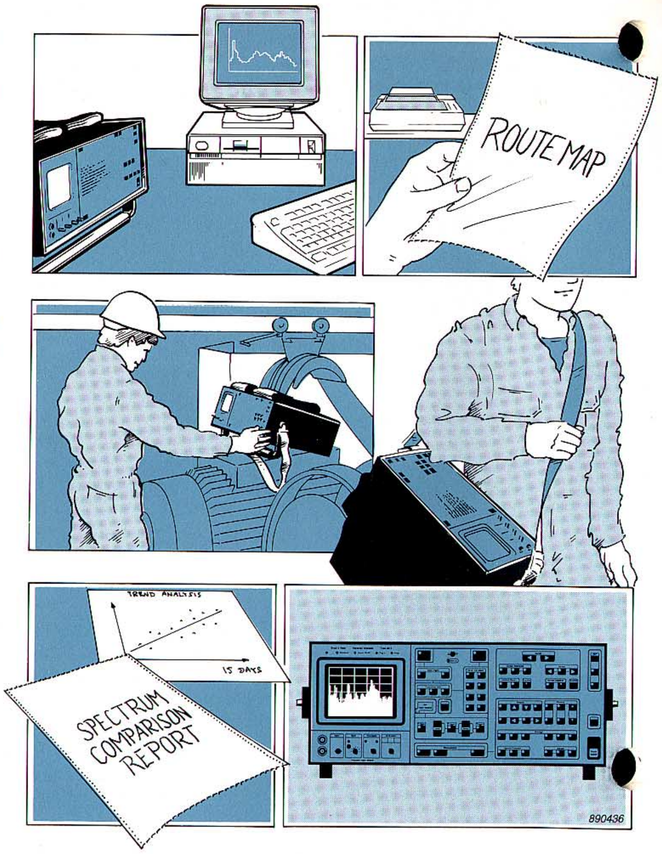
For Fault Correction:
Having detected and diagnosed the fault, it seems only proper that the analyzer should also have the ability to aid the correction of the fault. Obviously, where the nature of the fault dictates replacement of parts, its ability is limited to checking the operation of the machine after servicing. In the specific case of unbalance though, one of the most common of machine faults, it can be used as an integral part of the repair procedure, to calculate the correction masses and mounting angles necessary to rebalance the rotor. Balancing is discussed further on pages 34 and 35.

Interpreting Vibration Data
When interpreting vibration data, it is very important to select the correct type of display to perform the desired analysis. The constant percentage bandwidth (CPB) spectrum is ideally suited for fault detection, as it allows allows frequency components associated with the broadest range of machine faults to be resolved as separate peaks within a single spectrum. For diagnostic purposes, a far greater display resolution is required, allowing peaks to be measured with a greater accuracy and side–bands and harmonics to be detected more easily. Such displays are termed "Zoom" or narrowband spectra. Finally, the time signal can also yield valuable information. On certain occasions, the characteristic frequency of a fault is masked by background vibration or dominated by other frequency components, making it difficult to detect in the frequency domain. Using the time domain to present the same vibration information in a different manner will often lead to a quick resolution to such problems.



A Computer–Based, Machine–Monitoring System

A more sophisticated system, blending the flexibility of the portable vibration analyzer with the processing and storage power of a computer, is justified where large numbers of machines are to be monitored, or monitoring is to be enacted in a more organized fashion. The plant engineer decides which machines and measurement points to monitor, based on the importance of each machine to the facility, the cost of repair and the history of previous breakdowns. The portable vibration analyzer is used to study each machine's vibration content before deciding the best location for the measurement points and which type of measurement is best suited to monitoring that particular machine. Details on the machines and measurement points are then loaded into a central computer and the measurement points are arranged into measurement routes. A reference spectrum is measured and loaded into the computer for each measurement point as a reference against which to compare the newly recorded spectrum. With many modern systems, the software itself is capable of handling most of this setting–up process.



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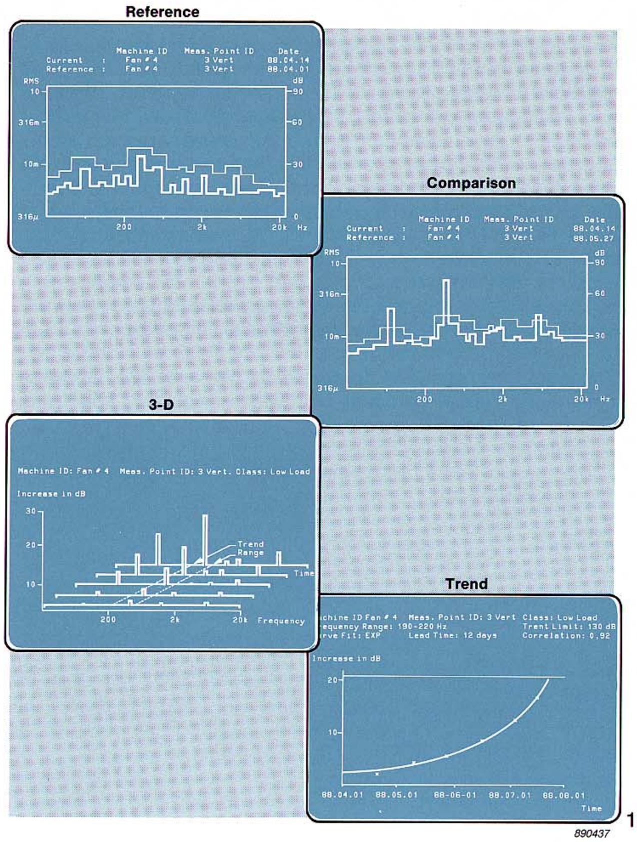
Data Collection: Who?, How?
The data can be collected by any member of the maintenance staff, a basic introduction to the theory behind such measurements being adequately covered by the information provided in this booklet. The operator connects the analyzer to the computer and selects the load routine for one (or more) of the measurement routes defined by the maintenance engineer. Overdue measurements can be added on request. Other machines and measurement points can be added if necessary.

The computer loads the analyzer with all the reference spectra for the route and issues a route map to a printer or pocket computer (Psion Organizer®). The operator disconnects the analyzer from the computer and, following the route map, makes a new measurement at each designated measurement point. The analyzer automatically recalls the original measurement parameters and gives the opportunity of comparing the new measurement with the reference before the measurement is stored. Where machines are run under different operating conditions i.e. different loads, speeds, temperature, pressure etc. spectra are separated into measurement classes, each class having its own reference spectrum. This ensures that newly recorded spectra are only compared with spectra recorded while the machine was operating under exactly the same conditions.

Data Interpretation
When the measurements are complete, the operator returns to the computer room and selects the unload routine. All data is stored on disc, allowing it to be used for further spectrum comparison, trend analysis or 3D plots. Where variable operating conditions such as those mentioned earlier apply, special trend plots are available to ascertain how, for example, different loads or temperatures affect the vibration level of the machine.

A Very Flexible System
Should the need arise at a future date, part or all of the system can be upgraded to a fully automatic permanent monitoring system. Accelerometers can be hard–wired to the monitored machines, and the vibration signals routed directly to the control room. The software sequentially compares each measurement point's newly recorded spectrum with a stored reference spectrum and issues a warning to a printer when an exceedance is detected. Permanent monitoring is discussed further on pages 20 and 21.



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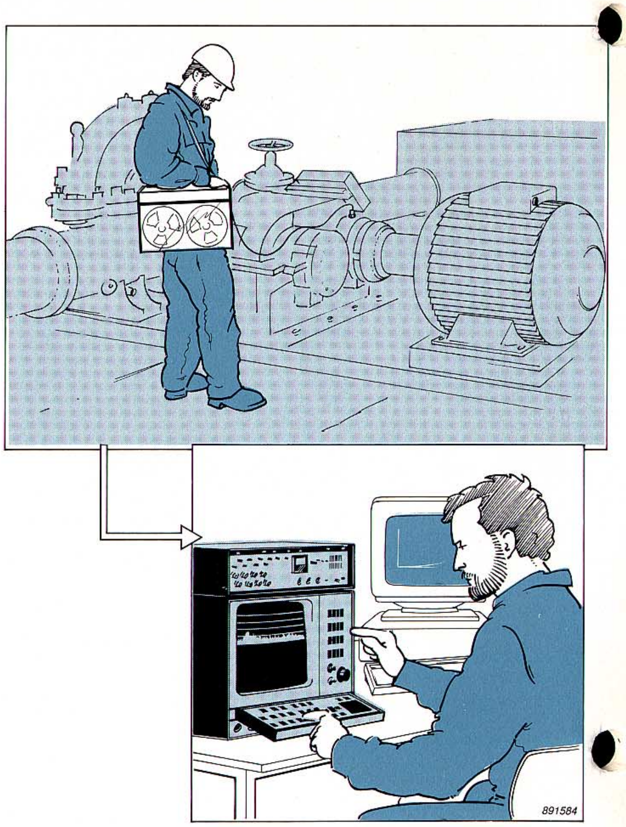
A Computer–Based System using Tape Recorded Inputs

An alternative way of implementing a large–scale, machine–condition monitoring program is to use a portable tape recorder (analogue or DAT) to record the vibration signal at each measurement point. One of the great benefits of this method of data collection is that the entire vibration signal is preserved on tape, allowing the data to be subjected to a very wide range of post–processing in the search for possible faults. Measurement collection is still organized along a route basis. The operator follows the route map about the plant and records the machine's vibration at each designated point. The tape is then returned to the plant–engineering office, where the taped signals are replayed through a vibration analyzer under the control of a computer.

The computer/analyzer combination converts the vibration time–signal into a constant–bandwidth frequency spectrum. The newly–recorded spectrum is compared with a previously established reference spectrum and an automatic warning is given if any component in the new spectrum exceeds a preselected level in any line of the reference spectrum.

An important consideration when comparing vibration spectra is that, for the comparison to be valid, the machine must operate under identical conditions when the measurements are taken. If small speed changes occur between the recording of two spectra, all speed related components in the spectrum will be shifted in the direction of the speed change. Direct comparison of two such spectra may lead to false results. Ideally, separate reference spectra should be stored for each machine running speed, but where only small speed changes occur between measurements, it is sufficient to broaden the frequency–bands in the reference spectrum – ensuring that they are wide enough to overlap the related components in the newly–recorded spectrum.

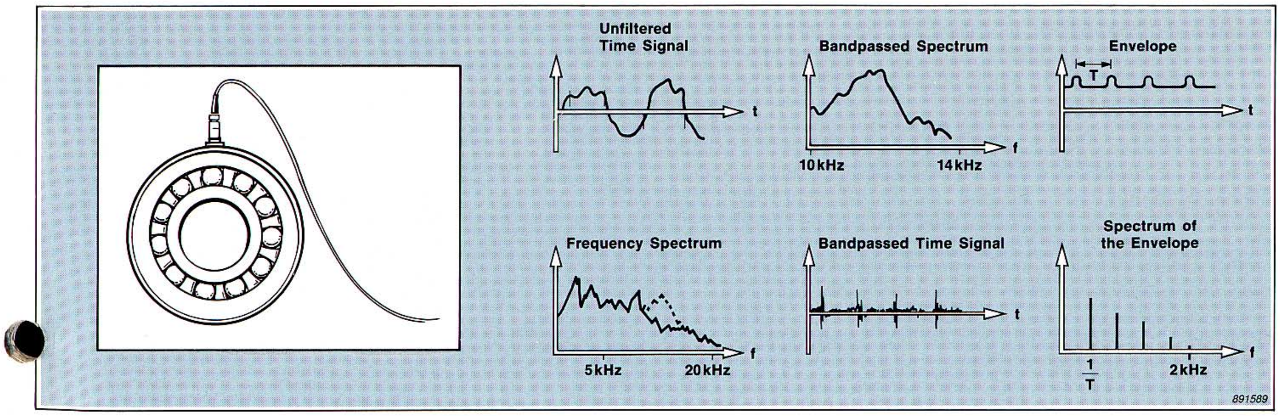


Additional Diagnostic Techniques

One diagnostic technique which has not been mentioned so far is *Envelope Analysis*, a technique used to detect faults in rolling–element bearings. Faults in these bearings produce a series of vibratory–impacts which repeat periodically at rates dependent on bearing geometry. The different repetition rates are characteristic of faults in the different bearing components – the outer–race; the inner–race; the ball and the cage. The repetition rates or bearing frequencies are unique for each type of bearing and are calculated according to fixed mathematical formulae.

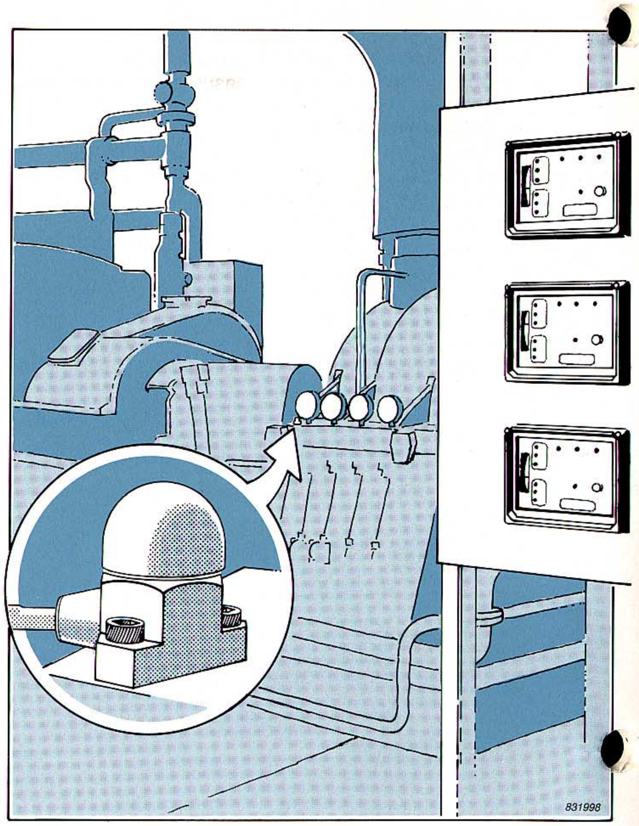
The first detectable signs of bearing deterioration in a frequency spectrum is a general increase in the vibration level in the 2 kHz to 20 kHz region. This is because each time a ball passes a fault, the resulting impact will excite structural resonances which appear in this part of the spectrum. These impacts modulate the time signal, the frequency of the modulation being directly related to the fault causing it. The modulation frequency creates an envelope around the time signal which is detected by an *envelope detector.*

To detect the envelope, the region of general increase in vibration level must be found, as described above. The envelope detector's band–pass filter is then tuned to this region's centre–frequency. The detector smoothes and rectifies the time-signal before transferring the altered signal to the analyzer. The signal displayed by the analyzer contains the fundamental and harmonics of all frequencies related to the bearing fault. These frequency components can then be cross–checked with the calculated bearing frequencies to ascertain the type of bearing fault.



Permanent Vibration Monitoring of Machinery

A technique which is closely related to the methods of machine monitoring so far discussed is *permanent vibration monitoring*. As the name suggests, permanent monitoring is permanently employed on specific machine(s) to continuously survey their condition. Its main purpose is to give early warning of incipient faults and immediate warning of sudden changes in the condition of expensive non–duplicated machinery whose continuous operation is vital to the production process. Fault conditions are detected immediately, or within seconds of occurrence, and trigger alert or alarm signals in the control room allowing the appropriate measures to be taken before catastrophic failure occurs. Such systems are widely used in the power–generation, pulp and paper and petro–chemical industries on turbines, paper machines, feed pumps, gas compressors etc.



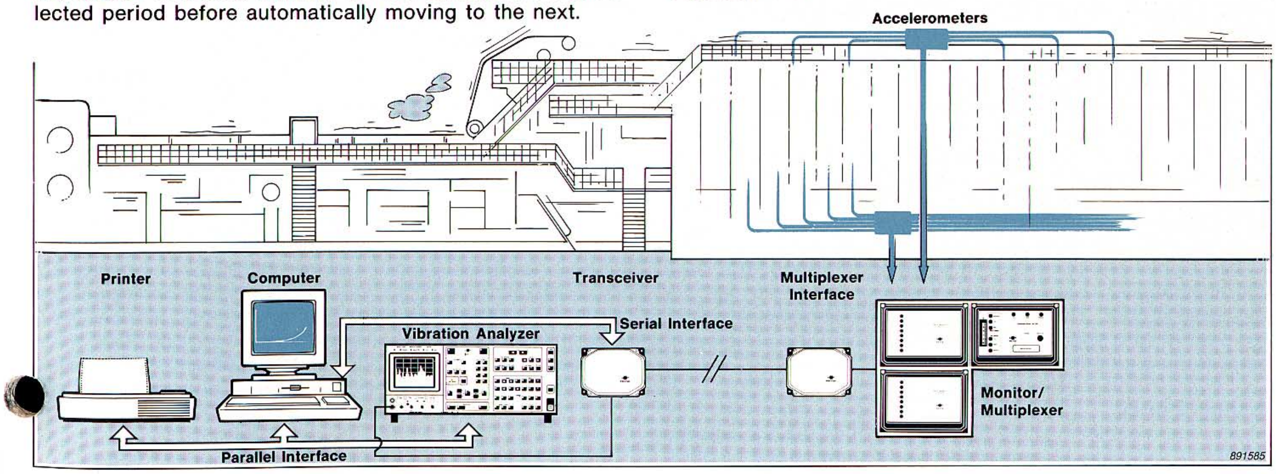
What Instruments are Required?
A prime requirement of all permanent monitoring systems is high operational–reliability, long–term stability and immunity to adverse environmental conditions and irregularities which can cause false alarms. They should be of sturdy mechanical design, capable of operating in humid and dust–laden conditions. Special "ruggedized" front–end ancillaries such as industrial accelerometers, cables and junction boxes, which can work at high temperatures, are essential requirements. Further, these systems should include an automatic test system to allow the plant operator to immediately check whether the instrumentation is functioning correctly in the event of an alarm.

What Should a Permanent Monitoring System Do?
Ideally, it should provide the maximum possible protection for the monitored machine, continuously monitoring each measurement point's overall vibration level and generating alarms when this level exceeds pre–set limits. This should be combined with fully automatic or operator directed cyclical spectrum comparison for each measurement point, generating printed warnings on detection of unacceptable increases within frequency bands.

Overall vibration levels (broadband levels) are continuously monitored over a user–specified frequency range. If preset limits are breached (for example Minimum, Alert, and Alarm), the system can trigger visual or audible alarms. Economical coverage of up to sixteen monitoring points can be achieved by multiplexing the inputs through a single monitor module. The Multiplexer continuously steps through the chosen channels, dwelling at each channel for a preselected period before automatically moving to the next.

In larger systems, these monitor/multiplexer blocks are connected to a serial data–bus – the system being controlled by an on–line computer. The computer, in conjunction with a vibration analyzer can cyclically access each vibration channel, record a frequency spectrum, compare the recorded spectrum with a stored reference spectrum, issue a printed warning on detection of component increases and then step to the next channel, continuously repeating the measurements. Since all reference and fault spectra are stored on disk, the system can also incorporate detection and diagnostic routines such as those discussed earlier.

Special systems are also available for explosive–risk and radioactive areas.



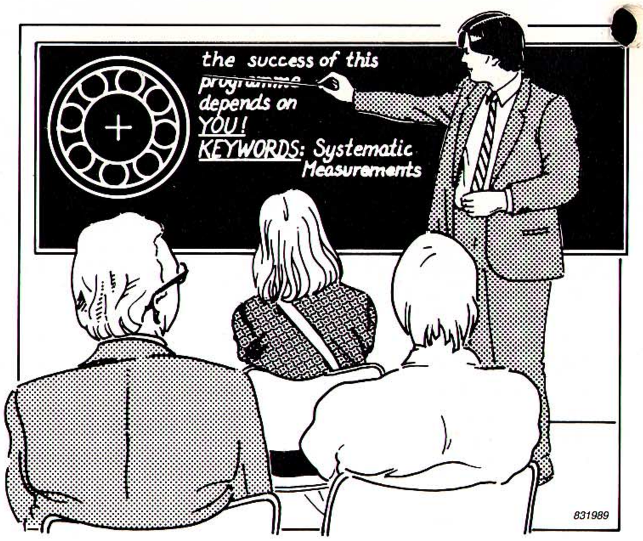
The Organisation of a Condition–Based Maintenance Programme

Personnel already employed in maintenance can usually take over the routine measurements on which condition–based maintenance schemes are founded. Their previous experience with machines will help them grasp the basic concepts more quickly. Tasks are usually divided. One or more persons perform the actual vibration measurements — following a standardised procedure, then a technician or engineer evaluates the results to detect machine faults.

Who?/How Long?/How Many?
In a pilot programme with fewer than 50 monitoring points to be measured and/or analyzed per month, the engineer usually performs the whole operation himself. Where only single–figure wide–band or crest factor measurements are being specified, one man can handle up to 1 500 points per month and two men can cover as many as 4 000 points per month. Using a portable analyzer to record vibration spectra at all points, one man can handle up to one thousand monitoring points per month.

As the number of monitoring points increases, computer–based systems will become more attractive. Vibration measurements are recorded by one or more persons who return the measurements to the automatic analysis system. Several users could share such a system or it could be utilised by several plants in the same organisation. The routine checking of incoming data need not be performed by engineering staff. The system prints out fault reports which are passed to a specialist who is able to run the diagnostic program and pinpoint the fault.

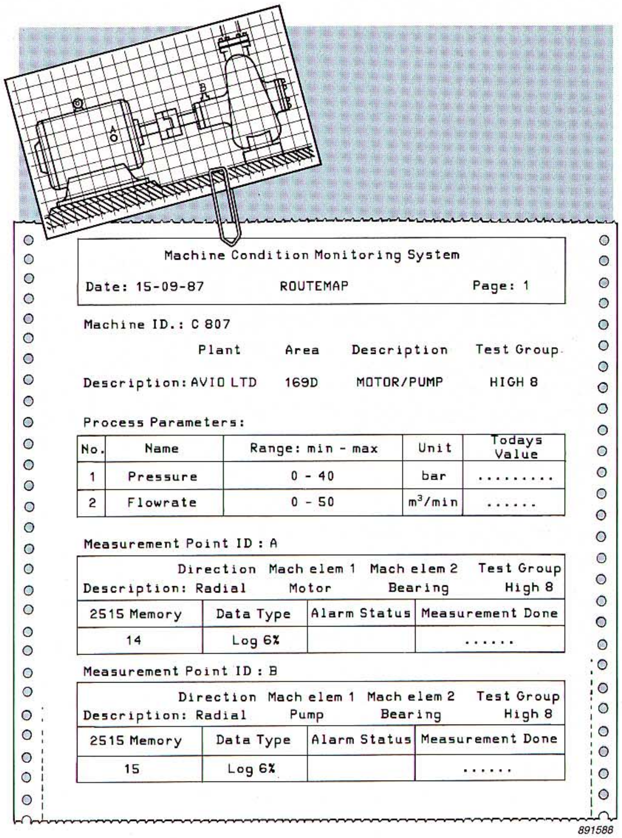
Getting Started
Firstly, the machines which are to be monitored are selected. Each machine is then considered individually to find points which will yield useful measurements — bearing housings are usually most suitable. Measurement points are prepared for easy attachment of the vibration transducer (accelerometer) and marked with a reference number. Permanent fixing points should be in the form of steel studs threaded into the machine element or in the form of glue–on threaded attachments known as cementing studs.



The sequence in which each machine and measuring point should be monitored is specified on the measurement route map together with information on required running conditions. Likewise, the various instrumentation settings should be standardised for each machine. As discussed, the system can be configured so that the computer automatically loads the analyzer with the correct measurement parameters for each measurement point along the route, thereby minimizing the possibility of incorrect measurements.

The machine's usual average operating time between failure dictates the periodic measurement intervals. At least six measurements should be planned for this period to give a reasonable predictive ability. For new machines, where guidance is not available from the manufacturer, monitoring should begin on a daily basis, then every second day, then every third etc. until stable operation is confirmed. The measurement interval can then be progressively extended until the most appropriate interval is discovered for the given machine.

Details of the dynamic characteristics like shaft speeds, numbers of rolling elements in bearings and their dimensions, and numbers of gear teeth should be recorded on a master card for each machine. This enables a diagnostic reference diagram to be drawn up so that the various frequency components making up the machine signature can be related to specific machine parts. Guidance on what are acceptable and non–acceptable vibration levels is discussed on pages 28 & 29.



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              Machine Condition Monitoring System

Date: 15-09-87            ROUTEMAP                  Page: 1

Machine ID.: C 807
                  Plant       Area   Description   Test Group

Description: AVIO LTD     169D    MOTOR/PUMP      HIGH 8

Process Parameters:
| No.|    Name    | Range: min - max |  Unit  | Todays Value |
|  1 |  Pressure  |      0 - 40      |  bar   |  .........   |
|  2 |  Flowrate  |      0 - 50      | m3/min |   ......     |

Measurement Point ID : A
              Direction  Mach elem 1  Mach elem 2  Test Group
Description:  Radial        Motor       Bearing       High 8
| 2515 Memory | Data Type | Alarm Status | Measurement Done |
|     14      |  Log 6%   |              |      ......      |

Measurement Point ID : B
              Direction  Mach elem 1  Mach elem 2  Test Group
Description:  Radial        Pump        Bearing       High 8
| 2515 Memory | Data Type | Alarm Status | Measurement Done |
|     15      |  Log 6%   |              |      ......      |
```

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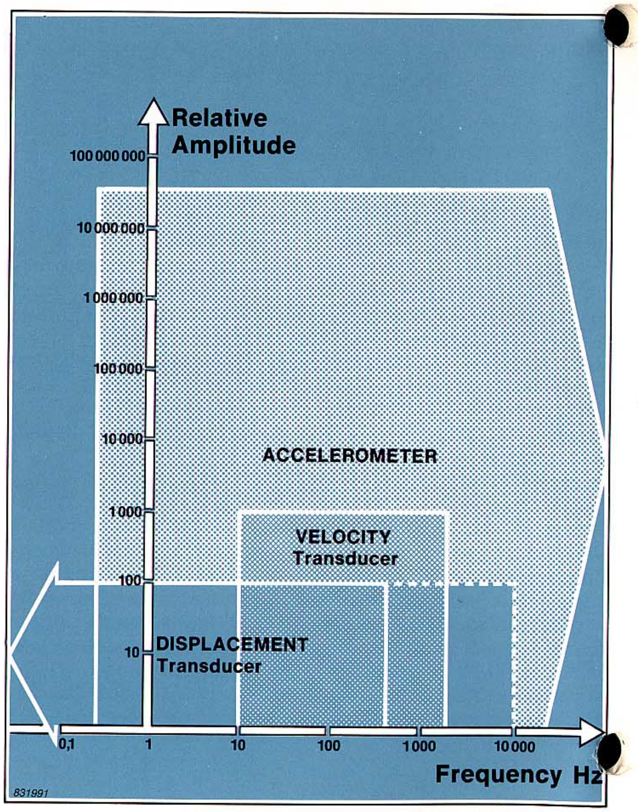
Vibration Transducers and Measurement Parameters

While relative displacement transducers are best for some specific shaft–monitoring applications, seismic transducers which measure absolute vibration are far more suitable for general machine condition monitoring duties. Although relative displacement transducers, such as eddy current or proximity probes, have a frequency range that can extend up to 10 000 Hz they can only effectively detect low frequency components as the higher harmonics usually fall outside the limited dynamic range of these transducers.

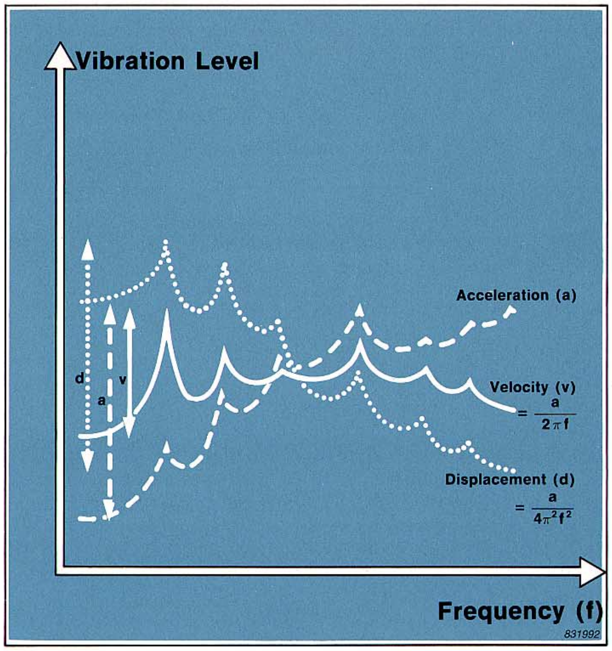
Popularly–used seismic transducers are the velocity pickup and the piezoelectric accelerometer. Piezoelectric accelerometers have in recent years become by far the most widely used transducer type for machine vibration measurements because of their superior frequency and dynamic ranges, their much smaller physical dimensions, their long–term reliability (no moving parts) and their general robustness. As many monitoring situations require frequency coverage well above 1 000 Hz and require to detect vibration amplitudes over a far greater range than 1 000:1, the piezoelectric accelerometer is the only practical choice.

Choice of Monitoring Parameter
With instrumentation based on the use of an accelerometer pickup, the user is normally free to choose between *acceleration, velocity,* and *displacement* as the measurement parameter. Different engineers have, from habit, different preferences, but let's look at the question from a purely technical viewpoint.



The drawing on the opposite page shows a typical vibration spectrum (plotted on logarithmic axes) from a machine, expressed in terms of the three different parameters. It can be seen that they have different average slopes, but nevertheless, they have peaks at the same frequencies and the amplitude of the peaks relative to the general slope of each spectrum is the same. Each curve gives an equally true picture of the vibration spectrum. There is a very simple mathematical relationship between the curves so that the value at any frequency on one curve can be converted to a value at the same frequency on one of the other curves (this is in fact done by the integrators in vibration meters).

Note that in the example illustrated, the amplitude range required to display the velocity curve is smallest and thus occupies the least dynamic range in the measuring system and gives a higher signal to noise ratio (more "room" for useful data). It also means that frequency components on this curve need a smaller relative change before they begin to influence the overall (wideband) vibration level. Most components on the other curves need to exhibit much larger changes before they influence the wideband vibration level. The conclusion is that in general, (and especially when using simple instruments giving a single reading over a wide frequency range) the flattest spectrum is the parameter which will enable the earliest detection of faults. This parameter is typically velocity but may sometimes be acceleration, especially where high frequency vibration such as that from rolling element bearings is of prime interest. Conversely if it is known that faults requiring monitoring occur at low frequencies, choose displacement.



When using an accelerometer, the associated vibration meter, analyzer or preamplifier will normally include integration networks so that the measurement parameter, either acceleration, velocity, or displacement, may be chosen simply by turning a switch. When investigating a new machine or monitoring point one should preferably record frequency spectra of all three parameters so that the parameter giving the flattest spectrum in the frequency range of interest can be selected for subsequent monitoring. If an analyzer is not available then choose velocity.

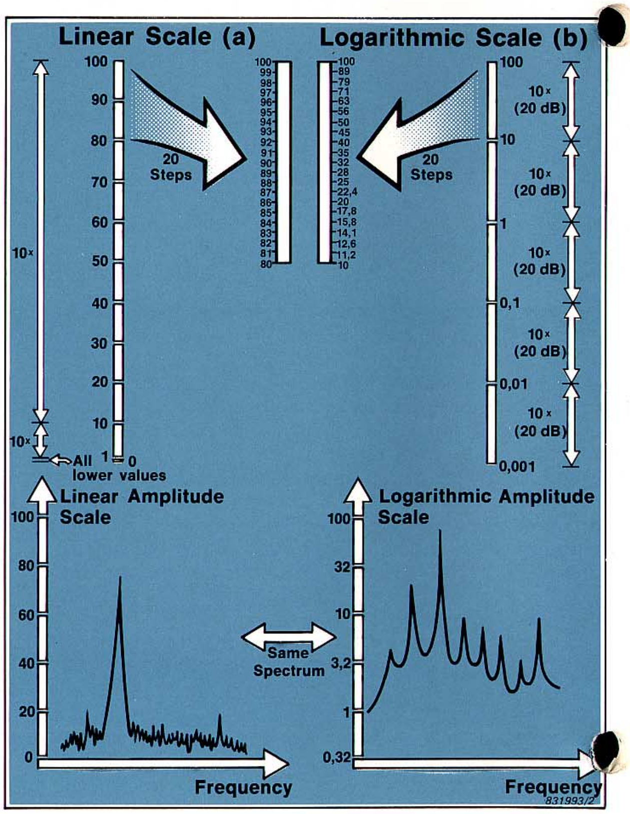
Choosing Appropriate Amplitude and Frequency Scales

As we have already noted, both large and small components in a vibration frequency spectrum are potential indicators of faults, so the same measuring accuracy is required over a wide amplitude range. Both linear and logarithmic amplitude scales are in common use, but only logarithmic amplitude scales allow vibration components within a sufficiently wide amplitude range to be measured with the necessary accuracy.

Linear versus Logarithmic
The adjacent figure illustrates two scale types having an accuracy and resolution of 1% of full scale, that is, there are 100 possible read–off values. If a read–off accuracy of 10% is required then scale (a), the linear scale, can only be used over a 10:1 range down to level 10 where one step in 10 gives the minimum allowable accuracy of 10%.

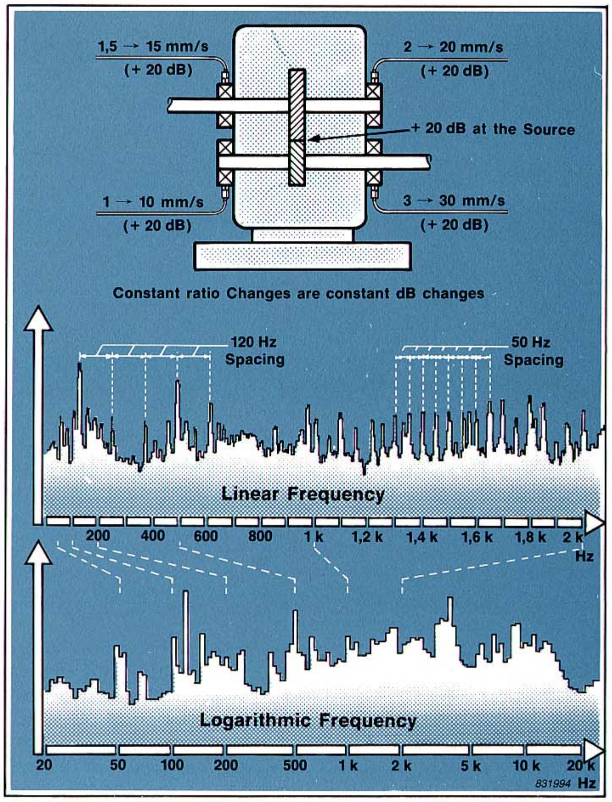
When a frequency spectrum is generated on a linear amplitude scale, as illustrated in the lower sketch, only the predominant peaks will usually be within the allowable accuracy range. We cannot hope to follow the relative changes of any but the high level frequency components, while other possibly important components only appear as small "blips" crowding the bottom of the spectrum.

Choice of Units
Moving to the logarithmic scale (b), each of the 100 scale values represents an 11% increase over the previous step. Thus, the first 20 steps below full scale cover a range of 10:1 (20 dB), the second 20 steps a further 10:1 range, and so on up to the full 100 steps which cover a dynamic range of 100 000:1 (100 dB). This would be totally impractical with a linear amplitude scale while still maintaining a reasonable accuracy. Such a wide range is not necessary in practice; a range of 300:1 to 10 000:1 (50 — 80 dB) will accommodate a sufficiently wide range of frequency components for machine–monitoring purposes. The lower sketch (on the opposite page) shows how low–level components can be and accurately measured with a logarithmic scale.



Logarithmic amplitude scales are often calibrated in mechanical units, such as m/s, but dB "units" (familiar from sound measurements) are also widely used. Using dBs, the considerable numerical span of a logarithmic scale is reduced to a compact linear numbering system such that a factor of 10:1 on a log. scale is equivalent to a 20 dB interval (as illustrated with scale (b) on the previous page). This is advantageous when working with vibration measurements for machine monitoring as it is *ratio* increases in levels (ie. a fixed number of dBs) which represent the degree of deterioration rather than the actual level itself.

Choice of Frequency Scales
Both linear and logarithmic scales are commonly used on the frequency axis of vibration spectra, and there are benefits with both types. In general, a logarithmic frequency–axis is most suitable for the *detection* and *prediction* of faults. As already discussed, such a spectral presentation allows the entire vibration signal to be resolved into percentage bandwidth components yielding high resolution at low frequencies, the part of the spectrum where most faults can be detected. For fault *diagnostic* purposes, especially with complex machinery, linear frequency scales are beneficial. They "spread out" the individual frequency components to ease the diagnosis of faults, particularly those which are characterized by a number of harmonically related components or "sidebands". The 120 Hz and 50 Hz component spacing on the adjacent drawing illustrate this.



Vibration Severity Criteria and the Evaluation of Vibration Levels

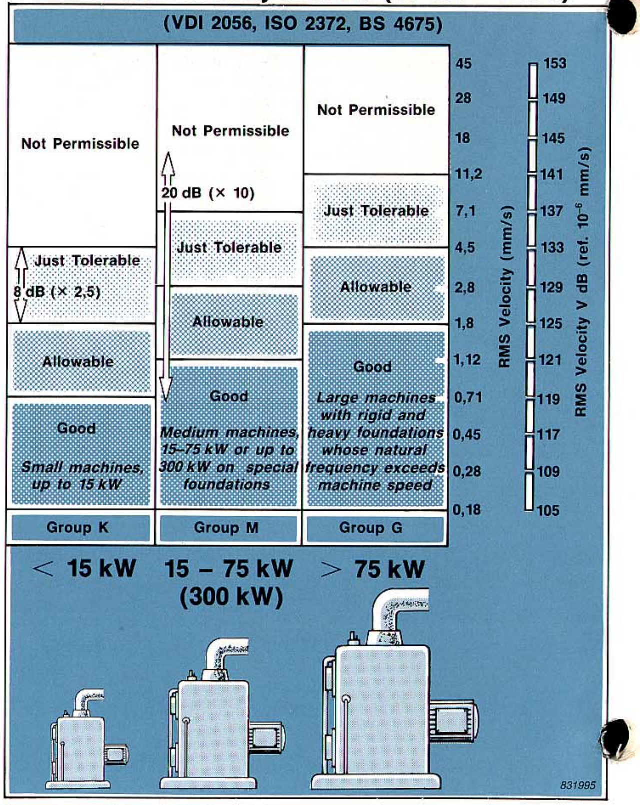
How Much Vibration is Too Much?
Many engineers start by using one of the published vibration severity standards as a guide for judging machine condition. Some standards, like ISO 2372 (and equivalent national standards) specify limits dependent solely on machine power and foundation type. Most general-purpose criteria are based on the RMS value of vibratory velocity over the frequency range 10 to 1 000 Hz, yet many important frequency components often occur at higher frequencies.

Another example of criteria made solely for judging machine condition is the Canadian Government Specification, "Vibration Limits for Maintenance". This defines limits for specific machine types and sizes as shown in the extract on page 30. It also uses RMS Velocity levels and covers the frequency range 10 Hz to 10 000 Hz.

Although the absolute values suggested by these criteria are not always relevant (note the discussion about variations in mobility on the opposite page), they are nevertheless useful in that they indicate the significance of various degrees of vibration level increase. For example, the previously mentioned ISO 2372 indicates that a level increase by a factor of 2,5 (8dB) is a significant change as it is the span of one quality class. Likewise, an increase by a factor greater than 10 (20dB) is serious as it can take the classification from "good" to "not permissible".

These factors apply to wideband measurements. For reasons which are discussed in the next section they should be applied with circumspection. The classifications are a useful guide to spot-checking machine-condition but are severely limited in their application to early fault detection and diagnosis in any specific machine.

Vibration Severity Criteria (10 Hz – 1 kHz)



Force × Mobility = Vibration
Vibration measurements on the surface of machine elements reflect the cyclic forces being transmitted at that point. The actual vibration velocity measured is proportional not only to the forces involved but also the *mobility* of the structure at that point. Mobility is a measure of the structure's willingness to be set into motion (and is the inverse of mechanical impedance). The relationship between Force, Mobility, and the resulting Vibration Velocity, with respect to frequency, is illustrated in the sketch. Using logarithmic scales one can add force and mobility spectra to get a resultant vibration spectrum. Note that in the example shown, the high force component (A) at frequency (n) is countered by a low mobility at frequency (n) so that no special peak is noted in the vibration spectrum.

It is therefore unwise only to look for high-level peaks in the vibration spectrum, low values may also contain information about important force changes. Mobility characteristics of machinery do not usually change significantly with time so one can safely assume that if the vibration level at a given point doubles, the force level has also doubled. For similar machines the mobility at a given point may differ by as much as a factor of 1000:1. Thus it is illogical to use the same absolute vibration limits to indicate the need for maintenance.

A much more reliable indication of machine condition is obtained by concentrating on relative changes, ie. by specifying a reference "baseline" spectrum or level and allowing certain fixed factor changes. Practice has shown that for frequency components up to 1 000 Hz (and sharp peaks in the 4 to 10 kHz range) an increase by a factor of 2,5 (8 dB) should be considered a significant change in condition warranting investigation, and an increase by a factor of 10 (20 dB) from the reference condition signifies the need for repair — as suggested by the ISO and other criteria. For frequency components above 4 000 Hz these factors can be cautiously increased to 6 (~16 dB) and 100 (40 dB) as shown in the sketch.

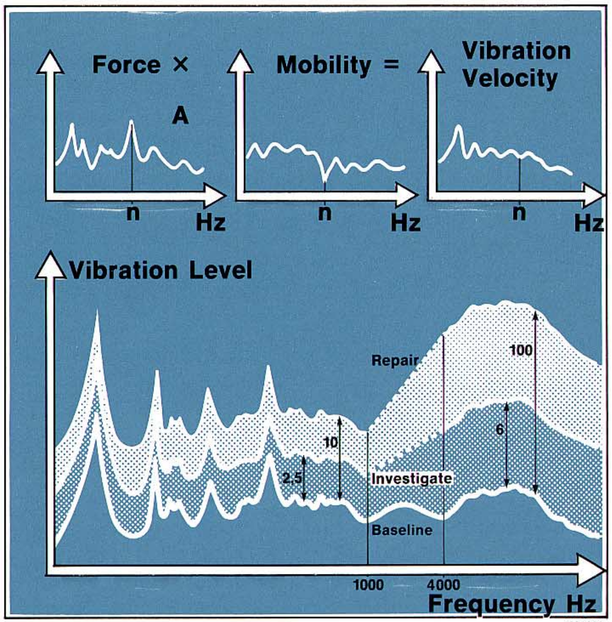


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Table of Criteria for Bearing Vibration Measurements (10–10 000 Hz)

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

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* 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 10 000 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.

Notes on Fault Diagnosis

Having recognised that a vibration level increase usually indicates a growing fault, the plant engineer will then wish to localize the fault to a particular machine element. Wideband vibration measurements provide very little information to help pinpoint faults. The (wideband) crest–factor measurements mentioned on page 10 can, however, often isolate the fault to a ball or roller bearing. Generally, a frequency spectrum is the key to diagnosis.

Tracing faults in all but the simplest machines involves a degree of detective work. The frequency spectrum holds the main clue, an increased vibration level at one or more known frequencies. This is analogous to a finger–print at the scene of a crime; all that's now necessary is for the detective to compare the finger–print with the prints of known criminals! In machine fault–diagnosis, this is equivalent to knowing the characteristic vibration frequencies of possible faults and finding the ones which match the frequency of the increasing components.

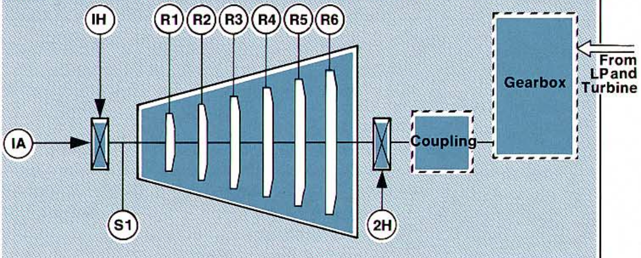
This entails an initial study of specifications and engineering drawings for each machine, making a schematic plan, and recording on it numbers of motor poles, shaft speeds, numbers of gear teeth, and ball/roller bearing data. By simple calculations these are converted to the expected characteristic frequencies of the machine and recorded for future reference.

The trouble–shooting charts on the following two pages list many common faults and their characteristic frequencies in terms of rotation speeds. These should be calculated, where relevant, for each machine in the monitoring programme.

Machine Details & Characteristic Frequencies

Plant: Petrochem **Section:** Ethylene **Date:** 5/1/80

Machine Nos.: 2 R1 HP (High pressure compressor)



Shafts		
Shaft No.	RPM	Rotation frequency (Hz)
S1	3500	58,3

Gears		
Gear No.	No. of Teeth	Mesh. frequency (Hz)

Rotors		
Rotor No.	No. Blades	Bladepass frequency (Hz)
R1	23	1342
R2	25	1458
R3	25	1458
R4	27	1575
R5	27	1575
R6	29	1692

Bearings									
Meas. Point	Bearing Type	D (Pitch dia.)	d (Ball dia.)	n (No. of balls)	ϕ (Contact angle)	f_o (Outer race)	f_i (Inner race)	f_b (Ball)	Discrete Defect frequency (Hz)
1	J								
2	J								

J = Journal bearing B = Ball bearing R = roller bearing

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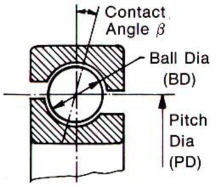
Vibration Trouble–Shooting Chart (A)

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 $f(Hz) = \frac{PD}{BD} f_r \left[1 - \left(\frac{BD}{PD} \cos\beta\right)^2\right]$ For Cage Defect $f(Hz) = \frac{f_r}{2} \left[1 - \frac{BD}{PD} \cos\beta\right]$ 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.

Vibration Trouble–Shooting Chart (B)

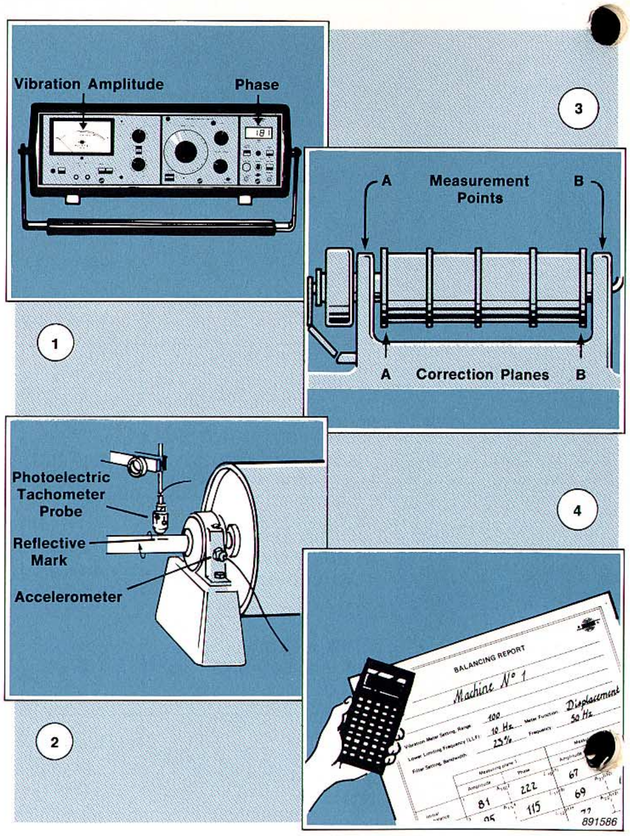
Nature of Fault	Frequency of Dominant Vibration (Hz=rpm/60)	Direction	Remarks
Hysteresis Whirl	Shaft critical speed	Primarily Radial	Vibrations excited when passing through critical shaft speed are maintained at higher shaft speeds. Can sometimes be cured by checking tightness of rotor components.
Damaged 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

Dynamic Balancing of Rotating Machines

What Causes Unbalance?
Unbalance in a rotor is caused by an uneven distribution of mass, causing the rotor to vibrate. The vibration is produced by the interaction of an unbalanced mass component with the radial acceleration due to rotation – which together generate a centrifugal force. Since the mass component rotates, the force also rotates and tries to move the rotor along the line of action of the force. The vibration thus caused will be transmitted to the rotor's bearings, and any point on the bearing will experience this force once per revolution.

Balancing – What/How?
Balancing is the process of attempting to improve the mass distribution of a rotor, so that it rotates in its bearings without uncompensated centrifugal forces. This is usually done by adding compensating masses to the rotor at prescribed locations. It can also be done by removing fixed quantities of material, for example by drilling.

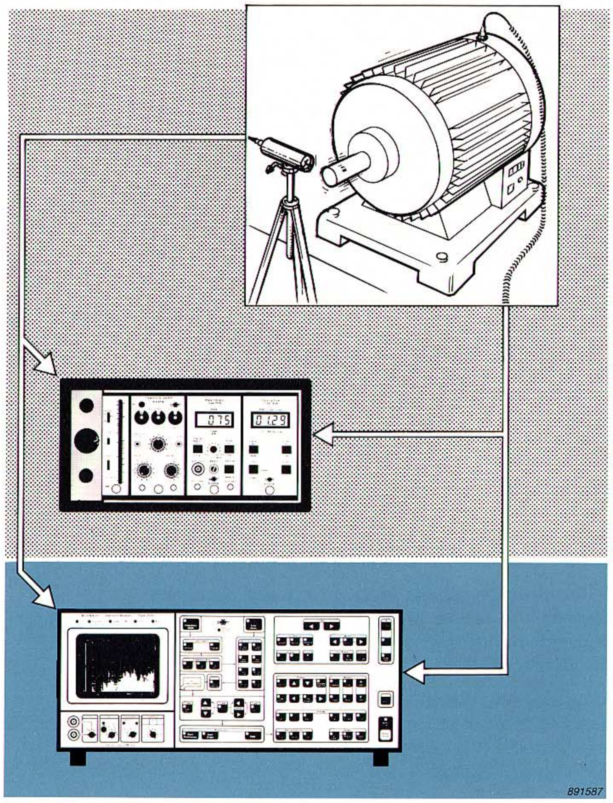
What Equipment is Required?
The minimal necessity for any balancing program is an instrument (or instruments) capable of measuring both vibration amplitude and phase in the frequency range of machine rotation.



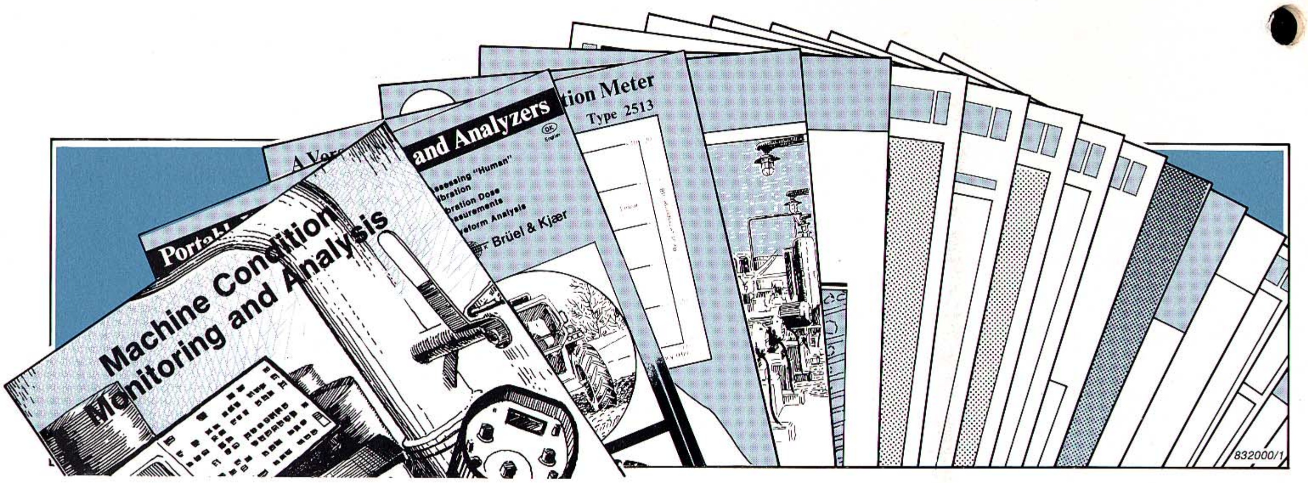
Balancing Procedure
The first step in balancing, for example a two–plane rotor, is to mount accelerometers on the bearing housings of both planes. A tacho probe is mounted at a convenient point on the shaft to act as a phase reference mark. The balancing instrument is then tuned to the frequency of rotation of the unbalanced rotor, and a narrow bandwidth selected. The phase and amplitude of vibration of both planes (the original unbalance) is measured. A trial mass is mounted on one plane and the phase and amplitude of both planes is again recorded. The trial mass is then placed on the other plane and the measurements repeated. The correction masses and mounting angles necessary to rebalance the rotor may be calculated directly by resolving the vector forces on the rotor or alternatively by using a programmable calculator running a dedicated balancing program.

If the unbalanced rotor is running at a fluctuating speed or background vibrations are a consideration, the balancing set should incorporate a tunable tracking filter. The use of such a filter ensures that the vibration meter is always "locked" to a particular frequency component, the fundamental frequency of rotation, regardless of the frequency fluctuations of that component.

Nowadays, portable vibration analyzers used in spectrum comparison monitoring have a built–in balancing capability. The tacho reference probe is connected to the analyzers external filter socket thereby synchronizing the recording of spectra with the rotation speed of the shaft. The technique applied to balance the rotor is very similar to that already discussed. The initial unbalance is measured in both planes, this time by recording a frequency spectrum and reading the amplitude and phase of the fundamental directly from the screen. Trial masses are attached to both planes in turn, the measurements repeated and the correction masses and mounting angles calculated as previously outlined.



Further Reading



Colour Brochures

"Machine Condition Monitoring and Analysis".
Details the range and uses of B &K's permanent and intermittent monitoring equipment. (16–sided).
Brochure BG 0391–11

"Permanent Vibration Monitoring".
Details the range and uses of B & K's permanent monitoring equipment. (12–sided).
Brochure BG 0250–11

"Vibration Analyzer Type 2515".
Uses, features and specifications of a portable vibration analyzer. (6–sided).
Brochure BG 0202–13

"Maintenance – be one step ahead of the production manager".
Use of a portable vibration analyzer as part of a computer-based machine condition monitoring system. (6–sided).
Brochure BG 0368–11

"Vibration Monitoring In Your Hand – quick, easy-to-use & effective".
Machine condition monitoring with a hand–held vibration meter, pocket computer and trending software. (2–sided).
Brochure BG 0560–11

"Predictive Maintenance of Pulp and Paper Machinery".
Description of the operation and results of a monitoring scheme at the Domtar Paper Mill in Canada. (12–sided).
Brochure BG 0104–12.

"Unbalance – Detected and Corrected on the Spot".
Description and use of B & K's balancing range for on–the–spot detection and correction of unbalance. (4–sided).
Brochure BG 0008–12.

"Vibration Monitoring Set Type 9612/13".
Machine condition monitoring with a hand–held vibration meter, stroboscope and headphones. (4–sided).
Brochure BG 0538–11.