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CONDITION MONITORING TECHNIQUES IN MAINTENANCE*

Prepared for the UNIDO Secretariat

by

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CONDITION MONITORING TECHNIQUES IN MAINTENANCE

SUMMARY

As a guide to the training required for personnel from developing countries this paper reviews the ways in which plant in these countries can have its life substantially increased by the application of condition monitoring, and the required skills and techniques that are necessary to enable this to happen.

Training courses in condition monitoring need to include lectures on:-

- The principles of condition based maintenance
- The methods which can be used:-
  - Vibration
  - Wear debris analysis
  - Performance measurement
- Practical aspects of interpreting the results
- Setting up a condition monitoring system
- Managing a condition monitoring activity.

In addition there would need to be practical demonstration sessions with condition monitoring instruments so that the trainees could become familiar with using them.

Such training courses would typically last for one full week and should be held in a developed country where the lecturers and instruments are readily available.

INTRODUCTION

In developing countries there is quite a lot of plant and machinery which is operating at a considerable distance from its place of original manufacture.

Sometimes, therefore, there may be limited availability of important spare parts and of specialist labour and advice for repairs. It is therefore very important that the plant is operated under careful control and maintained as well as possible. One very important aspect of this is that if a fault begins to develop, it needs to be recognised as soon as possible and certainly before it leads to any severe damage occurring.

Methods for monitoring the condition of plant while it is in operation is therefore a potentially very useful technology and this paper considers the principles and methods involved and provides suggestions on how appropriate systems can be selected and introduced into service.

THE PRINCIPLES OF CONDITION MONITORING

It is unusual for an item of plant or machinery to fail suddenly and catastrophically without any advanced warning. There is usually some deterioration of performance or signs of wear, leakage or vibration which indicates that all is not well. The general principle of condition monitoring involves the selection of some appropriate indicator of the machine condition, which can be measured at intervals. This measurement is recorded and is then usually plotted on a graph, against time in service, to indicate whether deterioration is occurring, as shown in Figure 1. If, however, the operators are very familiar with the machine and its various failure modes, it may be possible to check its condition from a single reading, which is then compared with known and established criteria for that particular machine in its operating situation.

The object of the condition monitoring activity is to achieve a lead time or advanced warning of failure to enable the machine or plant to be taken out of service in a planned manner. Failures in service can then be eliminated and the maintenance operation can also be much more efficient, because the necessary spares and skilled labour can be standing by to do the job.

There are three basic techniques which can be used to indicate that some form of deterioration is occurring and these are:

1. Vibration monitoring which detects faults in moving components inside a machine, from the way in which changes in the dynamic forces, which they generate, affect vibration levels at externally accessible points.

2. Wear debris monitoring used for components that generate particulate debris as a result of deterioration, which can be detected in a fluid stream, such as lubricating oil, which passes over the component surfaces.

3. Performance monitoring which monitors directly the way that components or systems are performing their intended function.

VIBRATION MONITORING

The movement of the components of machines generates vibration and the measurement of this vibration can be used to indicate the condition of the machine and its components. The vibration is generated at the moving component and the vibration signal therefore contains information on how the component is moving including any inconsistencies in this movement associated with component defects. For example, if a rolling bearing is pitted due to fatigue, the rolling elements will no longer rotate in a uniform and steady way, but will bounce in and out of the surface defects. This effect will be reproduced in the vibration signal generated by the bearing.

The vibration generated by a machine component travels out through the machine structure towards the outer surface. An appropriate transducer can therefore be fitted on the machine to pick up the vibration and convert it into an electrical signal for measurement and analysis. The same vibration will also cause the outer surface to the machine to generate noise which can be picked up by the human ear. While this provides a direct means of detecting certain faults, it is not as sensitive as picking up the vibration directly and using appropriate instruments to interpret it. This is because noise from one source is very sensitive to interference from other sources, and can also be distorted by resonances from panels and similar parts of a machine structure.

Vibration measurements are quite widely used for monitoring rotating machines because they can be taken relatively easily with portable equipment, which can be used on a wide range of machines. It is also possible to take a recording of vibration signals in the field, to be brought back for more convenient detailed analysis at an engineering base.

The simplest interpretation of a vibration signal is the measurement of its overall level in terms of the roughness of the running of the machine. This can give a useful indication of the existence of a problem in a machine, but is not as sensitive for problem detection as the measurement of the vibration level at particular frequencies associated with the main machine components. For example if a vibration detector is tuned to display signals at the rotational frequency of the shaft of a machine, it will detect any increase in its vibration level with greater sensitivity than an overall level measurement. This technique known as discreet frequency monitoring is readily applicable to machines, provided the important frequencies are known.

A more general method which can be applied to all machines in a plant to determine the source of a vibration once the existence of a problem has been detected, is spectral analysis of the vibration signal. Here the signal is scanned over a wide range of frequencies to look for those which contain a substantial level of signal. The process is analogous to turning the tuning knob on a radio to discover where there are signals being transmitted. Once the frequencies containing a substantial signal level have been discovered, the results can be compared with the expected frequencies that would be generated by various parts of the machine to indicate which of them is giving rise to the vibration. For example in a two shaft gear box, as in Figure 2, three possible frequencies would be expected corresponding to the low speed shaft RPM, the high speed shaft RPM and the gear tooth meshing frequency. The one which shows maximum signal content in a measurement taken on such a gearbox will indicate which component is developing a defect.

Another sensitive technique in the analysis of vibration signals is signal averaging, where the signal is analysed around a particular base frequency to see what kind of wave form exists at that frequency. In terms of a radio analogy, it is equivalent to tuning in to a particular radio station and listening to the music. In this way it is possible to tune in to a particular component in a machine and from the signal obtained, it is possible with experience to determine how it is operating or what particular defects it may be exhibiting, as shown in Figure 3.

Spectral analyses and signal averaging are both sensitive diagnostic techniques suitable for use by skilled engineers. They are not really suited to routine measurement of machine vibration in general industrial applications. Until the early 1980's overall level vibration measurements were used almost universally for routine regular measurements as they require the minimum skill and the instrumentation used is portable and robust. They have two major disadvantages however, which are their relatively low sensitivity and the need to make manual recordings of the readings which have been taken.

New measurement equipment developed a few years ago in the UK and now manufactured by companies based in the USA overcomes these two problems. The equipment consists of two components, one a portable measuring and data collection unit and the second a recording and trend analysis base unit. The portable unit can be preprogrammed by skilled engineers to take measurements at the particular discreet frequencies, which relate to the components of each machine and which are known to be critical. Each measuring point is numbered and this number is keyed into the instrument as it is connected to the measuring point to enable it to select the appropriate programme. Any special instructions for the operator can also be programmed in. After a tour of a large number of measuring points the instrument is brought back to the base unit and the data it has collected is unloaded and automatically analysed for trends and compared with critical allowable levels. This type of equipment is sufficiently sensitive to give good lead times on warnings of problems, reduces the errors and time wasting associated with hand written data collection, and also monitors the route and time that the operator has taken. It therefore readily overcomes the problems previously associated with the division of labour between routine work which may not be done to adequate standards, while saving the time of the skilled engineers, who are actually controlling the monitoring process.

WEAR DEBRIS MONITORING

Parts of machines which move relative to each other tend to generate wear debris from their interactions, particularly if their operation is not entirely smooth and well lubricated or if the surfaces are highly stressed and therefore prone to local fatigue or pitting. If the components are flushed with fluids, such as lubricating oils, the wear debris that is generated tends to be carried away by the fluid and can be extracted from it at some convenient place. By examining the quantity and the type of wear debris that has been generated useful guidance can be obtained on the condition of the interacting components.

In general terms, the amount of debris generated, and particularly the fraction of the debris consisting of larger particles, gives an indication of the existence of a problem. The composition and the form of the debris can give an indication of which component in a machine is experiencing some distress, together with an indication of what may be causing it.

There are two main methods of collecting and analysing wear debris and these are:

Magnetic plugs : where a removable magnetic plug is inserted in the oil drain path from important components and is withdrawn at regular intervals for examination to see what wear debris it has collected.

Spectrographic oil analysis: where a sample of oil is extracted from the machine at regular intervals and burnt in an electric arc to produce colours in the arc dependent on the elements present. The flame colour is analysed spectrographically to give an indication of the different elements present together with their concentration.

In addition to these specific methods it is also worth checking the content of deposits on lubricating oil filter elements as these will also contain a large number of wear particles as well as other material, as shown in Figure 4A.

The different methods tend to be particularly suitable for different machine components. Magnetic plugs are relatively ideal for monitoring the condition of ferrous components, which produce wear debris in large pieces, such as rolling bearings, and gears which produce ferrous debris as a result of surface pitting. See Figure 4B and 4C. These large particles are less likely to be picked up in an extracted oil sample, because they tend to fall to the bottom of the oil containment space and not remain suspended in the oil.

In contrast, spectrographic oil analysis is better for detecting smaller particles which remain in suspension in an oil sample and tend to derive from conforming bearing surfaces such as plain bearings, piston rings and cylinder liners.

Methods are also available using electrically conducting filter grids which can detect the presence of metallic particles collecting on the grid and is useful for picking up the larger wear particles that may be produced by any metal component, particularly when a failure condition is approaching.

The problem with all these methods however is that they all require some degree of regular manual intervention, either to withdraw a magnetic plug for examination or a grid for cleaning, or an oil sample for spectrographic or ferrographic analysis. The latest development in wear debris monitoring instrumentation overcomes this problem and produces a system which monitors a machine continuously without any attention. It gives a warning when the rate wear debris generation increases, indicating an incipient failure, and only then retains a sample for examination. This instrument incorporates a magnet which is positioned behind a fluid tight non-magnetic membrane on which it collects wear debris from the system. The amount collected is measured by the instrument, and when a fixed amount has been collected it withdraws the magnet for a short time to release the debris sample. The time between releases relates to the amount of debris entering the fluid system and can be programmed so that when the time becomes critically short, the instrument gives an alarm and retains a debris sample for analysis.

COMPONENT AND SYSTEM PERFORMANCE

In this method components and systems are monitored to ensure that they are performing their required function. In the case of components this may involve some form of visual inspection either directly or with some form of visual assistance such as a boroscope for looking inside machines through a convenient access hole. Visual inspection is a very powerful technique because of the extreme effectiveness of the human eye, but has a disadvantage for trend monitoring, that some method needs to be devised for recording what has been seen, preferably with some numerical measure associated with it, so that changes with time can be permanently recorded. Cracks in structural components can be recorded in terms of their length or photographed with a date card. Surface damage such as pitting on gear teeth can either be photographed, or simple prints or replicas can be taken from the surface. With gears, a convenient technique is to degrease them, wipe them with marking blue and then take a print with transparent adhesive tape, which can then be stuck on a record card with the date at which the print was taken.

For tribological components such as bearings, temperature measurement is an ideal simple monitoring method for checking that movement is taking place under load with the minimum of energy loss due to friction. For seals, leakage is the obvious indication of a breakdown of their function and apart from surface stains which often give a good indication of leakage, there are instruments available for measuring the concentration of hydrocarbon and halide gases, which can give an indication of trends in leakage rates.

For high temperature components where it may be necessary to check the function of the thermal insulation, a very good technique is infra red thermography This uses a camera which picks up infra red radiation from hot components and converts it to a coloured visual reproduction of the object with the colours representing various temperature levels. With such an instrument it is quite easy to discover any defective insulation or internal blockages in a hot vessel or gas duct.

For pressure vessels and piping carrying corrosive fluids, corrosive monitoring and wall thickness measurements can be used to indicate any impending risk of loss of containment of the fluid. A very simple technique is to drill small sentinel holes part way through the way thickness, so that when the internal corrosion reaches the bottom of a hole, a small leak occurs which can be plugged very simply with a taper pin. Another technique is to insert removable coupons of the component material into the fluid stream, so that by removing the coupons and weighing them at intervals, it is possible to estimate the likely corrosion rate of the system. In some cases a direct measurement of corrosion rate can be made by recording the electrolytic current generated by the corrosion process and by feeding this to a watt-hour meter or similar recorder to obtain a direct measure indicating the amount of corrosion that has taken place.

Systems can be monitored by checking their overall performance usually by comparing one characteristic with another. A common example would be the miles per gallon obtained from a motor vehicle which, if it showed a noticeable fall, would be an indication that it was becoming defective. Comparisons of output and input of this kind are a good basis for this kind of monitoring such as the comparison of the fuel consumption and the electrical output of a diesel generating plant. In the case of a pump it can be useful to compare delivery flow and pressure as an indication of pump condition, as shown in Figure 5. Also in a structure subject to dynamic loads the relationship between load and deflection can give an effective indication of the integrity of the structure or its foundations. This technique of comparing one parameter with another is particularly useful for another reason, which is that the data can be recorded graphically in a plot of one parameter plotted against the other. The graphical recording is therefore a single card which can be changed once per week or once per month. This avoids the production of large quantities of paper records which tend to be generated when plant parameters are recorded automatically on a time base.

Variations in the output under different operating conditions can also provide a useful indication of the condition of a machine. One special example of this technique is in textile weaving machines where wear in certain of the components shows up as pattern variations in the cloth which it is producing.

System performance monitoring techniques tend to be highly individual to a specific piece of plant and for this reason there is less proprietary equipment available on the market for carrying out this kind of monitoring. There is therefore greater scope for individual and effective methods to be developed by the engineers concerned in each case.

DECIDING WHETHER TO SET UP A SYSTEM FOR THE CONDITION MONITORING OF AN INDUSTRIAL PLANT

Before trying to set up a working system, a decision has to be made as to whether it is actually worthwhile for the particular organisation concerned. Basically this depends on the type of plant and on the money that is involved.

The sort of plant that is the most obvious for the application of condition monitoring is where at some part of the manufacturing process, one large machine handles the entire throughput. In a plant of this kind the rate of output depends on the machinery and there are generally relatively few employees. In accountancy terms an operation of this kind is referred to as being capital intensive, as distinct from a labour intensive operation, where the output depends mainly on the employees. An example of a labour intensive organisation would be a company making clothing by employing large numbers of ladies to operate sewing machines. In such an organisation it would obviously be more sensible to have a few spare sewing machines, rather than attempt to monitor the detailed condition of all the various machines.

As a guide to the possible economics of condition monitoring, it has been found that the annual savings that result, when the monitoring system is fully operational, are of the order of one percent of the annual added value of the organization. Added value is the amount of value added to the raw material by the manufacturing process. Also, companies who have applied condition monitoring to their plant have generally found that it is worth making an initial capital expenditure, for setting up the system, which is of the order of one percent of the capital value of the plant being monitored. In cases where there is a major safety risk involved as well, so that the condition monitoring has other advantages in addition to economic savings, users have found it worth spending more on the system and a capital expenditure of the order of five percent of the plant value has been fairly typical.

This initial study of the general type of plant and of the economics involved will give an indication of whether it is worth applying condition monitoring, and the order of expenditure that is likely to be involved. This gives a measure of the size of the activity that has to be planned. The next decision is usually whether to set up the operation within the organisation or whether to buy in a complete service from outside, or possibly a compromise solution of setting up a joint exercise between a number of related companies. As a very approximate guide it can be assumed to be worth setting up an internal activity, involving at least one man full time, if the added value output of the establishment exceeds £1 million per year.

SELECTION OF MACHINES WHICH NEED MONITORING

Once a decision has been made to go ahead, it is then important to realise that it is not economical to monitor everything and the critical machines which need monitoring have to be selected. There are two main factors to be considered in the selection of machines which need condition monitoring. The first is to identify which machines are most important to the continued operation of the plant. The second is to assess whether these machines are suitable for condition monitoring techniques.

The identification of the machines most critical to the plant operation is straighforward. For a production plant, a study of the material flow path through the plant should indicate which machines are critical in that their failure would result in a major disruption to production. Such machines are typically those which are in continuous operation, have minimum standby or parallel capacity, and have minimum work in progress stocks held either upstream or downstream. Major disruptions can also be caused by the failure of machinery which is remotely or inconveniently sited and for which repair is therefore difficult and slow.

The other main reason for considering machinery to be critical to plant operation is that of safety. The introduction of a condition monitoring system should therefore be considered for any machine if its failure would be hazardous to personnel or could result in serious consequential damage to other machines or to the product.

The determination of which types of machines are suitable for condition monitoring is dependent on the various possible failure modes of the machine. A machine is regarded as suitable for condition monitoring if it contains critical components which fail progressively rather than suddely. This is because monitoring is normally carried out at component level to give the maximum advance warning of an impending failure. This requirement of progressive failure of critical components tends to restrict the applicability of condition monitoring to machinery where satisfactory operation is dependent on the performance of a few critical mechanical components such as bearings, seals or gears. Large pumps and compressors are typical suitable applications. Electronic circuits, on the other hand, where there are large numbers of components which usually fail suddenly, are not suitable for condition monitoring and a simple fault diagnosis system would be a more appropriate maintenance tool.

Another point to be considered when identifying which machines to monitor is that there are differences between the criteria applied to new plant and those applied to existing plant. There is usually a considerable data bank of operating experience for existing plant, which both enables alarm levels for the monitored parameters to be accurately defined and also in some cases reduces the need for monitoring, as the machine operator may be in a position to make accurate subjective judgements on machine performance based on sight, sound and feel. Knowledge of previous failures also enables the monitoring system to be precisely targetted at those machine components which have been shown to be critical. No operating experience exists for new plant, and therefore a detailed study of the expected performance of the plant machinery components will be required. A more extensive monitoring system may be necessary, and the output from the system will have to be carefully interpreted, as the critical levels of the monitored parameters will not be known.

SELECTION OF MACHINE COMPONENTS TO BE MONITORED

Once those machines which are both critical to plant operation and are suitable for condition monitoring techniques have been identified, it is then necessary to determine which of the machine's components should be monitored.

Any failure which occurs in one of the selected machines will originate in a particular component and if the failure is to be detected in advance, the monitoring method to be used must be matched to the component and its mode of failure in order to achieve the greatest sensitivity.

Components which it is particularly important to monitor will be those where:-

(a) a failure is likely;

(b) the consequences of the failure are serious in terms of machine operation;

(c) the time required for a repair is long.

If all these conditions apply to any one component then monitoring its condition is absolutely essential and furthermore, some additional action should generally be taken to modify or re-design the component to obtain a more reliable performance.

If any one of these three conditions is totally absent for any one component, then condition monitoring of that component is usually unnecessary. Most machine components lie between these two extremes, and in order to establish a priority ranking, marks can be applied to the different components for:-

likelihood of failure
consequence of failure
repair time of failure.

Typically each factor can be marked on a scale of 1 to 5, with the highest mark indicating the worst condition. By direct multiplication of the three marks, an overall priority mark of between 1 and 125 can be established.

Such a marking system is obviously highly subjective and requires careful judgement on the part of the maintenance engineer. Detailed maintenance records for existing machines will provide some quantitative data for the more common failure modes, but these will not necessarily be the most critical ones. Despite these possible difficulties, a priority marking system such as this can be highly effective in identifying the most critical components This is best demonstrated by the following example, in which the components of a large NC machine tool are considered.

The main component systems of the machine tool under study are:-

(i) the chuck drive system including the electric motor, belt drive clutch and gearbox, main spindle and bearings and the associated lubrication systems;

(ii) the tool slides including the slide bearings, clamping systems, lubrication system and the hydraulic balance system;

(iii) the slide traverse drive system including motor drives and ball screws;

(iv) the electrical power system;

(v) the electronic control system.

For this example, systems (iv) and (v) are not suited to condition monitoring methods for the reasons given previously, and therefore further investigation is restricted to systems (i) and (iii). Having identified the components systems, the next stage is to identify all likely component failures. Table 1 shows a listing of the possible component failures of system (i), the chuck drive system. For each component failure, the likelihood of occurrence, effect of failure and repair time are assessed qualitatively. A table such as this is built up for each component system and then marks are allocated for the various failure factors to produce a priority table as shown in Table 2. The most critical components can then be easily identified.

SELECTION OF SUITABLE MONITORING METHODS

A list of components and failure mechanisms provides a basis for selecting condition monitoring methods and it will generally be found that more than one method can be used for each component. For example a rolling bearing failure could be monitored by magnetic plugs picking up the pitting debris, vibration measurement picking up the resulting vibration, or a thermocouple picking up a temperature rise. The object then, is to reduce the number of different monitoring methods required, for the whole plant to one or possibly two, with an exceptional special technique for perhaps one particularly critical machine.

If the monitoring methods used can be reduced to one common method the operation of the system is considerably simplified and a high level of expertise in handling and interpreting that particular method can be built up. However if the plant operation is very important and unnecessary shut downs are to be avoided at all costs, it may then be desirable to use two different methods of monitoring so that in a critical situation they can be used for comparative guidance for the decision on whether to close down the plant or not.

INTRODUCING CONDITION MONITORING

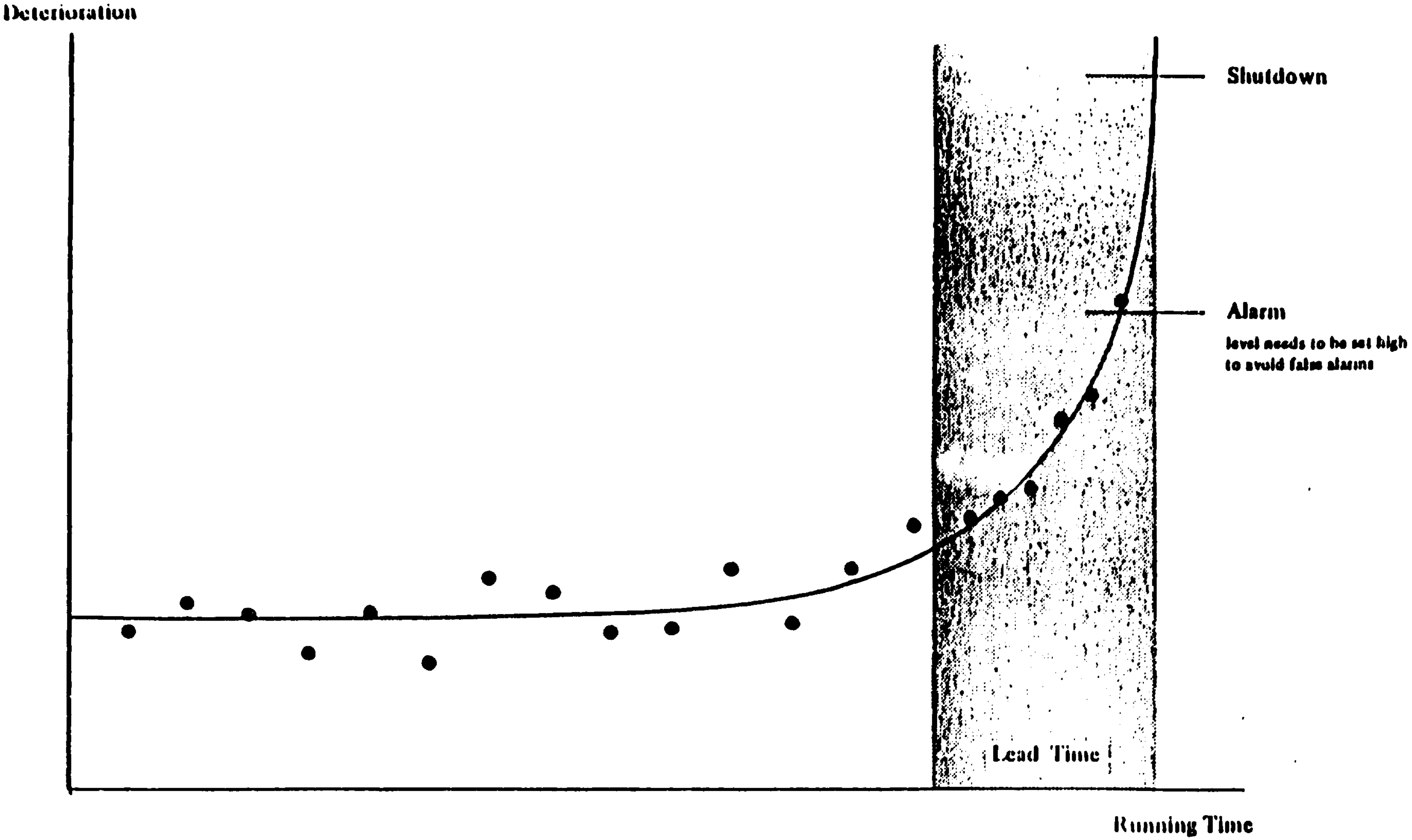
The most effective way of introducing condition monitoring on an existing plant is to do it gradually. This enables a progressive transition to be made to condition based maintenance, and gives the personnel involved the chance to acquire experience as the system develops. If, for example, regular preventive maintenance is already well established on the plant, the condition monitoring techniques can be introduced initially for defect diagnosis just before the regular overhaul. This can give useful guidance on job priorities during the overhaul, and in addition the staff can get an immediate experience of the relationship between a monitoring measurement and the observed condition of the plant when it is taken apart shortly afterwards. This will in time give them the confidence to trust the measurements and base their maintenance decisions upon them.

It must be expected that it may take two or three years before a monitoring system is fully operational and the staff have built up all the necessary experience. It is also worth remembering that more may be achieved by the very careful selection of personnel who can be provided with simple robust equipment which they can use with intelligence, rather than the purchase of complex, comprehensive and expensive equipment that purports to provide all the answers at the touch of a button.

One final and important point about condition monitoring systems is that they can not only save considerable amounts of money in maintenance and downtime costs, but they also make the work of the plant and maintenance engineers more interesting and fulfilling. This in turn can help to retain a higher standard of personnel and can raise the whole level of the maintenance functions within an organisation. The mental approach which the system engenders and the machine records which are kept also provide the plant engineer with a sound basis for being asked for his advice on future policy for plant replacement and selection.

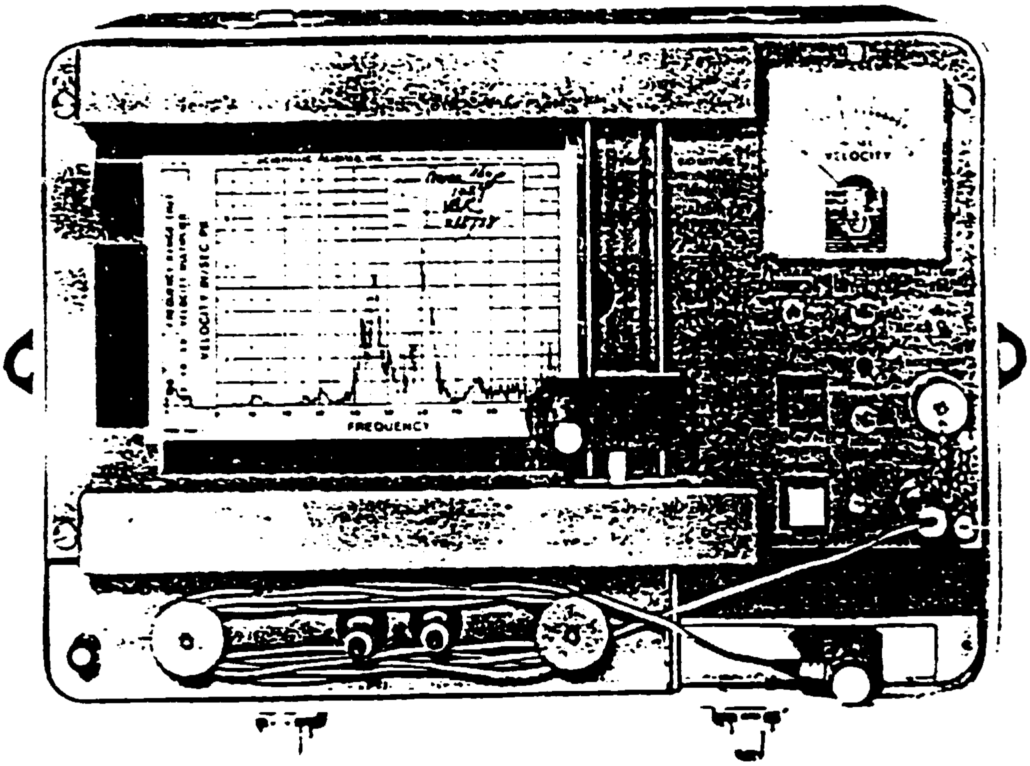
TRAINING COURSES

Training courses in condition based maintenance for maintenance staff from overseas countries would typically last about one week and would cost about £7500 plus £500 per student so that a typical course for 20 students would cost £17,500. This is for course lecture notes and accommodation.

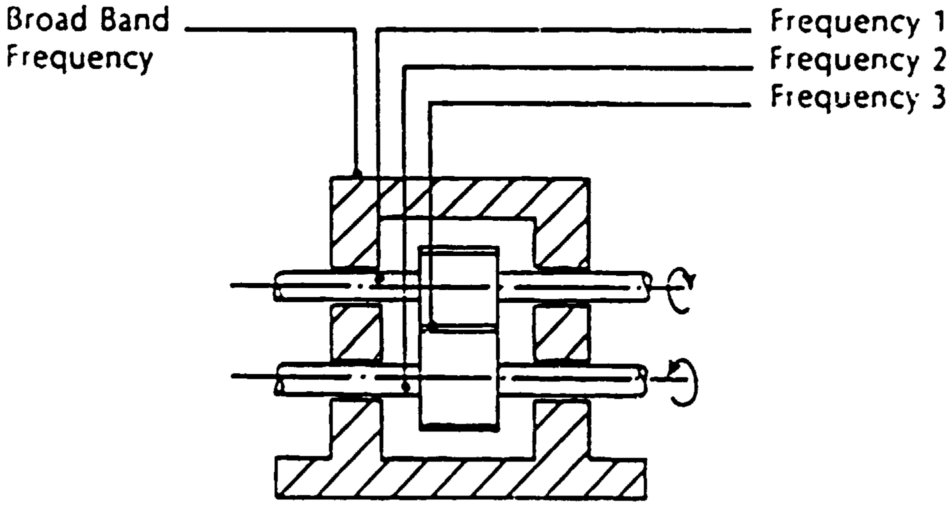


THE REGULAR MONITORING OF DETERIORATION
TO GIVE ADVANCED WARNING OF FAILURE

FIGURE 1

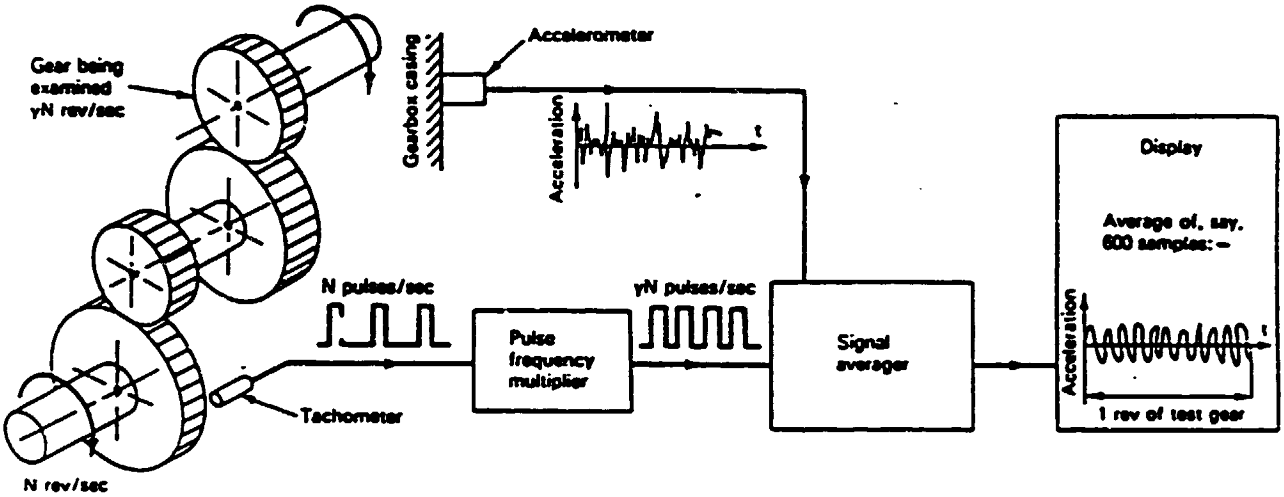


A vibration spectrum analyser

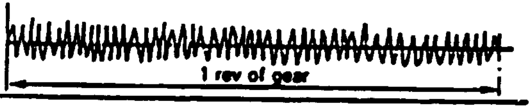
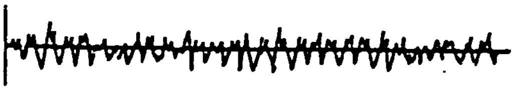
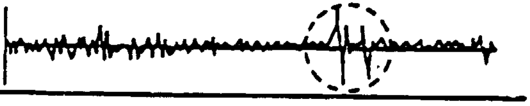


THE USE OF SPECTRAL ANALYSIS TO DETECT THE VIBRATION LEVELS OF INDIVIDUAL COMPONENTS

FIGURE 2



The type of gear defects which this method can detect, and their associated signal average plots, are:—

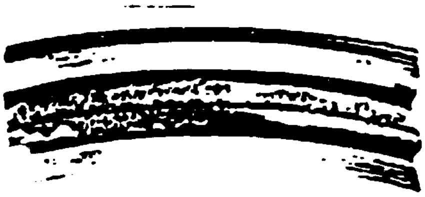
Gear condition	Typical signal average plot
Good	
Misaligned	
Worn	
Fractured tooth	

SIGNAL AVERAGING BEING USED TO INDICATE THE CONDITION OF A PARTICULAR GEAR IN A MULTISHAFT GEARBBOX

FIGURE 3

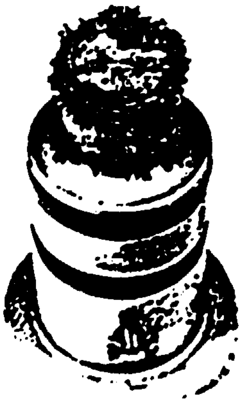
Oil filter debris can be washed off on to white absorbent paper for examination

FIGURE 4A



Bearing outer race
showing worn track

Selection of balls showing surface fatigue

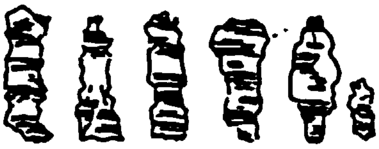


Magnetic Plug showing debris collected

BEARING FAILURE DETECTION BY A MAGNETIC PLUG

FIGURE 4B

BALL BEARING FLAKES

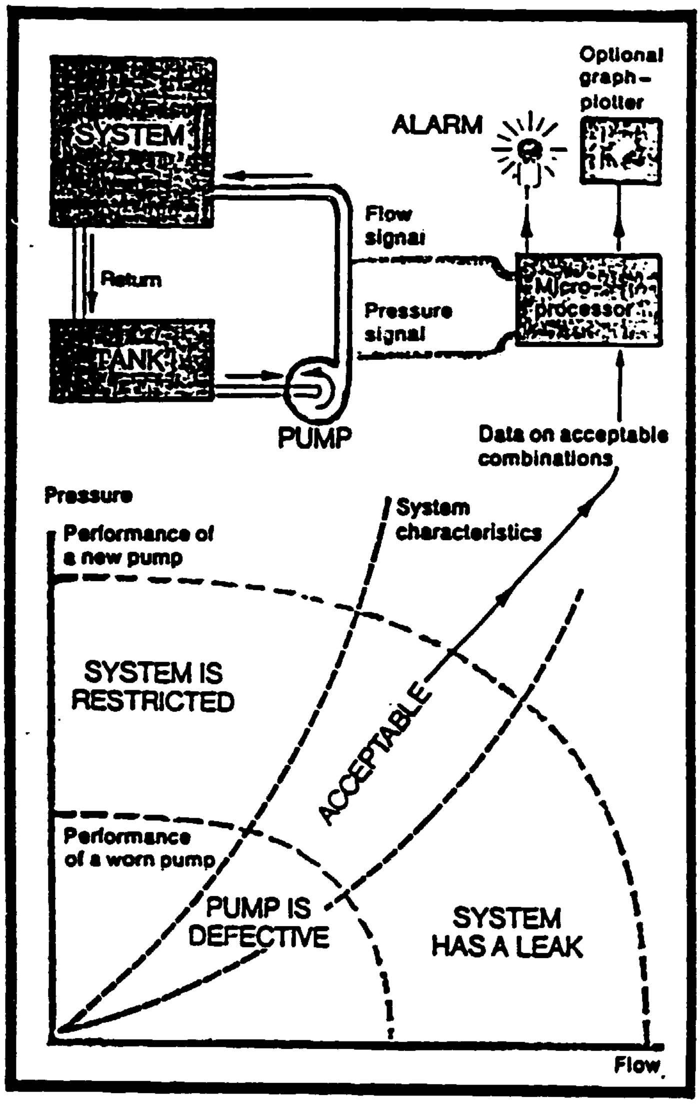


ROLLER BEARING FLAKES

With magnetic plugs the colour and shape of the wear particles tend to be the indicators of their origin and the wear mechanism. For example ball bearing particles tend to show rosette cracks, as a result of crushing in the rolling contact, while roller bearings tend to show parallel cracks. Gear tooth particles are more usually of a rounded pyramid shape. In terms of colour, particles from components at the hot end of a machine tend to be browner than those from the cold end.

THE TYPE OF PARTICLES GENERATED BY THE FAILURE OF ROLLING BEARINGS AND GEARS

FIGURE 4C



MONITORING A PUMP BY COMPARING FLOW WITH DELIVERY PRESSURE

FIGURE 5

TABLE 1. FAILURE MODES OF THE CHUCK DRIVE SYSTEM

SYSTEM COMPONENT	FAILURE MODES	LIKELIHOOD OF OCCURRENCE	EFFECT OF FAILURE	REPAIR TIME WITH ADEQUATE SPARES
ELECTRIC MOTOR				
Electrical components	Insulation/open circuit	Very unlikely	Total	½ day
Bearings	Fatigue/lubrication	Possible	Total	½ day
BELT DRIVE				
Pulleys	Wear looseness	Very unlikely	Becomes Total	2 hours
Belts	Wear/stretch/breakage	Very likely	Becomes Total	1 hour
GEAR BOXES				
Gears	Pitting/fracture/wear	Unlikely	Partial	1 day for unit change
Bearings	Fatigue/electrical pitting/wear	Unlikely now	Total	
Shafts	Wear	Unlikely	Partial	
CLUTCHES				
Plates	Wear/slip	Possible	Partial	
Solenoids	Insulation/open circuit	Unlikely	Partial	
Brushes	Wear/contamination	Very likely	Partial	
Slip rings	Wear/contamination	Likely	Partial	
HORIZONTAL SHAFT				
Shaft	Wear/fracture	Very unlikely	Total	1 day
Coupling	Wear/looseness	Unlikely	Becomes total	
Bearing	Fatigue/wear/lubrication	Unlikely	Becomes total	
TABLE DRIVE				
Bevel gears	Pitting/fracture/wear	Unlikely	Becomes total	1 day
Bearings	Fatigue/wear	Very unlikely		
	Lubrication	Unlikely		
Pinion	Pitting/fracture/wear	Unlikely		
Driven gear	Pitting/fracture/wear	Unlikely		
SPINDLE				
Chuck	Wear	Unlikely	Becomes total	1 day
Shaft	Wear	Very unlikely		
Bearings	Fatigue/wear	Very unlikely		
	Lubrication	Unlikely		

System Component	Likelihood	Effect	Repair time	Factor L X E X R
MAIN MOTOR				
Electrical	1	4	4	16
Bearings	3	4	4	48
BELT DRIVE				
Pulleys	1	4	2	8
Belts	5	4	1	20
GEAR BOXES				
Gears	2	3	8	48
Bearings	2	4	8	64
Shafts	2	3	8	48
Clutches				
Plates	3	3	8	72
Solenoids	2	3	8	48
Brushes	5	3	8	120
Slip rings	4	3	8	96
HORIZ. SHAFT				
Shaft	1	4	8	32
Coupling	2	4	8	64
Bearing	2	4	8	64
TABLE DRIVE				
Bevel gears	2	4	8	64
Bearings	2	4	8	64
Pinion	2	4	8	64
Driven gear	2	4	8	64
SPINDLE				
Chuck	2	4	8	64
Shaft	1	4	8	32
Bearings	2	4	8	64
ELEVATING SLIDE				
Slides	1	2	2	4
Lub. system	3	2	2	12
Slide clamps	2	1	0.5	1
Clamp hydraulics	2	1	4	8

System Component	Likelihood	Effect	Repair time	Factor L X E X R
CROSS SLIDE				
Slides	3	2	0.5	3
Lub. system	3	2	2	12
VERT SLIDE				
Slides	3	2	0.5	3
Lub. system	3	2	2	12
Counterbalance				
Chain etc.	2	3	8	48
Sprocket brgs.	2	2	4	16
Seals	3	2	4	24
Hydraulics	2	3	8	48
CROSS BALL SCR				
Motor	1	4	8	32
Couplings	0	4	8	0
D/E bearing	3	2	8	48
F/E bearing	3	2	8	48
Screw, nut, balls	3	2	8	48
Lub. system	3	2	2	12
Resolver	3	3	.1	1
VERT BALL SCR				
Motor	1	4	8	32
Couplings	0	4	8	0
D/E bearing	3	2	8	48
F/E bearing	3	2	8	48
Screw, nut balls	3	2	8	48
Lub. system	3	2	2	12
Resolver	3	3	.1	1

NOTES

(1) Any failure with a likelihood of less than 3 can usually be ignored.

(2) Repair time is actual repair time in hours, rather than a 1 to 5 rating.

TABLE 2 NUMERICAL RATING OF POSSIBLE COMPONENT FAILURE