المجلس الأعلى لمراكز ومعاهد البحوث
لجنة خدمة الإنتاج والجودة
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# دراسة عن أسلوب الصيانة الوقائية لرفع الإنتاجية وتقليل أعطال المعدات الإنتاجيـــــــــة

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# 1 MAINTENANCE TYPES AND STRATEGIES

# MAINTENANCE TYPES AND STRATEGIES

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- . TYPES OF MAINTENANCE
- . MAINTENANCE STRATEGIES
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## INTRODUCTION:-

Maintenance is a complex and many-faceted activity which until recently has attracted little serious study. However, over the past decade there has been a growing awareness of the Social and Economic importance of Maintenance and of the benefits to be derived from the application of more sophisticated management techniques to it, most of these sophisticated techniques use the computer to document and control the necessary information of the maintenance operation.

### The Maintenance Problem :-

The British Standards institution issuance no: BS 3811 : 1964 define maintenance as:"a combination of any actions carried out to retain an item in, or restore it to an acceptable conditions". The principal objectives of maintenance can be clearly defined as follows:-

1. To extend the useful life of ass-ets (i.e., every part of a site, building and contents). This is particularly important for developing countries in view of the lack of capital resources for replacement. In developed countries it is sometimes feasible to replace rather than to maintain.

2. To assure the optimum availability of installed equipments for production or service and obtain the maximum possible return on investment.

3. To ensure operational readiness of all equipments required for emergency use at all time, such as stand by units, fire fighting and rescue units, etc.

4. To ensure the safety of personnel using facilities.

Having defined the meaning and objectives of the maintenance function let us now consider the various forms of maintenance.

Until recent years there has been no universal terminology or vocabulary used for the various aspects of maintenance and this has tended to cause widespread misunderstanding amongst engineers.

In an endeavor to rectify this situation, the British Standards Institution issued BS 3811 : 1974, Glossary of General Terms used in Maintenance Organization, prepared with the cooperation of such organizations as professional engineering institutions, Government Departments and leading scientific and industrial organizations. The glossary is shown in Figure 1 and it should be studied in conjunction with the various forms of maintenance, illustrated in Figure .2

| | |
|---|---|
| Maintenance | A combination of any actions carried out to retain an item in, or restore it to, an acceptable condition. |
| Emergency maintenance | Maintenance which it is necessary to put in hand immediately to avoid serious consequences |
| Planned maintenance | Maintenance organized and carried out with forethought, control and records to a predetermined plan. |
| Breakdown | Failure resulting in the non-availability of an item. |
| Corrective maintenance | Maintenance carried out to restore (including adjustment and repair) an item which has ceased to meet an acceptable condition. |
| Preventive maintenance | Maintenance carried out at predetermined intervals, or to other prescribed criteria, and intended to reduce the likelihood of an item not meeting an acceptable condition |
| Running maintenance | Maintenance which can be carried out while the item is in service. |
| Shut-down maintenance | Maintenance which can only be carried out when the item is out of service. |
| Plant inventory | A list of all items, i.e., all parts of a site, building and contents, for the purposes of identification, including information such as constructional and technical details about each. |
| Maintenance programme | A list allocating specific maintenance to a specific period. |
| Maintenance schedule | A comprehensive list of maintenance and its schedule incidence. |
| History card | Record of usages, events and actions as appropriate relating to a particular item. |
| Job report | A statement recording the work done and the condition of the item. |
| Job specificat-ion | A document describing the work to be done. |
| Overhaul | A comprehensive examination and restoration of an item, or major part thereof, to an acceptable condition. |
| Downtime | The period of time during which an item is not in a condition to perform its intended function. |
| Maintenance planning | Deciding in advance the jobs, methods, tools, machines, labour, timing and time required. |

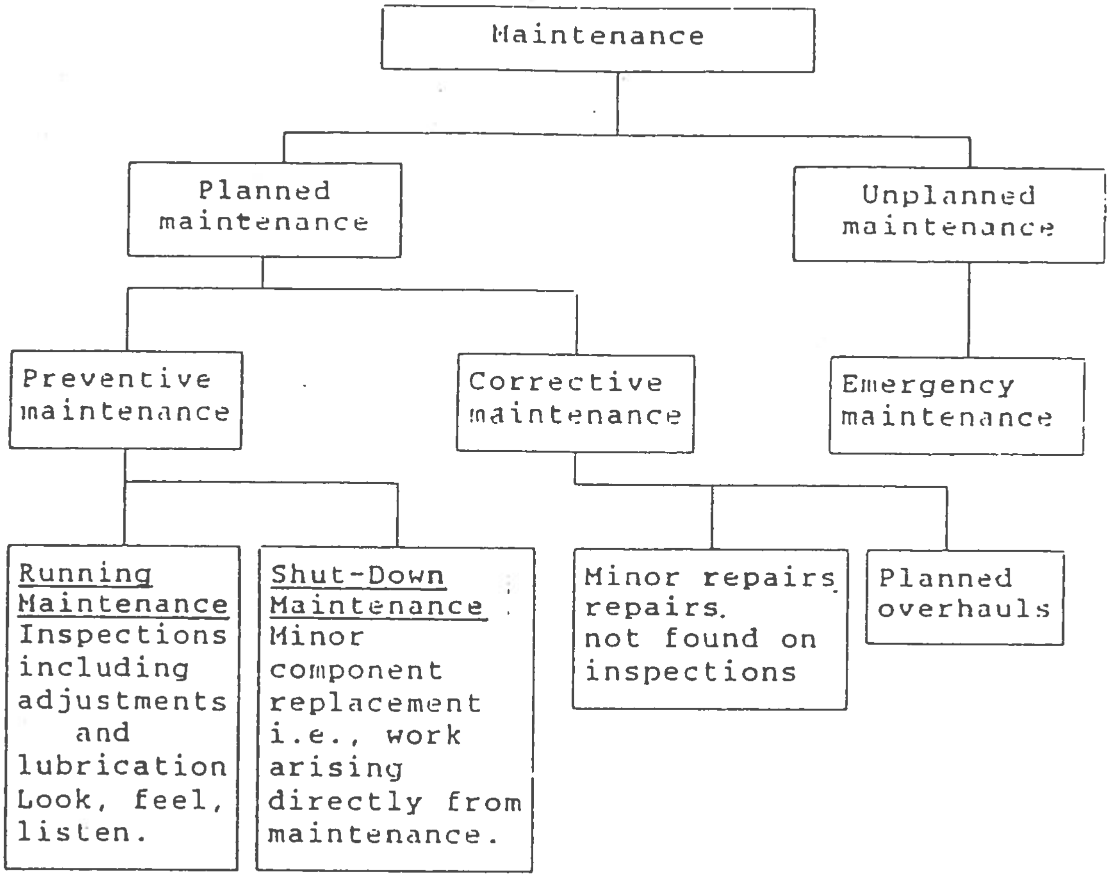



Figure 2: Relationship between various forms of maintenance.

## TYPES OF MAINTENANCE

The three major types of maintenance encountered in industry are discussed here :

(1)*Improvement Maintenance* ( IM )

Its objective is to reduce or eliminate entirely the need for maintenance . For example , many equipment failure occur at inboard bearings that are located in dark , dirty and inaccessible location . The oiler does not lubricate then as often as those that are easy to reach . Automatic oiler could be the solution to reduce or eliminate their maintenance .

(2)*Corrective Maintenance* ( CM )

At present , most maintenance is corrective . Repairs will always be needed . When the problem is obvious , it can usually be corrected easily . Intermittent failures and hidden defects are more time consuming but with diagnostics the causes can be isolated and then corrected .

(3)*Preventive Maintenance* ( PM )

The challenge is to detect incipient problems before they lead to total failures and to correct the defects at the lowest possible cost. There are three branches of preventive maintenance .

(a)***On-condition maintenance*** is done when equipment needs it .

Inspection through human sensor or instrumentation is necessary , with thresholds established to indicate when potential problems start . obviously , a relatively slow deterioration before failure is detectable by condition monitoring , whereas rapid , catastrophic modes of failure may not be detected . Inspection and monitoring should disassemble equipment only when a problem is detected . Also needed is a change in human though process . The following are general rules for on-condition maintenance : (a) inspect critical components , (b) regard safety as paramount , (c) repair defects and (d) if it works , don't fix it .

(b) ***Condition monitor or predictive maintenance*** is based on statistics and probability . Trend detection through data analysis often rewards the analyst with insight into the causes of failure and preventive action that will help avoid future failures . For example, stadium lights burn out within a narrow range of time . If 10% of the lights have burned out , it may be accurately assumed that the rest will fail soon and should , most effectively , be replaced as a group rather then individually .

(c) ***Scheduled or time based maintenance*** is a fixed interval preventive maintenance . It should be used only if there is opportunity for reducing failures that cannot be detected in advance , or if dictated by production requirements . It is different than fixed interval inspection that may detect a threshold condition monitor preventive maintenance . For example , 7500 mile oil change and 12000 mile spark plug changes on a car , whether it needs the changes or not .

In the summary , preventive maintenance can provide major benefits if it is properly applied and if it truly prevents failures , reduces costs and down times , and improves uptime , productivity , and profit . Inspection and detection of pending failures before they happen , monitoring of performance conditions and failure causes are the main elements of preventive maintenance .

The following diagram , Fig. ( 3 ) shows the relationship of design , maintenance , machine health monitoring , failure analysis and fault diagnosis .

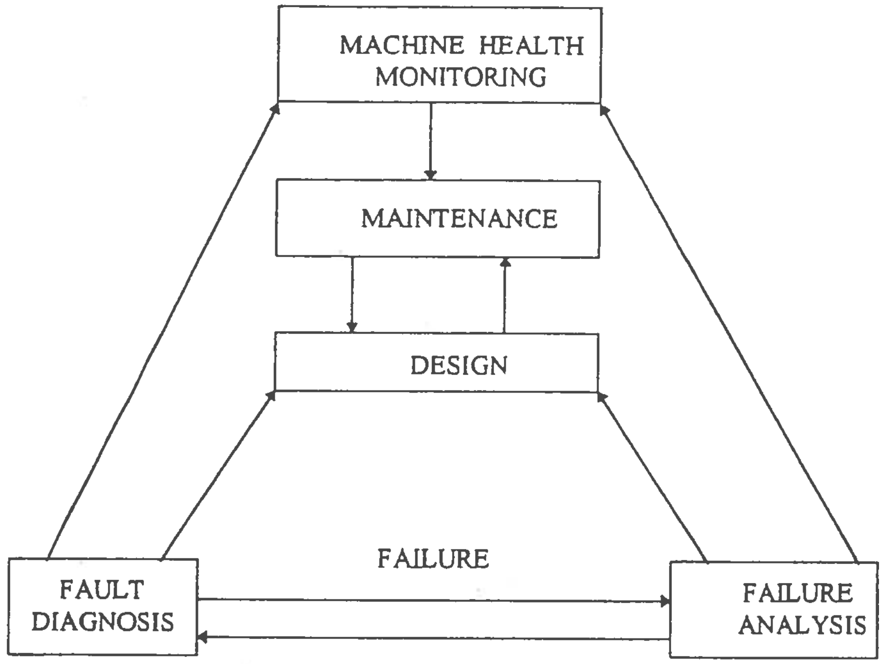



Fig. (3) Machinery Engineering Cycle

## MAINTENANCE STRATEGIES

A) Run - to - Break Maintenance (Breakdown Based Maintenance) (BBM)

In industries running many inexpensive machines and having all importantprocesses duplicated , machines are usually run until they break down .

B) Preventive Maintenance (Time Based Maintenance) (TBM)

Maintenance work is often performed at fixed time intervals such as every 3000 operating hours . The intervals are often determined statistically as the period in which no more than 2% of the machines will fail from being in new or fully serviced Condition .

C) Predictive Maintenance (Condition Based Maintenance) (CBM)

when machine condition measurements and analysis are performed systematically and intelligently they will not only allow determination of present machine condition , but also permit prediction of when such components most likely will have reached unacceptable levels . Predictive maintenance allows a long term planning of work to be done .

# MAINTENANCE SYSTEMS

## ELEMENTS OF PRIMITIVE SYSTEM

. MAINTENANCE SUPERVISOR AND CRAFTSMEN
. NO WORK ORDER SYSTEM
. INFORMAL PLANNING
. NO FORMAL COSTING SYSTEM
. NO PREVENTIVE MAINTENANCE
. OPERATES ON A BREAKDOWN - FIX IT BASIS

## ELEMENTS OF TYPICAL " MEDIUM " MAINTENANCE SYSTEM

. WORK ORDER SYSTEM
. FORMAL PLANNING
. DETAILED SCHEDULING
. BACKLOG CONTROL
. JOB COSTING SYSTEM
. PM

## ELEMENTS OF SOPHISTICATED SYSTEM

. WORK ORDER SYSTEM
. FORMAL PLANNING AND SCHEDULING
. DETAILED JOB COSTING SYSTEM
. WORK SAMPLING PROGRAM
. TIME SLOTTING
. STATISTICAL STANDARDS
. WEEKLY WORK PROGRAM
. EDP SUPPORTED MANAGEMENT REPORTING SYSTEM
. FAILURE ANALYSIS
. PREEMPTIVE REPLACEMENT
. SCHEDULED OVERHAUL
. PREDICTIVE - DIAGNOSTIC MAINTENANCE

## WORK ORDER PLANNING

IT IS IMPORTANT THAT ALL WORK ORDERS ARE ASSIGNED A CAUSE CODE (BY MAINTENANCE FOREMAN) AND A PRIORITY CODE (BY ORIGINATOR) BEFORE THE WORK ORDER IS FILED AWAY.

### EMERGENCY - PRIORITY 1

IMMEDIATE ACTION REQUIRED, OVERTIME AUTHORIZED; DO NOW, DO NOT WAIT FOR PAPER WORK - BREAK-IN JOBS.

THIS PRIORITY LEVEL SHOULD ONLY BE USED IN CASES OF SEVERE SAFETY HAZARDS OR ACTUAL LOSS OF PRODUCTION OR QUALITY. THE MONTHLY PRIORITY 1 JOBS SHOULD BE LESS THAT 5% OF MONTHLY MANHOURS. OPERATIONS SHOULD INITIATE PAPER WORK. IF THEY FAIL TO DO SO, IT WILL BE THE RESPONSIBILITY OF SHIFT OR AREA FOREMAN.

### URGENT - PRIORITY 2

START AS SOON AS POSSIBLE, COMPLETION REQUIRED WITHIN ONE WORK WEEK.

THIS CLASSIFICATIONS SHOULD BE USED ON EQUIPMENT WITH POTENTIAL LOSS OF PRODUCTION AND QUALITY WITHIN ONE WEEK'S TIME OR POTENTIAL MAJOR EFFECT ON COST. THE MONTHLY PRIORITY 2 JOBS SHOULD ACCOUNT FOR LESS THAT 15% OF TOTAL MANHOURS.

### NORMAL - PRIORITY 3

WORK IS PLANNED AND SCHEDULED TO OVERALL WORKLOAD. NO PRIORITY 3 WORK ORDER SHOULD BE RELEASED TO THE MAINTENANCE SUPERVISOR WITHOUT ASSURANCE THAT MATERIALS AND TOOLS ARE AVAILABLE.

THE JOBS WILL BE SCHEDULED IN WEEKLY MEETINGS BETWEEN OPERATING AND MAINTENANCE MANAGEMENT. THIS CLASSIFICATION SHOULD CONSTITUTE THE MAJOR BACKLOG FOR ALL CRAFTS.

### SHUTDOWN WORK - PRIORITY 4

A MAJOR PORTION OF THE OVERALL MAINTENANCE WORK MUST BE ACCOMPLISHED DURING A SHUTDOWN OF MAJOR EQUIPMENT. THE PREPARATORY WORK NECESSARY TO ACCOMPLISH THE WORK DURING THE SHUTDOWN WILL BE SCHEDULED INTO THE WEEKLY WORKLOAD.

PRIORITY CODE

PRIORITY 1. EMERGENCY - DO NOW

PRIORITY 2. URGENT - AS SOON AS POSSIBLE

PRIORITY 3. NORMAL - PLANNED & SCHEDULED ACCORDING TO OVERALL WORK LOAD

PRIORITY 4. OVERHAULS - SHUT DOWNS - TURN AROUNDS

NOTE -

A PERFECT SYSTEM EXPECTS 3 AND 4 IN THE 80% RANGE
- VERY GOOD SYSTEM EXPECTS 3 AND 4 IN THE 75% RANGE
- GOOD SYSTEM EXPECTS 3 AND 4 IN THE 70% RANGE
- FAIR SYSTEM EXPECTS 3 AND 4 IN THE 60% RANGE
- POOR SYSTEM EXPECTS 3 AND 4 IN THE 50% RANGE

BELOW 50% IS UNACCEPTABLE IN A MANUFACTURING PLANT

# 2 VIBRATION AS A MACHINE HEALTH MONITORING TECHNIQUE

# VIBRATION AS A MACHINE HEALTH MONITORING TECHNIQUE

By

Dr. Abuelela Mohmmed Abuelnaga

## I. INTRODUCTION

Today plants and machinery are becoming larger and more complex. This implies that each hour of down time is more expensive and that the source of a malfunction or fault is more difficult to locate. As industrial systems enlarge, the total amount of energy and material being handled increases, making advanced machine health monitoring (including early-warning devices and correct fault detection and diagnosis techniques) imperative both from the view point of plant safety as well as reduced manufacturing costs.

The objective of the machine health monitoring is to be able to detect, identify and diagnose faults of mechanical systems; during their performance, before they lead to a serious or a catastrophic failure.

Information gained from fault detection and diagnosis will help in directing and scheduling maintenance programs to increase the performance of the mechanical system under considerations, and at the same time, to reduce the maintenance and running costs of the system.

Various methods and techniques are now well advanced to be accepted as rotating machinery health monitoring systems. Among these techniques mechanical vibration has proved to be one of the most reliable parameters to use in machine health monitoring to check the machine condition. A doubling of dynamic force will typically result in a doubling of vibration measured at the forcing frequency.

## II. FAILURE CLASSIFICATION AND TYPES

### II.1 Failure Classifications

The terms 'failure' or 'fault' may be viewed from different angles according to the effect which the lack of performance has on the overall functional capability. Such aspects as economic viability, safety, engineering complexity, speed, causal influences all provide classifications leading to a description of failure.

#### II.1.1 Engineering failure classification

There are two distinct classes of failure:

(1) *Intermittent failure*: failures which result in a lack of some function of the component only for a very short

period of time, the component reverting to its full operational standard immediately after failure;

(2) *Permanent failure*: failures which result in a lack of some function which will continue until some part of the component is replaced.

### II.1.2 Degree of failure classification

Permanent failures may be further subdivided into the following two types:

(1) *Complete failure*: failure which causes the complete lack of a required function. (It should be noted that in certain cases the limit when a lack of function is said to be complete is open to interpretation, which depends upon the application);

(2) *Partial failure*: failure which leads to a lack of some function but not such as to cause a complete lack of the required function.

### II.1.3 Speed of failure classification

Both complete and partial permanent failure may be further classified according to the suddenness with which the failure occurs:

(1) *Sudden failure*: failure which could not be forecast by prior testing or examination;

(2) *Gradual failure*: failure which could have been forecast by testing or examination.

### II.1.4 Degree and speed of failure classification

Both failure forms can be combined to give the following further classification:

(1) *Catastrophic failures*: failures which are both sudden and complete;

(2) *Degradation failures*: failures which are both partial and gradual.

### II.1.5 Cause-of-failure classification

According to the manner by which failure develops, so it be further classified:

(1) *Wear-out failures*: failure attributable to the normal processes of wear as expected when the device was designed;

(2) *Misuse failure*: failure attributable to the application of stresses beyond the item's stated capabilities;

(3) *Inherent weakness failure*: failure attributable to a lack of suitability in the design or construction of the system or component itself when subjected to stresses within its stated capabilities.

### II.1.6 Hazard classification

Possible faults (major or minor failures) may be divided into two broad hazard groups, namely dangerous-failures or safe-failures:

(1) *Dangerous faults*: (a) protection system-failure to protect when needed, (b) machine tool-failure causing damage to work and/or operator, (c) traction system-failure to brake;

(2) *Safe faults*: (a) protection system-failure to operate when not needed, (b) machine tool-failure to start, (c) traction system-failure of brakes to apply when not needed.

## II.2 Types of Failure

The three types of failure recognized in system and component reliability studies are summarized below:

(1) *Infant mortality (early failures)*: This failure arises when a new type of defect escapes through the quality control filter, or when assembly methods lead to unsatisfactory construction.

(2) *Random-failures*: Failure of a component on the lower limit of quality acceptance subject to an upper stress limit. They are also due to misuse of component.

(3) *Time-dependent failures*: Normal life distribution failures due to service conditions and component design function. Wear and fatigue are good examples for such failure type.

## II.3 Failure Patterns

There are several failure patterns that give some warning before a disaster occurs. Figures 1-a, 1-b, 1-c, 1-d, 1-e and 1-f, are failure patterns and their percentage of occurrence for aircraft industry (after extensive data gathering). Fig. 1-a has long been regarded as the standard reliability failure plot. However only 4% of aircraft component follow this pattern. About 68% of the aircraft components follow the pattern of Fig. 1-b. The failures occur during early use can be weeded out by good quality control. The best prevention from failure for these is malfunction detection and diagnosis when needed. The flat pattern failure shown in Fig. 1-c occurs on about 14% of the parts. Again machine health monitoring is sufficient to control it. Figure 1-d shows 7% of components that fail became of operator and human reliability problems. Five percent have a failure pattern that trends higher over-life, as shown in Figure 1-e. Finally, the remaining 2 percent is a rare pattern which has few early failures and run for a long stable life

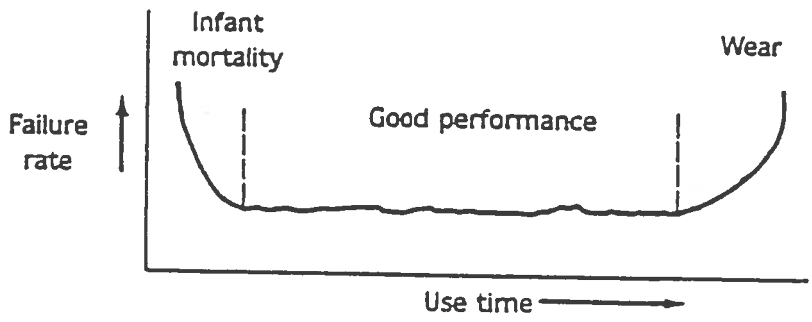



Fig. 1-a Infant mortality-stable-wear pattern: 4 percent.

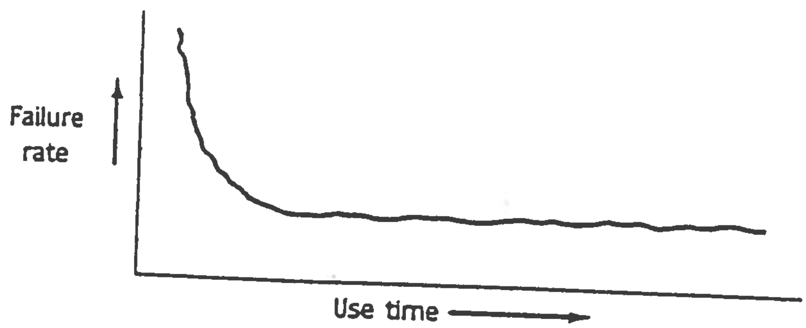



Fig. 1-b Early failures, then stable life: 68 percent.

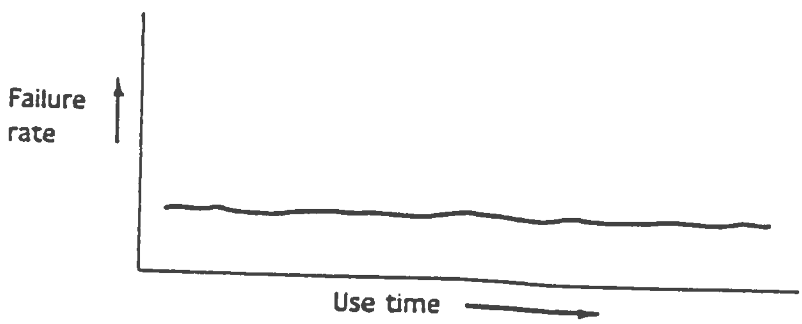



Fig. 1-c. Consistent failure rate: 14 percent

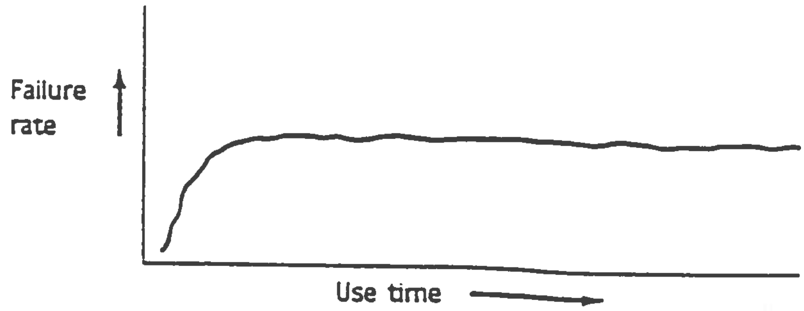



Fig. 1-d. User-caused failures: 7 percent.

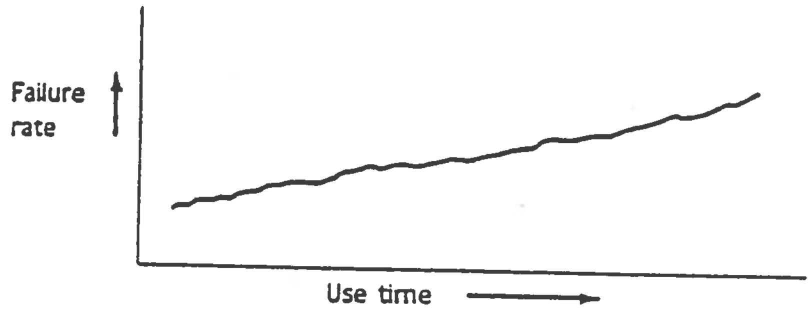



Fig. 1-e. Increasing failures over life: 5 percent

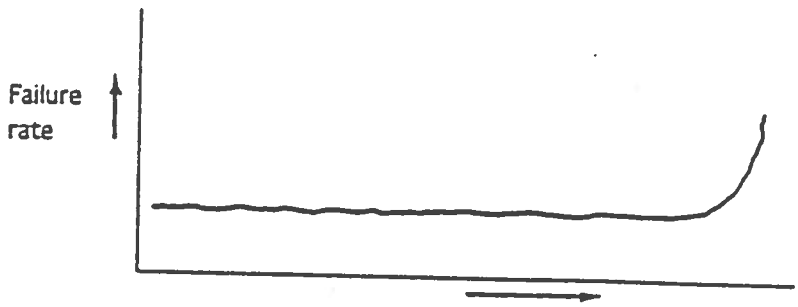



Fig. 1-f. Wear after a good run life: 2 percent.

before wear sets in and increases failure, as shown in Fig. 1-f. Only the 11 percent of Figures 1-a-e and f that have wear-out failures, are good candidates for preventive maintenance done on a predetermined schedule, fixed intervals, periodic overhaul basis along with inspection. The 89% is best handled by machine health monitoring to track operating conditions, and then maintenance done when the quantitative criteria indicate a need for it.

## III. TYPES OF MAINTENANCE

The three major types of maintenance encountered in industry are briefly discussed here:

(1) *Improvement Maintenance*

Its objective is to reduce or eliminate entirely the need for maintenance. For example, many equipment failure occur at inboard bearings that are located in dark, dirty and inaccessible location. The oiler does not lubricate them as often as those that are easy to reach. Automatic oiler could be the solution to reduce or eliminate their maintenance.

(2) *Corrective Maintenance*

At present, most maintenance is corrective. Repairs will always be needed. When the problem is obvious, it can usually be corrected easily. Intermittent failures and hidden defects are more time consuming but with diagnostics the causes can be isolated and then corrected.

(3) *Preventive Maintenance*

The challenge is to detect incipient problems before they lead to total failures and to correct the defects at the lowest possible cost. There are three branches of preventive maintenance.

(a) *On-condition maintenance* is done when equipment needs it. Inspection through human sensor or instrumentation is necessary, with thresholds established to indicate when potential problems start. Obviously, a relatively slow deterioration before failure is detectable by condition monitoring, whereas rapid, catastrophic modes of failure may not be detected. Inspection and monitoring should disassemble equipment only when a problem is detected. Also needed is a change in human though process. The following are general rules for on-condition maintenance; (a) inspect critical components, (b) regard safety as paramount, (c) repair defects and (d) if it works, don't fix it.

(b) *Condition monitor or predictive maintenance* is based on statistics and probability. Trend detection through data analysis often rewards the analyst with insight into the causes of failure and preventive action that will help avoid future failures. For example, stadium lights burn out within a narrow range of time. If 10% of the lights have burned out, it may be accurately assumed that the rest will fail soon and should, most effectively, be replaced as a group rather than individually.

(c) *Scheduled or time based maintenance* is a fixed interval preventive maintenance. It should be used only if there is opportunity for reducing failures that cannot be detected in advance, or if dictated by production requirements. It is different than fixed interval inspection that may detect a threshold condition monitor preventive maintenance. For example, 7500 mile oil change and 12000 mile spark plug changes on a car, whether it needs the changes or not.

In the summary, preventive maintenance can provide major benefits if it is properly applied and if it truly prevents failures, reduces costs and down times, and improves uptime, productivity, and profit. Inspection and detection of pending failures before they happen, monitoring of performance conditions and failure causes are the main elements of preventive maintenance.

The following diagram, Fig. 2 shows the relationship of design, maintenance, machine health monitoring, failure analysis and fault diagnosis.

## IV. MACHINE HEALTH MONITORING

Machine health monitoring is a key to predict the need for preventive maintenance. The purpose of machine health monitoring and fault diagnosis can therefore be listed as follows:

(1) Dangerous situations in which personnel are put at risk can be avoided by reducing the occurrence of sudden, disruptive, and dangerous outrages equipment damage.

(2) Unforeseen plant stoppages which disrupt product schedules can be reduced if not eliminated.

(3) Catastrophic damage to plant can be cut down by identifying faults before serious failures occur.

(4) Savings can be made by reducing the need to strip serviceable machines for condition inspection during the annual overhaul periods.

(5) Failed components can be identified when a breakdown does occur by using equipment in a trouble-shooting role.

Fault detection and machine health monitoring usually makes use of measurements taken by instruments not necessarily installed for this purpose alone. Thus, some techniques of detection use only the regular plant instrumentation, some only special instrumentation, and some a mixture of the two. The detection of incipient malfunction may be based on periodic equipment testes. Spot checks can be performed by special equipments.

*Monitoring Intervals*

The monitoring interval and scheduling may be in terms of time-hourly, weekly, monthly, or based on amount of use-every 5000 parts, or every lot. The interval should be based on stability, purpose, and degree of usage. If initial records indicate that the equipment remains within the required accuracy for successive calibrations or repair, then the intervals may be lengthened. On the other hand, if equipment requires frequent adjustment or repair, the intervals should be shortened. The monitoring intervals should be adjusted in such a way that a minimum of 95% of equipment or standards of the same type is within tolerance when submitted for regularly scheduled remonitoring.

Other methods of intimating monitoring intervals includes; manufacturer's recommendations, national standards, and historical experience of failures.

The planning for machine health monitoring and preventive maintenance has two slightly different philosophies. One is to fix them on the spot. The other is to identify them clearly for later corrective action. Maintenance management should establish a guide line such as, "Fix anything that can be corrected within ten minutes, but if it will take longer, write a separate work request". Many small repairs can be fixed quickest by the inspector who finds them. This avoids the need for someone else to travel to the location, reidentify the problem, and correct it.

*Thresholds*

Now that instrumentation is becoming available to measure equipment performance, it is still necessary to determine when that performance is "go" and when it is "no go". A human must establish the threshold point which can then be controlled by manual, semiautomatic, or automatic means. First, let's decide how the threshold is set and then discuss how to control it. To set the threshold, one must gather information on what measurements can exist while equipment is running safely and what the measurements were just prior to or at the time of failure. Equipment manufacturers, and especially their experienced field representatives, will be good starting source of information. Most manufacturers will run equipment until failure in their laboratories as part of their tests to evaluate quality, reliability, maintainability, and maintenance procedures. Such data are necessary to determine under actual operating conditions how much stress can be put on a device before it will break. There are many devices, such as nuclear reactors and flying airplanes, that should not be taken to the breaking point under operating conditions, but they can be made to fail under secure test conditions so that knowledge can be used to keep them safe during actual use.

Once the breaking point is determined, a margin of safety should be added to account for variations in individual components, environments, and operating conditions. Depending on the severity of failure, that safety margin could be anywhere from one to three standard deviations before the average failure point.

Once the threshold set point has been determined, it should be monitored to detect when it is exceeded. The investment in monitoring depends on the time period over which deterioration may occur, means of detection, and benefit value. Figure 3 illustrates the need for automatic monitoring.

If failure conditions built up quickly, the condition may not be easily detected by a human, and the relative high cost of automatic instrumentation will be repaid.

The monitoring signal may be used to activate an annunciator that rings a bell or lights a red light. It may activate a feedback mechanism that reduces temperature or other parameters. A thermostat connected to a heating and air-conditioning system provides this feedback function to regulate temperature. The distinction between operational controls and maintenance controls is not important since the end result is reduced need for maintenance and notification that a problem is building up to a point where maintenance should be scheduled when convenient.

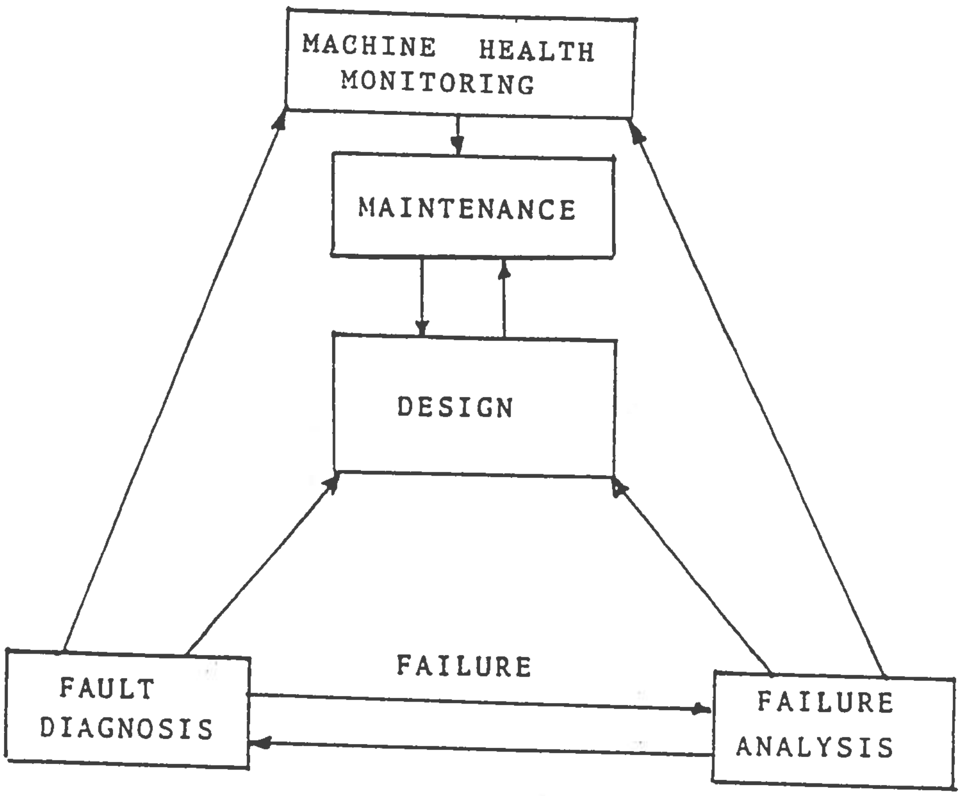



Fig. 2. Machinery Engineering Cycle

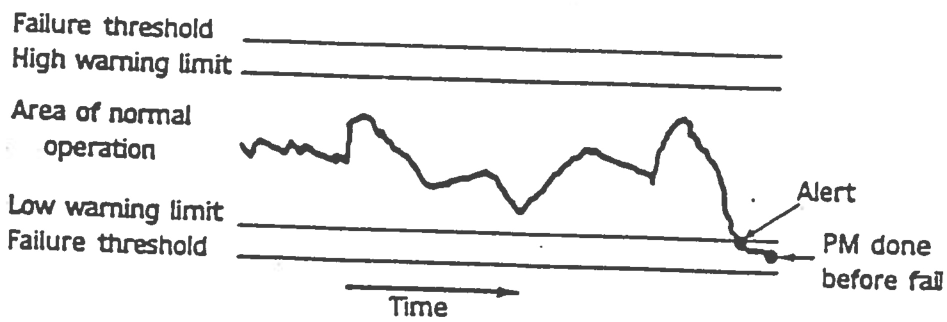



Fig. 3. Control chart warning of possible failure before it occurs.

## V. FAULT DETECTION AND DIAGNOSIS TECHNIQUE

Various monitoring and fault detection techniques are now well advanced to be accepted as reliable means for detecting and diagnosing incipient failures in mechanical systems. They should be nondestructive so that they will not harm the equipment.

All these methods rely on sensing or monitoring some physical characteristic which changes as faults develop. These include:

- Performance monitoring including temperature, pressure, power and efficiency.
- Contaminant monitoring including debris analysis, oil analysis, magnetic chip and ferrography.
- Corrosion monitoring.
- Force monitoring.
- Gas leakage monitoring.
- Air pollution monitoring.
- Sound measurement including noise and acoustics.
- Vibration monitoring.
- Nondestructive testing techniques including eddy current and ultrasonic detection.

Monitoring and tests may be made on functionally related components or on the output product. For example, most printing presses, copiers, and duplicators are intended to produce high-quality images on paper. Inspection of those output copies can show whether the process is working properly. Skips, smears, blurs, and wrinkles will show up on the copy. A good inspector can tell from a copy exactly what roll is wearing or what bearing is causing the skips. Careful inspection, which can be done without "tearing down" the machine, saves both technician time and exposure of the equipment to possible damage.

Rotating components find their own best relationship to surrounding components. For example, piston rings in an engine or compressor cylinder quickly wear to the cylinder wall configuration. If they are removed for inspection, the chances are that they will not easily fit back into the same pattern. As a result, additional wear will occur and the rings will have to be replaced much sooner than if they were left intact and performance-tested for pressure produced and metal particles in the lubricating oil.

### *Human Senses*

We humans have a great capability for sensing unusual sights, sounds, smells, tastes, vibrations, and touches. Efforts should be made by every maintenance manager to increase the sensitivity of his own and his personnel's human senses. Experience is generally the best teacher.

Human senses are able to detect large differences but are generally not sensitive to small changes. Time tends to have a dulling effect. Have you ever tried to determine if one color was the same as another without having a sample of each to compare side by side? If you have, you will understand the need for standards. A standard is any example that can be compared to the existing situation as a measurement. Quantitative specifications, photographs, recordings, and actual samples should be provided. The critical parameters should be clearly marked on them with display as to what is good and what is bad.

*Sensors*

Since humans are not continually alert or sensitive to small changes, and cannot get inside small spaces, especially when operating, it is necessary to use sensors that will measure conditions and transmit information to external indicators. Sensor technology is progressing rapidly; there have been considerable improvements in capability, accuracy, size, and cost. Pressure transducers, temperature thermocouples, electrical ampmeters, revolution counters, and a liquid height level float are examples found in most automobiles.

# VI. VIBRATION AS A MACHINE HEALTH MONITORING TECHNIQUE

## VI.1 Vibration Monitoring

Vibration monitoring and analysis is one of the most useful and powerful techniques for fault diagnosis of rotating machinery. Excessive vibration is an indication of some malfunction. Mechanical vibration sensors which signal a warning when a preset level has been exceeded can be attached to a machine. These units respond to all vibration frequencies, generally in a nonlinear fashion. They provide a basic protection. Electronic systems provide greater flexibility of operation, and usually consist of an accelerometer attached to a suitable point on the machine, and linked by cable to a remote monitoring unit. This unit enables overall vibration level for the whole frequency range of the transducer to be determined, or by switching in a suitable filter, the vibration level in a selected frequency band can be measured. It is common for two filter circuits to be provided, turned to important frequencies, motor-drive speed for example. The value displayed on the monitor is generally vibration velocity (peak, average or rms value) since it has been found that acceptable vibration velocity is independent of frequency. Alarm levels are commonly set 50% above the normal vibration level at the severest operating condition.

The vibration velocity of a bearing housing compounds a measure of both the size of the displacement and the frequency of vibration and it gives a measure of fatigue stresses. The normal procedure is to measure the vertical horizontal, and axial vibration of the bearing housing, and to take the largest measurement as the most significant.

Accelerometers, eddy-current proximity sensors and velocity seismic transducers are enabling the techniques of motion, position, and expansion analysis to be increasingly applied to large numbers of rotating equipments. Motors, turbines, compressors, jet engines, and generators can use vibration analysis. Figure 4 shows accelerometers placed on a rotating shaft. The accelerometers are usually permanently attached to equipment at two positions 90° apart, perpendicular to the rotating axes. Measurement of their output may be taken by portable test meters and chart recorders, or by permanently attached recorders, often with alarms that indicate when problem thresholds are exceeded. Such devices may automatically shot down equipment to prevent damage.

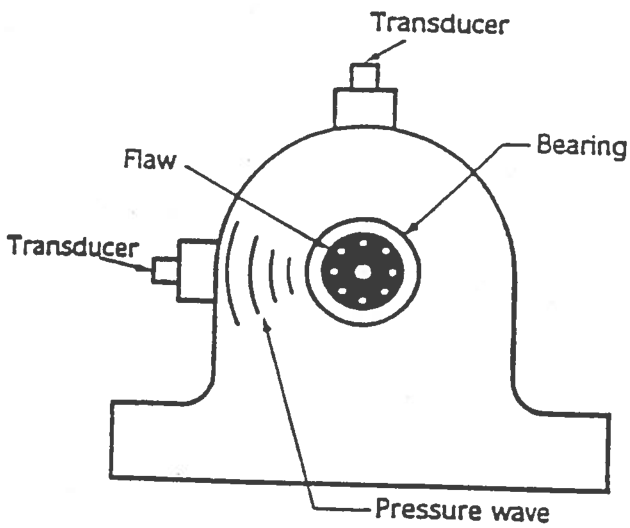



Fig. 4. An accelerometer to measure the vibration of a rotating shaft.

The normal pattern of operation, called its "signature", is established by measuring the performance of equipment under known good conditions. Comparisons are made at routine intervals, such as every thirty days, to determine if any of the parameters are changing erratically, and further, what the effect of such changes may be.

## VI.2 Causes of Vibration

Mechanical defects, even though very slight, cause rotating machinery to vibrate. These vibrations range from those that are very small and essentially insignificant to those that are severe enough to tear the machine apart. The severity and frequency of those vibrations depend upon the cause of the malfunction. The fundamental mechanisms that cause vibration are given in the following:

(1) *Unbalance*

Unbalance is a most common malfunction in rotating machinery, which will cause severe radial vibration at the running frequency of the rotor.

(2) *Rubs in Rotating Machinery*

A rub in a rotating machine is, in general, any load on the shaft that will prevent the shaft from moving in some direction. Rubs are generally classified in two types, partial and full. Partial rubs occur first and may quickly lead to a full rub.

(3) *Misalignment*

Misalignment represents another important source of vibration in rotating machinery. Single-shaft misalignment can exist if the bearings through which the shaft passes are not properly aligned with the shaft. Two shafts may be misaligned in either offset or angular misalignment. Misalignment usually creates double-frequency vibration.

(4) *Looseness*

This malfunction magnifies any misalignment or unbalance.

(5) *Excitation of Resonances due to Insufficient Damping*

Any poorly damped resonance will sooner or later get excited. The most common resonance excited in machinery is the translational balance resonance or the first critical speed of the rotor.

(6) *Oil Whirl and Oil Whip in Journal Bearing*

Oil whirl is a hydrodynamic instability at approximately 43% of operating speed. Oil whip exists due to the excitation of the natural translational balance resonance of the rotor. It occurs within few percent of the oil whirl speed, and will produce very severe vibrations leading to fatigue failure.

(7) *Toothed Gears*

Toothed gears will have two main malfunctions. The first due to one tooth fault and will show up at the shaft operating speed and its harmonics. The second malfunction is due to all teeth fault and will show up at the meshing frequency and its harmonics.

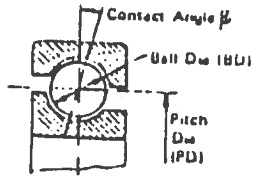
(8) *Rolling Elements*

Rolling elements malfunction is the cause of uneven vibration levels at high frequencies often related to radial resonances in bearings. Fig.5 gives a summary of main causes of vibration in rotating machinery.

## VI.2 Vibration Measuring and Analyzing System

Two main modes of vibration measurement are carried out in industry. The first is the machine total vibration level which will give an indication of the total vibration severity of the machine regardless of the causes. The second mode is to obtain the machine vibration spectrum for the frequency range of the machine.

# FIG.5. VIBRATION TROUBLE SHOOTING CHART (B & K)

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

A general purpose vibration measuring and analyzing system to be used for machine health monitoring may be consists of the following items.

(1) *Vibration Transducers*

Transducers for the measurement of vibration employ electromagnetic, electrodynamic, capacative, piezoelectric or strain gauge principles of operation. Of these, the most widely used in recent years for vibration work is the piezoelectric accelerometer, largely by virtue of the fact that it is self-generating, is small in size and weight, can be designed to be free of resonances over a wide frequency range, has good stability, low sensitivity to strain, temperature variations, airborne sound and magnetic fields, a large dynamic range and is not easily damaged.

(2) *Fillers and Signal Analyzers*

Filters may be classified as of low-pass, high-pass, band-pass, or band-rejection type with fixed-band or octave-band. Signal analyzers may be divided to serial or level analyzers, and real time or spectrum analyzers.

(3) *Indicating and Recording Instruments*

These instruments include moving-coil galvanometer and recorders, magnetic-tape recorders, cathode-ray oscilloscope.

(4) *Computer System*

Including hardware and software.

## VI.3 Vibrations Limits and Standards

Mechanical vibration can be measured in terms of Displacement, Velocity and Acceleration. Displacement measurements are traditionally used for low frequency phenomena such as unbalance or shaft misalignment on rotating machines while acceleration measurement are used to reveal high frequency phenomena such as the condition of rolling element bearings. Most of the standards concerning machine vibration consider the RMS value of the vibration velocity as the most suitable parameter to evaluate the severity of the vibration over a wide frequency range. In general, the most suitable parameter to represent mechanical vibration is that which covers the smallest dynamic range over the frequency range measured; this is particularly important when only the overall (wide-band) level is being measured.

Threshold vibration levels in excess of which a machine can be regarded as in a bad condition have been recommended by various bodies from empirical data. It has been stated that the failure of a machine is preceded by an increase in its vibration level in more than 90% of the cases. All machines vibrate regardless of how well they are designed and assembled, and it has been found in industrial practice that good correlation exists between the characteristic vibration signatures of machines and their relative condition.

A practical method for judging vibration severity is to establish baseline signatures for a machine known to be in good operating condition (this is not necessarily a new machine as some machines 'wear in' to their normal operating levels) and to monitor changes in these signatures with time.

In deciding upon the significant magnitude of change in a signature component the Canadian Navy determined that an increase in vibration level is not significant unless it doubles. As important as the absolute level of change is the rate of change. The Canadian Navy has data which indicates that the mean level of a signature component as a function of time is a straight line with a slight positive slope for 75% of a machine useful life at which point it starts an exponential rise to the point of failure. Therefore, trend monitoring of vibration signatures is a more useful maintenance tool than a one-time survey of absolute magnitudes.

*VDI Severity Criteria*

For many machines the Best Parameter is velocity and this is one reason why many standards (e.g. VDI 2056) specify this parameter (Fig.6). Standards such as VDI 2059 relying on relative displacement measurement put main emphasis on unbalance and misalignment and are forced to disregard large parts of the spectrum.

*IRD Mechananalysis Severity Limits*

Another aid to critical vibration limit decision making is used by IRD Mechanalysis Inc. Columbus, Ohio. The General Machinery Vibration Severity Chart (Figure 7) applies to machinery where vibration does not directly influence the quality of a finished product, can be used in establishing vibration tolerances. The degrees of vibration severity are based upon information and historical records of vibration readings taken on many machines. A classification of vibration severity is not a vibration tolerance. This means that the value for each machine on the list has to be selected. A reasonable rule to follow in setting the limit of vibration is one and a half to two times the normal vibration level - assuming of course, the normal level is acceptable.

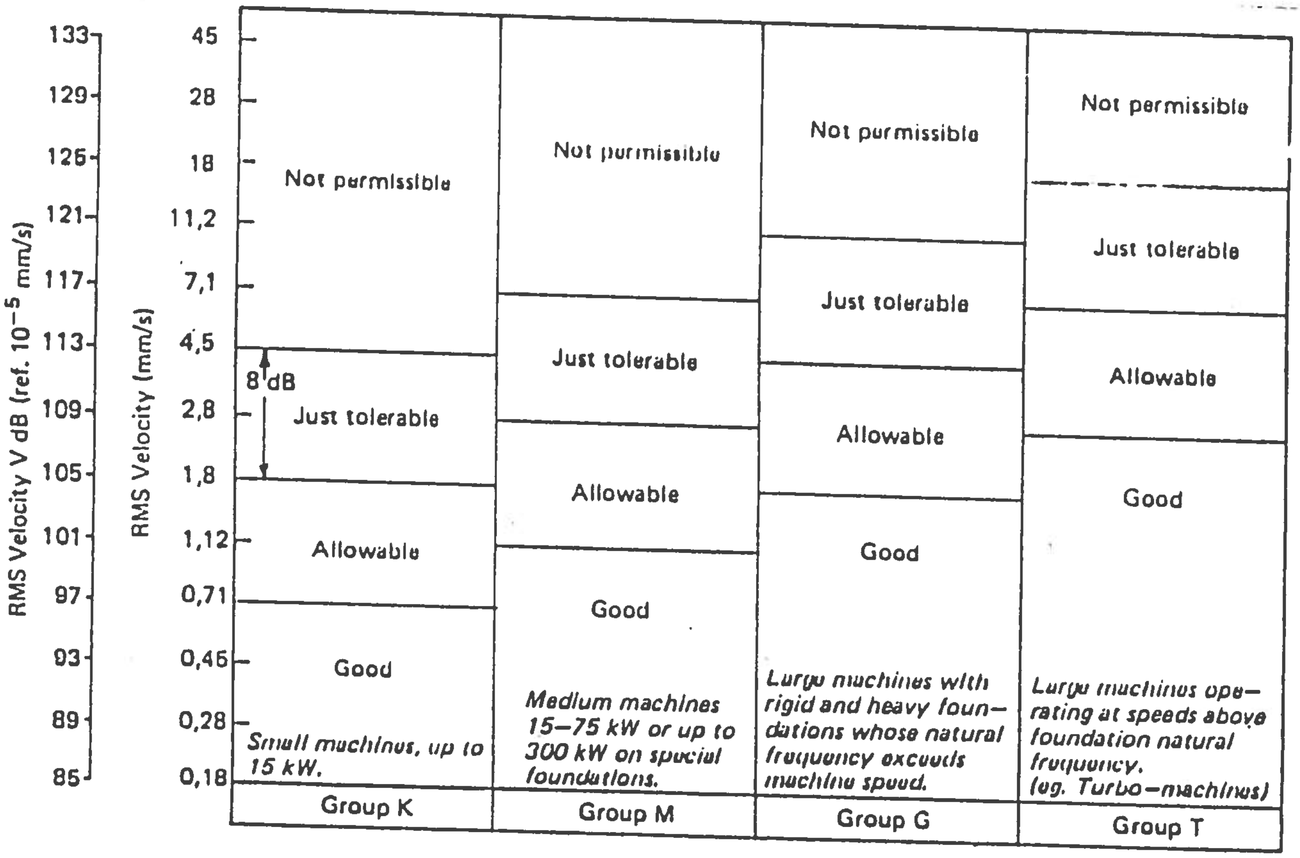



Fig. 6 Vibration Criterion Chart (from VDI 2056)

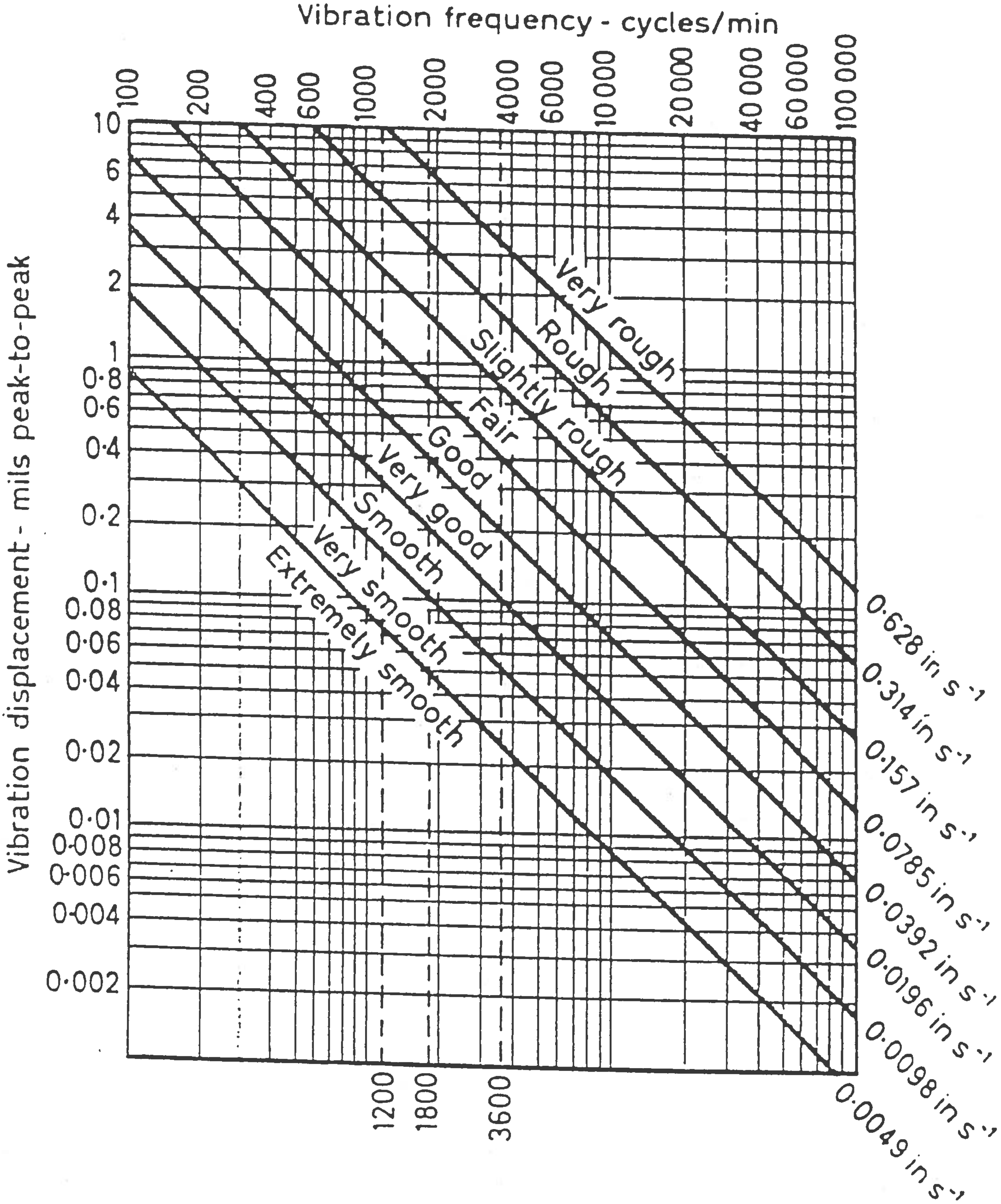



Figure. 7. *General machinery vibration severity chart*
(IRD Mechanalysis Inc., Colombus, Ohio)

Although some standards recommend comparison between overall vibration levels over a wide frequency range it is much more appropriate to make a frequency analysis and compare the level in a number of narrow frequency bands with corresponding levels recorded when the machine was new or recently overhauled. It is thus possible to detect changes in important, but not necessarily dominant, frequency components which would not have affected the overall level. It is generally considered that for frequency components up to 1 KHz an increase in vibration level by a factor 2.5 (8 dB) is significant and a change by a factor 10 (20 dB) is serious. Experience has indicated that for higher frequency components the corresponding figures are 16 dB and 40 dB.