Alexander Arnfinn Olsen

Equipment Conditioning Monitoring and Techniques

Guidance for the Maritime Domain

Springer

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Introduction

The guidance provided in this book is intended to provide the reader with information related to condition monitoring, trending and diagnostics of onboard equipment, machinery and systems. Condition monitoring consists of various tasks which are scheduled activities used to monitor machine condition and to detect a potential failure in advance so that action can be taken to prevent that failure. This book therefore summarises:

(1) The various condition-monitoring techniques applied to machinery.
(2) The condition-monitoring tasks most applicable for particular machinery.
(3) The effectiveness of condition-monitoring tasks.
(4) The failure condition monitored; and
(5) The framework for network-based data collection.

By improving equipment and machinery systems, reliability onboard vessels and other marine structures can be expected through the proper application of condition-monitoring tasks where condition-monitoring techniques are appropriate, applicable and correctly implemented.

Southampton, UK
2024

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Abbreviations and Acronyms

°C	Degrees Celsius
°F	Degrees Fahrenheit
AC	Alternating current
ASTM	American Society for Testing and Materials
CAN	Controller area network
CBM	Condition-based maintenance
CM	Condition monitoring
CMS	Continuous machinery survey
DC	Direct current
FMEA	Failure mode effects analysis
FMECA	Failure mode effects and criticality analysis
HAZID	Hazard identification
HAZOP	Hazard and operability analysis
I/O	Input/output
IACS	International Association of Classification Societies
ISO	International Organisation for Standardisation
kW	Kilowatt
MTTF	Mean time to failure
OEM	Original equipment manufacturer
OLE PC	Object linking and embedding for process control
OLE	Object linking and embedding
P-F	Potential-failure
PLC	Programmable logic controller
PM	Preventative maintenance
PPM	Parts per million
PROFIBUS	Process field bus
RBM	Reliability-based maintenance
RCM	Reliability centred maintenance
RMS	Root mean square
RTD	Resistance temperature detector

SI	International system of units (metric system)
TAN	Total acid number
TBN	Total base number
TCP/IP	Transmission control protocol and Internet protocol
UA	Unified architecture

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Chapter 1
General

Since the late 1970's, marine and offshore operators have increasingly applied various proactive maintenance techniques to prevent failures before they occur, detect the onset of failures, or discover failures before they impact system performance. There have been numerous advances in condition monitoring technology, trending, and increasingly more powerful planned maintenance software and machine diagnostics solutions as a result of increased computing power and networking. In 1978, the American Bureau of Shipping (ABS) pioneered a new form of cooperation with vessel owners with the intention of developing and implementing preventative maintenance programmes that would incorporate condition monitoring techniques. This cooperation produced, in 1984, the *Guide for survey based on preventative maintenance techniques* with subsequent updates following in 1985, 1987, 1995. Since then, periodic updates have been ensured the theory and process of preventative maintenance is current with the latest technologies and maintenance procedures in the maritime domain. This is of course crucial as machinery systems continue to become larger and ever more complex, requiring operators with increasingly specialised knowledge of the machinery and systems onboard. Accordingly, the industry has and continues to progress towards reliability-centred maintenance which provides vessel and other marine installation owners, managers and operators with a framework for the development of maintenance programmes using techniques which have been successfully applied in other industries for machinery systems.

The purpose of this book is to provide readers with a single source of guidance and information relating to condition monitoring techniques when designing, implementing and managing a reliability-centred maintenance programme. The topics addressed in this book include a summary of the types of condition-monitoring techniques used by the marine industry, in addition to guidance on the selection of appropriate technique(s), measurement frequency, personnel skills, company resources, and risk assessment. Through the application of condition-monitoring techniques, vessel owners, onshore managers, and marine asset operators should be able to see improved equipment and system reliability onboard their vessels or other marine installations. Moreover, consideration should be given to enrolling vessels and assets

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in either a reliability-centred maintenance programme or a preventative maintenance programme to take advantage of the additional cost saving benefits for equipment maintenance together with receiving credit towards Class mandated continuous survey for machinery.

> It is worth noting condition-monitoring tasks may be applied (in theory) to any equipment, machinery and/or system. Where it is not possible to enrol equipment, machinery or systems, Chap. 12 may be referenced, as applicable, for equipment that is not permitted for enrolment in either respective programme for reasons of statutory regulations or Class Survey policy. If the machinery is intended to be enrolled in a machinery maintenance programme or the preventative maintenance programme, it may be a prerequisite that the machinery is recorded on a Special Continuous Survey of Machinery (CMS) cycle in accordance with the appropriate Class Rules

Defining Condition-Monitoring Tasks

A condition-monitoring task is a scheduled task used to detect the potential onset of a failure so that action can be taken to prevent such failure. A potential failure is an identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring. Condition-monitoring tasks should only be chosen when a detectable potential failure condition will exist before failure and the applicable task has a reasonable probability of detecting the failure. The first maintenance types that should be considered are those recommended by the manufacturer. Condition monitoring tasks should only be considered if they can be proven to be applicable and effective. Some condition-monitoring tasks may be identified from previous risk studies such as hazard and operability analysis (HAZOP), hazard identification (HAZID) and failure mode effects analysis (FMEA) and failure mode effects and criticality analysis (FMECA) conducted during the system design. Failure-finding tasks may be considered to supplement some of the identified condition-monitoring tasks for increased robustness of the maintenance scheme. It is worth noting that at times condition-monitoring tasks may be referred to by practitioners in some countries as “predictive maintenance” tasks. Chapter 3 provides additional details.

Machinery Condition Monitoring Techniques

A summary of the machinery condition monitoring techniques listed in this publication, including the applicable equipment, is listed in this chapter, Table 1.1.

Table 1.1 Machinery condition monitoring applications

Technique	Reference	Roller bearings	Journal bearings	Belt drives	Circuit breakers	Diesel generators	Electric motors	Electrical systems	Gears
Temperature measurements	**4**								
Point temperature devices	2	•	•	•	•	•	•	•	•
Infrared photography	2	•	•	•	•	•	•	•	•
Dynamic monitoring	**5**								
Time wave form analysis	2	•	•	•		•	•		•
Broad band vibration analysis	2	•	•	•		•	•		•
Spectrum analysis	2	•	•	•		•	•		•
Shock pulse analysis	2	•(1)				•(2)			
Ultrasonic analysis	2	•							•
Other techniques	2	*See Chap. 5, Table 5.3*							
Oil analysis	**6**								

(continued)

Table 1.1 (continued)

Technique	Reference	Roller bearings	Journal bearings	Belt drives	Circuit breakers	Diesel generators	Electric motors	Electrical systems	Gears
Atomic emissions spectroscopy	2			•	•	•	•		
Dielectric strength tests	2						•		•
Ferrography	2		•	•	•				
Infrared and ultraviolet spectroscopy	2	•		•	•				
Moisture measurement	2	•(3)		•	•				
Kinematic viscosity test	2			•	•				
Microbial analysis	2				•			•	
Particle counter	2		•	•	•				
Total acid/total base number	2	•		•	•				
Sediment tests	2	•							•
Other techniques	2	*See Chap. 6, Table 6.3*							

(continued)

Table 1.1 (continued)

Technique	Heat exchangers	Heavy equipment/ cranes	Pumps	Reciprocating equipment	Steering gears	Tanks and piping	Transformers	Turbine (gas or steam)
Temperature measurements								
Point temperature devices	•	•	•		•	•	•	
Infrared photography	•	•	•		•	•	•	
Dynamic monitoring								
Time wave form analysis			•	•	•			•
Broad band vibration analysis			•	•	•			•
Spectrum analysis			•	•	•			•
Shock pulse analysis								
Ultrasonic analysis								
Other techniques								

(continued)

Table 1.1 (continued)

Technique	Heat exchangers	Heavy equipment/ cranes	Pumps	Reciprocating equipment	Steering gears	Tanks and piping	Transformers	Turbine (gas or steam)
Oil analysis								
Atomic emissions spectroscopy		•			•			
Dielectric strength tests	•						•	
Ferrography			•	•	•	•		
Infrared and ultraviolet spectroscopy		•			•		•	•
Moisture measurement								
Kinematic viscosity test		•	•	•	•	•		•
Microbial analysis		•	•	•		•		•
Particle counter		•	•	•	•	•		
Total acid/total base number		•	•	•	•	•	•	•
Sediment tests	•						•	
Other techniques								

(continued)

Table 1.1 (continued)

Technique	Reference	Atmospheric corrosion monitor	Cathodic protection monitoring	Electrical generating systems	Freshwater or seawater cooling	Underwater/ undersea structures	Cathodic protection monitoring	Electrical generating systems	Freshwater or seawater cooling	Underground/ undersea structures
Corrosion monitoring	7									
Coupon testing	2	•	•	•	•	•	•	•	•	•
Corrometer (electrical resistance)	2	•	•	•	•	•	•	•	•	•
Potential monitoring(4)	2			•		•		•		•

Technique	Reference	Weld defects	Gas porosity	Surface shrinkage	Lack of weld penetration	Cracks, crack formation	Subsurface defects in plates, shafts and castings	Integral corrosion	Corrosion fatigue
Non-destructive testing	**8**								
X-ray radiography	2	•	•		•	•	•	•	
Liquid dye penetrants	2								•
Ultrasonic leak detection	2								
Ultrasonic flaw detection	2	•	•					•	
Magnetic particle inspection(5)	2			•		•			•

(continued)

Table 1.1 (continued)

Technique	Reference	Weld defects	Gas porosity	Surface shrinkage	Lack of weld penetration	Cracks, crack formation	Subsurface defects in plates, shafts and castings	Integral corrosion	Corrosion fatigue
Eddy current testing	2								
Acoustic emission	2					•			
Hydrostatic and pneumatic testing	2								
Visual inspection—borescope	2	•				•			
Other techniques	2	*See Chap. 8, Table 8.2*							

Technique	Stress corrosion	Hydrogen embrittlement	Surface cracks	Surface defects	Embrittlement	Defects in pressure boundary and leaks	Metal thickness loss due to wear, corrosion or both	Lamination	Corrosion
Non-destructive testing									
X-ray radiography									
Liquid dye penetrants	•	•	•	•	•				
Ultrasonic leak detection						•			
Ultrasonic flaw detection	•	•		•					
Magnetic particle inspection(5)	•	•						•	
Eddy current testing							•		•
Acoustic emission									

(continued)

Table 1.1 (continued)

Technique	Stress corrosion	Hydrogen embrittlement	Surface cracks	Surface defects	Embrittlement	Defects in pressure boundary and leaks	Metal thickness loss due to wear, corrosion or both	Lamination	Corrosion
Hydrostatic and pneumatic testing						•			
Visual inspection—borescope			•						
Other techniques									

Technique	Reference	Strain	Surface and shallow subsurface defects	Pipe and tube thickness	Wear	Fatigue	Plastic deformation	Stress	Oxide films
Non-destructive testing	**8**								
X-ray radiography	2	•	•		•	•	•	•	
Liquid dye penetrants	2								
Ultrasonic leak detection	2								
Ultrasonic flaw detection	2			•					
Magnetic particle inspection(5)	2		•		•	•			
Eddy current testing	2	•	•	•	•				
Acoustic emission	2				•	•	•	•	

(continued)

Table 1.1 (continued)

Technique	Reference	Strain	Surface and shallow subsurface defects	Pipe and tube thickness	Wear	Fatigue	Plastic deformation	Stress	Oxide films
Hydrostatic and pneumatic testing	2								
Visual inspection—borescope	2				•	•			•

Technique	Reference	DC armatures	Induction/ synchronous motors	Flow or machine output restrictions	Machinery misalignment	Battery wet cell deterioration	Resistance of equipment insulation
Electrical testing	**8**						
Megohmmeter testing	2						•
High potential testing	2						
Surge testing	2	•	•				
Power signature analysis	2			•	•		
Motor circuit analysis	2	•	•				
Battery impedance testing	2					•	

Technique	Synchronous field poles	Motor winding resistance	Various coils and coil groups	Compressors	Pumps	Motor operated valves	Wound rotor electric motors
Electrical testing							
Megohmmeter testing							
High potential testing		•					

(continued)

Table 1.1 (continued)

Technique	Synchronous field poles	Motor winding resistance	Various coils and coil groups	Compressors	Pumps	Motor operated valves	Wound rotor electric motors
Surge testing	•		•				
Power signature analysis					•	•	•
Motor circuit analysis		•					•
Battery impedance testing							

Technique	Reference	Loose or worn marts	Fluid or gas leaks	Missing parts	Poor electrical connections	Poor pipe connections	Bearings	Steam leaks
Observation and surveillance	**10**							
Visual inspection	2	•	•	•	•	•		
Audio inspection	2						•	•
Touch inspections	2							
Performance trending	11	Monitoring of equipment or system performance indicators for trending						
Engine performance monitoring/ diagnostics	12	Monitoring of engine parameters so as to optimise performance or alert operator of impending maintenance						

(continued)

Table 1.1 (continued)

Technique	Pressure relief valve leaks	Coupling leaks	Overloaded pumps	Poor mechanical alignment	Heat	Scaling	Roughness changes
Observation and surveillance							
Visual inspection							
Audio inspection	•	•	•	•			
Touch inspections					•	•	•
Performance trending							
Engine performance monitoring/diagnostics							

Notes
(1)This technique is reported to work well on bearings by themselves but has some serious limitation on bearings in gearboxes, pumps, motors, etc., because of the other "normal" frequencies that are in most common machines, such as blade pass frequency, gear mesh frequency, and slot pass frequency, for example
(2)Internal combustion engine valves or components for which metal-to-metal contact is a source of wear
(3)Use the coulometric Karl Fischer titration method for insulating liquids (ASTM D1533-00(2005) or ISO 12937-00 Petroleum products—determination of water—coulometric Karl Fischer titration method)
(4)It is reported potential monitoring is best suited to use on stainless steel, nickel-based steel alloys and titanium materials
(5)Suitable for ferromagnetic materials only
(6)Reported to be suitable for hydraulic pipes and tubes

Chapter 2
Equipment Failure

A brief introduction to equipment failure theory is given in this chapter. The theory presented in this chapter can be applied to systems which comprise two or more equipment sets. A combination of one or more equipment failures, human errors, or both, may cause a loss of system function. The following factors are liable to influence the likelihood of equipment failure:

(1) Design error.
(2) Faulty material.
(3) Improper fabrication and construction.
(4) Improper installation.
(5) Improper operation.
(6) Inadequate maintenance.
(7) Maintenance errors.

It should be noted that maintenance in, and of itself, does not influence many of these factors. Therefore, maintenance is merely one of the many approaches that may be taken to improve equipment reliability and, hence, system reliability. To that end, reliability-centred maintenance or RCM is a process which analyses and places a distinct focus on reducing failures resulting from inadequate maintenance. In addition, RCM aids in identifying premature equipment failures introduced by maintenance errors. In these cases, RCM analyses may recommend improvements for specific maintenance activities, such as refining maintenance procedures, improving personnel performance, or adding quality assurance/quality control (QA/QC) tasks to verify the correct performance of critical maintenance tasks. While the objective of this book is to improve maintenance, RCM analyses may recommend design changes and/or operational improvements when equipment reliability cannot be wholly ensured through maintenance alone. To effectively improve equipment reliability through maintenance, design changes, or operational improvement, one must have an understanding of the potential equipment failure mechanisms, their causes and associated system impacts.

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Table 2.1 Typical hardware-related equipment failure mechanisms

Mechanical loading failure	Wear	Corrosion	Temperature-related failure
Ductile fracture Brittle fracture Mechanical fatigue	Abrasive Adhesive Fretting Pitting Cavitation	Galvanic Uniform Stress corrosion cracking	Creep Metallurgical transformation Thermal fatigue

Equipment failure may be defined as a state or condition in which a component no longer satisfies some aspect of its design intent (e.g., when a functional failure has occurred due to the equipment failure). RCM focuses on managing equipment failures that result in functional failures. To develop an effective failure management strategy, the strategy must be based on an understanding of the failure mechanism. Equipment will typically exhibit one or more different failure modes (e.g., *how* the equipment fails). Moreover, the failure mechanism may be different for the different failure modes, and the failure mechanisms may vary during the lifecycle of the equipment. To help understand this relationship, Table 2.1 summarises some of the most typical hardware-related equipment failure mechanisms.

Equipment Failure Rate and Patterns

Depending on the dominant system failure mechanisms, system operation, system operating environment and system maintenance, specific equipment failure modes exhibit a variety of failure rates and patterns. Statistically, failure rate is expressed in terms of operating time (or some other pertinent operating parameter) elapsed before an item of equipment fails. Due to the variable nature of failure time, it is usual to analyse failure density distribution providing the probability of an item failing after a given operating time. Depending on the equipment failure mode, a variety of distributions (e.g., normal, exponential, Weibull, lognormal) can be used to statistically model the probability of failure. To that end, failure density distributions measure the probability of failure within a given interval (e.g., between time zero and 8000 h of operation). Figure 2.1 provides illustrative normal, exponential, and Weibull failure distributions. One of the most common failure distribution methods used to model equipment failures is the *Weibull distribution.* This distribution is used when equipment exhibits a constant failure rate for a portion of its life followed by an increasing failure rate due to wear-out. In addition, Weibull analysis is used when there is only a small amount of failure data available. The Weibull plot can be used to determine if the failure is due to:

(1) Infant mortality or wear-in.
(2) Random event.

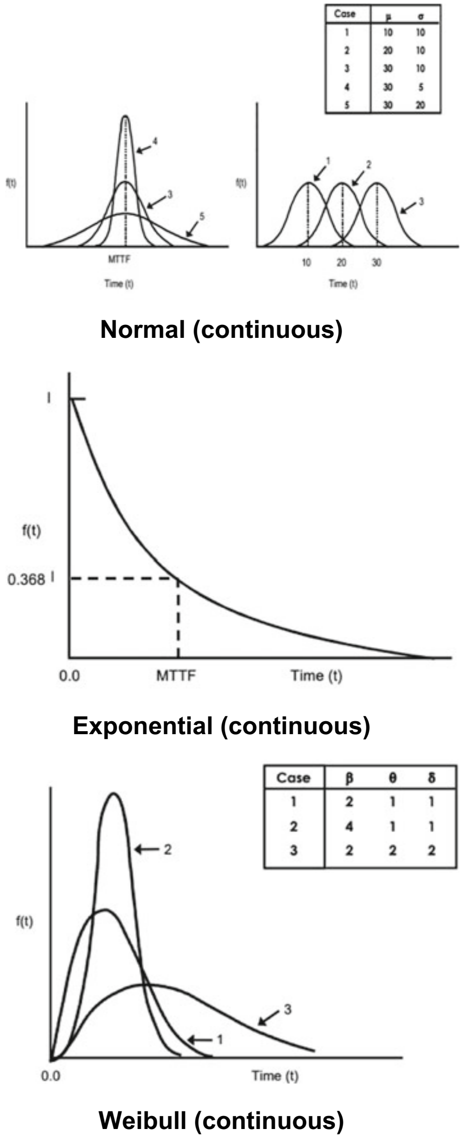


Fig. 2.1 Normal, exponential and Weibull failure distributions

(3) Early wear-out.
(4) Exhaustive wear-out.

This information is helpful in determining an appropriate maintenance strategy. The Weibull plot can also be correlated between the probability of failure and equipment operating time. These datasets can be valuable in establishing task intervals for certain types of maintenance tasks (e.g., rebuilding tasks). Another common statistical measure associated with these distributions is *mean time to failure* (MTTF).

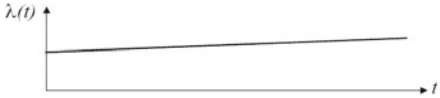
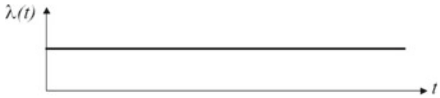
MTTF is the average life to failure for the equipment failure mode. Thus, it represents the point at which the areas under the failure distribution curve are equal to above and below the point of failure. Determining the MTTF will, therefore, depend on the type of failure distribution used to model the failure mode. Figure 2.1 identifies the MTTF for normal and exponential failure distributions. MTTF datasets are helpful in determining when to perform certain types of maintenance tasks. For example, if the appropriate maintenance strategy is to rebuild an equipment item, the MTTF data can be used to help set the rebuilding task interval. If the MTTF is represented by a normal distribution and the interval is set at the MTTF, then we can assume that there is a 50% chance of the item failing before it is rebuilt. If the interval is set less than the MTTF, then the probability of the item failing before being rebuilt is <50%. If the interval is more than the MTTF, then the probability is more than 50%.

The increase or decrease in probability as the interval is moved before or after the MTTF depends on the standard deviation of the distribution. An arguably more useful measurement, which is derived from the failure distribution, is the conditional failure rate or lambda (λ). The conditional probability failure rate is the probability that a failure occurs during the next instant of time, given that the failure has not already occurred before that time. The conditional failure rate, therefore, provides additional information about the survival life and is used to illustrate failure patterns. Table 2.2 shows six classic conditional failure setup patterns. The vertical axis represents the conditional failure rate as a function of time ($\lambda(t)$), and the horizontal axis represents the operating time (t) or another variable (e.g., operating cycles). Understanding that equipment failure modes can exhibit different failure patterns has important implications when determining appropriate maintenance strategies. For example, rebuilding or replacing equipment items that do not have distinctive wear-out regions (e.g., patterns C through F) is of little benefit and may actually increase failures as a result of infant mortality and/or human errors during maintenance tasks. For most equipment failure modes, the specific failure patterns are not known and, fortunately, are not needed to make maintenance decisions. Nevertheless, certain failure characteristic information is needed to make maintenance decisions. These characteristics may include (but are not limited to):

(1) Wear-in failure, which is dominated by “weak” members related to problems such as manufacturing defects and installation/maintenance/startup errors. Also known as “burn in” or “infant mortality” failures.
(2) Random failure, which is dominated by chance failures caused by sudden stresses, extreme conditions, random human errors, etc. (e.g., failure is not predictable by time).
(3) Wear-out failure, which is dominated by end-of-useful life issues for equipment.

By simply identifying which of the three equipment failure characteristics is representative of the equipment failure mode, we gain insight into the proper maintenance strategy. For example, if an equipment failure mode exhibits a wear-out pattern, rebuilding or replacing the equipment item may be an appropriate strategy. However, if an equipment failure mode is characterised by wear-in failure, replacing

Table 2.2 Six classic failure rate patterns(1)

	**Pattern A: bathtub** Infant mortality, then a constant or increasing failure rate, followed by a distinct wear-out zone *Example*: overhauled reciprocating engine
	**Pattern B: traditional wear-out** Constant or slowly increasing failure rate followed by a distinct wear-out zone *Example*: reciprocating engine, pump impeller
	**Pattern C: gradual rise with no distinctive wear-out zone** Gradually increasing failure rate, but no distinct wear-out zone *Example*: gas turbine
	**Pattern D: initial increase with a leveling-off** Low failure rate initially, then a rapid increase to a constant failure probability *Example*: complex equipment under high stress with test runs after manufacture or restoration, such as hydraulic systems
	**Pattern E: random failure** Constant failure rate in all operating periods *Example*: roller/ball bearings
	**Pattern F: infant mortality** High infant mortality followed by a constant or slowly rising failure rate *Example*: electronic components

(1) Reliability-centred Maintenance, F. Stanley Nowlan and Howard F. Heap, 29 December 1978, US Department of Commerce, National Technical Information Service

or rebuilding the equipment item may not be advisable. Finally, a basic understanding of failure rate helps in determining whether maintenance or equipment redesign is necessary. For example, equipment failure modes that exhibit high failure rates (e.g., fail frequently) are usually best addressed by redesign rather than applying more frequent maintenance (Fig. 2.2).

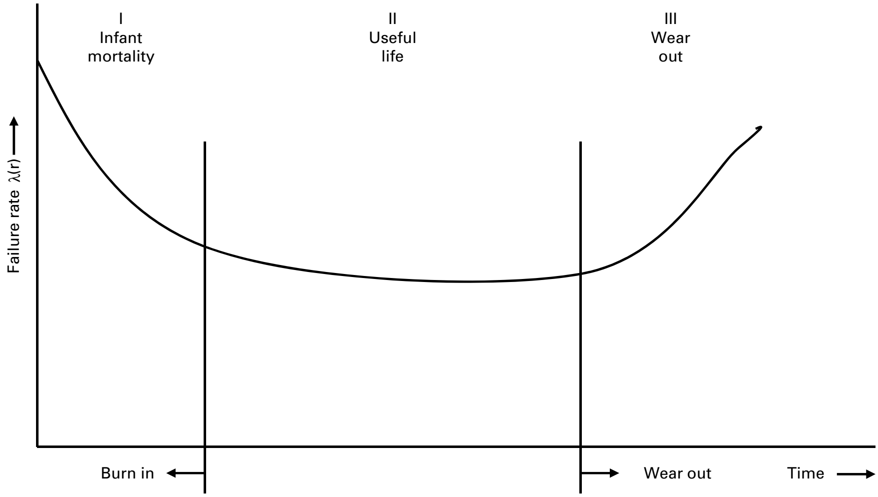


Fig. 2.2 Equipment life periods

Failure Management Strategy

Understanding failure rates and failure characteristics allows the determination of an appropriate strategy for managing the failure mode. Developing and using this understanding is fundamental to improving equipment reliability. It is no longer considered to be true that the more an item is overhauled, the less likely it is to fail. Unless there is a dominant age-related failure mode, age limits do little or nothing to improve the reliability of complex items. Sometimes, scheduled overhauls may increase overall failure rates by introducing infant mortality, human errors or both into otherwise stable systems. In RCM, the failure management strategy can consist of:

(1) Appropriate proactive maintenance tasks.
(2) Equipment redesigns or modifications; or
(3) Other operational improvements.

The purpose of the proactive maintenance tasks in the failure management strategy is to (1) prevent failures before they occur or (2) detect the onset of failures in sufficient time so that the failure can be managed before it occurs. Equipment redesigns, modifications and operational improvements (RCM refers to these as one-time changes) are attempts to improve equipment whose failure rates are too high or for which proactive maintenance is not effective/efficient. The key questions to ask when determining whether a specific failure management strategy is effective are:

(1) Is the failure management strategy technically feasible?

(2) Is an acceptable level of risk achieved when the failure management strategy is implemented?
(3) Is the failure management strategy cost-effective?

In addition to proactive maintenance tasks and one-time changes, servicing tasks and routine inspections may be important elements within the failure management strategy. These activities help determine that the equipment failure rate and failure characteristics are as anticipated. For example, the failure rate and failure pattern for a bearing drastically changes if it is not properly lubricated. These proactive maintenance tasks, run-to-failure, one-time changes, and servicing and routine inspections are summarised in the following paragraphs.

Proactive Maintenance Tasks

Proactive maintenance tasks are divided into four categories:

(1) Planned maintenance tasks.
(2) Condition-monitoring tasks.
(3) Combination of tasks.
(4) Failure-finding tasks.

Each of these tasks are briefly discussed below.

Planned-Maintenance Tasks

A planned-maintenance task is performed at a specified interval, regardless of the equipment's condition. The purpose of this type of task is to prevent functional failure before it occurs. Often this type of task is applied when no condition-monitoring task is identified or justified, and the failure mode is characterised with a wear-out pattern. Planned maintenance can be divided into the following two subcategories:

- *Restoration task.* A scheduled task that restores the capability of an item at or before a specified interval (age limit) to a level that provides a tolerable probability of survival to the end of another specified interval. For the case of scheduled restoration of a diesel engine, rebuilding the fuel injectors would be an example.
- *Discard task.* A scheduled task involving discarding an item at or before a specified age limit regardless of its condition at the time.

It is worth noting that the terms "restoration" and "discard" can be applied to the same task. For example, if a diesel engine's cylinder liners are replaced with new ones at fixed intervals, the replacement task could be described as "scheduled discard of the cylinder liner" or "scheduled restoration of the diesel engine".

Condition-Monitoring Tasks

A condition-monitoring task is a scheduled task used to detect the potential onset of a failure so that action can be taken to prevent the functional failure. A potential failure is an identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring. Condition-monitoring tasks should only be chosen when a detectable potential failure condition will exist before failure. When choosing maintenance tasks, condition-monitoring tasks should be considered first, unless a detectable potential failure condition cannot be identified. Condition monitoring tasks are also referred to as "predictive maintenance". Chapter 3 provides additional guidance on condition-monitoring (i.e., predictive) tasks.

Combination of Tasks

Where the selection of either condition-monitoring or planned-maintenance tasks on their own do not seem capable of reducing the risks of the functional failure of the equipment, it may be necessary to select a combination of both maintenance tasks. Usually, this approach is used when the condition-monitoring or planned-maintenance task is insufficient to achieve an acceptable risk by itself.

Failure-Finding Tasks

A failure-finding task is a scheduled task used to detect hidden failures when no condition monitoring or planned-maintenance task is applicable. It is a scheduled function check to determine whether an item will perform its required function if called upon. Most of these items are standby or protective equipment. An example would be testing the safety valve on a boiler.

Run-to-Failure

Run-to-failure is a failure management strategy that allows an equipment item to run until failure occurs at which point a repair or replacement is made. This maintenance strategy is acceptable only if the risk of a failure is tolerable without any proactive maintenance tasks. An example would be permitting a local pressure gauge on a cooling water line, also fitted with a remote-reading pressure gauge, to fail.

One-Time Changes

One-time changes are used to reduce the failure rate or manage failures in which appropriate maintenance tasks are not identified or cannot effectively and efficiently manage the risk. The fundamental purpose of a one-time change is to alter the failure rate or failure pattern through:

- Equipment redesigns or modification; and/or
- Operational improvements, or both.

One-time changes most effectively address equipment failure modes that result from the following failure mechanisms:

(1) Faulty design, materials; or both.
(2) Improper fabrication, construction; or both.
(3) Mis-operation.
(4) Maintenance errors.

These failure mechanisms often result in a wear-in failure characteristic, and thus, require a one-time change. When no maintenance strategy can be found that is both applicable and effective in detecting or preventing failure, a one-time change should be considered. The following briefly describes each type of one-time change:

- *Equipment redesign or modifications.* Redesign or modifications entail physical changes to the equipment or system. An example would be mitigating main engine bearing damage caused by no or low lube oil flow by adding a low-pressure sensor in the lubricating oil pump outlet that would start a standby pump to maintain lube oil flow to the main engine bearings.
- *Operational improvements.* Operational improvements are changes in the way equipment is operated, modifications in the way maintenance are performed on the equipment, or both. Operational improvements usually entail changing the operating context, changing operating procedures, providing additional training to the operator or maintainer, or any combination thereof. For example, in the case of a main propulsion engine provided with a non-continuous rating nameplate, the engine could be operated at a lower output closer to its continuous rating so as to reduce downtime for maintenance.

Servicing and Routine Inspection

These are simple tasks intended to (1) maintain the failure rate and failure pattern as predicted by performing routine servicing (i.e., lubrication, filter changing, other replenishment tasks); (2) spot accidental damage; (3) spot problems resulting from ignorance or negligence; or (4) respond to unsatisfactory condition monitoring techniques results. They provide the opportunity to maintain the general standards of maintenance at a satisfactory level. These tasks are not based on any explicit potential failure condition. Servicing and routine inspection may also be applied to items that have relatively insignificant failure consequences, yet should not be ignored (minor leaks, drips, etc.).

Chapter 3
Planned and Condition-Monitoring (Predictive) Maintenance

Planned Maintenance

Planned maintenance is a failure management strategy that restores the inherent reliability or performance of the equipment item. These tasks are best employed on equipment items suffering from age-related failure (e.g., wear-out failure characteristic). The basic principle of planned maintenance is that restoring or discarding the item at a specific time before failure is expected can best manage the probability of failure. Following this principle, the planned-maintenance tasks are performed at set intervals, regardless of whether or not a failure is impending. Restoring the item or discarding it and replacing it with a new item prevent the failure.

Age-to-Failure Relationship

The age-to-failure relationship (or wear-out failure characteristic) is distinctive in failure patterns A and B, discussed in Chap. 2. Other equipment failure modes may exhibit a less distinctive wear-out characteristic, such as that in failure pattern C. Conceptually, though, performing planned maintenance restores equipment reliability for these failure patterns. For planned maintenance to be effective in managing the failure, the failure mode must exhibit a clear life and most of the equipment items must survive to that life. Figure 3.1 illustrates the wear-out period for failure pattern B.

Planned maintenance provides an effective failure management strategy for wear-out failures because the conditional probability of failure is reduced to approximately its initial failure rate (e.g., failure rate at time zero). Figure 3.2 illustrates the "resetting" of the failure rate curve that results from performing a planned-maintenance task.

A. A. Olsen, *Equipment Conditioning Monitoring and Techniques*,
https://doi.org/10.1007/978-3-031-57781-9_3

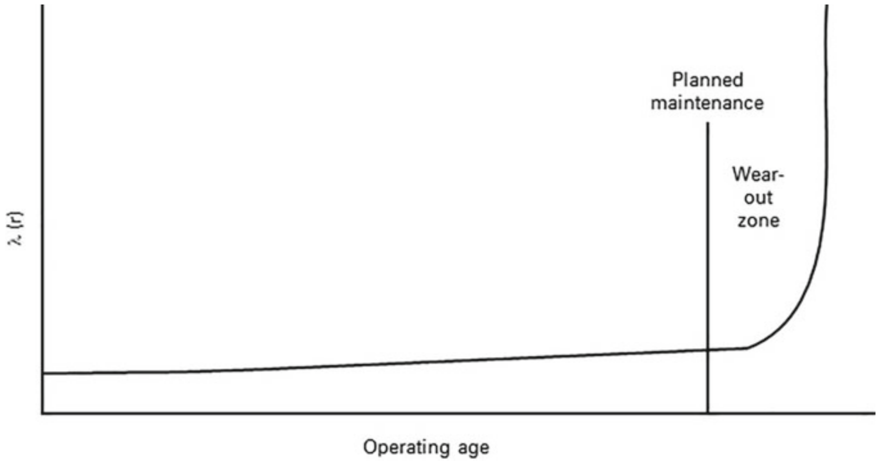


Fig. 3.1 Classic failure profile used for planned maintenance

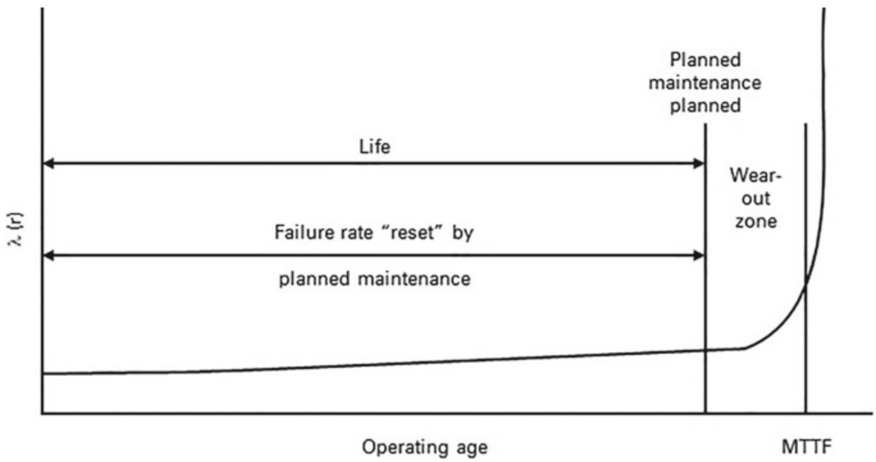


Fig. 3.2 Failure profile illustrating the effect of performing a planned task

The assumption is that the restoration and discard task restore the equipment item to nearly "new" condition. However, if the equipment failure mode exhibits both wear-in and wear-out failure patterns (e.g., failure pattern A), additional tasks or a one-time change may be required to manage the wear-in that is likely to occur after the planned-maintenance task (for example, the recommissioning of a gas turbine or a diesel engine after an extensive repair/overhaul).

Planned-Maintenance Task Applicability and Effectiveness

For a planned-maintenance task to be considered applicable and effective, the following considerations should be made:

(1) *Is the task technically feasible to perform?* The age-to-failure relationship must be reasonably consistent, and the task must be physically capable of being performed.
(2) *Does the task reduce the probability of failure (and therefore the risk) to an acceptable level?* The tasks must be carried out at an interval that is less than the age at which the equipment or component shows a rapid increase in its conditional probability of failure. Agreed-upon risk acceptance criteria should be determined and recorded.
(3) *Is the task cost-effective?* The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure.

Alternatively, when determining whether the planned-maintenance task should be a restoration or discard task, the following considerations should be made:

(1) *Does the task ensure the reliability and performance of the equipment?* If the equipment is restored, it must be restored to a nearly new condition.
(2) *Is the task cost-effective?* The cost of restoring the equipment should be less than discarding the equipment and replacing it with a new item.

Determining Planned-Maintenance Task Interval

We can determine the interval at which planned-maintenance tasks should be performed using a variety of methods:

(1) Equipment manufacturer information.
(2) Expert opinion.
(3) Published reliability data.
(4) Statistical analysis (e.g., Weibull) of actual failure history, including the MTTF data.

Regulatory requirements (e.g., Class Rules) should also be considered, especially if data are insufficient to determine a planned-maintenance interval. In addition, the potential consequence (e.g., the resulting effect) and the risk associated should be considered when determining a planned-maintenance interval. RCM employs two concepts when determining a planned-maintenance interval: safe life limit and economic life limit. These limits are illustrated in Figs. 3.3 and 3.4.

If the failure mode could result in a severe safety or environmental effect or a highest-risk event, the planned-maintenance task interval is set using the safe limit concept. That is, the task interval is set to ensure there is little chance of failure occurring before the planned-maintenance task is performed. This usually means

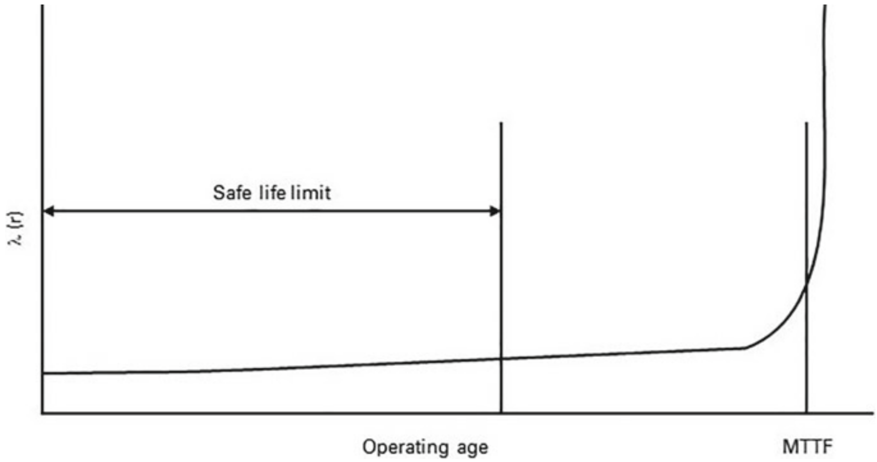


Fig. 3.3 Safe life limit

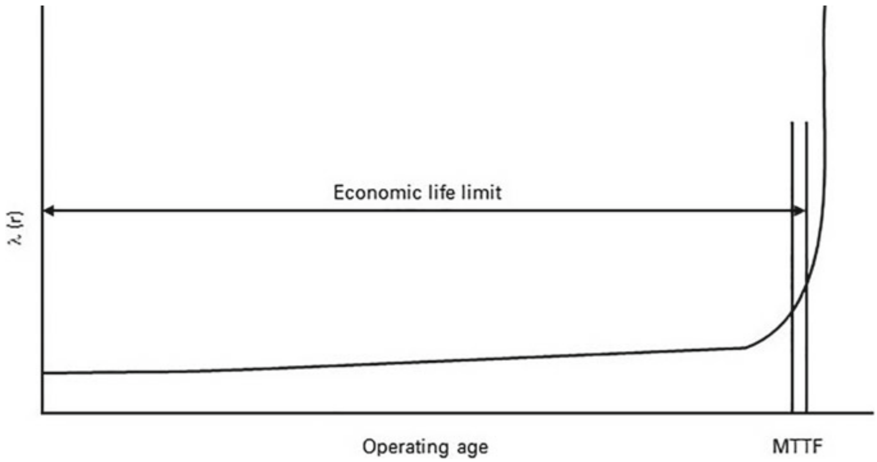


Fig. 3.4 Economic life limit

setting the interval well before the MTTF point. The economic life limit is used for all other failure modes. In this model, the task interval is based on the economics of the task and the expected equipment life. In this case, the task interval may be before, at, or after the MTTF point. Because few operations currently have enough data to determine optimal planned-maintenance task intervals, the initial task frequency is typically set at a conservative value (especially for highest-risk failure modes) and then optimised as the task is performed. However, performing planned maintenance too frequently can result in an increased failure rate. This increased failure rate results from human errors during the task and/or wear-in failures.

Condition-Monitoring (Predictive) Maintenance

Potential Failure (P–F) Diagram

Although many failure modes are not age-related, most of them give some sort of warning that they are in the process of occurring or about to occur. If evidence can be found that something is in the final stages of a failure, it may be possible to take action to prevent it from failing completely so as to avoid the consequences. Figure 3.5 illustrates the final stages of failure, called the P–F curve. Figure 3.5 illustrates how a condition deteriorates to the point at which it can be detected (Point P) and then, if it is not detected and corrected, continues to deteriorate until it reaches the point of functional failure (Point F). (A functional failure is a description of how the equipment is unable to perform a specific function to a desired level of performance.) In practice, there are many ways of determining whether failures are in the process of occurring (i.e., hot spots showing deterioration of furnace refractories or electrical insulation, vibrations indicating imminent bearing failure, increasing level of contaminants in lubricating oil). If a potential failure is detected between Point P and Point F, it may be possible to take action to prevent the functional failure (or at least to minimise the effects) before the failure occurs. Tasks designed to detect potential failure are known as condition-monitoring tasks.

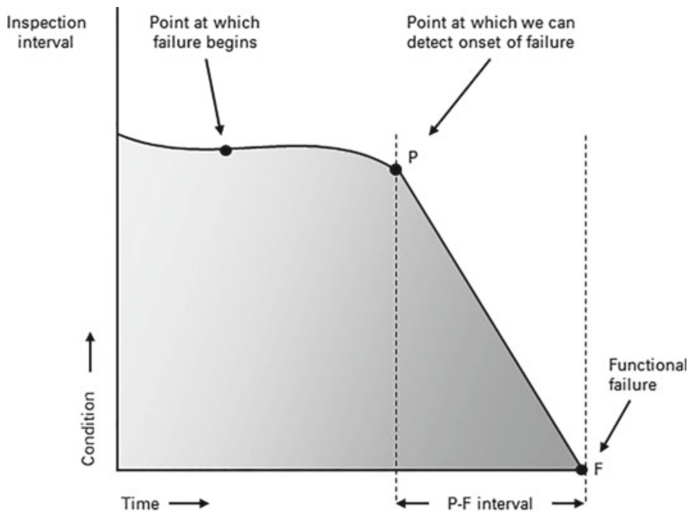


Fig. 3.5 P–F diagram selection of task frequency

The P–F Interval

The time interval between Point P and Point F in Fig. 3.5 is called the “P–F interval”. This is the warning period (i.e., the time between the point at which the potential failure becomes detectable and the point at which it deteriorates into a functional failure). If a condition-monitoring task is performed on intervals longer than the P–F interval, the potential failure may not be detected. On the other hand, if the condition-monitoring task is performed too frequently compared to the P–F interval, resources are wasted. Industry practice is to select an interval of about one-half of the P–F interval. In the event the condition degrades, the condition-monitoring task will be performed prior to a functional failure occurring at Point F. It should be noted that the P–F interval can vary in practice, and in some cases, it can be very inconsistent. In these cases, a task interval should be selected that is substantially less than the shortest of the likely P–F intervals. Technology improvements have eased the storage limitations for large quantities of condition monitoring data collected on a continual basis instead of periodically. Additionally, this data can be transmitted ashore via satellite for analysis by the equipment manufacturer or another third-party service firm. The analyst can verify satisfactory operation of the equipment or system and in the event of degradation occurring, notify the operator of the affected component with suggestions for verifying and repairing the component.

Condition-Monitoring Maintenance Categories

Condition-monitoring maintenance techniques can be organised into the following categories:

- Temperature measurements.
- Dynamic monitoring.
- Oil analysis.
- Corrosion monitoring.
- Non-destructive testing.
- Electrical testing.
- Observation and surveillance.

Chapters 4 through 10 provide overviews of these categories together with listings of commonly used techniques in the marine industry. Tables of other related techniques applied in shore-based industries are also provided for consideration.

Condition-Monitoring Maintenance Task Applicability and Effectiveness

For a condition-monitoring maintenance task to be considered applicable and effective, the following should be accounted for:

(1) *Onset of failure is detectable.* There is some measurable parameter that can detect the deterioration in the equipment's condition. In addition, maintenance personnel should be able to establish limits to determine when corrective action is needed.
(2) *Reasonably consistent P–F interval.* The P–F interval is such that corrective actions are not implemented prematurely or that failure occurs before corrective actions are implemented.
(3) *Practical interval in which condition-monitoring tasks can be performed.* The P–F interval is sufficient to permit a practical task interval. For example, a failure with a P–F interval of minutes or hours would not be an appropriate candidate for manually collected data from a condition-monitoring maintenance task. However, an automated device that assesses condition very frequently with ability to shut down the equipment would be appropriate to install.
(4) *Sufficient warning so that corrective actions can be implemented.* The P–F interval is long enough to allow corrective actions to be implemented. This can be determined by subtracting the task interval from the expected P–F interval and then judging whether sufficient time remains to take necessary corrective actions.
(5) *Reduces the probability of failure (and therefore the risk) to an acceptable level.* The tasks are carried out at an interval so that the probability of failure allows an acceptable risk level to be achieved. Agreed-upon risk acceptance criteria should be determined and recorded.
(6) *Cost-effectiveness.* The cost of undertaking a task over a period of time should be less than the total cost of the consequences of failure.

Determining Condition-Monitoring Maintenance Task Intervals

Condition-monitoring maintenance task intervals should be determined based on the expected P–F interval. The following sources may be referred to as an aid to determine the P–F interval:

(1) Expert opinion and judgment (i.e., manufacturer's recommendations)
(2) Published information about condition-monitoring tasks
(3) Historical data (i.e., estimated MTTF from existing data, current condition-monitoring task intervals).

Condition-Monitoring Task Interval

The interval for a condition-monitoring task should be set at no more than half the expected P–F interval and should be adjusted based on the following considerations:

(1) Reduce the task interval if the P–F interval minus the task interval (P–F interval) does not provide sufficient time to stop the equipment and implement corrective actions.
(2) Reduce the task interval if there is low confidence in the "guesstimate" of the expected P–F.
(3) Reduce the task interval for higher risk failure modes.
(4) Set the task interval at half the expected P–F interval (or slightly above) for lower risk failure modes.

Initial Condition-Monitoring Task Intervals

Because few organisations will have detailed knowledge about the equipment failure mode P–F interval, the following guidelines can be used to establish initial condition-monitoring task intervals:

(1) If an existing condition-monitoring task is being performed and has proven to be effective (i.e., no unexpected failures have occurred), use the existing task interval as the initial default task interval.
(2) If an existing condition-monitoring task is being performed and some functional failures have occurred, reduce the task interval based on the experience.
(3) If there is no existing condition-monitoring task being performed or a new condition-monitoring task is being proposed, the task interval will have to be based on the team's estimate of the P–F interval and guidelines. The following questions can help the team estimate the P–F interval:

   - How quickly can the condition deteriorate and result in a functional failure? Will it deteriorate in minutes, hours, days, weeks, months, or years?
   - What is the capability of the condition-monitoring task in detecting the onset of failure? High or low?
   - How confident is the team in its judgment?

Improving the Understanding of P–F Intervals

As data from condition-monitoring tasks are collected and corrective actions are implemented, vessel operators will improve their understanding of the P–F interval. For example, assume that vibration testing is performed weekly on pumps in similar service. On several occasions, the vibration analysis detects the onset of failures. However, due to scheduling delays, corrective action is not taken for an additional six (6) to eight (8) weeks. During this period of delay, the pumps continue to operate properly. The P–F interval for these pumps is then known to be probably at least six

(6) weeks, and the task interval can be changed to three (3) weeks (1/2 of 6 weeks). The condition monitoring techniques in the following sections list the necessary skill level for the personnel taking and collecting data. The skill levels are categorised into four levels as follows:

(1) *No specific training needed*. Collecting and recording of data are simple and require minimal or little training to use equipment.
(2) *Trained semi-skilled worker to take the readings.* Collecting and recording of data require training in the use of the equipment. The personnel require some training for interpretation of data results to verify data is correct and relevant.
(3) *Trained skilled worker or trained lab technician.* Collecting and recording of data require comprehensive training in the use of the equipment. The personnel require training for interpretation of data results to verify data is correct and relevant.
(4) *Trained and experienced technician.* Collecting and recording of data require comprehensive training in the use of the equipment. Experience is necessary to properly collect or evaluate data for special or unusual equipment installations or when evaluating unusual or suspect data. The personnel also require training for interpretation of data results to verify data is correct and relevant.

Establishing Condition-Monitoring Maintenance Task Action Limits

Another aspect of a condition-monitoring maintenance task is establishing action limits. This involves establishing limits that result in corrective actions when they are exceeded. The actions may involve any of the following:

(1) Re-performing the condition-monitoring task to verify the results
(2) Altering the task interval for closer/lesser monitoring of the equipment as warranted
(3) Initiating corrective actions to prevent the impending equipment failure.

Establishing limits should heighten the effectiveness of condition-monitoring tasks in detecting and preventing the failure.

Chapter 4
Temperature Measurements

Temperature measurement (i.e., through the use of sensors and thermography) helps to detect potential failures that are related to a temperature change in equipment. Measured temperature changes can indicate problems such as excessive mechanical friction (i.e., faulty bearings, inadequate lubrication), degraded heat transfer (i.e., fouling in a heat exchanger), or poor electrical connections (i.e., loose, corroded, or oxidised connections).

Temperature Measurement Techniques

Point Temperature Overview

Point temperature measurement refers to the temperature of an object using a device applied to its surface or the interior. A comparison of several characteristics of temperature sensors is provided in Table 4.1. The selection of an appropriate device is dependent on the purpose for obtaining the temperature; for example, when choosing the correct device, it is important to ascertain whether the temperature data collected is to be used for system (process) control or are the temperatures to be taken only periodically?

Installation Considerations

Temperature measurement accuracy can be affected by the placement of the device on or in the equipment, in addition to the presence of the power supply and/or signal wires. Below is a list of various sources of temperature measurement error

A. A. Olsen, *Equipment Conditioning Monitoring and Techniques*,
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Table 4.1 Comparison of temperature measurement techniques[1,2]

Device type	Output/sensitivity	Range °C	Accuracy ± °C	Robustness	Cost[(1)]
Thermocouple	40 µV/°C	−270 to 2300	1.5 to 2.2	High	Low
Resistance temperature detector (RTD)	0.385 Ω/°C (Pl) 0.806 Ω/°C (Ni) 0.039 Ω/°C (Cu)	−200 to 600	0.2 (Pt) 0.5 (Ni) 0.7 (Cu)	Medium	Medium (Pt) Low (Ni)
Thermistor	−70 to −1500 Ω/°C	−50 to 200	0.2	High	Medium
Gauges bimetallic magnetic	Displacement	−100 to 300	2	High	Low
Paint/stickers	Colour change	−30 to 1200	1 to 20	Medium	Low
Infrared thermography	Colour or grey scale image	−20 to 500 (1500 with filter)	Varies with camera	High	Medium–High

Note
[(1)]Low cost on the order of US $10’s; Medium cost on the Order of US $100’s; High cost on the Order of US $1000’s

[1] www.capgo.com/Resources/Temperature/.

[2] www.minco.com/uploadedFiles/Products/sensors_ts103a_full.pdf.

that should be taken into consideration when selecting, locating, and installing a temperature measurement testing device:

1. Device calibration errors are attributable to offset, scale, and linearity errors. Additionally, each of these errors can drift with time and temperature cycling. Hysteresis may be noticed with some devices such as bimetallic gauges.
2. Thermal gradients can occur especially when measuring fluids with poor thermal conductivity, such as air, most liquids and non-metallic solids (i.e. insulation and onboard processing systems).
3. Heat conduction in device leads can allow heat to flow into or out of the device body. Aim to use the thinnest wires practical for device installation. Place the wires in or adjacent to the object measured. Minimise the thermal gradient along the device wires by placing the wires at an angle to the gradient.
4. Radiation can contribute to errors in temperature measurement. To reduce this effect the device should be provided with a coating highly reflective of infrared radiation, shielded if possible, and in good thermal contact with the material or object being measured.
5. For those devices that require excitation power such as resistance temperature detectors (RTDs) and thermistors, device self-heating can occur. In some cases, the self-heating effect can be calibrated. In other cases, a lower excitation power can be applied, or consideration given to turning off excitation power between readings.
6. Thermal contact with the material or object being measured is vital. Parasitic thermal connections such as the device's lead conduction, direct contact with other materials, such as air, and radiant energy transfer can affect measurements.
7. The thermal time constant refers to the time it takes for a device to reach 63% of the way to the new temperature. This varies from device to device. If rapid temperature changes are anticipated, consider using a device with a low thermal time constant; improve thermal contact, reduce the device's thermal mass, and compensate the readings by applying an inverse matching filter.
8. Read-out errors can be reduced by calibrating the readout device against a known reference and calibrating the total device-readout system against a known reference.
9. Electrical noise or interference can induce errors. This can be reduced by use of shielded twisted pair cable, installing wire away from power cables, transformers, and other electrical machinery, installing low pass filters into the measuring device, and avoiding ground loops.
10. At times, condensation in the device and wiring can collect, particularly for installations cycling through the dew point. The device and wiring should be sealed. Evaporating condensation can lead to measurement errors.
11. Some devices such as film type RTDs can be affected by mechanical stress. The device should not be subject to deformation after installation. Avoid the use of adhesives in attaching devices. The differences in coefficient of linear

expansion will induce mechanical stress. Use devices less sensitive to stress, such as thermocouples.

12. Calibration can be applied so that the devices provide correct results.

Point Temperature Devices

The point temperature devices used by the maritime industry are discussed in the following paragraphs. A brief explanation is provided of the theory of operation along with the advantages and disadvantages for each device.

Thermocouple

A thermocouple is a device consisting of two wires of dissimilar metals joined near the measurement point (junction), a reference junction, and a measuring device. The output is a small voltage measured between the two wires which is converted to a temperature readout by an instrument.

- Typical P–F interval: provides a continuous output, data recorded several times per day.
- Skill level: no specific training needed.

The advantages of this technique include the following:

(1) Thermocouples can be rugged and immune to shock and vibration.
(2) They are useful over a wide temperature range.
(3) No excitation power or self-heating is required.
(4) They can be made very small.

The disadvantages of this technique include the following:

(1) They produce a low, non-linear output signal. This requires a sensitive and stable measuring device able to provide a reference junction compensation and linearisation.
(2) A higher level of care is required when determining installation location to minimise potential noise sources.
(3) The measuring device requires good noise rejection capability.

Resistance Temperature Detectors (RTDs)

A resistance temperature detector (RTD) consists of a stretched, fine wire coil supported and protected in a ceramic tube together with a measuring device. Film

RTDs consist of a thin metal film on a ceramic or glassy substrate. The electrical resistance of metals changes with temperature in a predictable and repeatable phenomenon. RTDs made from platinum are the most accurate, however nickel and copper RTDs are also available, though they tend to suffer from somewhat less accuracy. Refer to Table 4.1.

- Typical P–F interval: provides a continuous output, data recorded several times per day.
- Skill level: no specific training needed.

The advantages of this technique include the following:

(1) They are useful over a smaller temperature range.
(2) They produce a larger and more linear output signal when compared to thermocouples.

The disadvantages of this technique include the following:

(1) RTDs are less robust than thermocouples when installed in locations subject to shock and vibration.
(2) They produce a low, non-linear output signal. This requires a sensitive and stable measuring device able to provide a reference junction compensation and linearisation.
(3) A higher level of care is required when determining installation location to minimise potential noise sources.
(4) The measuring device requires good noise rejection capability.

Thermistor

Thermistor temperature sensors are manufactured from sintered metal oxide in a ceramic matrix that changes the electrical resistance when the temperature changes. Although these devices are sensitive to small temperature changes, they are highly non-linear. Thermistors are reliable, rugged and easy to use. It is reported there is a lack of interchangeability between manufacturers, which limits their application in industry. The typical P–F interval and skill level are the same as for thermocouples and RTDs.

Bimetallic and Magnetic Temperature Sensors

A bimetallic temperature sensor is a mechanical element constructed from two different metals bonded together. As the temperature changes, the two metals expand at different expansion rates causing movement at the free end of the bimetallic pair.

Magnetic temperature sensors refer to devices fitted with magnets to allow attachment of the temperature gauge to any ferrous metallic object for which its local temperature is desired.

- Typical P–F interval: provides a continuous output, data recorded several times per day (permanently installed) Weeks to months (magnetic—not permanently installed).
- Skill level: no specific training needed.

Temperature-Indicating Paint

This contact measurement technique is used to indicate the surface temperature of objects upon which a special paint has been applied. The paint will change colours as the surface temperature of the monitored object increases, and it retains the colour of the highest temperature the surface has encountered. This technique can be used to locate hot spots and insulation failures.

- Typical P–F interval: weeks to months.
- Skill level: no specific training needed.

The advantages of this technique include the following:

(1) The test is simple, and no special training is required to observe the results.
(2) The paint retains the colour of the highest temperature reached, providing a permanent record.

The disadvantages of this technique include the following:

(1) Once the paint colour changes, it does not change back to the original colour.
(2) The effective life of an application of the paint is usually one (1) or two (2) years, or until the paint changes colour.

Infrared Thermography

This non-contact technique uses infrared cameras to measure the temperature of heat-radiating surfaces within the line of sight of the camera. [***Note***: *infrared radiation is emitted from all objects above the temperature of absolute zero (−273 °C (−459 °F))*].

The camera measures temperature variations on the surface of the object being monitored and converts the temperature data into video or audio signals that can be displayed or recorded in a wide variety of formats for future analysis. This form of condition monitoring produces colour or grey-scale images that identifies temperature differences in the surface being examined. The sensitivity of the technique is affected by the reflectivity of the object being observed. The cameras are available for a wide range of temperature sensitivities and resolutions. This technique can be used to scan elevated, large, distant, or hot surfaces. Recommended limits vary for particular applications. However, ± one full colour band from that associated with the normal temperature range of operation is usually a satisfactory envelope. Figures 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7 and 4.8 show several types of equipment with thermograph images to demonstrate how this technique can be applied.

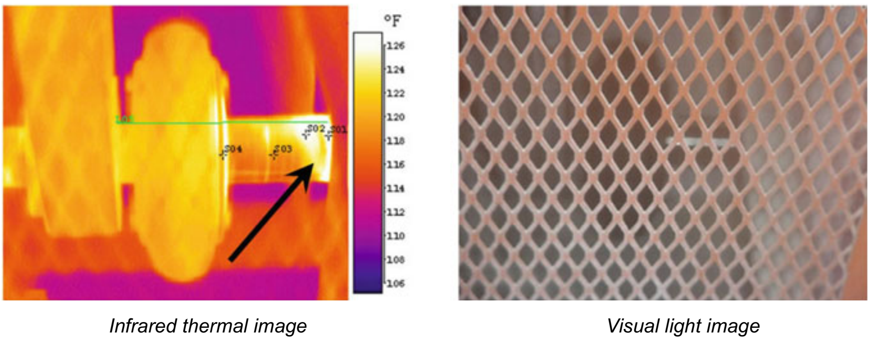

Fig. 4.1 Infrared thermograph—coupler alignment.[3] Photographs used with permission of Peterson predictive maintenance

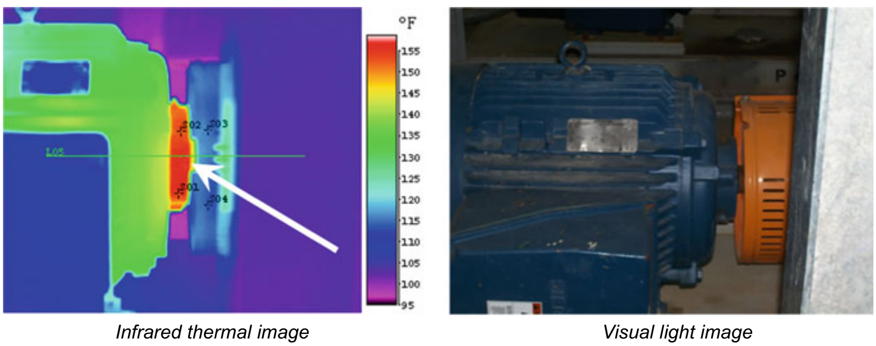

Fig. 4.2 Infrared thermograph—electric motor bearing.[4] Photographs used with permission of Peterson predictive maintenance

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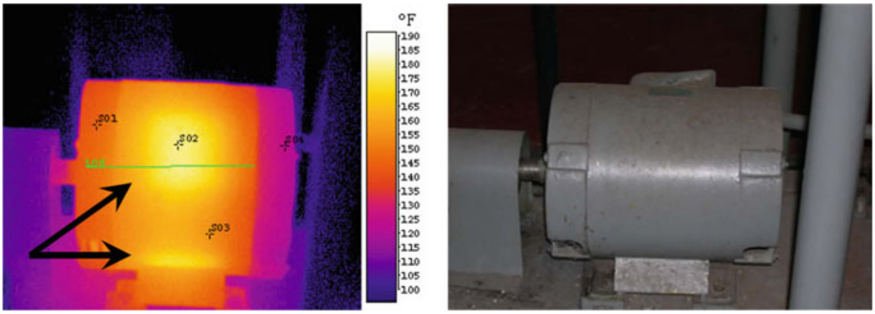
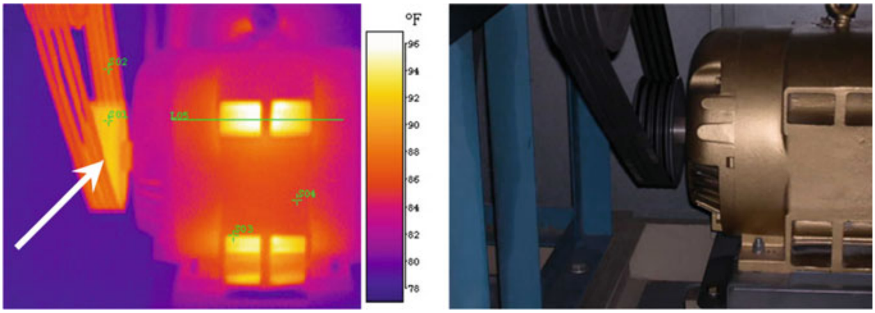
[3] http://petersonpredict.com/gallery.htm.

[4] http://petersonpredict.com/gallery.htm.



Infrared thermal image *Visual light image*

Fig. 4.3 Infrared thermograph—hot electric motor.[5] Photographs used with permission of Peterson predictive maintenance



Infrared thermal image *Visual light image*

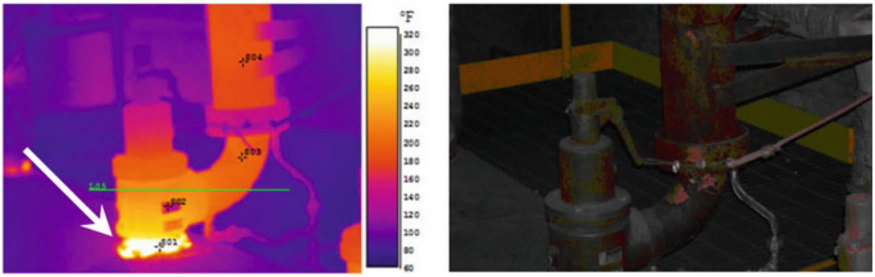
Fig. 4.4 Infrared thermograph—belts slipping.[6] Photographs used with permission of Peterson predictive maintenance

Note that the commentary provided with each figure is for illustrative purposes only. Interpretations of thermographs require an understanding of the equipment's design, function, operating characteristics and its operating context within the system. Infrared thermography should only be performed in a diagnostic function by trained, certified, and experienced personnel. Using thermography techniques to validate repairs or check general area temperatures is applicable but should be done with caution and with a full knowledge of the limitations. Infrared cameras utilise two ranges of the infrared band:

- Long wavelength (8–14 μm) for temperatures below the ambient temperature.
- Short wavelength (2–5 μm) for temperatures above the ambient temperature.

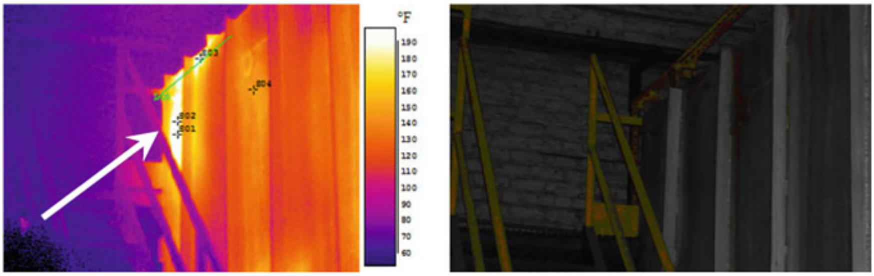
[5] http://petersonpredict.com/gallery.htm.

[6] http://petersonpredict.com/gallery.htm.



Infrared thermal image *Visual light image*

Fig. 4.5 Infrared thermograph—boiler valve.[7] Photographs used with permission of Peterson predictive maintenance



Infrared thermal image *Visual light image*

Fig. 4.6 Infrared thermograph—boiler refractory.[8] Photographs used with permission of Peterson predictive maintenance

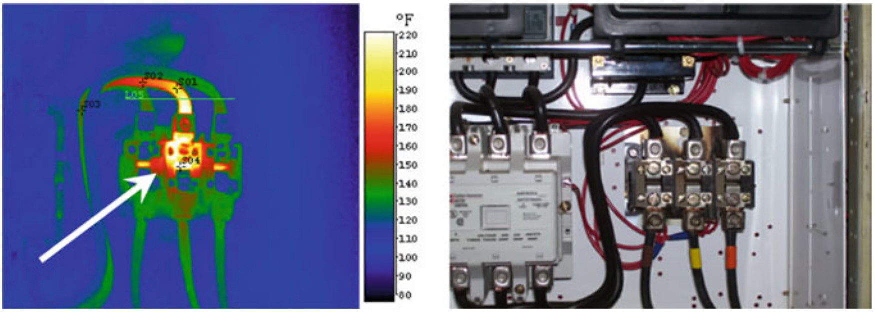
Infrared cameras have to be programmed with the emissivity factor of the object being evaluated. Emissivity is a measure of an object's ability to emit radiation. For example, the emissivity of a black body, which is a perfect emitter and absorber, is 1. The camera will only measure the true temperature if the emissivity correction is accurate. The thermal image quality can be affected by the following factors:

- The distance between the camera and the object.
- Excess humidity in the measured environment from rain or condensed steam, for example.
- Extraneous radiation emitted from surrounding objects or bright sunlight.
- The presence of insulation material between the camera and the object.
- The shape (such as angular relation to the camera) and surface condition.

When considering the performance of an infrared camera, the following characteristics are recommended for consideration:

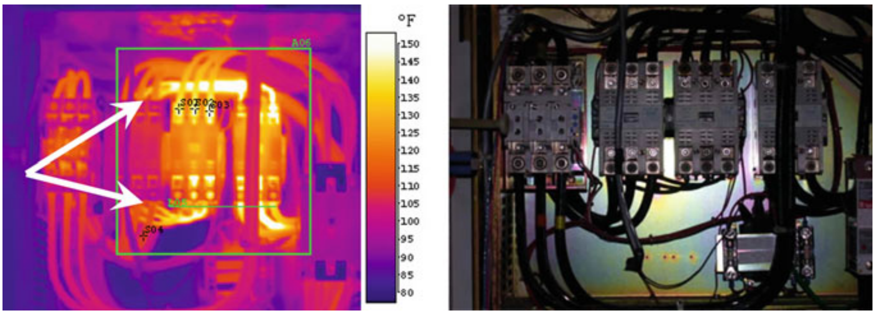
[7] http://petersonpredict.com/gallery.htm.

[8] http://petersonpredict.com/gallery.htm.



Infrared thermal image *Visual light image*

Fig. 4.7 Infrared thermograph—heater block.[9] Photographs used with permission of Peterson predictive maintenance



Infrared thermal image *Visual light image*

Fig. 4.8 Infrared thermograph—variable speed drive.[10] Photographs used with permission of Peterson predictive maintenance

- *Accuracy*. The measure of the difference between the true temperature and the measured temperature.
- *Environmental temperature*. The temperature range in which the camera may be safely operated.
- *Spatial resolution*. The measure of the fineness of detail directly proportional to the number of pixels representing the image.
- *Spot size ratio*. The ratio representing the maximum distance the camera can be from a target of a given size and still maintain temperature measurement accuracy.
- *Temperature range*. Temperature measurement from −40 °C (−40 °F) to 2000 °C (3632 °F) is possible with modern cameras. Many cameras are capable of −20 °C (−4 °F) to 500 °C (932 °F) and with the use of a filter extending the upper range to 1500 °C (2732 °F).

[9] http://petersonpredict.com/gallery.htm.

[10] http://petersonpredict.com/gallery.htm.

- *Thermal resolution.* The smallest difference in temperature possible to be expressed between two measurements.
- *Thermal sensitivity.* The smallest change in radiation level the instrument is capable of registering expressed in terms of temperature.

- Typical P–F interval: minutes* to months (* for permanently mounted cameras).
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) Cameras can be portable and are generally considered easy to operate.
(2) It provides dramatic images of the object's temperature profile.
(3) It provides non-contact testing (i.e., safe to measure energised electrical systems, can measure object without disturbing its temperature).
(4) The temperature of large surface areas can be observed quickly and continuously.
(5) A wide variety of equipment options is available, including various lenses and zoom-view capabilities.
(6) Test data can be recorded, printed, logged, or fed to other digital equipment.

The disadvantages of this technique include the following:

(1) Equipment costs are considered moderate to expensive. Price ranges from US $400 to US $10,000 depending on instrument sensitivity and various features.[11,12]
(2) Interpretation of the results requires training and experience.
(3) The cameras do not measure well through metal or glass housings or barriers.

Observation: observe the heat (white) to the right of this coupler. This high heat on a bearing beside a coupler usually indicates a slight misalignment in these shafts. This machine will continue to operate in this manner; but the life of these bearings will be severely shortened because of the additional loading placed on them.

Observation: observe the heat developed in this internal bearing. It is necessary to determine design bearing loading to properly assess these observations. These results may indicate either poor lubrication or a misalignment problem. If misalignment is significant, the coupling itself, being the most flexible component, will heat up first. Bearings should always be cooler than the centre of the motor that they are inside.

Observation: the thermograph for this electric motor indicates it may be running too hot. However, the thermograph does not indicate the ambient temperature, so as

[11] American Infrared.

[12] http://www.americaninfrared.com/Home.asp.

to determine if the motor temperatures indicated exceeds the specified 40 °C (104 °F) ambient for maximum heat rise. Once a motor reaches that maximum for any length of time, the life expectancy of the motor is cut in half. For every 10 °C (50 °F) above that maximum heat rise, the life expectancy is cut in half again. Overheating by 20 °C (68 °F) can take a 20-year expected service life motor and reduce it to a 5-year service life. Electric motors exceeding their ambient ratings may be overloaded or over-greased.

Observation: this is a common problem for belt driven equipment. The belts in this image are slipping a little, resulting in the pulley heating from the friction associated with slippage. If this condition is not corrected, the belts will become hotter, and the slip will increase resulting in belt failure.

Observation: this image shows a boiler pressure valve that is leaking at its connection to the boiler header. This is not only dangerous but very costly in lost steam production. This condition must be corrected quickly.

Observation: in the upper corner of this boiler there is an indication that the refractory is breaking down, allowing the heat to conduct through the outer casing. The efficiency of this boiler is reduced and continued operation may result in damage to the outer casing.

Observation: the B phase connection on this heater block appears to have a poor connection. Note how the heat dissipates the farther away from the connection. That usually indicates that the wire connection is loose or corroded.

Observation: this is a new installation, and several wire connections appear to be poor. This can happen often on new installations because the wire expands with the heat of the load and then cools when the load is off. The securing screw does not move so the wire becomes loose. All new installations should be checked after they have been in operation.

Chapter 5
Dynamic Monitoring

Dynamic monitoring (i.e., spectrum analysis, ultrasonic analysis) is a process which involves measuring and analysing the energy emitted from mechanical equipment in the form of waves (such as vibrations, pulses, and acoustic effects) over a period of time. The measured changes in the vibration characteristics from equipment over time can indicate problems such as wear, imbalance, misalignment, and damage. These measurements may vary from simple to complex measurements and analyses, and can be collected continuously or periodically.

General

Vibration Parameters

The characteristic describing the severity of vibration is referred to as the 'vibration amplitude'. This can be explained as the 'peak-to-peak level', the 'peak level', the 'average level', and the 'root mean square' (RMS) level. Figure 5.1 shows the relationship between these descriptions. The peak-to-peak amplitude is useful for describing the maximum amplitude of the vibratory displacement. This can be applied towards a machine component to determine maximum stress or mechanical clearance considerations. The peak velocity amplitude is useful for indicating the level of short duration shocks. However, it is worth noting the peak amplitude only indicates what maximum level has occurred and does not account for the time history of the wave. Though the average value (at times referred to as the 'rectified average value') takes account of the time history of the wave, it is considered of limited practical interest because there is no direct relationship with any useful physical quantity. The RMS amplitude is the most useful measure because it accounts for the time history of the wave and therefore provides an amplitude value directly related to the energy content.

A. A. Olsen, *Equipment Conditioning Monitoring and Techniques*,
https://doi.org/10.1007/978-3-031-57781-9_5

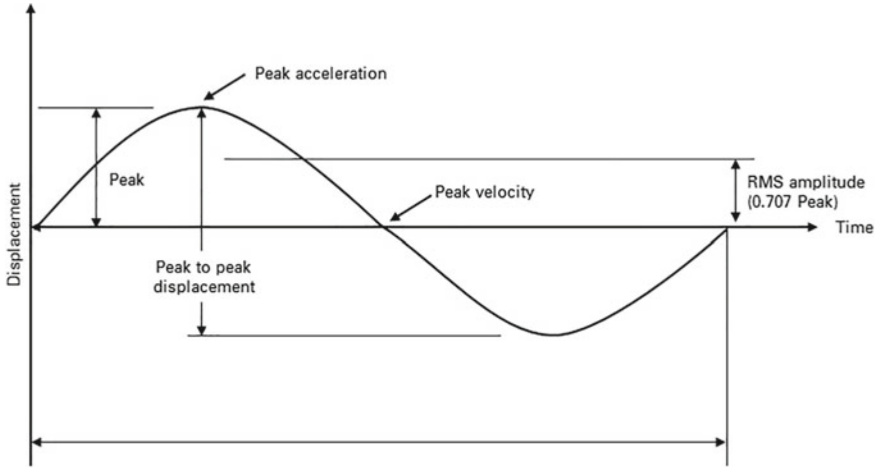


Fig. 5.1 Relationships for vibration amplitude for sinusoidal wave

Subsequrntly, the RMS amplitude can provide information concerning the destructiveness of the vibration. From this, the vibration parameters can be measured in terms of displacement, velocity, and acceleration. For a sinusoidal wave[1] the mathematical relationships between these three terms are shown in Table 5.1.

Baseline Measurement

Baseline data are collected with the equipment operating satisfactorily at its normal steady state load and speed with surrounding equipment also operating normally. For equipment designed for variable speed, load, or indeed both, it will be necessary to choose a test operating state known as the "standard test condition". Future data collected can then be compared to the baseline data for a determination of changes in the "health" of the equipment. If the equipment is new, or has been overhauled or repaired, time may be necessary to permit the equipment to "wear in" before baseline measurements are collected. Equipment that may have been operating for a long period of time, and is relatively healthy, may still have baseline data collected from previous analyses which can be used as a reference point to detect any future changes. Baseline data from machines that are identical can be averaged together to form a statistical baseline that may be more accurate than each machine having its own baseline.

[1] A sine wave or sinusoidal wave is the most natural representation of how many things in nature change state. For example, a sine wave shows how the amplitude of a variable (for instance, an audio sound) changes over time.

Table 5.1 Vibration parameter comparison for a sinusoidal wave[2,3]

Vibration parameter (peak)	Units	Displacement	Velocity	Acceleration	Frequency range[(4)]
Displacement (D_p) (amplitude)[(1)] Displacement (D_{p-p}) (peak to peak)	µm or mm (in)	D_p D_{p-p}	$0.159\frac{V_p}{f}$ $0.138\frac{V_p}{f}$	$0.0253\frac{A_p}{f^2}$ $0.0358\frac{A_{rms}}{f^2}$ $0.0507\frac{A_p}{f^2}$ $0.0716\frac{A_{rms}}{f^2}$	1 to < 200 Hz
Velocity (V_p) (peak)	mm/s (in/s)	$6.28 f D_p$ $3.14 f D_{p-p}$	V_p	$0.159\frac{A_p}{f}$ $0.225\frac{A_{rms}}{f}$	10 to < 2,000 Hz[(5)]
Acceleration (A_{rms})[(2,3)] Acceleration (A_p)	mm/s^2 (in/s^2)	$27.9 f^2 D_p$ $14.0 f^2 D_{p-p}$	$4.44 f V_p$ $6.28 f V_p$	A_{rms} A_p	1,000 to < 20,000 Hz[(5)]
Frequency (f)	$Hz(s^{-1})$				

Notes
[(1)] $D_{p-p} = 2\ D_p$
[(2)] $A_{rms} = 0.707\ A_p$
[(3)]To obtain acceleration in terms of gravity "g", divide result by 9,806.65 mm/s^2 (386.089 in/s^2)
[(4)]Based on *Introduction to Online machinery vibration textbook, vibration transducers, Overview*. Refer to footnote 2
[(5)]For range 1000–2000 Hz, measurements in both velocity and acceleration should be recorded

Measurement Data Collection

Dynamic monitoring systems may collect data that utilises permanent, semi-permanent, or portable measuring equipment. For permanently installed systems, the transducers, cabling, and associated signal processing and analysing equipment are permanently installed with data collected continuously or periodically. Typical installations are often found on complex machinery, critical machinery, or both (for example, systems used for dynamic positioning and the vessel's main propulsion). Reference may be made to Chap. 12 for guidance regarding the remote monitoring of data. With portable measuring equipment, machinery data are collected manually on a periodic basis on preselected permanently marked or affixed locations. Semi-permanent systems may also utilise portable measurement equipment, although the sensors are generally permanently mounted to account for safety concerns or access limitations. An example of this might be a motor-fan that is located inside a plenum,

[2] The International System of Units (SI), NIST Special Publication 330, 2001 Edition, page 29: http://physics.nist.gov/Document/sp330.pdf.

[3] Introduction to Online Machinery Vibration Textbook, DLI Engineering Corp: http://www.dliengineering.com/vibman.htm.

or an embedded pump inside a tank. With portable measuring systems, the collected data is transferred to other hardware (i.e., a PC) for analysis and data storage, and in some cases for distribution to a shoreside database. The portable approach is commonly used for equipment with longer P–F intervals and permanently installed systems which are used for equipment with shorter P–F intervals. It should be borne in mind that measurement results are frequently affected by the operating conditions for the examined machinery, or by nearby operating machinery, as well as the weather and environmental conditions experienced by the vessel. Therefore, successive measurements should be taken with the equipment and vessel being operated in a consistent manner insofar as is practicable. As an example, vibration measurements taken on equipment when the vessel is docked could be lower than measurements on the same equipment when the vessel is at sea. Moreover, vibration measurements on a generator with 30% rated load will likely be lower than measurements taken on the same generator operating at 80% load.

Data Collection Equipment Calibration

Vibration measurement displacement probes, velocity sensors, and accelerometers are typically provided with a detailed calibration certification letter from the manufacturer. If the equipment is stored and operated within its specified environmental limits (i.e., not subjected to excessive shocks, temperature, humidity, etc.), the literature should report minimal changes in characteristics over a given period of several years to the order of $< 2\%$. However, it is necessary to periodically check the calibration of the equipment to verify proper operation, particularly where the equipment has been repaired or operated near its specified environmental limits. The equipment manufacturer can provide guidance concerning calibration frequency and calibration equipment to conduct testing. A single or multi-frequency precision reference signal generator can be used to verify the signal processing equipment is measuring the frequency within its stated accuracy. If the measurements of the precision reference are outside the accuracy limits, then the equipment must be sent to the manufacturer for calibration, and repair, where necessary.

Vibration and Balancing Limits

For the various dynamic monitoring techniques listed in the section *Dynamic monitoring techniques* below, the operator must establish limit maximums at which maintenance intervention should take place to prevent the functional failure of the equipment or system. The limits listed in Tables 5.2 and 5.3 are provided for guidance only. Further additional guidance is provided in the section *Vibration limit resources* which are adapted from various ISO standards. These limits may be required to be adjusted based on the particular circumstances under which the equipment/system

Table 5.2 Criteria for overall condition rating [overall velocity—RMS (mm/s)][1,2,3,6]

Equipment[1]	Good	Fair	Low alarm[4,5,7]	High alarm[4,5,8]
Compressors				
Reciprocating	< 5.9	5.9–9.0	9.0	13.5
Rotary screw	< 4.9	4.9–7.6	7.6	11.7
Centrifugal with or without external reduction gear	< 3.6	3.6–7.6	7.6	11.4
Centrifugal—integral reduction gear (axial measurements)	< 3.6	3.6–7.6	7.6	11.4
Centrifugal—integral reduction gear (radial measurements)	< 2.7	2.7–4.5	4.5	6.7
Blowers				
Lobe—type rotary	< 5.4	5.4–8.1	8.1	12.1
Belt driven blower	< 4.9	4.9–7.6	7.6	11.7
General direct drive fan (with couplings)	< 4.5	4.5–6.7	6.7	9.9
Primary air fan	< 4.5	4.5–6.7	6.7	9.9
Large, forced draft fan	< 3.6	3.6–5.4	5.4	8.1
Large, induced draft fan	< 3.1	3.1–4.9	4.9	7.2
Shaft-mounted integral fan (extended motor shaft)	< 3.1	3.1–4.9	4.9	7.2
Vane—axial fan	< 2.7	2.7–4.5	4.5	6.7
Motor generator sets				
Belt driven	< 4.9	4.9–7.6	7.6	12.1
Direct coupled	< 3.6	3.6–5.4	5.4	8.1
Chillers				
Reciprocating	< 4.5	4.5–7.2	7.2	10.7
Centrifugal (open-air)—motor and compensating separate	< 3.6	3.6–5.4	5.4	8.1
Centrifugal (hermetic)—motor and impellers inside	< 2.7	2.7–4.0	4.0	6.3
Large turbine/generators				
3600 RPM turbine/ generator	< 3.1	3.1–4.9	4.9	7.2

(continued)

Table 5.2 (continued)

Equipment[1]	Good	Fair	Low alarm[4,5,7]	High alarm[4,5,8]
1800 RPM turbine/ generator	< 2.7	2.7–4.0	4.0	6.3
Centrifugal pumps				
Vertical pump (12'–20' height)	< 6.7	6.7–10.7	10.7	16.2
Vertical pump (8–12' height)	< 5.9	5.9–9.0	9.0	13.5
Vertical pump (5'–8' height)	< 4.5	4.5–7.2	7.2	10.7
Vertical pump (0'–5' height)	< 3.6	3.6–5.4	5.4	8.1
General purpose horizontal pump direct coupled	< 3.6	3.6–5.4	5.4	8.1
Boiler feed pump	< 3.6	3.6–5.4	5.4	8.1
Hydraulic pump	< 2.3	2.3–3.6	3.6	5.4

Notes
(1)Applicable for equipment speeds 600–60,000 RPM
(2)Measurements obtained through accelerometer or velocity pickup as close to bearing housing as practicable
(3)Equipment is not mounted on vibration isolators. For equipment mounted on vibration isolators, consider increasing Alarm Points 30–50% higher
(4)Set motor alarm the same as for equipment unless otherwise noted in the table
(5)For individual external reduction gears, set Alarm Points 25% higher than for the equipment they are attached to
(6)These criteria are based on applied experience from Technical Associates of Charlotte, Inc.
(7)Equipment requires maintenance to determine cause of high vibration and to repair
(8)Equipment failure is imminent and should be shut down so as to determine cause of high vibration and to repair

is operated. Vibration limits may be applied to an overall vibration reading or to a specific frequency band, which is usually related to some multiple or fraction of the equipment's operating speed (i.e., 0.5 times, 1.0, 2.0, 3.0, 10–20 times). Typically, an overall reading will be taken first and if the result is "high" then a more detailed analysis will be undertaken to pinpoint the cause of the high reading. For reference, balancing limit guidance from various ISO standards is provided in the section *Mechanical vibration, shock, and condition monitoring*. These limits may be required to be adjusted based on the particular circumstances under which the equipment/system is operated.

Table 5.3 Criteria for overall condition rating [overall velocity—peak (in/s)][1,2,3,6]

Equipment[1]	Good	Fair	Low alarm[4,5,7]	High alarm[4,5,8]
Compressors				
Reciprocating rotary screw	< 0.325	0.325–0.500	0.500	0.750
Centrifugal with or without external red. gear	< 0.275	0.275–0.425	0.425	0.650
Primary air fan	< 0.200	0.200–0.300	0.300	0.450
Centrifugal—integral reduction gear (axial measurement)	< 0.200	0.200–0.300	0.300	0.450
Centrifugal—integral reduction gear (radial measurement)	< 0.150	0.150–0.250	0.250	0.375
Blowers				
Lobe—type rotary	< 0.300	0.300–0.450	0.450	0.675
Belt driven blower	< 0.275	0.275–0.425	0.425	0.650
General direct drive fan (with couplings)	< 0.250	0.250–0.375	0.375	0.550
Primary air fan	< 0.250	0.250–0.375	0.375	0.550
Large, forced draft fan	< 0.200	0.200–0.300	0.300	0.450
Large, induced draft fan	< 0.175	0.175–0.275	0.275	0.400
Shaft-mounted integral fan (extended motor shaft)	< 0.175	0.175–0.275	0.275	0.400
Vane—axial fan	< 0.150	0.150–0.250	0.250	0.375
Motor generator sets				
Belt driven	< 0.275	0.275–0.425	0.425	0.675
Direct coupled	< 0.200	0.200–0.300	0.300	0.450
Chillers				
Reciprocating	< 0.250	0.250–0.400	0.400	0.600
Centrifugal (open-air)—motor and compensating separate	< 0.200	0.200–0.300	0.300	0.450
Centrifugal (hermetic)—motor and impellers inside	< 0.150	0.150–0.225	0.225	0.350
Large turbine/generators				
3600 RPM turbine/ generator	< 0.175	0.175–0.275	0.275	0.400
1800 RPM turbine/ generator	< 0.150	0.150–0.225	0.225	0.350

(continued)

Table 5.3 (continued)

Equipment[1]	Good	Fair	Low alarm[4,5,7]	High alarm[4,5,8]
Centrifugal pumps				
Vertical pump (12'–20' height)	< 0.375	0.375–0.600	0.600	0.900
Vertical pump (8'–12' height)	< 0.325	0.325–0.500	0.500	0.750
Vertical pump (5'–8' height)	< 0.250	0.250–0.400	0.400	0.600
Vertical pump (0'–5' height)	< 0.200	0.200–0.300	0.300	0.450
General purpose horizontal pump direct coupled	< 0.200	0.200–0.300	0.300	0.450
Boiler feed pump	< 0.200	0.200–0.300	0.300	0.450
Hydraulic pump	< 0.125	0.125–0.200	0.200	0.300

Notes
(1)Applicable for equipment speeds 600–60,000 RPM
(2)Measurements obtained through accelerometer or velocity pickup as close to bearing housing as practicable
(3)Equipment is not mounted on vibration isolators. For equipment mounted on vibration isolators, consider increasing Alarm Points 30–50% higher
(4)Set motor alarm the same as for equipment unless otherwise noted in the table
(5)For individual external reduction gears, set Alarm Points 25% higher than for the equipment they are attached to
(6)These criteria are based on applied experience from Technical Associates of Charlotte, Inc.
(7)Equipment requires maintenance to determine cause of high vibration and to repair
(8)Equipment failure is imminent and should be shut down so as to determine cause of high vibration and to repair

Dynamic Monitoring Techniques

Time Waveform Analysis

Time waveform analysis can identify a wide range of mechanical instabilities, including problems such as chipped, cracked, or broken teeth; misalignment; looseness; or eccentricity. This technique uses an oscilloscope connected to the output of a vibration analyser or real-time analyser. Through manipulation of the analyser output signal, the oscilloscope can generate a wave form representing vibration in the dynamic system being monitored. This technique can be used to monitor gearboxes, pumps, and roller bearings.

- Typical P–F interval: weeks to months.
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) The analysis is effective when looking for beats, pulses, instabilities, and a multitude of other conditions of interest.
(2) The technique often provides more information than frequency analysis.

The disadvantages of this technique include the following:

(1) The time waveforms can be complex and confusing.
(2) Testing can consume a considerable amount of time.
(3) Personnel need considerable practice and experience to interpret complex waveforms.
(4) False positive or negative diagnoses can result if test occurs under different operating state than baseline test.

Broad Band Vibration Analysis

By using broad band vibration analysis, it is possible to identify problems by comparing a device's current overall vibration level to its previously recorded overall vibration level and initial (baseline) level. This technique can be used to monitor changes in vibrational characteristics attributed to fatigue, wear, imbalance, misalignment, mechanical looseness, turbulence, etc., in shafts, gearboxes, belt drives, compressors, engines, roller bearings, journal bearings, electric motors, pumps, and turbines. This technique is be employed in conjunction with a *Time wave form* or *spectrum analysis* whenever a problem is suspected. For equipment enrolled in a preventative maintenance programme or RCM programme, when applying this technique, a spectrum analysis must also be conducted on an annual basis to verify the equipment condition. Some overall vibration criteria by equipment type(s) are listed in Tables 5.2 and 5.3. Note that the SI unit values are based on RMS while the US unit values are peak because of present practices and conventions. Conversion formulae are listed in Table 5.1.

- Typical P–F interval: weeks to months.
- Skill level: trained semi-skilled worker to take the readings.

The advantages of this technique include the following:

(1) The equipment is inexpensive, portable, and easy to use.
(2) Minimal vibration data are recorded.

(3) Effective in detecting a major imbalance of rotating equipment.
(4) Interpretation and assessments can be based on published criteria.

The disadvantages of this technique include the following:

(1) Random noise and vibration from nearby equipment do interfere with the tests.
(2) The broad band signal provides little information concerning nature of the fault.
(3) For the baseline (initial) reading, the highest spectral peak (usually $\times$ 1 rotation rate) contribute most to the broad band amplitude. Lower amplitude spectral peaks contribute little towards the overall broad band amplitude. Therefore, when these lower spectral peaks grow but still remain below $\times$ 1, the equipment may be in an advanced state of deterioration, and this will not be seen by an increase in the overall vibration.
(4) This technique lacks sensitivity and is difficult to set alarm levels.
(5) The ISO specification for overall measurement only considers vibration between 10 and 1000 Hz. Components in machinery can generate vibration outside this range, and therefore degradation of these components will not affect the overall vibration amplitude.
(6) False positive or negative diagnoses can result if test occurs under different operating state than the baseline test.

Spectrum Analysis

Spectrum analysis transforms data that are in the time domain to the frequency domain, using the fast Fourier transform algorithm, either by the data collector itself or through a host computer. After the data is collected and transformed (i.e., organised by frequency), it is compared to the baseline or expected values. Problems may then be identified by comparing the device's current spectra to its previous spectra or by using an averaged baseline spectra to detect changes in amplitude at selected frequencies. The literature that accompanies each device will include specific spectral patterns for each failure mode. Signals indicating damage, or injury to machinery components are not acceptable and should not be present in any vibration signature. This technique can be used to monitor shafts, gearboxes, belt drives, compressors, engines, roller bearings, journal bearings, electric motors, pumps, fans, turbines, purifiers, and just about any other rotating machinery.

- Typical P–F interval: weeks to months.
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) The equipment is portable and, if pre-programmed with a route, it is easy to use.
(2) Hardware is readily available that makes the sampling and mathematical transformation of the data rapid and accurate.
(3) Small performance changes in the equipment being tested can be identified by these tests.
(4) Characteristic frequencies and spectral patterns usually allow the analyst to isolate the problem to a component.

The disadvantages of this technique include the following:

(1) Random noise and vibrations of nearby equipment can interfere with the tests unless standard test conditions are followed.
(2) False positive or negative diagnoses can result if test occurs under different operating state than baseline test.
(3) Personnel need considerable practice and experience to interpret complex spectra and generate accurate and actionable diagnostic conclusions.

Shock Pulse Analysis

Shock pulse analysis is used to monitor roller bearings, impact tools, and internal combustion engine valves or components for which metal-to-metal contact is a source of wear. Measurements of the impact of the rollers are taken with the bearing raceway or any other rolling contact between equipment components producing a shock pulse reading that changes as the conditions within the bearing or component deteriorate. This technique uses a shock pulse analyser that is set up specifically for the type and size of bearings being tested and is fed a signal from an accelerometer placed on a bearing housing. It can identify issues such as lubricant problems, problems with oil seals and packings, incorrect bearing installation or alignment. The technique works off the principle that bearing damage can excite the bearing ring frequency, which then vibrates at a precise frequency, based on the bearing geometry. The frequencies are typically somewhere between 8 to 30 kHz.

This technique is reported to work well on bearings by themselves but suffers some serious limitation on bearings in gearboxes, pumps, motors, etc., due in part to the other "normal" frequencies (for example, blade pass frequency, gear mesh frequency, and slot pass frequency) that are common to most machines. Shock pulse analysis should be used in conjunction with other methods (i.e., spectrum analysis, time-waveform analysis, etc.) in the assessment of bearing damage. A limit of 30.0 dB is widely used in the maritime industry for the shock pulse aspects of bearing damage assessment. The placement of the shock pulse measurement probe should be in the load zone of the bearing, which may not be possible and could be dangerous due to the positioning of coupling guards and other rotating components on the machinery.

- Typical P–F interval: weeks to months.
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) Test equipment is portable and easy to operate.
(2) Test results are essentially immediate.
(3) The sensitivity of the test is generally considered better than conventional vibration analysis.

The disadvantages of this technique include the following:

(1) The test is limited to roller-type bearings.
(2) The test is highly dependent on accurate bearing size and speed information.
(3) Test results can be affected by equipment operating nearby or other components operating within the equipment as well as cavitation, new bearings, incorrect greasing, flow instabilities and gear noise.
(4) Locating the instrument probe near the loaded part of the bearing may be difficult.

Ultrasonic Analysis

When used as a dynamic monitoring technique, ultrasonic analysis helps to detect changes in sound patterns caused by problems such as wear, fatigue and the deterioration of moving parts. Ultrasound (i.e., high frequency sound waves that are above human perception from 20 to 100 kHz) is detected by an ultrasonic translator which is then converted to audible or visual output. This technique can be used to monitor bearing fatigue or wear.

- Typical P–F interval: highly variable.
- Skill level: trained skilled worker.

The advantages of this technique include the following:

(1) Tests are quick and easy to do.
(2) The location of the noise source can be pinpointed accurately.
(3) Equipment is portable, and monitoring can be done from a long range.

One disadvantage of this technique is that random noise and vibrations of nearby equipment can interfere with the tests.

Note: *refer to the section on* Ultrasonic leak detection *and* Ultrasonic flaw detection *in Chap. 8, for non-destructive condition monitoring techniques for additional capabilities.*

Other Techniques

There are numerous other dynamic monitoring techniques for measuring vibration. A selected listing of these additional techniques is shown in Table 5.4. In general, these techniques have been developed to address particular component failures in equipment or systems. The careful application of these other techniques is required for proper monitoring of failures.

Vibration Limits Resources

Listed below are selected references pertaining to condition monitoring and vibration measurement. ISO standards are listed by subcommittee topic for ease of reference. These standards are applicable to some of the techniques listed throughout this chapter. As these standards are periodically revised or superseded, users of a standard should check the ISO's website (www.iso.org) to verify whether the listed standard is current.

Mechanical Vibration, Shock, and Condition Monitoring

- ISO 1925: Mechanical vibration—balancing—vocabulary.
- ISO 1940: Mechanical vibration—balance quality requirements for rotors in a constant.
  Part 1: Specification and verification of balance tolerances; balance quality requirements of rigid rotors.
  Part 2: Balance errors.
- ISO 2017: Mechanical vibration and shock—resilient mounting systems.
  Part 1: Technical information to be exchanged for the application of isolation systems.
  Part 2: Technical information to be exchanged for the application of vibration isolation associated with railway systems.
- ISO 2041: Vibration and shock—vocabulary.

Table 5.4 Additional dynamic monitoring techniques[4]

Dynamic monitoring techniques	Conditions monitored	Typical P–F levels	Skill level	Advantages	Disadvantages
Acoustic emission	Plastic deformation and crack deformation caused by fatigue, stress, and wear	Weeks to months	Trained and experienced technician	Remote detection of flaws Can assess entire structures Measuring systems installation sets up quickly High sensitivity Detects active flaws At times can be used to forecast failure loads	Structure must be loaded Technique's activity dependent on materials Irrelevant electrical and mechanical noise can interfere with measurements Provides limited information for type of flaw Interpretation of results may be difficult
Amplitude	Bearing tones masked by noise, cracks in bearing races, eccentric or damaged gears, mechanical looseness	Weeks to months	Trained and experienced technician	Early detection for gearboxes and bearings problems can be identified Detects periodic impulses related to machine speed with high frequency signatures Works well in low-speed applications	High skill necessary to interpret results Difficult to implement on low-speed bearings because of short-term transient stress waves

(continued)

[4] Table developed from Moubray, John, Reliability-centred maintenance, 2nd Edition, Industrial Press Inc. 1997, Appendix 4.

Table 5.4 (continued)

Dynamic monitoring techniques	Conditions monitored	Typical P–F levels	Skill level	Advantages	Disadvantages
Cepstrum	Wear causing harmonics and sidebands in vibration spectra	Weeks to months	Trained and experienced technician	Can analyse harmonics and sidebands that overlap in complex machines Sidebands are easy to locate in the spectra of roller element bearings Can be performed with some expert system software	Skill and experience necessary to interpret harmonics and sidebands
Constant bandwidth analysis	Changes in vibrational characteristics attributed to fatigue, wear, imbalance, misalignment, mechanical looseness, turbulence, etc.	Weeks to months	Trained semi-skilled worker to take the reading experienced technician to interpret readings	Simple to use when measurement parameters are determined Good for large frequency ranges and detailed investigation at high frequencies Identifies multiple harmonics and side bands which occur at constant frequency intervals Portable equipment	Relatively long analysis time To interpret results, in-depth understanding of machine harmonics and side bands are required

(continued)

Table 5.4 (continued)

Dynamic monitoring techniques	Conditions monitored	Typical P–F levels	Skill level	Advantages	Disadvantages
Constant percentage bandwidth analysis	Shock and vibration	Weeks to months	Trained semi-skilled worker to take the reading Experienced technician to interpret readings	Analysis can be done in "real time" and is faster than FFT Spectra are very good for rapid fault detection Portable equipment	High skill required to interpret results
Frequency analysis	Changes in vibrational characteristics attributed to fatigue, wear, imbalance, misalignment, mechanical looseness, turbulence, etc.	Weeks to months	Trained and experienced technician	Portable equipment Expert software. systems can simplify data interpretation Use of waterfall plots can detect changes in machine condition at an early stage	Considerable practice and experience to interpret the results Spectra from impacts and random noise can look similar
Kurtosis	Shock pulses (restricted to bearings)	Weeks to months	Trained semi-skilled worker to take the reading	Applicable to materials with a hard surface Portable equipment Kurtosis value is related to the shape of the shock pulse but, not related to signal's amplitude Easy to use	Limited application and affected by impact noise from other sources Recommended to monitor the RMS value of the signal at the same time Will provide erroneous results for steadily increasing signals without shock pulses Considered to be too sensitive by some users

(continued)

Table 5.4 (continued)

Dynamic monitoring techniques	Conditions monitored	Typical P–F levels	Skill level	Advantages	Disadvantages
Octave band analysis	Changes in vibrational characteristics attributed to fatigue, wear, imbalance, misalignment, mechanical looseness, turbulence, etc.	Weeks to months	Trained semi-skilled worker to take the reading	Simple to use when measurement parameters are determined beforehand Portable equipment Good detection abilities using fractional octave filters	Limited information for diagnostic purposes Logarithmic frequency scale limits diagnostic ability Relatively long analysis time
Peak value (peak value) analysis	Stress waves caused by metal-to-metal impacts or metal tearing, stress cracking or scuffing, spalling and abrasive wear	Weeks to months	Trained and experienced technician	Reveals some faults that may have been undetected through other dynamic monitoring techniques Reported as more consistent than demodulation Outputs are independent of machine speeds Applicable to a broad range of frequencies from very low speeds shaft speeds to high speeds	High skill and experience required to interpret results
Proximity analysis	Misalignment, oil whirl, rubs, imbalance/bent shafts, resonance, reciprocating forces, eccentric pulleys and gears, etc.	Days to weeks	Trained and experienced technician	Determines specific problems Can be used for balancing Portable equipment Simple to use	P–F interval is short Relatively long analysis time Diagnostic ability limited

(continued)

Table 5.4 (continued)

Dynamic monitoring techniques	Conditions monitored	Typical P–F levels	Skill level	Advantages	Disadvantages
Real time analysis	Acoustic and vibrational signals Measurement and analysis of shock and transient signals	Weeks to months	Experienced engineer to operate equipment and interpret results	Analyses all frequency bands over entire analysis range simultaneously Instantaneous graphical display of analysed spectra Suited for analysis of short duration signals Recorded data can be electronically stored	Equipment may not be portable and is relatively expensive High level of skill Off-line analysis
Spike energy	Dry running pumps, cavitation, flow change, bearing loose fit, bearing wear causing metal-to-metal contact, surface flaws of gear teeth, high pressure steam or air flow, control valves noise, poor bearing lubrication	Weeks to months	Trained and experienced technician	Sensitive high frequency measurement parameters for detection of seal-less pump problems which are difficult to detect with velocity meters/accelerometers	High skill and experience required to interpret results
Time synchronous averaging analysis	Wear, fatigue, stress waves emitted as a result of metal-to-metal impacting, micro welding, etc. Also, looseness, rubs, and beats in systems	Weeks to months	Trained and experienced technician	Reduction gears—specifically for individual gears—can be analysed in detail Useful for analysing equipment with many components rotating at nearly the same speed	Not intended for unbalance or misalignment on normal speed machines or with roller element bearings as the bearing tones are not synchronous with the RPM and will be averaged out

- ISO 3719: Mechanical vibration—symbols for balancing machines and associated instrumentation.
- ISO 7475: Mechanical vibration—balancing machines—enclosures and other protective measures for the measuring station.
- ISO 8821: Mechanical vibration—balancing—shaft and fitment key convention.
- ISO 11342: Mechanical vibration—methods and criteria for the mechanical balancing of flexible rotors.
- ISO 21940: Mechanical vibration—rotor balancing.
  Part 21: Description and evaluation of balancing machines (revision of ISO 2953: (1999)).

Condition Monitoring and Diagnostics of Machines

- ISO 13372: Condition monitoring and diagnostics of machines—vocabulary.
- ISO 13374: Condition monitoring and diagnostics of machines—data processing, communication and presentation.
  Part 1: General guideline.
  Part 2: Data processing.
  Part 3: Communication.
- ISO 13379: Condition monitoring and diagnostics of machines—data interpretation and diagnostics techniques.
  Part 1: General guidelines.
- ISO 13380: Condition monitoring and diagnostics of machines—general guidelines on using performance parameters (WITHDRAWN: Replaced by ISO 17359:2011).
- ISO 13381-1: Condition monitoring and diagnostics of machines—prognostics.
  Part 1: General guidelines.
- ISO 17359: Condition monitoring and diagnostics of machines—general guidelines.
- ISO 18436: Condition monitoring and diagnostics of machines—requirements for qualification and assessment of personnel.
  Part 1: Requirements for certifying bodies and the assessment process.
  Part 2: Vibration condition monitoring and diagnostics.
  Part 3: Requirements for training bodies and the training process.
  Part 4: Field lubricant analysis.
  Part 5: Lubricant laboratory technical/analyst.
  Part 6: Acoustic emission.
  Part 7: Thermography.
- ISO 22096: Condition monitoring and diagnostics of machines—acoustic emission.

Measurement and Evaluation of Mechanical Vibration and Shock as Applied to Machines, Vehicles, and Structures

- ANSI S2.29-2003: Guidelines for the measurement and evaluation of vibration of machine shafts on shipboard machinery.
- ISO 4867: Code for the measurement and reporting of shipboard vibration data.
- ISO 4868: Code for the measurement and reporting of local vibration data of ship structures and equipment.
- ISO 6954: Mechanical vibration—guidelines for the measurement, reporting and evaluation of vibration with regard to habitability on passenger and merchant ships.
- ISO 7919: Mechanical vibration of non-reciprocating machines—measurements on rotating shafts and evaluation criteria.
  Part 1: General guidelines.
  Part 2: Land-based steam turbines and generators in excess of 50 MW with normal operating speeds of 1500 r/min, 1800 r/min, 3000 r/min and 3600 r/min.
  Part 3: Coupled industrial machines.
  Part 4: Gas turbine sets with fluid-film bearings.
  Part 5: Machine sets in hydraulic power generating and pumping plants.
- ISO 10055: Mechanical vibration—vibration testing requirements for shipboard equipment and machinery components.
- ISO 10816: Mechanical vibration—evaluation of machine vibration by measurements on non-rotating parts.
  Part 1: General guidelines.
  Part 3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15 000 r/min when measured in situ.
  Part 4: Gas turbine driven sets excluding aircraft derivatives.
  Part 5: Machine sets in hydraulic power generating and pumping plants.
  Part 6: Reciprocating machines with power ratings above 100 kW.
  Part 7: Rotodynamic pumps for industrial applications, including measurements on rotating shafts.
  Part 8: Reciprocating compressor systems.
- ISO 13373: Condition monitoring and diagnostics of machines—vibration condition monitoring.
  Part 1: General procedures.
  Part 2: Processing, analysis and presentation of vibration data.
- ISO 20283-3: Mechanical vibration—measurement of vibration on ships.
  Part 3: Pre-installation vibration measurement of shipboard equipment.
  Part 4 and 1:2014: Measurement and evaluation of vibration of the ship propulsion machinery.
- Society of Naval Architects and Marine Engineers T&R Bulletin 3–42, 1987, “Guidelines for the Use of Vibration Monitoring for Preventive Maintenance” (www.sname.org).

Use and Calibration of Vibration and Shock Measuring Instruments

- ISO 5347: Methods for the calibration of vibration and shock pick-ups.
  Part 5: Calibration by Earth's gravitation.
  Part 7: Primary calibration by centrifuge.
  Part 8: Primary calibration by dual centrifuge.
  Part 10: Primary calibration by high impact shocks.
  Part 11: Testing of transverse vibration sensitivity.
  Part 12: Testing of transverse shock sensitivity.
  Part 13: Testing of base strain sensitivity.
  Part 14: Resonance frequency testing of undamped accelerometers on a steel block.
  Part 15: Testing of acoustic sensitivity.
  Part 16: Testing of mounting torque sensitivity.
  Part 17: Testing of fixed temperature sensitivity.
  Part 18: Testing of transient temperature sensitivity.
  Part 19: Testing of magnetic field sensitivity.
  Part 22: Accelerometer resonance testing—general methods.
- ISO 5348: Mechanical vibration and shock—mechanical mounting of accelerometers.
- ISO 8042: Shock and vibration measurements—characteristics to be specified for seismic pick-ups.
- ISO 10817: Rotating shaft vibration measuring systems.
  Part 1: Relative and absolute sensing of radial vibration.
- ISO 16063: Methods for the calibration of vibration and shock transducers.
  Part 1: Basic concepts.
  Part 11: Primary vibration calibration by laser interferometry.
  Part 12: Cor 1:2008 Primary vibration calibration by the reciprocity method.
  Part 13: Primary shock calibration using laser interferometry.
  Part 15: Primary angular vibration calibration by laser interferometry.
  Part 16: Calibration by Earth's gravitation.
  Part 21: Cor 1:2009 Vibration calibration by comparison to a reference transducer.
  Part 22: Shock calibration by comparison to a reference transducer.
  Part 31: Testing of transverse vibration sensitivity.
  Part 41: Calibration of laser vibrometers.

Chapter 6
Oil Analysis

Oil analysis (i.e., Ferrography or particle counter testing) can be performed on many different types of oils including lubricating oil, hydraulic oil, and/or electrical insulation oils. It can indicate problems such as machine degradation (i.e., wear), oil contamination, improper oil consistency (i.e., incorrect or improper amount of additives), and oil deterioration. Oil analysis is most often based on regularly scheduled sampling. Regular sampling allows for the monitoring of the rate of change of the measured parameters. There are no absolute guidelines for the frequency of sampling, therefore the frequency of analysis should be based on the recommendations for determining intervals provided in Chap. 3, in addition to the manufacturer's recommendations, equipment criticality, risk factors and/or the equipment history.

Aspects of Oil Analysis

The tests described in this chapter monitor all or some of the following three aspects of oil:

- Lubricant condition; and/or
- Contaminants; and/or
- Machine wear.

Assessing lubricant condition provides information on whether the oil is fit for continued service, reconditioned, filtered, dewatered, or due to be replaced. Contaminants refers to foreign body particles or fluids from the surrounding environment and can include dirt, water, or process gases and liquids (i.e., combustion gases, cooling fluids). The presence of an increasing contamination rate should alert the operator to take appropriate remedial action to save the oil and avoid unnecessary machine wear. Machine wear refers to particles generated from its components. Detection and

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analysis of these particles can identify the worn components. This means maintenance decisions can be made to determine whether maintenance is to be undertaken to avoid machine failure. The quality of the oil sample directly affects the quality of the analysis results. Therefore, care must be taken to ensure the sample is representative of the oil that is in contact with the machinery components. Additionally, the receptacle into which the sample is to be drawn must be sterile so as to prohibit the inadvertent contamination of the oil sample. The accompanying list of information to be included with the sample should be agreed in advance between the sampling facility and the testing laboratory. The typical information to be provided for this purpose includes (but not limited to) the following:

- Company name.
- Vessel name.
- System name.
- Component name (if applicable).
- Sampling point with an identification number (if available).
- Date of sample extraction.
- Lubricant brand.
- System/component operating hours.
- Number of hours the oil was in service.

Not every sample must be sent onshore for laboratory testing. Some tests may be performed onboard through the use of portable sampling equipment. For those tests performed onshore, the samples will be sent to a laboratory in accordance with the safest transportation/mailing regulations. The expected receipt of the analysis data must be within time for the chief engineer to take action to prevent damage to the monitored equipment. Alternate condition monitoring techniques or the installation of local testing equipment would need to be considered if timely reports are not practical given the operational routines of both the vessel and the testing laboratory. To avoid complications arising from these situations, inline monitoring oil analysis technology is available. In these circumstances the sensor is installed and wired so as to transmit analysis data to an onboard terminal. Upon completion of the analysis, the vessel's chief engineer or their designated representative should then review the analysis report and determine whether maintenance actions are necessary. Any such reviews should be documented and stored onboard.

Oil Analysis Condition-Monitoring Techniques

A summary of relevant oil deterioration conditions and the suggested oil analysis condition-monitoring techniques necessary to detect these conditions is provided in Table 6.1. The table is organised in accordance with the condition to be monitored, its condition-monitoring subcategory, and the technique to be used. Additional information regarding the techniques and the necessary skill sets to execute them is provided throughout the following paragraphs (Table 6.2).

Table 6.1 Oil analysis and tribology

Condition	Condition monitoring subcategory	Technique(i)	Condition change	Cause	Action	Fixed/portable equipment	P-F interval	Skill
Contamination Corrosion Particles Fatigue Particles in hydraulic, lubricating oil Wear	Wear particle analysis	Ferrography	Increase	Typically carried out on clean systems such as hydraulic, turbine, or steering gear Increases in this are directly associated with filtration inefficiencies	Check filter by-pass system Check filter ratings Check dirt holing capacity of filter Check for sources of contamination	Portable	Portable	Months
		Particle counting				Portable	Portable	Weeks to months
Oil contamination Oil deterioration	Chemical analysis	Sediment (ISO 3734 Fuel Oils) (ASTM D-1698-03 Insulating Oils *[withdrawn]*) (ASTM D-1796 Fuel Oils)	Increase	Dirt, blow by products, wear debris, dirty fuel, lubricant degradation, poor oil/air filtration, worn seals	Check for blow-by Check wear debris Check filters Check seals	Portable	Weeks	Trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis
Presence of wear metals Oil additive depletion Oil contamination Corrosion	Chemical analysis	Atomic emission spectroscopy	Increase	Metallic elements can be found in additives or from wear debris/contaminants By comparing known metallurgy with elemental analyses certain component wear signatures may become apparent	Check filters Review historical data trend Consider microscopic evaluation, ferrography In extreme cases inspect Check for rust	Portable	Weeks to months	Trained semi-skilled worker to take the sample and experienced technician to perform and interpret the analysis

(continued)

Table 6.1 (continued)

Condition	Condition monitoring subcategory	Technique[(i)]	Condition change	Cause	Action	Fixed/portable equipment	P-F interval	Skill
Electrical insulating oil deterioration Electrical insulating oil oxidation Electrical insulating oil additive depletion	Chemical analysis	Infrared spectroscopy, including FT-IR (ASTM E2412)	Depends on property measured	Change in oil properties attributable to oil type, equipment application, voltage, power, construction, and service conditions	Check seals Verify suitability of oil for application and service	Portable	Weeks to months	Trained semi-skilled worker to take the sample and experienced technician to perform and interpret the analysis
Lubricating oil deterioration	Chemical analysis	Potentiometric Titration Total Acid Number (TAN)/Total Base Number (TBN) ISO 3771, (ASTM D664 [Acid Number] ASTM D4739, ASTM D2896, [Base Number])	High acid	Present if all alkalinity exhausted. Rarely present in non-engine oils	Change oil Select higher TBN oil Check oil tank for contamination	Portable	Weeks to months	Trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis

(continued)

Table 6.1 (continued)

Condition	Condition monitoring subcategory	Technique[i]	Condition change	Cause	Action	Fixed/portable equipment	P-F interval	Skill
Lubricating oil deterioration	Chemical analysis	Potentiometric Titration Total Acid Number (TAN)/Total Base Number (TBN) ISO 3771, (ASTM D664 [Acid Number] ASTM D4739, ASTM D2896, [Base Number])	Acid increase	The build-up of weak acids in a lubricating oil can be indicative of oxidation caused by high operating temperature, hot spots, low oil level, contamination, etc.	Check temperature of bulk fluid, and local component temperatures Differentials of more than 10 °C (50 °F) could indicate component problems Check level Change oil to more thermally stable grade			
Lubricating oil deterioration	Chemical analysis	Potentiometric Titration Total Acid Number (TAN)/Total Base Number (TBN) ISO 3771, (ASTM D664 [Acid Number] ASTM D4739, ASTM D2896, [Base Number])	Alkalinity decreases	Poor combustion, cold running, exhaust valve failure, high water contamination, increase in fuel sulphur level, low oil consumption	Check and obtain correct combustion Increase lube oil temperature by reducing cooling Check exhaust valves Remove water Check fuel for Sulphur content Consider higher Base Number lubricant			

(continued)

Table 6.1 (continued)

Condition	Condition monitoring subcategory	Technique[(i)]	Condition change	Cause	Action	Fixed/portable equipment	P-F interval	Skill
Lubricating oil deterioration	Chemical analysis	Potentiometric Titration Total Acid Number (TAN)/Total Base Number (TBN) ISO 3771, (ASTM D664 [Acid Number] ASTM D4739, ASTM D2896, [Base Number])	Alkalinity increase	Contamination with higher Base Number product (Most common in crosshead engines where make-up includes cylinder oil drains)	Monitor Base Number and resist using high BN drains as make-up			
Water contamination Salt	Chemical analysis	Crackle Test Karl Fischer titration test (ISO 6296:2000 (ASTM D1744-92	Presence of water	Saltwater coolant ingress Deck machinery guards ineffective	Check coolant system for leaks Replacement/repair or install shields to prevent water ingress	Portable	Weeks to months	Trained laboratory technician to perform and interpret the analysis

(continued)

Table 6.1 (continued)

Condition	Condition monitoring subcategory	Technique[i]	Condition change	Cause	Action	Fixed/portable equipment	P-F interval	Skill
Water contamination Fresh	Chemical analysis			Cooling ingress Purifier faulty Rain/wash water ingress Condensation (often in standby systems that are not fully utilised)	Check for coolant additives and seal efficiency Check purifier temperatures, flowrate, and efficiency Check tank tops and guttering Fit guards Check grade of lubricant vs. application Drain and refill small systems, purify others			
Water contamination	Chemical analysis	Moisture (ISO 12937-00 [Electrical] ASTM D 1533	Presence of water	Cooling ingress Condensation	Check for coolant additives and seal efficiency Drain and refill small systems, purify others	Portable	Days to weeks	Trained semi-skilled worker to take the sample Trained laboratory technician to perform and interpret the analysis

(continued)

Table 6.1 (continued)

Condition	Condition monitoring subcategory	Technique$^{(i)}$	Condition change	Cause	Action	Fixed/portable equipment	P-F interval	Skill
Flash point	Chemical analysis	Flash point (closed cup) (ASTM D56, ASTM D93, ISO 2719)	Decrease	Potential contamination with distillate fuel	Check fuel injectors	Portable	Days to weeks	Trained semi-skilled worker to take the sample. Trained laboratory technician to perform and interpret the analysis
Oil viscosity changes	Viscosity	Kinematic viscosity (ASTM D 445, DIN 51562)	Increase	Oil Oxidation Contamination by residual fuel Contamination with heavier grade oil Contamination with emulsified water	Check for blow-by, injectors, hot spots Check oil storage for contaminants Check cooling system for leaks	Portable	Weeks to months	Trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis
			Decrease	Contamination with distillate fuel Contamination with a lighter grade of oil	Check fuel injectors Check oil storage for contaminants			

(continued)

Table 6.1 (continued)

Condition	Condition monitoring subcategory	Technique[(i)]	Condition change	Cause	Action	Fixed/portable equipment	P-F interval	Skill
Insulating oil contamination	Dielectric strength	Dielectric Strength (ASTM D 117) (2)	Decrease	Contaminants in electrical equipment prior to filling with oil Water from cooling system or air humidity collects in the tank	Filter oil after filling equipment Filter oil continuously, install centrifuge or heat the oil to evaporate water particles, as practicable	Portable	Months	Electrician to take the sample and trained laboratory technician to perform and interpret the analysis
Biological activity in fluid	Microbial analysis (water or oil)	Determine quantity of micro-organisms (ASTM D6469)	Increase	Environmentally friendly additives in lubricants and fuels are not as tolerant to infestation by micro-organisms These can degrade the lubricant/fuel, block filters, increase corrosion and lead to system malfunctions	Check for water/oil contamination Treat with biocides Consider other preventative actions to minimise future infestations	Various depending on test specified	Weeks to months depending on test specified	Varies depending on test specified

Note
[(i)]Suggested Contaminants Alert Levels are for guidance only. Where "None" is indicated, no alert levels were found in the literature. For these contaminants, in the event of increasing levels consult with equipment manufacturer or fluid supplier, as appropriate, for guidance

Table 6.2 Contaminants in fluids

Oil test condition	Element symbol	Potential source/cause in fluid tested fuel oil (FO), lubricating oil (LO), and coolant water (CW)	Possible problems	Alert level (approximate) (ppm)[(i)]
Aluminium	Al	LO—pistons, journal bearings, shims, thrust washers, accessory casings, bearing cages of planetary gears, pumps, gears, gear lube pumps CW—from atmosphere contamination	LO—excessive wear, corrosion CW—leaks, corrosion	None
Antimony	Sb	LO—some bearing alloys and grease compounds	LO—excessive wear	None
Boron	B	CW—anti-corrosion in coolants	LO—coolant leaking into oil	None
Calcium	Ca	FO—generally indicates contamination by seawater detergent/dispersant additive	FO/LO—seawater contaminating FO/LO	None
Chromium	Cr	LO—wear plated components such as shafts, seals, piston rings, cylinder liners, bearing cages, and some bearings	LO—excessive wear	> 10
Copper	Cu	LO—journal bearings, thrust bearings, cam and rocker arm bearings, piston pin bushings, gears, valves, clutches, and turbocharger bearings Present in brass alloys in conjunction with zinc and bronze alloys in conjunction with tin CW—from oil cooler cores—cooling water in oil	LO/CW—excessive wear, corrosion, leaks	> 50
Iron	Fe	LO—cast cylinder liners, piston rings, pistons, camshafts, crankshafts, valve guides, antifriction bearing rollers and races, gears, shafts, lube pumps, and machinery structures, etc.	LO/CW—excessive wear, corrosion	> 30
Lead	Pb	LO—journal bearings and seals, anti-wear gear	LO—excessive wear	> 10

(continued)

Table 6.2 (continued)

Oil test condition	Element symbol	Potential source/cause in fluid tested fuel oil (FO), lubricating oil (LO), and coolant water (CW)	Possible problems	Alert level (approximate) (ppm)[(i)]
Magnesium	Mg	LO—turbine accessory casings, shafts, valves LO—detergent additive LO—coolant additive	LO—excessive wear	> 30
Manganese	Mn	LO—valves and blowers, at times found along with iron as a result of corrosion of steel	LO—excessive wear, corrosion	None
Molybdenum	Mo	LO—plated upper piston rings in some diesel engines LO—additive for EP gear oils	LO—excessive wear	None
Nickel	Ni	LO—valves, turbine blades, turbocharger cam plates, and bearings LO—additive for EP gear oils	LO—excessive wear	> 10
Phosphorus	P	LO—anti-wear additive, additive for EP Gear oils	LO—coolant leak in oil	None
Potassium	K	LO—contamination by seawater CW—coolant additive	LO—coolant leak in oil	None
Silicon	Si	LO—contamination by silica from induction systems or cleaning fluids LO—sand, dirt defoamant additive	LO/CW—contamination	> 40
Silver	Ag	LO—some bearings, solder	LO—excessive wear, corrosion	None
Sodium	Na	LO/CW—from anti-corrosion agents in engine cooling solutions LO/CW—detergent additive LO/CW—coolant additive	LO—usually as a result of a coolant leak	> 80
Tin	Sn	LO—bearing alloys, bearing cages, brass, oil seals and solder	LO—excessive wear	> 10
Titanium	Ti	LO—bearing hubs, turbine blades and compressor discs of gas turbines	LO—excessive wear	None

(continued)

Table 6.2 (continued)

Oil test condition	Element symbol	Potential source/cause in fluid tested fuel oil (FO), lubricating oil (LO), and coolant water (CW)	Possible problems	Alert level (approximate) (ppm)[(i)]
Vanadium	V	LO—turbine blades FO—catalyst fines from refining process	LO/FO—excessive wear	None
Zinc	Zn	LO—from brass components, neoprene seals, anti-wear additive	LO—excessive wear, corrosion	None

Note
[(i)]Suggested Contaminants Alert Levels are for guidance only. Where "None" is indicated, no alert levels were found in the literature. For these contaminants, in the event of increasing levels consult with equipment manufacturer or fluid supplier, as appropriate, for guidance

Atomic Emissions Spectroscopy

Atomic emissions spectroscopy identifies problems with contaminants and additives, and to a limited extent, corrosion and wear metals in lubrication and hydraulic oil samples. It achieves this by measuring the characteristic radiation emitted when samples are subjected to high energy and temperature conditions. The test results are shown in parts per million (ppm) for a wide variety of elements of interest including iron, aluminium, chromium, copper, lead, tin, nickel, and silver, as well as components of oil additives such as boron, zinc, phosphorus, and calcium. This technique can be used to analyse oil used in diesel and gasoline powered engines, compressors, transmissions, gearboxes, and hydraulic systems.

- Typical P-F interval: weeks to months.
- Skill level: trained semi-skilled worker to take the sample and experienced technician to perform and interpret the analysis.

The advantages of this technique include the following:

(1) The tests are fairly low cost.
(2) The tests yield rapid and accurate results.
(3) The range of elements identified is large.

The disadvantages of this technique include the following:

(1) The tests do not identify the wear process that contaminated the oil.
(2) Large particles (greater than 5 to 7 μm) in the sample may not be counted in the results.
(3) The level of additive elements is not necessarily indicative of additive package depletion.

(4) The element detected could be part of an additive or contaminant (e.g. Na, K, Silicon).

Dielectric Strength Tests

Dielectric strength tests are used to measure the insulating quality of electrical insulating oils. Potential quality deterioration is often caused by contamination or oil breakdown. The test is performed by subjecting the sample to an electrical stress at a given temperature by passing voltage through the sample. This technique can be used to test insulating oils in transformers, breakers and cables.

- Typical P-F interval: months.
- Skill level: electrician to take the sample and trained laboratory technician to perform and interpret the analysis.

The advantages of this technique include the following:

(1) The test is rapid and simple.
(2) The equipment does not need to be offline to perform the test.

The disadvantages of this technique include the following:

(1) The sampling technique can affect the test results.
(2) The test must be completed in the lab.
(3) The materials and equipment used to complete the test are hazardous.

Ferrography

Ferrography is a technique that identifies the density and size ratio of particles in oil or grease that are caused by problems such as wear, fatigue, corrosion or any combination thereof. A representative sample is diluted with a fixer solvent which is then passed over an inclined glass slide that is subjected to a magnetic field. The magnetic field provides for the separation of the ferrous particles (ferrous particles align with the magnetic field lines) and distributes them along the length of the slide (non-magnetic and non-metallic particles are distributed randomly along the slide). The total density of the particles and the ratio of large-to-small particles indicates the type and extent of wear. Analysis of the test sample is done through biochromatic, microscopic examination using both reflected and transmitted light sources (which may be used simultaneously). Green, red, and polarised filters are also used to distinguish the size, composition, shape, and texture of both the metallic and non-metallic particles. An electron microscope may also be employed during the analysis to determine particle shapes and to provide an indication of the cause of failure. This technique can be used to analyse the grease and oil used in diesel and gasoline engines, gas turbines, transmissions, gearboxes, compressors, and hydraulic systems. As ferrography is time-consuming and expensive, it is common practice to conduct a particle counter test first. If the wear particle count is above a predetermined maximum, it may be determined appropriate to conduct the ferrography analysis.

- Typical P-F interval: months.
- Skill level: trained semi-skilled worker to take the sample and experienced technician to perform and interpret the analysis.

The advantages of this technique include the following:

(1) Ferrography is more sensitive than many other tests at identifying early signs of wear.
(2) The slide provides a permanent record and allows the measurement of particle size and shape.

The disadvantages of this technique include the following:

(1) The test is time-consuming and requires expensive equipment.
(2) In-depth analysis requires an electron microscope.
(3) The primary target is limited to ferromagnetic particles.

Infrared and Ultraviolet Spectroscopy (ASTM E2412)

Infrared spectroscopy involves placing the oil sample in a beam of infrared light. Ultraviolet spectroscopy involves the application of ultraviolet light. Measurements are taken of the absorbent light energy at various specific wavelengths to determine the molecules present in the oil by measuring the relative absorption of energy through the stimulation of bonds in the molecules. Mathematical manipulations of the absorption data result in a "fingerprint" of the sample oil, which can then be compared to prior samples or standards by intelligent software. The analysis provides information about oil deterioration, oxidation, water contamination, or the presence and consistency of oil additives. This technique can be applied to turbine generators, sulphur hexafluoride or nitrogen sealed systems, transformer oils, and breakers. The levels of oxidation, nitration, sulphates, soot, and glycol (i.e., demonstrative of coolant leaks into oil sample) can therefore be quantified.

- Typical P-F interval: weeks to months.
- Skill level: trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis.

The advantages of this technique include the following:

(1) Data can be used to determine ASTM parameters.
(2) The test is highly repeatable.
(3) Data can be used to generate a total acid number (TAN) and a total base number (TBN) (Ultraviolet Spectroscopy).

The disadvantages of this technique include the following:

(1) Test equipment manufacturers are not consistent in the processing of data.
(2) Typically, the test is limited to about 1,000 ppm water contamination.
(3) Equipment is expensive and considerable experience and skill is necessary in analysing results.

Moisture Measurement

The presence of even small quantities of moisture in hydraulic and lubricating oils will lead to the degradation of lubricant base-stock and additives, the corrosion of component surfaces, and the acceleration of wear caused by the reduced fluid film strength. Moisture limits are typically determined by the system designer or the equipment manufacturer. There are three key tests that can be performed to measure the moisture content within the oil. These are briefly discussed below.

Crackle Test

The crackle test provides a simple field method to detect and quantify the presence of moisture in lubrication or hydraulic oil samples, which are placed on a hot plate. The recommended hot plate temperatures are between 150 and 205 °C (300–400 °F). When conducting multiple tests over time, the same hot plate temperature should be used to achieve consistent results. To conduct the test, the oil sample should be agitated to achieve a homogenous suspension of water in the oil. A drop of oil is placed on the hot plate. If no crackling or vapour bubbles are produced after a few seconds, this is presumptive that no free emulsified water is present in the sample. If very small bubbles or larger bubbles are produced, this may indicate the presence of water from as little as approximately 0.05–0.1% (500–1000 ppm) to 0.2% (2000 ppm). If higher moisture levels are present, bubbling and crackling may result. It should be noted this test cannot detect the presence of chemically dissolved water.

Karl Fischer Titration Test (ISO 6296:2000)

The Karl Fischer titration test measures moisture in lubrication or hydraulic oil samples. It is used as an indicator of a degraded oil condition by measuring the electrical current flow between two electrodes that are immersed in the sample solution. The recognised standard for this test is ISO 6296:2000 Petroleum products—Determination of water—Potentiometric Karl Fischer titration method. This method was developed by Karl Fischer and introduced in ASTM D1744-92 as the standard test method for the determination of water in liquid petroleum products. In 2000 the ASTM D1744-92 test standard was replaced by ISO 6296:2000. In this test, Karl Fischer reagent is metered into the sample until all the entrained water is reacted with the reagent. Results are reported in terms of ppm of water. This technique can be used to analyse enclosed oil systems such as engines, gearboxes, transmissions, compressors, hydraulic systems, turbines, and transformers.

- Typical P-F interval: days to weeks.
- Skill level: trained lab technician.

The advantages of this technique include the following:

(1) The test is accurate for small quantities of water contamination. Accuracy can be 0.001% (10 ppm). The test quantifies both emulsified and free water.
(2) The test can be completed fairly quickly.
(3) Results are repeatable.

The disadvantages of this technique include the following:

(1) Sulphur, acetones, and ketones in the oil sample can sometimes trigger erroneous readings.
(2) Considerable skill is required to interpret the results.
(3) Automated equipment is expensive and not portable.

Petroleum Products—Determination of Water—Coulometric Karl Fischer Titration Method (ISO 12937-00)

This test method is applied to insulating oils found in electrical equipment. A high-water content may make a dielectric insulating liquid unsuitable for some electrical applications due to the deterioration of properties such as dielectric breakdown voltage. Another similar recognised standard for this test is ASTM D1533 Standard test method for water in insulating liquids by coulometric Karl Fischer titration.

- Typical P-F interval: days to weeks.
- Skill level: trained lab technician.

The advantages of this technique include the following:

(1) The test is accurate for small quantities of water contamination. Accuracy can be 0.001% (10 ppm). The test quantifies both emulsified and free water.
(2) The test can be completed fairly quickly.
(3) Results are repeatable.

The disadvantages of this technique include the following:

(1) Sulphur, acetones, and ketones in the oil sample can sometimes trigger erroneous readings.
(2) Considerable skill is required to interpret the results.
(3) Automated equipment is expensive and not portable.

Kinematic Viscosity Test

The kinematic viscosity test provides an indication of oil deterioration over time or contamination of the oil by fuel or other oils. The test measures the fluid's resistance to flow under known pressure and temperature conditions and involves forcing a sample to flow through a capillary viscometer. Based on the test results, the dynamic viscosity of the oil sample can be calculated. Viscosity acceptance limits are typically in the order of ± one viscosity grade unless specified otherwise by the designer or equipment manufacturer. This technique can be used to test oil used in diesel/gasoline engines, turbines, transmissions, gearboxes, compressors, and hydraulic systems.

- Typical P-F interval: weeks to months.
- Skill level: trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis.

The advantages of this technique include the following:

(1) The test can be used for most lubricating oils, both transparent and opaque.
(2) Results are repeatable.

The disadvantages of this technique include the following:

(1) The test is not done in the field.
(2) Flammable solvents are used.

Microbial Analysis

Due to the proliferation of environmental regulations, modern lubricants utilise additives that are susceptible to infestation by microorganisms. These microorganisms can degrade the lubricant's properties causing blocked filters and increased corrosion in the equipment thereby leading to system malfunctions. Fuel oils are also susceptible to microorganisms, and with the use of bio-diesel class fuels, an increasing number of infestations have been noted. The guide, ASTM D6469-14 Standard guide for microbial contamination in fuels and fuel systems, provides instructions on how to take fuel or lubricating oil samples for testing to determine microorganisms content. The ASTM guide applies the testing method used in ASTM D5259 in which a membrane filter is used to trap the microorganisms, after which a presumptive count is carried out.

- Typical P-F interval: weeks to months.
- Skill level: trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis.

The one advantage of this technique is:

(1) The test may be completed onboard or in the lab.

The disadvantages of this technique include the following:

(1) Testing is limited to liquid fuels with kinematic viscosities $\leq 24\ mm^2\ s^{-1}$ at ambient temperature.
(2) Test results should not be interpreted as absolute values. Testing should be conducted over a period of time to establish trends in micro-organism growth and environmental factors such as temperature, humidity, and type of oil.
(3) A single testing procedure has to be utilised in order to obtain consistent results.

Particle Counter

Particle counter (also referred to as light extinction particle counter) testing monitors particles in both lubricating and hydraulic oils caused by problems such as corrosion, wear, fatigue, and the presence of foreign body contaminants. There are several types of particle-counting tests available. Two of the most common tests are the light extinction and light scattering particle counters. In a light extinction particle counter test, an incandescent light is shined on an object cell through which the oil sample fluid moves under controlled flow and volume conditions. A particle counter (i.e., photo diode) receives the light passing through the sample, and based on the amount of light blocked, indicates the number of particles in a predetermined size range. A direct reading of the ISO 4406 Hydraulic fluid power—fluids—method for coding the level of contamination by solid particles cleanliness value can be determined from this test. In a light scattering particle counter test, a laser light shines on an object cell through which the oil sample fluid moves under controlled flow and volume conditions. When opaque particles pass through the laser, the scattered light that is created is measured and translated into a particle count by the photo diode. A direct reading of the ISO cleanliness value can be determined from this test. This technique may be used to analyse the oil used in engines, compressors, transmissions, gearboxes, and hydraulic systems to evaluate the effectiveness of the filtration system. The cleanliness of oil for equipment with components operating with small clearances and high pressures is of utmost importance to ensure continued operation. When the particle count exceeds a predetermined maximum, ferrography testing may be used to determine the source of the particles.

- Typical P-F interval: weeks to months.
- Skill level: trained skilled worker.

The advantages of this technique include the following:

(1) Test results are quickly available.
(2) Tests are accurate and reproducible.
(3) Tests are more accurate than graded filtration.

The disadvantages of this technique include the following:

(1) The tests are dependent on good fluid conditions and are hampered by air bubbles, water contamination and translucent particles.
(2) The tests provide no information on the chemical nature of the contamination.
(3) Resolution is limited to particles greater than about 5 μm.

Potentiometric Titration—Total Acid Number (TAN) (ASTM D664) and Total Base Number (TBN) (ASTM D4739)

Potentiometric titration—TAN or TBN—may be used to determine the extent of breakdown in lubrication or hydraulic oil by determining the level of acidity or alkalinity in the oil sample. For determining acidity, the test involves mixing the oil sample with solvents and water and then measuring the change in the electrical conductivity as the mixture is titrated with potassium hydroxide (KOH). The more KOH a sample uses, the higher the acid number and oil deterioration. This technique can be used to test oil used in diesel/gasoline engines, gas turbines, transmissions, gearboxes, compressors, hydraulic systems, and transformers. ASTM D4739 was developed as an alternative to the TBN portion of ASTM D664.

- Typical P-F interval: weeks to months.
- Skill level: trained semi-skilled worker to take the sample and trained laboratory technician to perform and interpret the analysis.

The advantages of this technique include the following:

(1) The test can be performed on any colour oil.
(2) The test is considered accurate within 4% applying ASTM D664 and 15% applying ASTM D4739.

The disadvantages of this technique include the following:

(1) The test is limited to petroleum-based oils.
(2) Some of the chemicals used to complete the tests are hazardous.

Sediment Tests (ASTM D1698-03) (2008)

Sediment testing provides information about the sediment (i.e., inorganic sediment from contamination and organic sediment from oil deterioration or contamination) and soluble sludge from electrical insulating oil deterioration. It involves the use of a centrifuge to separate the sediment from the oil, with the sediment-free portion subject to further analysis (i.e., dilution, precipitation, and filtration) to measure the soluble sludge. The total sediment is then weighed and baked to remove the organics. This provides the organic/inorganic composition. This technique can be used to analyse petroleum-based insulating oils found in transformers, breakers, and cables.

- Typical P-F interval: weeks.
- Skill level: electrician to take the sample and trained laboratory technician to perform and interpret the analysis.

The advantages of this technique include the following:

(1) The test is quick and easy to complete.
(2) Samples can be taken with equipment online.

The disadvantages of this technique include the following:

(1) Only low-viscosity oil can be sampled, for example 5.7 to 13.0 cSt at 40 °C (32 °F).
(2) Testing must be performed in a laboratory.

Alternative Analysis Techniques

There are numerous other oil analysis techniques for the assessment of oil condition. Some of these techniques have been developed to assess particular conditions of the oil or involve the application of proprietary design test equipment. A number of additional techniques are listed in Table 6.3 for reference.

Additional Resources

Acronyms

Additional information may be sought from the following standards:

- ASTM—ASTM International, an acronym that formerly was American Society for Testing and Materials—http://www.astm.org/cgi-bin/SoftCart.exe/index.shtml?E+mystore
- IEEE—An acronym for the Institute of Electrical and Electronic Engineers, Inc.—http://www.ieee.org/portal/siteDIN
- ISO—International Organisation for Standardisation—http://www.iso.org/iso/home.htm
- NAS—National Aerospace Standard of the Aerospace Industries Association—http://www.aiaaerospace.org/

Standards Listing

- ASTM D56: Standard test method for flash point by tag closed cup tester.
- ASTM D93: Standard test methods for flash point by Pensky-Martens closed cup tester.
- ASTM D117: Standard guide for sampling, test methods, and specifications for electrical insulating oils of petroleum origin.
- ASTM D445: Standard test method for kinematic viscosity of transparent and opaque liquids (and calculation of dynamic viscosity).
- ASTM D664: Standard test method for acid number of petroleum products by potentiometric titration.
- ASTM D877: Standard Test method for dielectric breakdown voltage of insulating liquids using disk electrodes.
- ASTM D924: Standard test method for dissipation factor (or power factor) and relative permittivity (dielectric constant) of electrical insulating liquids.
- ASTM D971: Standard test method for interfacial tension of oil against water by the ring method.

Table 6.3 Additional oil analysis monitoring techniques

Oil analysis technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Acid and base number by colour-indicator titration	Acid and base number	Oils used in diesel and petrol engines, gas turbines (ASTM D974-12)	Weeks to months	The sample is dissolved into a mixture of toluene, isopropyl alcohol, and water and titrated with a solution Upon colour change of solution, acidity or alkalinity is determined	Trained semi-skilled worker to collect sample Trained and experienced technician to analyse	Test is reported to be accurate within a margin of error of 15%	Not suitable for measuring the basic constituents of many basic additive-type lubricating oils Dark-coloured oils cannot be analysed by this test method due to obscurity of the colour indicator
All-metal debris sensors	Ferrous and non-ferrous particles caused by wear and fatigue	Gas turbine bearings	Weeks to months	A sensor head consisting of two stimulus coils and one sensor coil wound around an insulating section of pipe When ferrous or nonferrous particles pass through the sensor head, the field created by the stimulus coils is disturbed and recorded by the sensor coil	Experienced skilled worker/ technician to trend results	Detects and quantifies both ferrous and non-ferrous wear metal particles Low chance of false indications Onboard sensors can store time domain plots of various damage modes for identification of wear sources in near real time	Unable to determine chemical composition and size of particles

(continued)

Table 6.3 (continued)

Oil analysis technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Blot testing	Wear metals, fatigue, and at times corrosion particles, sludge	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, and hydraulic systems	Days to weeks	One or two drops of oils are placed on blotting or filter paper and allowed to disperse for 24 h Dispersion pattern indicates size of particles, presence of sludge and oil dispersants	Trained semi-skilled worker to collect sample Trained and experienced technician to analyse	Cheap Easy to set up and use Provides a record Moderately accurate indicator of oil oxidation	24 h required for oil to blot High skill required to interpret results Only a rough indication of sludge level No identification for chemical composition of particles
Crackle test	Water in non-water-based oils	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, hydraulic systems, and transformers	Days to weeks	Several drops of oil are placed on a hot plate heated from 121 °C (250 °F) to 315 °C (600 °F) If water is present, it will quickly vapourise and make a crackling or popping sound which can be heard by a worker If the test is conducted with an audio data recorder the sound is converted to an electronic signal for analysis by data collector	Trained semi-skilled worker (human senses) Trained and experienced technician (audio detector)	Cheap, quick, and easy to use Effective and economical Good screening test to determine need for further moisture analysis Can detect moisture levels as low as 25 ppm and high as 10,000 ppm (audio detector)	Danger of handling oil around a hot surface Does not quantify the amount of water present Samples with entrained gas often result in false positive results Moisture under 300–500 ppm cannot be heard easily (human senses) Test is subjective from user to user (human senses)

(continued)

Table 6.3 (continued)

Oil analysis technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Direct reading ferrograph	Machine wear, fatigue, and corrosion particles	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, and hydraulic systems	Months	This device quantitatively measures the concentration of ferrous particles in a sample by precipitating the particles onto the bottom of a glass tube subjected to a strong magnetic field Fibre optic bundles direct light through the glass tube at two positions corresponding to the positions of large and small particles deposited by magnet Two readings are provided for the large and small particles (above and below 5 μm)	Trained semi-skilled technician	Compact, portable, online technique Less sensitive to fluid opacity and water contamination compared with other techniques	Measures only ferromagnetic particles Further analytical ferrographic analysis required when readings are high
Graded filtration	Particles in lubricating and hydraulic oil systems caused by wear, fatigue, corrosion, and contaminants	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, and hydraulic systems	Weeks to months	A sample of oil is diluted and passed through a series of standard filter disks Each disk is microscopically examined, and any particles found are counted manually A statistical distribution is created in the form of a graph Analysis determines whether wear is normal or not	Sampling: laboratory assistant Experienced laboratory technician or engineer to analyse results	Contaminants can be identified visually Inexpensive	Results can be subjective as operator has to determine visually the particle sizes Setting up and examining each filter disk sample takes several hours Specific skills to interpret test results Particle identification can be difficult

(continued)

Table 6.3 (continued)

Oil analysis technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
LIDAR (light detection and ranging)	Presence of particles in the atmosphere	Quality and dispersion of smoke	Variable depending on application	Single wavelength of light directed to area under investigation Quantity of particulate matter is determined by measuring backscatter Particulate location is determined by triangulation based on readings taken from two points	Experienced engineer	A remote sensing technique that can cover large areas	Expensive Requires high-level of skill
Light extinction particle counter	Particles in lubricating and hydraulic oil systems caused by wear, fatigue, corrosion, and contaminants	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, and hydraulic systems	Weeks to months	The counter consists of an incandescent light source, an object cell, and a photo detector The sample fluid passes through the object cell under controlled flow and volume conditions The number and size of particles is determined by amount of light blocked and reflected This information is compared with the ISO 4406 cleanliness value	Trained skilled worker to operate instrument	Faster than visual graded filtration Results available within minutes Test results accurate and reproducible	Unable to identify chemical composition of particles Lacks intensity and consistency of laser Accuracy affected by fluid opacity and quantity of translucent particles, air bubbles and water contamination Count and size dependent on orientation of long, thin, or unusually shaped particles in light beam Resolution limited to 5-micron particle range

(continued)

Table 6.3 (continued)

Oil analysis technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Light scattering particle counter	Particles in lubricating and hydraulic oil systems caused by wear, fatigue, corrosion, and contaminants	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, and hydraulic systems	Weeks to months	The counter consists of a laser light source, an object cell, and a photo diode The sample fluid passes through the object cell under controlled flow and volume conditions When opaque particles pass through the laser beam, the scattering of light is measured and translated into a particle count From this information a direct reading of the ISO 4406 cleanliness value is automatically determined	Trained skilled worker to operate instrument	Reliable performance in settings where conditions are controlled Resolution limited to 2 μm particle range Results available within minutes Test results quite accurate and reproducible	Unable to identify chemical composition of particles Accuracy affected by fluid opacity and quantity of translucent particles, air bubbles and water contamination Count and size dependent on orientation of long, thin, or unusually shaped particles in light beam Dilution often required for high particle concentrations to avoid coincidence error

(continued)

Table 6.3 (continued)

Oil analysis technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Magnetic chip Detection	Wear and fatigue	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, and hydraulic systems	Days to weeks	A magnetic plug is mounted in the circulating fluid of the lubricating system Metal particles adhere to the plug which is removed periodically for microscopic examination of the captured particles Type, quantity, and size of the particles can indicate condition of the equipment	Trained semi-skilled worker to collect sample Trained and experienced technician to analyse	Cheap Low powered microscope to analyse debris	Short P-F interval High skill to analyse sample
Mesh obscuration particle counter (pressure differential)	Particles in lubricating and hydraulic oil systems caused by wear, fatigue, corrosion, and contaminants	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, and hydraulic systems	Weeks to months	The device measures differential pressures across three high precision 5, 15, 25 µm screens, each with a known number of pores Particles are trapped on each mesh surface, increasing the pressure drop across the screen Sensors measure the pressure change which is converted to reflect the number of particles larger than the screen size This is converted to an ISO 4406 cleanliness value	Trained semi-skilled worker to operate instrument Trained and experienced technician to interpret results	No pre-sample preparation Particle counts calibrated per ISO 4406 Most oils can be analysed quickly Not affected by bubbles, emulsions, or dark coloured oils Portable equipment	Unable to identify chemical composition of particles Must use with a circulating oil system Equipment moderately expensive

(continued)

Table 6.3 (continued)

Oil analysis technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Patch test	Wear metals, fatigue, and at times corrosion particles, sludge	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, and hydraulic systems	Days to weeks	A vacuum is used to draw a standard volume of test fluid through a disc filter The degree of discolouration on the filter is compared with a filter colour rating scale and particle assessment scale to determine contamination level The filter is microscopically examined for type and size of particles	Trained and experienced skilled worker	Test results are dependable, repeatable, and sensitive to detect significant changes in cleanliness Good qualitative measure of contamination Portable equipment	Wear particles are counted using a microscope Results cannot be calibrated, resulting in high-levels of user-to-user variance
Pore-blockage (flow decay) technique	Particles in lubricating and hydraulic oil systems caused by wear, fatigue, corrosion, and contaminants	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, and hydraulic systems	Weeks to months	The test fluid is pressurised and allowed to flow through a selected precision calibration screen (5, 10, 15 μm) depending on oil viscosity in a sensor assembly Particles larger than the selected screen accumulate and restrict flow Smaller particles adhere to larger particles restricting flow further A flow-decay time curve is analysed by a computer and a corresponding particle size distribution is determined which is converted to an ISO 4406 cleanliness value	Trained skilled worker to operate instrument Trained and experienced technician to interpret results	No pre-sample preparation Particle counts calibrated per ISO 4406 Most oils can be analysed quickly Portable equipment	Unable to identify chemical composition of particles Must use with a circulating oil system Equipment moderately expensive

(continued)

Table 6.3 (continued)

Oil analysis technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Real time ferromagnetic sensor	Ferromagnetic particles caused by wear and fatigue	Oils used in diesel and petrol engines, gas turbines, transmissions, reduction gears, compressors, and hydraulic systems	Weeks to months	An analogue ferromagnetic sensor attracts metal particles with an electromagnet The collected particles on the sensor coil change its oscillating frequency The frequency is calibrated to indicate the mass of ferrous particles collected Particles are released into fluid after measurement is taken	Trained skilled worker to operate instrument	Online technique	Limited to collecting ferromagnetic particles only Indicates mass of ferromagnetic particles only
Rotating pressure vessel oxidation	Resistance of oil to oxidation	All lubricants	Quarterly to annually	The test fluid is placed in a sealed chamber filled with pure oxygen under pressure at an elevated temperature As the fluid absorb oxygen, pressure in the sealed chamber drops Test results are reported as the time (minutes) until the pressure drops to a predetermined level	Trained skilled worker to operate instrument	Determine remaining useful life of oil Standardised in ASTM D2272	Danger of handling oil under high pressure and elevated temperature Test is time consuming and expensive so equipment with copious quantities of oil is tested

(continued)

Table 6.3 (continued)

Oil analysis technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Linear sweep voltammetry	Resistance of oil to oxidation	All lubricants	Weekly to quarterly	The analyst adds a sample of oil to a vial containing an electrolyte solution The sample is voltammetrically analysed to determine the concentration of antioxidant by weight remaining The voltammeter exposes the sample and electrolytic solution to variable sweep voltage, which causes the additives to electrochemically oxidise The current passing between the electrodes is a function of the additive concentration A drop in the amplitude of current as compared to the baseline amplitude at the voltage of interest is indicative of depletion of the antioxidant additive	Trained skilled worker to operate instrument	Less expensive than rotating pressure vessel oxidation Standardised in ASTM D6810 and is to be further standardised in ASTM D6971	Not all testing laboratories have the equipment to conduct tests per the new ASTM standards

- ASTM D974: Standard test method for acid and base number by colour-indicator titration.
- ASTM D1698: Standard test method for sediments and soluble sludge in service-aged insulating oils (withdrawal balloted 2014).
- ASTM D1524: Standard test method for visual examination of used electrical insulating oils of petroleum origin in the field.
- ASTM D1533: Standard test method for water in insulating liquids by coulometric Karl Fischer titration.
- ASTM D1744: Standard test method for determination of water in liquid petroleum products by Karl Fischer reagent (withdrawn 2000).
- ASTM D1796: Standard test method for water and sediment in fuel oils by the centrifuge method (laboratory procedure).
- ASTM D1816: Standard Test method for dielectric breakdown voltage of insulating oils of petroleum origin using VDE electrodes.
- ASTM D2272: Standard test method for oxidation stability of steam turbine oils by rotating pressure vessel.
- ASTM D2896: Standard test method for base number of petroleum products by potentiometric perchloric acid titration.
- ASTM D4739: Standard test method for base number determination by potentiometric titration.
- ASTM D5259: Standard test method for isolation and enumeration of enterococci from water by the membrane filter procedure.
- ASTM D6469: Standard guide for microbial contamination in fuels and fuel systems.
- ASTM D6810: Standard test method for measurement of hindered phenolic antioxidant content in non-zinc turbine oils by linear sweep voltammetry.
- ASTM D6971: Test method for measurement of hindered phenolic and aromatic amine antioxidant content in non-zinc turbine oils by linear sweep voltammetry.
- ASTM E2412: Standard practice for condition monitoring of used lubricants by trend analysis using Fourier transform infrared (FT-IR) spectrometry.
- IEEE Standard 95: Recommended practice for insulation testing of AC electric machinery (2300 V and Above) with high direct voltage.
- ISO, 2719: Determination of flash point—Pensky-Martens closed cup method.
- ISO 3734: Petroleum products—determination of water and sediment in residual fuel oils—centrifuge method.
- ISO 3771: Petroleum products—determination of base number—perchloric acid potentiometric titration method.
- ISO 4406: Hydraulic fluid power—fluids—method for coding the level of contamination by solid particles.
- ISO 6618: Petroleum products and lubricants—determination of acid or base number—colour indicator titration method.
- ISO 7537: Petroleum products—determination of acid number—semi-micro colour-indicator titration method.

- ISO 12937: Petroleum products—determination of water—coulometric Karl Fischer titration method.
- NAS 1638: Cleanliness requirements of parts used in hydraulic systems (August 2001) (superseded by SAE AS 4059).
- SAE AS 4059, Revision E, (May 2005): Aerospace fluid power—cleanliness classification for hydraulic fluids. Society of Automotive Engineers.

Chapter 7
Corrosion Monitoring and Non-destructive Testing

Corrosion monitoring techniques (i.e., coupon testing and/or corrometer testing) can support equipment and machinery operators by providing early warning that damaging conditions exist which may result in a corrosion-induced failure. It is a technique which also examines the correlation of changes in process parameters and their effect on system corrosivity. It also works by determining the root cause(s) of a particular corrosion problem, and by identifying the rate controlling parameters such as pressure, temperature, pH, flow rate, etc. Moreover, the technique evaluates the effectiveness of corrosion control/prevention techniques in systems such as chemical inhibition and the determination of optimal applications. Finally, it also provides the operator and shoreside management with information relating to the maintenance requirements and ongoing condition of the equipment/system.

> It must be noted that corrosion monitoring as described in this chapter does not waive any of the close-up surveys required by the relevant Class Rules.

Corrosion Monitoring Techniques

Coupon Testing

Coupon testing involves placing sacrificial coupons, which are usually made from low-carbon steel or from a grade of material that duplicates the material of construction of the equipment being monitored, into the process so that the corrosion from the equipment can be monitored. The coupons are periodically measured and observed to understand the process environment's effect on these test pieces. Measurements

A. A. Olsen, *Equipment Conditioning Monitoring and Techniques*,
https://doi.org/10.1007/978-3-031-57781-9_7

include checking weight loss, dimensional changes, and the presence of physical damage such as pitting. This technique can be used to perform tests at process facilities, on underground/undersea structures, freshwater or seawater cooling systems, and electrical generating systems, and for cathodic protection monitoring, abrasive slurry transport, and atmospheric corrosion monitoring.

- Typical P-F interval: weeks.
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) Corrosion effects can be accurately predicted when the environment is consistent over the test period.
(2) Testing is relatively inexpensive and yields vivid examples of the corrosion to expect.

The disadvantages of this technique include the following:

(1) Testing can take a long time to complete.
(2) Determining the corrosion rates can take several weeks or months of testing.
(3) The tests involve working directly with the potentially hazardous corrosive material streams.

Corrometer (Electrical Resistance)

Corrometer testing helps measure the corrosion rate of equipment by monitoring the change in the electrical resistance of a sample material. As the sample material's cross-section is reduced due to corrosion, the electrical resistance of the sample will increase. The measured resistance change corresponds to the total metal loss and can be converted to a corrosion rate. This technique can be used to perform tests at process facilities, underground/undersea structures, seawater cooling systems, and electrical generating systems, and for cathodic protection monitoring, abrasive slurry transport and atmospheric corrosion monitoring.

- Typical P-F interval: months.
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) Portable equipment is available.
(2) Testing works in many environments.

(3) Testing can be made continuous with an online monitor.
(4) Results are easily converted to corrosion rates.

The disadvantages of this technique include the following:

(1) Portable equipment does not provide permanent records.
(2) The test does not typically indicate changes in the corrosion rate.

Potential Monitoring

Potential monitoring helps to identify the corrosion state (i.e., active or passive) of material by monitoring localised corrosion and indicating when active corrosion is in progress. This test takes advantage of the fact that metals in an active corrosion state (i.e., higher corrosion rate) have a different electrical potential than when they are in a passive corrosion state (i.e., lower corrosion rate). A voltmeter is used to measure the potential of the sample area. This technique can be used to perform monitoring at process facilities and electrical generating systems. The technique is best suited to stainless steel, nickel-based alloys, and titanium.

- Typical P-F interval: varies depending on material and rate of corrosion
- Skill level: trained and experienced technician

The advantages of this technique include the following:

(1) The test provides a rapid response to change.
(2) Localised corrosive effects are monitored.

The disadvantages of this technique include the following:

(1) The test does not provide corrosion rates.
(2) Testing is influenced by changes in temperature and acidity.

Ultrasonic Thickness and Gauging

Refer to the section on *Ultrasonic thickness gauging* for information relating to assessing corrosion. For further guidance, refer to Table 7.1 for condition monitoring.

Table 7.1 Condition monitoring

	Weld defects	Gas porosity	Surface shrinkage	Lack of weld penetration	Cracks, crack formation	Subsurface defects in plates, shafts, and casings	Intergranular corrosion	Corrosion fatigue	Stress corrosion	Hydrogen embrittlement	Surface cracks	Surface defects
X-ray radiography	•	•		•	•	•	•					
Liquid dye penetrants					•			•	•	•	•	•
Ultrasonic leak detection												
Ultrasonic flaw detection	•	•					•		•			
Magnetic particle detection			•		•			•	•	•		
Eddy current testing												
Acoustic emission					•							
Hydrostatic/ pneumatic testing												
Visual inspection (borescope)	•				•						•	

(continued)

Table 7.1 (continued)

	Embrittlement	Defects in pressure boundary, leaks	Metal thickness loss due to wear, corrosion, or both	Lamination	Corrosion	Strain	Surface and shallow subsurface defects, plates	Tube thickness	Wear	Fatigue	Plastic deformation	Stress	Oxide films
X-ray radiography													
Liquid dye penetrants	•												
Ultrasonic leak detection		•											
Ultrasonic flaw detection			•					•					
Magnetic particle detection				•			•		•	•			
Eddy current testing			•		•	•	•	•	•				
Acoustic emission									•	•	•	•	
Hydrostatic/pneumatic testing		•											
Visual inspection (borescope)									•	•			•

Non-destructive Testing Methods and Techniques

Non-destructive testing involves performing tests (i.e., x-ray's and ultrasonic analysis) that are non-invasive to the test subject. Many of these tests can be performed whilst the equipment is online. Moreover, these tests can be conducted on structural (stationary) components as well as the rotating/reciprocating components of equipment for which the condition monitoring is to be conducted. This section lists the most common non-destructive testing techniques used onboard vessels and offshore structures. Table 7.1 lists the recommended techniques covered in this section together with the common conditions to be monitored. In all cases, the Class approved Surveyor must be notified in advance for additional instructions where non-destructive testing techniques will be used to show compliance with Class Rules.

X-Ray Radiography

X-ray radiography helps identify surface and subsurface flaws caused by problems such as stress, corrosion, inclusions, fatigue, poor or incomplete welds, and trapped gases. In addition, it can be used to locate semiconductor faults and loose wires. The technique produces a radiograph by passing x-rays through opaque materials which produces an image of those materials on film, special screens, or a cathode ray tube. Typically, film exposed to x-rays captures a shadow-like image. The darkest parts are where the object is thinnest and absorbs the least radiation. This technique can be used to analyse welds, steel structures, plastic structures, and metallic wear components of engines, compressors, gearboxes, pumps, and shafts.

- Typical P-F interval: months.
- Skill level: trained and experienced technician to take the radiographs and trained and experienced technician or engineer to interpret the radiographs.

The advantages of this technique include the following:

(1) The technique examines the inside of test materials to locate hidden flaws (i.e., areas that cannot be seen externally).
(2) The technique provides a permanent record of the test.

The disadvantages of this technique include the following:

(1) Sometimes several views are required to locate the flaw.
(2) Safety with regard to radiation exposure is very important.
(3) The test is not very sensitive to crack-type flaws.
(4) Two-sided access is needed at times depending upon the location of the material to be examined.

(5) Special care must be taken to store or archive the information. New modern filmless methods are able to store the information electronically.

Liquid Dye Penetrants

The use of liquid dye penetrants can help detect surface discontinuities or cracks which have formed due to problems associated with fatigue, wear, surface shrinkage, and grinding. The technique involves applying liquid dye penetrant to a test surface and then allowing sufficient time for the dye to penetrate the surface. The next step is to remove excess penetrant from the surface. The surface is retreated with a developer that draws the penetrant to the surface revealing the location of imperfections. Liquid penetrants are categorised according to the type of dye (i.e., visible dye, fluorescent penetrant, and dual sensitivity penetrant) and the type of processing (i.e., water washable, post-emulsified, or solvent removed) required to remove the dye from the surface. Electrostatic fluorescent penetrant is another type in which opposing electrostatic polarity is induced between the test surface and the penetrant. This technique can be used to analyse ferrous and nonferrous materials such as welds, machined surfaces, steel structures, shafts, boilers, plastic structures, and compressor receivers.

- Typical P-F interval: days to months.
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) Visible dye penetrant kits are cheap (***note***: *fluorescent kits are more sensitive but significantly more expensive).*
(2) Surface problems on nonferrous materials can be detected.
(3) For electrostatic fluorescent penetrants, the polarity results in more complete and even disposition of penetrant and developer providing greater sensitivity.

The disadvantages of this technique include the following:

(1) Testing will not work on highly porous materials.
(2) It is important to prepare the surface of the equipment to be tested as this has to be very clean and free of any contaminants such as paint, oil, or grease. Good degreasers are useful for this task.
(3) The technique is not conducive to online testing.
(4) Only surface breaking flaws of greater than 1.9 μm are detectable.

(5) Experienced personnel are required to evaluate the results.
(6) A dark work area is required for fluorescent dye testing.

Ultrasonic Leak Detection

Ultrasonic analysis may be used to detect changes in sound patterns caused by problems such as leaks, wear, fatigue or deterioration. Ultrasound (i.e., high-frequency sound waves that are above human perception from 20 kHz to 100 kHz) is detected by an ultrasonic translator and converted to audible or visual output. This technique can be used to detect leaks in pressure/vacuum systems and underground pipes or tanks, and to detect static discharge.

- Typical P-F interval: highly variable.
- Skill level: trained skilled worker.

The advantages of this technique include the following:

(1) The tests are quick and easy to do.
(2) The location of the noise source can be pinpointed accurately.
(3) Equipment is portable and monitoring can be done from a long range.

The disadvantages of this technique include the following:

(1) Some tests can only be done under vacuum.
(2) The test requires a minimum of 0.7 bar (10 psi) differential pressure to be successful.
(3) In general, test results do not indicate the size of a leak.

Note: *Refer to* Chap. 5*, section Ultrasonic analysis as a dynamic analysis condition-monitoring technique for additional capabilities.*

Ultrasonic Flaw Detection

Ultrasonic testing uses the generation of high frequency sound vibrations in the frequency range of 25 kHz to 20 Mhz. This technique can measure to an accuracy of ± 0.025 mm. The technique helps to detect surface and subsurface discontinuities caused by problems such as fatigue, heat treatment, inclusions and lack of penetration, gas porosity welds, and general weld flaws. It can also measure material thickness in test subjects. The test involves using a transducer to apply an ultrasound vibration to a test object and then receiving the signal back and analysing it for changes that might indicate the presence of discontinuities in the test object. Ultrasonic techniques include pulse echo, transmission, resonance, and frequency modulation. This technique can be used to inspect ferrous and nonferrous welds, steel structures, boilers, tubes, plastic structures, and vessels/tanks. Most plastics absorb ultrasonic energy more quickly, so their thickness range is limited.

- Typical P-F interval: weeks to months.
- Skill level: trained and experienced technician.

One advantage of this technique is that the tests are applicable to a majority of materials. One disadvantage of this technique is that the test results must be interpreted by highly skilled technicians as it is difficult to clearly distinguish between types of flaws. ***Note***: *Refer to* Chap. 5*, section Ultrasonic analysis as a dynamic analysis condition-monitoring technique for additional capabilities.*

Ultrasonic Phased Array

The ultrasonic phased array probe consists of a transducer assembly with 16 to as many as 256 individual elements that can each be pulsed separately. A phased array system uses a computer-based instrument that is capable of driving the multi-element probe, receiving and digitising the returning echoes, and plotting the echo information in various formats. Unlike conventional flaw detectors, phased array systems can sweep a sound beam through a range of refracted angles or along a linear path, or dynamically focus at a number of different depths, thus increasing both flexibility and capability in inspection setups.

- Typical P-F interval: months.
- Skill level: trained and experienced technician.

Magnetic Particle Inspection

Magnetic particle inspection helps detect the location of surface/near-surface cracks and discontinuities that may be caused by problems such as fatigue, wear, inclusions, laminations, heat treatment, hydrogen embrittlement, seams, and corrosion. The technique involves magnetising the test piece and spraying it with a solution containing very fine iron particles. Discontinuities on the surface of the test piece will cause the iron particles to accumulate and form an indication of the flaw. The results are then interpreted. This technique can be used to analyse ferromagnetic metals such as vessels/tanks, welds, machined surfaces, shafts, steel structures, and boilers.

- Typical P-F interval: days to months.
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) The test is reliable.
(2) The test is sensitive.
(3) The test is widely used.

The disadvantages of this technique include the following:

(1) The test is limited to detecting surface imperfections.
(2) The test can only be conducted on ferrous based materials
(3) The test is time-consuming.
(4) The test is not applicable as an online test.

Eddy Current Testing

Eddy current testing helps detect surface and near subsurface flaws caused by problems such as wear, fatigue, and stress. It also helps detect dimensional changes that result from problems such as wear and strain. Furthermore, it can help determine material hardness. The technique involves applying high-frequency alternating current to conductive material test objects and inducing eddy currents around discontinuities. The electrical effects in the test part are amplified and shown on a cathode ray tube or a meter. This technique can be used to analyse boilers, heat exchangers, hydraulic tubes, and hoist ropes.

- Typical P-F interval: weeks.
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) The test can be performed on a wide variety of conductive materials.
(2) Permanent records can be made via data recorders.

The disadvantages of this technique include the following:

(1) Nonferrous materials respond poorly to the test.
(2) Sensitivity to surface roughness, it will be difficult to detect the flaw if the surface roughness is greater than the flaw's depth.
(3) Inspection of weld bead difficult.

Acoustic Emission

Acoustic emission testing monitors the plastic deformation crack formation and corrosion caused by problems such as fatigue, stress, and wear. The technique involves subjecting the test object to a stimulus such as temperature, pressure, chemical reaction (rust) loads and listening to the audible stress waves that are emitted by the structure. The test results can be displayed on a monitor as an x-y plot. This technique can be used to test vessel tanks, crane booms, other structures, pressure vessels, and pipelines.

- Typical P-F interval: weeks.
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) The test can be performed remotely in relation to the flaws and can cover the entire structure.
(2) Active flaws can be detected.
(3) Relative loads used in testing can be used to estimate failure loads in some cases.

The disadvantages of this technique include the following:

(1) The test object has to be loaded.
(2) Special software is needed to filter extraneous noise from mechanical rubbing, etc.
(3) Results analysis can be difficult without this software.

Note: *refer to* Chap. 5, Table 5.3 *as a dynamic monitoring technique for additional conditions monitored and capabilities.*

Hydrostatic and Pneumatic Testing

Hydrostatic testing helps detect breaches in a system's pressure boundaries caused by problems such as fatigue, stress, wear, and manufacturing or material defects. The testing process involves filling the system to be tested with water or operating fluid. The system is then sealed, with increasing pressure applied to approximately 1.5 times the system's operating limit or other predetermined test pressure. This is done for a defined time period in accordance with the Class Rules or Flag Administration regulations. For cases where the vessel's tank is tested, the test pressure is determined by the height of the tank's vent. The pressure is held for a defined time period while inspections and monitoring are conducted for visible leaks, a system pressure drop and makeup water/operating fluid additions. The principle of hydrostatic testing can also be used with compressed gases. This technique can be used to test components (i.e., tanks, vessels, pipelines) and completely assembled systems that contain pressurised fluids or gases.

- Typical P-F interval: days to weeks.
- Skill level: trained skilled worker.

One advantage of this technique is that the results are easy to interpret. The disadvantages of this technique include the following:

(1) The test has the potential to over-pressurise and damage the system.
(2) The test will not identify defects that have not penetrated a pressure boundary.
(3) The test is not applicable as an online test.
(4) When testing with a gas, care must be taken to prevent over-pressurisation and damage to the component or system being tested.
(5) Small leaks are difficult to detect.

Visual Inspection (Borescope)

Visual inspections using a borescope allow internal inspections of the surface of narrow tubes, bores, pipes, chambers of engines, pumps, turbines, compressors, boilers, etc. The inspection helps locate and orient surface cracks, oxide films, weld defects, corrosion, wear, and fatigue flaws. The borescope provides a system to channel light from an external light source to illuminate parts not easily visible to the naked eye and provides a means to magnify, photograph or do both tasks.

- Typical P-F interval: weeks.
- Skill level: trained and experienced technician.

The advantages of this technique include the following:

(1) The equipment provides excellent views.
(2) The parts being examined can be photographed and magnified.

The disadvantages of this technique include the following:

(1) The inspection is limited to surface conditions.
(2) The lens systems are often inflexible.
(3) Technicians can suffer eye fatigue during prolonged inspections.

Other Techniques

There are various other non-destructive condition monitoring techniques for assessment of structural integrity. These additional techniques are listed in Table 7.2.

Table 7.2 Additional non-destructive monitoring techniques

Non-destructive technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Cold light rigid probes	Surface cracks and orientation, oxide films, weld defects, corrosion, wear, and fatigue	Internal visual inspection of narrow tubes, bores and chambers of engines, pumps, turbines, compressors, boilers, condensers, etc.	Weeks to months depending on application	Light is channeled from external light source along a flexible fibre cable to the borescope Photographs or videos can be taken Images may be magnified Forward, fore-oblique, sideways, and retro-viewing versions of this equipment available Various lengths and diameters	Trained and experienced technician	Inspection performed with clear illumination Parts not visible to the naked eye can be photographed and magnified No heat is generated when the cold light is used Avoid dismantling equipment Pan-view fiberscopes' flexibility permit more detailed inspections	Inspection of surfaces only Resolution is limited Lens system is relatively inflexible Equipment generally cannot be operating when conducting testing

(continued)

Table 7.2 (continued)

Non-destructive technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Pan-view fiberscopes				Light is channelled through flexible fibre cable into the fiberscope which is provided with a remote-controlled prism in its tip to allow viewing forwards and sideways as desired Photographs or television viewers or videos may be recorded. An ultraviolet light may be utilised along with fluorescent penetrant to detect flaws			
Deep-probe endoscope		In addition to above listing, piping in boilers and heat exchangers		Various lengths to as much as 21 m (68 ft)			

(continued)

Table 7.2 (continued)

Non-destructive technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Electron fractography	Fatigue crack growth	Metallic components subjected to cyclic stresses	Dependent on application	The history of a fracture process is apparent from the fracture surface Through study of a replica of the fracture using an electron microscope, it is possible to determine the causes and circumstances of failure	Replica of the fracture surface—trained technician Analysis and reading—experienced engineer	Failures can be analysed with a high degree of certainty No damage to fracture surface when replica is made	Electron microscope is expensive Analysis of results requires high degree of specialisation Not an online technique Inaccessible components must be dismantled

(continued)

Table 7.2 (continued)

Non-destructive technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
Strippable magnetic film	Surface discontinuities and cracks caused by fatigue, wear, surface shrinkage, grinding, heat treatment, hydrogen embrittlement, laminations, corrosion fatigue, corrosion stress, laps, and seams	Ferromagnetic metals such as compressor receivers, welds, machined surfaces, shafts, gears, steel structures, boilers, etc.	Weeks to months	Self-curing silicon rubber solution with fine iron oxide particles is poured into/onto area under inspection and a magnetic field is induced The magnetic particles in the solution migrate to cracks under the influence of the magnetic field Upon curing, the rubber is removed Cracks will appear on the rubber as intense black lines Analysis of small cracks may require a microscope	Solution application—semi-skilled worker Evaluation—experienced technician	Can be used on areas with limited visual access Provides a record	Detects surface cracks only Not an online technique

(continued)

Table 7.2 (continued)

Non-destructive technique	Condition monitored	Applications (equipment)	Typical P-F level	Theory of operation	Personnel skill level	Advantages	Disadvantages
X-ray radiographic fluoroscopy	Refer to *X-ray radiography*			Component is placed between radiation source and fluorescent screen Transmitted radiation produces a fluorescence of varying intensity on the coated screen The brightness of the image is proportional to the intensity of the transmitted radiation		Quick results Scanning capability Widely applicable technique Relatively low cost	No record produced Image quality is generally inferior Less sensitive than X-ray radiography

Chapter 8
Electrical Testing

Electrical condition-monitoring techniques (i.e., high potential testing, power signature analysis) involve measuring changes in the system properties such as resistance, conductivity, dielectric strength, and potential. Some of the problems that these techniques help to detect are electrical insulation deterioration, broken motor rotor bars, and shorted motor stator lamination. For temperature measurements of electrical equipment applying infrared thermography, readers are referred to Chap. 4.

Electrical Testing and Monitoring Techniques

Megohmmeter Testing

A megohmmeter can be used to test the insulation resistance of electrical circuits. The technique involves applying a known voltage to electrical circuits of the equipment being tested and measuring the current flow. Based on the leakage current flowing to ground, the resistance of the equipment insulation can be determined.

- Typical P-F interval: months to years.
- Skill level: semi-skilled technician, technician or engineer.

One advantage of this technique is that it is simple and well understood. The one major disadvantage of this technique is that online testing cannot be conducted.

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High Potential Testing

High potential testing helps detect motor winding ground wall insulation deterioration. The test involves applying high direct current voltage to the stator windings in graduated steps to help determine the voltage at which nonlinearity in the test current or a drop in the insulation resistance occurs. If the insulation withstands a specified voltage, it is considered to be safe, and the motor can be returned to service. Also, trending the voltage at which the current becomes non-linear, or the resistance drops can be used to predict the remaining motor life. This technique can be applied to AC and DC motors.

- Typical P-F interval: months to years.
- Skill level: experienced electrical technician.

One advantage of this technique is that the test results usually correlate with surge comparison tests. The disadvantages of this technique include the following:

(1) Motors must be offline for testing.
(2) The test voltage is destructive to motor parts.
(3) The test is very intrusive to the motor.
(4) Testing equipment is extremely expensive.

Surge Testing

Surge testing helps identify insulation faults in induction/synchronous motors, DC armatures, synchronous field poles, and various coils or coil groups. The technique involves using a high-frequency transient surge applied to two separate but equal parts of a winding, and then the resulting reflected waveforms are compared on an oscilloscope. Normally, if no problems are detected at twice the operating voltage, plus 1000 V, the winding is considered good.

- Typical P-F interval: weeks to months.
- Skill level: trained and experienced test operator.

One advantage of this technique is that the test is portable. The disadvantages of this technique include the following:

(1) The test is complex and expensive.
(2) Careful repetition is required to determine the location or severity of a fault.

Power Signature Analysis

Power signature analysis can be used to detect motor problems such as broken rotor bars, broken/cracked end rings, flow or machine output restrictions, and machinery misalignment. This online technique involves monitoring current flow in one of the power leads at the motor control centre or starter. The electrical current variations identified in the test indicate changing machine operating conditions and can be trended over time. Also, line frequencies can be compared with motor frequencies to help detect various motor flaws. This technique can be used to analyse AC induction motors, synchronous motors, compressors, pumps, and motor-operated valves.

- Typical P-F interval: weeks to months.
- Skill level: experienced electrician to connect the test equipment and experienced technician to perform the analysis and interpret the data.

Advantages of this technique include the following:

(1) Testing is conducted online.
(2) Test readings can be taken remotely for large or high-speed machines.

The disadvantages of this technique include the following:

(1) Equipment is expensive.
(2) Analysis results are complex and often subjective.

Motor Circuit Analysis

A motor circuit analysis helps to yield a complete picture of motor conditions by performing a series of tests. The test applies voltage at the motor control centre power bus to measure resistance to ground, circuit resistance, capacitance to ground, inductance, rotor influence, DC bar-to-bar, and polarisation index/dielectric absorption. The results can identify changes in conductor path resistance caused by loose or corroded connections and loss of copper (turns) in the stator; phase-to-phase inductance caused by magnetic interaction between the stator and rotor; stator inductance affected by rotor position, rotor porosity and eccentricity, stator turn, coil and phase shorting; and winding cleanliness/resistance to ground. This technique can be used to analyse electric motors (i.e., DC, AC induction, synchronous, and wound rotor).

- Typical P-F interval: weeks to months.
- Skill level: experienced electrical technician to perform the test.

The advantages of this technique include the following:

(1) The test is low voltage and non-destructive.
(2) Tests can be performed at the motor control centre, which does not require motor disassembly.

The disadvantages of this technique include the following:

(1) The test cannot be performed online.
(2) Performing the test onboard is expensive.

Battery Impedance Testing

Battery impedance testing helps detect battery cell deterioration. The test involves injecting an AC signal between the battery posts and measuring the resulting voltage. The battery impedance is then calculated and compared to (1) the battery's last test and (2) the impedance of other batteries in the same bank. If the comparison results are outside a certain percentage, then this could indicate a cell problem or capacity loss.

- Typical P-F interval: weeks.
- Skill level: experienced electrical technician to perform the test.

The one major advantage of this technique is that the test can be performed online. The one major disadvantage of this technique is that the tests are lengthy for large batteries.

Chapter 9
Observation and Surveillance

Observation and surveillance condition-monitoring techniques (i.e., visual, audio, and touch inspections) are based on human sensory capabilities. They can serve as a supplement to other condition monitoring techniques. The use of human sensory techniques helps detect problems such as loose/worn parts, leaking equipment, poor electrical/pipe connections, steam leaks, pressure relief valve leaks, and surface roughness changes. Often the first indications of faults and problems can be identified through sight, smell and touch. Furthermore, human sensory techniques can be adopted as secondary confirmation.

Observation and Surveillance Techniques

Visual Inspection

Visual inspection practices are the oldest and most common corrective maintenance techniques employed in the maritime industry. Human observation helps identify a broad range of potential problems, including loose or worn parts; leaks of lubricating oils, hydraulic fluids and process liquids; missing parts; poor electrical or pipe connections; etc. Inspection standards are easy to establish and communicate to assigned personnel. Essentially, all machines and equipment in the maritime (and offshore/onshore industry) setting can be monitored with this technique. Also, human sensory-based inspections can verify the results from other corrective maintenance techniques. Readers may wish to refer to Chap. 7 for a description of visual inspections using a borescope.

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- Typical P-F interval: varies widely.
- Skill level: trained semi-skilled workers are normally required.

One advantage of this technique is that the versatility of human observation combined with experience can identify an extremely wide range of problem types. One disadvantage of this technique is that unless inspections are scheduled and recorded, observers can become so familiar with their surroundings that changes of interest go unnoticed.

Audio Inspections

Audio inspection practices are common corrective maintenance techniques employed in the maritime industry. The monitoring of machinery and equipment by listening to it operate helps identify a broad range of potential problems, including worn high-friction bearings, steam leaks, pressure relief valve leaks or discharges, coupling leaks, excessive loading on pumps, poor mechanical equipment alignment, etc. Humans are particularly sensitive to new or changed sounds and are easily taught to report and investigate unusual sounds. This technique is often a supplemental inspection to visual inspections. The inspection can be enhanced through the use of directional microphones. Also, human sensory-based inspections can verify the results from other corrective maintenance techniques.

- Typical P-F interval: varies widely.
- Skill level: trained semi-skilled workers are normally required.

One advantage of this technique is that the versatility of human hearing combined with experience can identify an extremely wide range of problem sounds. Disadvantages of this technique include the following:

(1) The inspections must be assigned so that the inspectors gain sufficient experience to be able to detect new or changed noises.
(2) In high noise environments auditory inspections can be difficult or impossible to perform.

Touch Inspections

Using touch as an inspection technique can be extremely useful. Heat, scaling, and roughness changes can all be detected by touch. Human touch is extremely sensitive and able to differentiate surface finish differences not discernible by eye. This technique is often a supplemental inspection to visual inspections. Also, human sensory-based inspections can verify the results from other corrective maintenance techniques.

- Typical P-F interval: varies widely.
- Skill level: trained semi-skilled workers are normally required.

One advantage of this technique is that the hands and fingers are extremely sensitive to surface finish and to heat. One disadvantage of this technique is that the inspectors can be burned by touching hot objects and can be injured or shocked by touching operating equipment.

Process Variable and Performance Trending

Monitoring equipment and systems process variables and performance is a condition-monitoring technique that predicts problems by monitoring changes in any combination of these variables such as pressure, temperature, flow rate, electrical power consumption, fuel consumption, and equipment/system power production or capacity. By collecting time associated with the operation, unavailability and maintenance, and costs associated with labour for operation, maintenance, repair, and spare parts procurement and storage, for the equipment and systems additional performance measures may be assessed and trended. This data can be used to assess additional aspects of performance such as specific fuel oil consumption, mechanical or thermal efficiency of targeted equipment, equipment availability, system availability and revenue generation and costs associated with maintenance and repair and investments.

Data Collection

The information to be analysed and trended is initially identified, with the corresponding variables identified thereafter. One example relating to condition monitoring is estimating the remaining time to a component failure based on extrapolating the condition monitoring variables over time. The extrapolation is modelled as a mathematical function which is chosen as a result of prior experience or through the application of an appropriate regression analysis method. Another example is a relative ranking analysis which can be developed for those items having the highest operational cost or cost impact to a system. A number of measurement parameters can be considered in developing this ranking, including:

- Maintenance man-hours.
- Maintenance man-hours per operating hour.
- Equipment downtime.
- Maintenance actions per operating hour.
- Cost of lost production.
- Cost of repair.
- Measurement parameters listed above associated with unplanned maintenance (emergency maintenance).

The identification of the highest contributors entails detailed data analyses and communication with operators and maintainers. This analysis is limited to identifying only the worst performing items, and not those in the process of degradation. Some items by their very nature and use may appear at the top of the list. Further analyses of these items may prove to be beneficial, applying other analysis techniques. The data to collect are dependent upon the system attributes desired to be measured and trended. Some organisations desire to evaluate all data produced initially but, these efforts quickly overwhelm the reviewers with the resulting inability to trend any meaningful information.

Performance Techniques

Performance Trending

Performance trending as a corrective maintenance technique involves collecting and analysing data on some or all of the variables listed in this chapter for the equipment/ system of interest. Data are often collected by operations personnel for other reasons (i.e., energy management, maintenance program effectiveness) and may already be available for analysis. Performance trend data are often coupled with other test results to confirm the identification of problems (i.e., equipment degradation, performance deterioration). Monitoring the performance indicators over a long period of time can provide indications of improper maintenance or poor operations practices. Virtually all industrial machines can be monitored in this fashion, and targets for data collection include diesel and gasoline engines, pumps, motors, compressors, etc. Test data can also be used to optimise performance. In addition, most of the computer control equipment (i.e., distributed control systems, programmable logic controllers) has data analysis and alarming features that can be used to trend equipment performance.

- Typical P-F interval: varies widely (hourly, daily, weekly to monthly).
- Skill level: trained semi-skilled workers are normally required.

One advantage of this technique is that the data are often already collected. One disadvantage of this technique is that baseline data may not exist, which necessitates longer time periods to develop trends.

Chapter 10
Engine and System Performance Monitoring

Various diesel engine manufacturers and third-party service providers offer engine monitoring and auxiliary system monitoring services which utilise proprietary instrumentation and diagnostic software. In response, a number of vessel owners and operators have developed similar monitoring programmes for their fleets. The common goals for these monitoring programmes are to:

- Optimise engine performance so as to improve fuel efficiency, emissions, or both.
- Overhaul equipment when the components need to be replaced prior to failure.
- Improve diesel engine or system availability by reducing planned and unplanned downtime.
- Optimise the storage of spare parts.

The complexities of performance monitoring and diagnostics programmes can be transitioned into a simple standardised process for data collection and reporting processes. This solution facilitates automated data collection and the analysis required to meet the demands of both efficient operations and system monitoring. A simplified process is illustrated in Fig. 10.1. The effort of direct sensor data collection, analysing the data to create information and then transferring this information into actionable vessel and fleet level intelligence requires a new data management process. The combined solution defines these steps and creates a means to manage the newly defined process. By identifying and understanding the key standards and implementation details, the process of integrating ships systems and utilising such data to improve system availability can better be explained.

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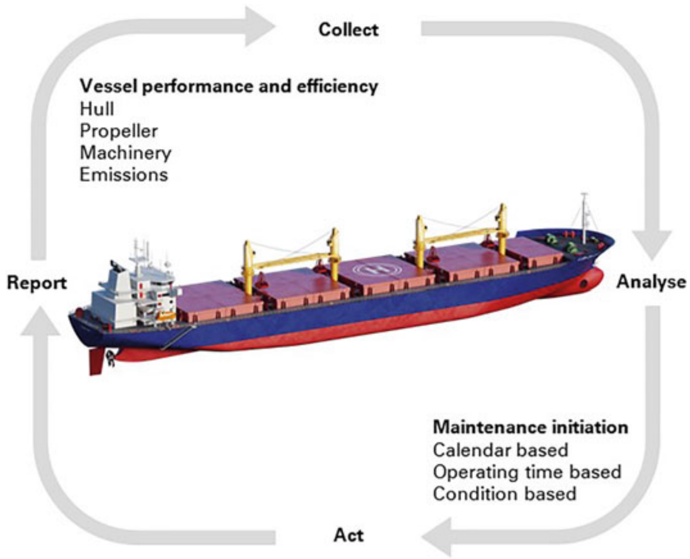


Fig. 10.1 Engine and system performance monitoring simplified process

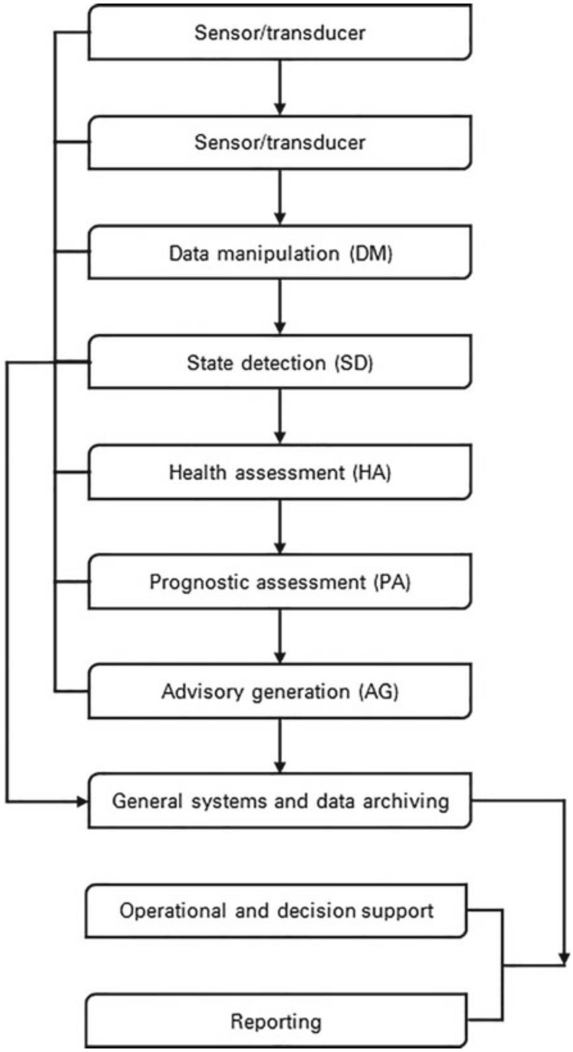
Data Collection and Transmittal

Vessel Level Data

Vessel information technology and communication architecture enables the controlling and monitoring of vessel operating parameters by integrating the various technologies amongst the different system components. There are several open operations and maintenance information systems protocols for standardising data transfer and format for communications between equipment for the sensors, controls, data manipulation and assessment. The key standards and implementation details used in vessel data management are identified in the process of utilising such data for secondary or next tier purposes. Accordingly, ISO 13374 identifies the functional blocks that shape data collection and processing for condition and performance-based maintenance applications. This standard pertains to the direct capture of operational data. Once captured in the prescribed process, the information can feed the operational decision support infrastructure. The low-level functional blocks identified in Fig. 10.2 are used as the building blocks for operational event identification and capture scenarios.

The initial building block in data acquisition consists of the sensors and transducers that interface with the physical systems of interest. The analogue and digital signals from these sensors are transmitted to a physical input/output (I/O) device that converts analogue signals to digital values or receives digital values directly from the sensors for use on a serial data bus. Individual I/O devices are wired to an I/O module that contains many I/O devices. The I/O modules are normally integrated into

Fig. 10.2 ISO 13374 functional blocks



a single serial data bus using one of many standard process automation technologies. Typical marine implementations include RS232/485 serial data interfaces or fibre optic cables and hubs. Each of the I/O modules is physically wired in a ring bus with unique IDs to allow data transfer to/from each module. The wire protocol and messages utilised are determined by the original equipment manufacturer (OEM) of the control systems (automation, control, and monitoring). There are multiple process protocols that exist which describe the messages transmitted on the serial bus including MODBUS, CANbus, and PROFIBUS. In short, a vessel's serial bus thus provides the data pathway between physical sensors and the hardware/software interfaces to enable automated data collection. However, not all process automation technologies and protocols are compatible with each other. Some manufacturers employ proprietary solutions. For these instances, there are hardware and software solutions available that can bridge different device types and protocols, to permit different OEM supplied equipment to communicate on a common bus.

To enable network-ready devices to interface with data from the serial data bus, the data must be converted to a higher-level Ethernet protocol to bridge the serial data protocols. Through this bridge, the data are converted to a standard Ethernet protocol to receive or send data by request, or broadcast throughout the network to be read by external third-party software applications. Established serial data process automation protocols have a companion Ethernet standard. MODBUS RTU devices can easily have data converted to MODBUS TCP and CANbus devices to CAN open networks. Standard TCP/IP network devices and software interested in receiving or communicating data can provide interfaces to the network protocols and the data sources. Next-level or summary software and monitoring applications in this scenario are required to interface with multiple protocols to receive the necessary data. This may necessitate a shift for these applications from their primary goal of data manipulation and (machine) state detection. An open interface specification is required for interoperability between various devices, network protocols, data manipulation and (machine) state detection applications. One current solution for consideration is OPC Data Acquisition (DA), a specification for providing real time data streaming. The OPC Foundation is an organisation which develops open interoperability standards. The technology is based on the Microsoft Windows® COM/DCOM specification and provides the ability for commodity PC Technology to be used in data monitoring and analysis. The latest advancements in this standard include the OPC Unified Architecture (UA) addressing cross platform protocols for binary data and web service interfaces. The use of the OPC Standards allows hardware process automation vendors and higher-level software applications to share data in a standard protocol.

After the data has transitioned from sensor to summary software, the data must be manipulated and have additional computational analyses completed. Supporting sensor data from the data acquisition functional data block (refer to Fig. 10.2) are used for these computations. For example, inlet and outlet pressures of a pump that are provided by the OPC Server can be processed to determine an average differential pressure that can be used to trigger certain physical events such as a maintenance task or simply to perform additional data analysis. The next step in the process is state detection. The primary function of state detection software is to utilise the data available from the data acquisition and data manipulation functional blocks to determine the operational state of equipment operating within boundary conditions.

Vessel Data Capture

The limiting variable to automated data collection is the extent of installed sensors for control and monitoring. The goals for the analysis and use of data must be initially identified followed by identification of sensor data required to achieve these goals. The identified data may include manually collected data besides the automated data. The data are associated with its collection time (e.g., time stamped) and stored in the data historian for trending and future analyses as required.

Analysis and Qualification Software

Analysis and qualification software focuses on the data manipulation and state detection functional blocks. There are several sources of data acquisition software which read sensor data from a server on a network. This software utilises a configurable logic to implement an engineering knowledge base. The knowledge base is used to map tags and to define calculations, event definitions, and rules. Sensor data can be utilised to generate virtual tag values in additional event determination. The vessel operating sensor data and virtual data calculations are processed and analysed in real time to determine if any configured event states are triggered to enable data collection. The knowledge base's qualification of data prevents excess amounts of data that do not meet defined rules for data from being collected. This reduces storage requirements while maintaining relevant data for review. Once "qualified" data have been collected, trending and analyses can begin.

State Trending

Identification of an engine or system's specific failure modes requires stable and qualified operational data. Therefore, it is recommended only data collected during full load operations should be utilised in the fault mode analysis. The software monitors the data from the server to determine when certain parameters such as engine speed and load values meet pre-defined parameters. When the conditions are met, these values and associated data points are logged periodically while the operating conditions remain true. Additional rules are then applied on only the data collected during the operational state previously defined to identify potential failure modes. Without automated data capture, data would be manually collected or extracted from the database and analysed to extract the data collected meeting the pre-defined parameters. Long-term trending of an operating diesel engine may require data to be collected when the engine is running at single or multiple load configurations. As described previously, the real time data can be monitored from the OPC data interface to determine when certain parameters such as engine speed and load values meet pre-defined parameters. This provides a standard and reviewable set of data on all diesel engines on a vessel that have been performing within defined operating ranges. Once the qualified data are collected and stored, a second or third level of rules may be programmed to run. These rules can include analysis that may take longer to process than the real time data collection rules. It is in this stage where data relevant to energy and environmental performance can be further analysed.

At times, transient analyses are performed for unexpected events occurring instantaneously or in a short time period resulting in a total loss of system function. The sensors and monitoring equipment selected must be suitable to measure any transients and record the data for analysis after the event. Potential causes of these events are inadequately designed components or sub-systems, unknown component failure, faulty logic in the control system, or operation outside of predetermined parameters.

From Client to Fleet Management Software

Fleet and maintenance management tools allow users to record data pertaining to events which occur during operations. Based on the operational conditions and relevant data requirements, users enter information in data forms that are customisable. Data are received from vessels periodically in the shoreside office. The data pertinent to reports of interest are analysed and then typically compiled in reports and onboard record books. Extending the fleet management software to read from an intelligent data historian that communicates with the vessel's automated data bus provides an opportunity to reduce crew burden and improve data integrity. Once a communication channel is established between the two systems, event forms can be automatically updated. Capturing accurate and qualified data are the key for further statistical analysis and decision making by the shore-side personnel. With an integrated system, on-board users can query the historian for event data using date and time parameters. The application sends out a request to the data historian and in response, receives sensor data. It then passes through a processor, for further refining and aggregation where applicable, and is then applied to the relevant reporting form(s) for end user review. A built-in alert engine assists users by pointing to any discrepancies. For example, it will initiate an alert if the sensor fails or is interrupted for a short interval in the time period. Optional meta-data can notify users which sensor(s) is not operating. The operation then provides the mechanism for transporting data from ship to shore for a fleet wide perspective on these data.

Data Review and Governance

With the data flow established from sensor to a fleet management solution, it has passed through the following steps: sensor-bus-qualification-trend-web service-fleet management. All data points are qualified prior to collection and analysis. Such data can be trended and reported upon and is also available to both vessel and shore-side personnel as decision points for improved operations and maintenance. When dealing with vessels' location and operational data, a robust data security mechanism has to be in place. This becomes even more important because this information is used for reporting to third-party stakeholders and port State authorities. Authorisations allow users to selectively make changes to data. An audit trail of what, when, and who made the modifications has to be maintained. Data transfers, from ship to shore, require industry standard encryptions.

Performance Monitoring

Performance Parameters

Numerous engine performance parameters are monitored through a series of sensors by the engine's control system so as to allow precise control over the principle elements of engine operation such as fuel injection and emissions. The following lists these systems along with some of the monitored parameters for crosshead type engines (Table 10.1).

Only some of this data is indicated to the operator by gauges, displays, or alarms. By continuous monitoring and archiving of this data, performance degradation trends can be detected, and corrective action taken to prevent imminent component or equipment failure. This data can also be compared with similar engines operating onboard other vessels in an operator's fleet.

Table 10.1 Performance parameters

System	Monitored parameters
Engine operating parameters	Speed, power, rotation direction
Fuel oil system	Pressures in various parts of system, temperature, viscosity, leakage
Cooling water system (fresh water and sea water)	Pressures, temperatures
Piston cooling parameters	Pressure, temperature, flow
Cylinder freshwater cooling system	Pressure, temperature, flow
Fuel valve coolant	Pressure, temperature
Lubricating oil system	Pressures, temperatures, flow
Compressed air system	Pressures
Scavenging air system	Pressures, temperature
Exhaust gas	Temperatures
Turbocharger parameters	Lubricating oil temperatures, pressures, speed

Performance Reporting

Depending upon the goals identified for the engine performance monitoring programme, the reports can be custom designed to indicate:

- Engine power versus fuel consumption, exhaust gas emissions, or both for the goal of optimised engine performance.
- Thermal efficiency of various heat recovery equipment, such as economisers.
- Temperature/pressure trending for various systems to identify component replacement; and
- Early warning signs identification, such as increasing bearing temperatures indicating premature component failure is in progress, to alert the operator to take corrective actions. Some of these monitoring programmes include diagnostic capabilities utilising the failure modes effects analysis (FMEA) approach.

Remote Monitoring

Engine performance data can be collected and transmitted to the vessel operator's shore-side office or to a service provider's diagnostic centre for further analysis. Alerts can be issued to the vessel personnel advising proactive maintenance tasks to be performed to avoid premature component/equipment failure. Figure 10.3 shows a representative process for transmitting data from a vessel's machinery space to shore. In the example, main engine operating data are monitored by the engine sensor module or electronic control module. This data can be extracted and sent to a separately installed data collector and analyser. Other sources of data can include engine emissions data, automatically or manually collected condition monitoring data and environmental data. The data can be analysed for suitability, preliminary diagnostics performed and prepared for satellite transmission to a service company or the vessel operator's shore side office for further analysis and diagnostics. Then the analysed results are transmitted back to the vessel's chief engineer for information and action as required. The data from one vessel can be compared to data from other vessels with similar equipment to confirm maintenance intervals and to determine overall fleet performance and performance trends.

Future Trends

The trends for vessel systems transmitting key performance data to the managing office has been underway since the 1980's and will continue to involve more vessels as ship management companies recognise the benefits of monitoring vessel fuel consumption and machinery status. Regarding machinery efficiency and reliability, there have been a number of studies in the manufacturing industries to assess the

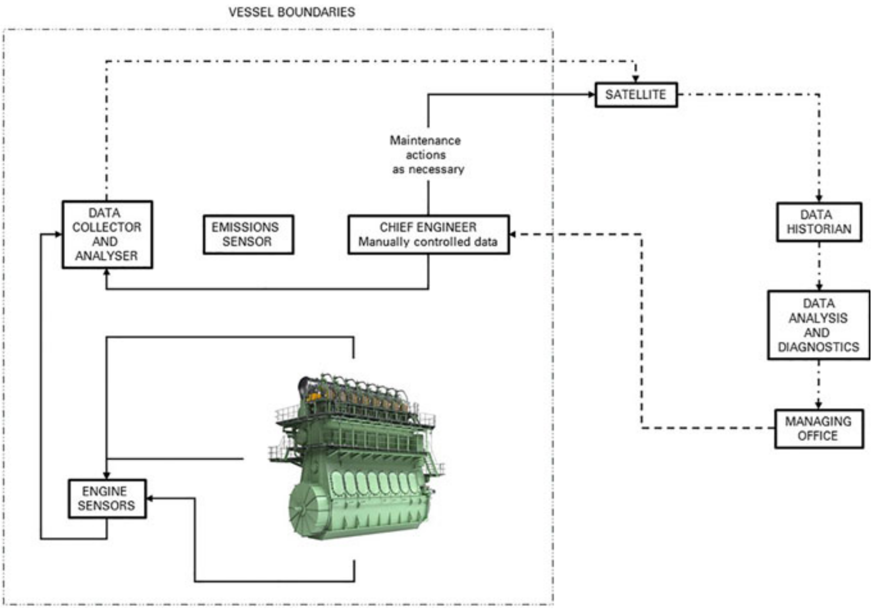


Fig. 10.3 Remote monitoring and data transmission

reliability and availability of machines using various mathematical models applying system reliability theory. From these studies secondary and tertiary analyses are performed to estimate expected times to perform maintenance so as to improve vessel energy efficiency and repair machinery. These analyses are based on appropriate statistical distributions, Bayesian and stochastic theories including economic models to maximise revenues and minimise costs.

Chapter 11
Evaluating New Condition Monitoring Techniques

Periodically, most Classification Societies receive requests to review proposed condition-monitoring techniques for applications intended to enrol equipment and machinery in preventative maintenance programmes or reliability centred-maintenance programmes. This chapter provides guidance to vendors and/or vessel owners/operators who are proposing to evaluate the technique and whose intention is to submit the results of the evaluation to the appropriate Class technical office for review.

Applicability of Technique

In order for the proposed condition-monitoring technique to be considered applicable and effective, the proposed technique(s) should ensure the following characteristics are complied with:

(1) Onset of failure is detectable.
(2) The P-F interval is reasonably consistent.
(3) There is a practical interval in which condition-monitoring tasks can be performed.
(4) There is sufficient warning so that corrective actions can be implemented.
(5) There is a reduction in the probability of failure (and therefore the risk) to an acceptable level; and
(6) The technique is cost-effective.

Readers may wish to refer to Chap. 3 for more detailed explanations of each characteristic.

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Consistency/Repeatability of Measurements

Measurement results from the proposed condition-monitoring technique should be consistent with measurements taken on the same equipment/system for similar operating conditions. The results should also be repeatable for measurements taken over a short period of time. The criteria for setting consistency and repeatability results are to be discussed with Class prior to the review.

Statutory Regulations

Some Flag State Administrations have regulations requiring the inspection of certain equipment (i.e., safety valves on boilers) to be held at specific intervals regardless of the condition of the equipment. In these circumstances, Class may allow the condition-monitoring technique to be applied, however, the equipment may still require inspection in accordance with Flag State Administration regulations.

Cost Effectiveness

The cost effectiveness of the condition-monitoring technique is often paramount to the vessel owner/operator's decision to implement the proposed technique(s). To that end, Table 11.1 provides a summary procedure for evaluating the cost effectiveness of proposed condition-monitoring tasks.

Table 11.1 Evaluating cost effectiveness of a condition-monitoring technique

Serial	Subject	Description/instruction	Value	Results
1	Condition monitored	Indicate the condition being monitored and the failure mode that is being prevented from occurring		NA
2	Relative effectiveness	When comparing two or more techniques, a factor for comparison can be listed here For example, assign a letter or a number to describe ease of use, accuracy of results, etc.		NA
3	P-F interval (days, weeks, months)	Indicated the estimated or actual P-F interval If the equipment/system does not have a consistent P-F interval, CM is not applicable		CM Applicable? Y/N

(continued)

Table 11.1 (continued)

Serial	Subject	Description/instruction	Value	Results
4	Estimated total number of pieces of equipment technique is applicable to	Indicate total number of equipment this technique can be applied to		
5	Required test equipment/ software/facilities	List all the required equipment and software necessary to apply the technique Also list any special modifications to the equipment and vessel to incorporate this technique		
6	Capital cost of equipment/software/ facilities	For each item in line 5, provide the associated cost		Total ($)
7	Expected equipment life with normal vessel use (years)	For each item in line 5, provide the expected life		NA
8	Depreciation (annual straight line)	For each item listed in line 5, divide associated capital cost in line 6 by corresponding expected life in line 7		Sum of depreciation ($/Year)
9	Required shipboard personnel	Enter number of personnel necessary to apply CM, if shipboard personnel will be used		
10	Hourly rate	Indicate shipboard personnel hourly rate		
11	Annual training cost	Indicate training costs, if shipboard personnel will be used		Sum of training costs ($/Year)
12	Equipment calibration/ maintenance/damage allowance	Estimate annual equipment calibration costs If calibration interval is greater than a year, divide cost by interval to obtain annualised cost Maintenance/damage allowance can be estimated as 3–5% of capital cost in line 6		Sum of maintenance costs ($/Year)
13	Technique frequency (times per year)	Indicate the number of times the CM technique will be used		NA
14	Average data collection time (Hrs)	Estimate the time to collect data for one equipment/system Include all time associated with collection, (i.e., set-up, and take down, evaluation)		NA

(continued)

Table 11.1 (continued)

Serial	Subject	Description/instruction	Value	Results
15	Shipboard labour (man-hrs)	Multiply line 14 by number of personnel in line 9		NA
16	Annual labour cost for data collection	Multiply frequency in line 13 by line 15		Sum of annual labour costs ($/Year)
17	Ongoing off-site support/ diagnostic services	If an off-site service will be used, indicate annual cost		Annual cost ($/Year)
18	Required service personnel	Enter number of personnel necessary to apply CM		
19	Service engineer/ consultant hourly rate	Indicate hourly rate		
20	Technique frequency for service engineer (times per year)	Indicate the number of times the CM technique will be used		
21	Average data collection time for service engineer/ consultant (hrs)	Estimate the time to collect data for equipment/system Include all time associated with collection, (i.e., set-up, and take down, evaluation) Also include travel time, if applicable		
22	Service engineer/ consultant labour (man-hrs)	Multiply Line 21 by number of personnel in line 18		
23	Annual labour cost for service engineer/ consultant data collection	Multiply frequency in line 20 by line 22		Sum of annual labour costs ($/Year)
24	Total annualised cost of CM technique	Add the sums of lines 8, 11, 12, 16, 17, 23		Total annual cost ($/Year)
Risk assessment results				
25	Risk for equipment/ systems identified in line 4	Determine the risk associated with the failure of all the equipment identified in line 4 All applicable consequences should account for (i.e., operations, damage, effect on environment, safety, etc.)		Total annual risk ($/Year)
26	Estimated resulting risk	Implementing a CM technique should reduce the associated frequency of failure to 1/5 to 1/10 Accordingly, multiply the total annual risk in line 25 by 0.2 to 0.1		Estimated resulting risk ($/Year)

(continued)

Table 11.1 (continued)

Serial	Subject	Description/instruction	Value	Results
27	Estimated risk reduction	Line 25–line 26		Estimated risk reduction ($/Year)
Cost effectiveness of CM technique				
28	Compare total annualised risk reduction with annualised cost of CM technique	Line 27–line 24 If the result is a positive number, the CM technique is economically feasible		
29	CM technique is economically feasible		Yes	No

Chapter 12
Class Surveys Based on Preventative Maintenance Techniques

This chapter sets out the framework of procedures and conditions under which a properly conducted preventative maintenance plan may be credited as satisfying the Class requirements pertaining to the special continuous survey of machinery, or specific Class equivalent. No preventative maintenance plan may supersede the judgment of a Class approved and appointed Surveyor, nor does the existence of the preventative maintenance plan waive the Class approved Surveyor from attending inspections for damage, representative overhaul of main engines, generator engines, steering gear, general insulation condition and resistance tests, electrical devices functional tests, reduction gear teeth examinations, hydrostatic tests of pressure vessels, tests and verification of safety devices such as relief valves, overspeed trips, emergency shut-offs, low-oil pressure trips, etc. Indeed, the preventative maintenance plan is designed to supplement and support Class approved Surveyor inspections as required by Class for the recognition of appropriately installed and maintained onboard systems.

> The reference to a Class Recognised Condition Monitoring Company refers to those companies whom Class has identified as an External Specialist with the requisite expertise to make judgements for and on behalf of Class.

Survey and Maintenance Intervals

This chapter recommends that surveys are carried out on the basis of intervals between overhauls as recommended by the system and equipment manufacturer; as documented by the operator's experience; and in accordance with the condition monitoring system, as appropriate. In general, the intervals for conducting the preventative maintenance programme should not exceed those specified for special continuous

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surveys of machinery as determined by Class. However, for components where the maintenance schedule is based on running hours, longer intervals may be accepted provided the intervals are based on the manufacturer's own recommendations. In such circumstances where an approved condition monitoring system is in effect, the machinery survey intervals based as on the special continuous surveys of machinery cycle period may be extended accordingly.

Programme Requirements

For a preventative maintenance programme in lieu of a conventional special continuous survey of machinery to be accepted, the following conditions may be required by Class and/or the Flag State Administration.

Age of Vessel

Generally, there is no limit on the age of a vessel to be entered into a special continuous survey of machinery. However, an existing vessel applying for entrance into the special continuous survey of machinery will typically be subject to a review of the vessel's Survey Status records with the aim of ascertaining the historical performance of the machinery which could affect the integrity of the preventative maintenance programme. Provided there are no historical problems related to the maintenance of the machinery, the vessel in question should ordinarily be considered eligible.

Surveys

To maintain the currency of the preventative maintenance programme, surveys related to the vessel must be up-to-date, and without any outstanding recommendations, which could adversely affect the conduct of the preventative maintenance programme. The machinery in the programme should ideally be on a special continuous survey of machinery cycle. If the vessel is not on a special continuous survey of machinery cycle, the vessel owner/operator may be strongly advised to place the vessel into such a special continuous survey of machinery cycle. For machinery for which an outstanding recommendation exists, confirmation must be made that repairs have been performed, or if repairs have not been performed, the vessel owner/operator is aware that an outstanding recommendation exists. Any machinery items not covered by the preventative maintenance programme should be surveyed and credited in the usual way.

Damages

There must be no record of unrepaired damage to the vessel or its machinery which would ordinarily adversely affect the vessel's ability to participate in the preventative maintenance programme.

Electronic and Computerised Systems

The preventative maintenance programme should be programmed into and maintained by a wholly-computerised system. Details of the computerised system should be submitted to the responsible Class technical office for review and approval. However, this need not be applied to existing Class approved schemes. Computerised systems should include automatic back-up, such as in a cloud storage database, which are to be updated at regular intervals.

Implementation Surveys

At the outset, the implementation survey should be carried out by a Class approved Surveyor within 1 year from the date of the issuance of the letter approving the preventative maintenance programme, as issued by the responsible Class technical office. In doing so, the Class approved Surveyor is expected to verify the following:

(1) The preventative maintenance programme is implemented according to the approval documentation and is adapted to the type and complexity of the components/system onboard the vessel.
(2) The preventative maintenance programme is producing the documentation required for the Annual Confirmation Survey and the requirements of surveys and testing for retention of Class are complied with.
(3) The onboard personnel are familiar with the preventative maintenance programme.

When the survey is carried out and the implementation found to be in order, a report confirming the implementation of the preventative maintenance and/or condition monitoring system must be submitted by the attending Class approved Surveyor to the appropriate Class technical office, upon receipt of which, the system may be put into service.

Programme Implementation

When the preventative maintenance programme is approved by Class, and the implementation survey has been satisfactorily completed, the attending Class approved Surveyor should advise Class that the items covered by the planned maintenance programme are to be exhibited by a preventative maintenance indicator; for items covered by a condition monitoring programme, these are to be exhibited by a condition-monitoring indicator respectively.

Cancellation of Programme

The survey arrangement for machinery under the preventative maintenance programme may be cancelled by Class whenever the programme is not satisfactorily managed, as evidenced either from (1) the vessel's maintenance records or through general inspection and condition of the machinery, or (2) when the agreed intervals between overhauls are exceeded. The sale or change of management of the vessel or the transfer of the vessel from one Class or Flag to another are also typically cause for the reconsideration of approval. The vessel owner/operator may at any time cancel the survey arrangement for machinery under the preventative maintenance programme by informing the appropriate Class technical office, usually in writing. For this case, items which have been inspected under the programme since the last Annual Survey may be credited by Class at the discretion of the Class approved Surveyor.

Submission Requirements

Programme Description

When seeking to implement a preventative maintenance programme, a comprehensive preventative maintenance programme design document must be submitted to the responsible Class technical office for review and approval. Usually, only machinery that may be subject to special continuous survey of machinery should be included in the programme unless a review of any non-essential machinery is specifically requested by the vessel owner/operator. This programme will generally include the following provisions:

(1) For items covered by a planned maintenance programme:

   (a) A list and description of the machinery.
   (b) Organisation chart identifying areas of responsibility.

(c) Schedule of servicing and overhaul. This schedule is to meet at least the servicing and overhaul intervals specified by the manufacturer and a statement to this effect is to accompany the plan.
(d) Description of the work to be performed at each interval.
(e) Machinery identification method and record keeping procedures.
(f) Planned maintenance sheet(s)/record(s) for each machine to be considered.

(2) For items covered by a condition monitoring programme:

(a) A list and description of the machinery covered including:
  (i) Method of data collection and analysis tools.
  (ii) Nominal RPM.
  (iii) Horsepower.
  (iv) Location and orientation of sensor attachments, which are to be permanently marked on machinery.
  (v) Sampling procedures for oil analysis.
(b) Organisation chart identifying areas of responsibility.
(c) Schedule of data collection.
(d) Type and model of data collection instrument, including sensor and attachment method and calibration schedule.
(e) Acceptance criteria of data.
(f) Class approved Surveyor and/or a representative specialist of a Class Recognised Condition Monitoring Company and are to be compared to the acceptable vibration levels shown in SNAME's T&R Bulletin 3–42 *Guidelines for the use of vibration monitoring for preventative maintenance* or other equivalent national or international standards. The vessel owner is to be notified of all machinery that does not meet acceptance criteria (i.e., machinery with high vibration levels).

Vessel Owner's Annual Preventative Maintenance Report

The Annual Confirmation of the Preventative Maintenance Programme should be carried out by the attending Class approved Surveyor upon the anniversary of the preventative maintenance programme. In this situation the vessel's owner/operator or qualified representative may be required to present an Annual Preventative Maintenance Report containing the following information to the attending Class approved Surveyor, whose responsibility is to review and verify the contents of the report at the time of the Annual Confirmation Survey of the Preventative Maintenance Programme. At Class's sole discretion, reports submitted without all of the following information may be returned pending remedial action:

(1) Planned maintenance programme report (annual):

(a) A summary list of all machinery covered under the planned maintenance programme, including a complete description of work completed on each machine since the last submitted report. The vessel owner may add or delete equipment subject to the approval of the attending Class approved Surveyor, who will also notify the appropriate Class technical office of any machinery additions or deletions, as necessary.

(b) Machinery identification procedure.
(c) Planned maintenance sheet(s)/record(s) for each machine.
(d) Exceptions, notes and comments noted during work.
(e) Modifications and justifications to the schedule, such as might be recommended by a machinery manufacturer's technical bulletin.
(f) Full trend analysis of machinery displaying operating parameters exceeding acceptable tolerances.
(g) Summary and analysis of machines that failed prior to scheduled maintenance or servicing.

(2) Condition monitoring programme report (annual):

(a) A summary list of all machinery covered under the condition monitoring programme, clearly stating the overall condition of the machinery based on the most recent vibration measurement data (i.e., Satisfactory, Marginal, Suspect, Unacceptable, etc.).[1] Data for the report must have been collected within three months of the submission date of the report by a Class Recognised Condition Monitoring Company.
(b) Machinery identification procedure.
(c) Original baseline data for equipment.
(d) Condition monitoring data including all data since last opening of the machine.
(e) Vibration spectral data must be reviewed by a representative specialist of a Class Recognised Condition Monitoring Company.
(f) Full trend analysis (including spectral analysis for vibration) of machinery displaying operating parameters exceeding acceptable tolerances. Also, alarm criteria.
(g) Relevant operational data during data recording, such as sea state, machine temperature, other equipment affecting the data, etc. should be included.
(h) Quarterly overall vibration meter readings recorded by vessel personnel. The type of recording device, method of data collection and calibration of the data collector must be provided.

If the machinery included in the planned maintenance or condition monitoring programme has changed, this must be clearly stated. Any machinery to be added to the system is usually subject to the same requirements outlined above, pending approval by the attending Class approved Surveyor. Moreover, the responsible Class technical office is to be advised of any machinery due to be added to, or deleted from, the planned maintenance/condition-monitoring programme. For planned maintenance, the vessel owner should be advised of all machinery for which periodic maintenance

[1] Alternative terms and definitions may be applied.

is not indicated or is incomplete as per the initial planned maintenance report. In the meantime, the condition of the machinery may be deemed satisfactory at the sole discretion of the attending Class approved Surveyor. For condition monitoring, vibration readings are to be compared to the baseline readings provided in the initial report. The vessel owner/operator is to be advised that maintenance or additional monitoring is needed for machinery wherever the vibration readings are above those in the machinery vibration standard. Any machinery unavailable for measurement are to be noted and the vessel owner/operator advised that such readings are required to be submitted for Class review. In the meantime, the condition of the machinery is to be deemed satisfactory at the sole discretion of the attending Class approved Surveyor.

Onboard Documentation

In respect to onboard documentation, the chief engineer is the responsible person onboard the vessel in charge of the preventative maintenance programme. Wherever a computerised system is used for updating the maintenance documentation and maintenance programme, it is essential to the maintenance of the integrity of the programme that access is limited exclusively to the chief engineer or their duly appointed deputy. In maintaining the currency of the programme, the following documentation and records must be kept onboard:

(1) Planned maintenance programme:

- (a) The latest up-to-date information.
- (b) A copy of the manufacturer's service manuals and/or shipyard's maintenance instructions.
- (c) Reference documentation (trend investigation procedures, etc.).
- (d) All records showing compliance with the programme (including repairs and renewals carried out) are to be made available for review by the attending Class approved Surveyor at the Annual Survey of Machinery.

(2) Condition monitoring programme:

- (a) The latest up-to-date information as required by the programme.
- (b) For vessels with onboard vibration meters or FFT vibration analysers, manuals supplied by manufacturers for use of data collectors and computer programs, as well as guidance for machine operating and diagnosis of machine faults.
- (c) Condition monitoring data, including all data since last opening of the machine and the original baseline data.
- (d) Reference documentation (trend investigation procedures, etc.).

(e) Records of lube oil analysis, rotor positioning readings, interstage bleed system pressures and vibration readings are to be recorded by the vessel's personnel at least on a quarterly basis and retained onboard for review annually by the attending Class approved Surveyor.
(f) Complete vibration data are to be taken at least annually, or more frequently when warranted by abnormal conditions and operational parameters, reviewed by a representative specialist of a Class Recognised Condition Monitoring Company and retained onboard for review annually by the attending Class approved Surveyor.
(g) If the vessel includes internal combustion engines in the programme, the appropriate data must be retained onboard for review annually by the attending Class approved Surveyor.
(h) Calibration date of equipment. Calibration is to be in accordance with the manufacturer's recommendations or annually, whichever is more frequent.
(i) Any repairs or changes to any machines must be reported, and a summation and analysis of all unscheduled maintenance and/or breakdowns of monitored equipment.
(j) All records showing compliance with the programme, including a copy of the most recent vessel owner's annual report are to be made available for review by the Class approved Surveyor during the Annual Survey of Machinery.

Special Conditions

Steam Turbines

In respect to steam turbines, the condition monitoring of turbines must provide information in accordance with the section, *Onboard documentation.* The main propulsion turbine rotor journal bearings, thrust bearings, and flexible couplings are to be opened up for examination. The low-pressure exhaust trunk is to be opened for the examination of the last row of low pressure and astern wheels. Providing vibration readings, lubrication oil analysis and rotor position checks and turbine operating records are reviewed, and all considered satisfactory by the Class approved Surveyor, the lifting of the main propulsion turbine casings may be waived at alternate, subsequent special periodical surveys. On turbines where variable or abnormal readings are noted, readings are to be recorded by the vessel's personnel more frequently, as appropriate to properly monitor the performance range or establish the trend. The turbines are usually required to be operationally tested.

Table 12.1 Submission requirements for internal combustion engines

Operating time (running hours) Power output (MCR) RPM Cylinder pressure as function of crank angle Injection pressure as function of crank angle Cylinder liner and piston ring wear (on basis of compression/firing pressures or proximity readings) Scavenging air pressures and temperatures	Lubricating oil and cylinder oil consumption Bearing temperatures (main, crank pin, crosshead and internal thrust, as fitted) Cylinder exhaust temperatures Turbocharger vibration and T/C RPM Lubricating oil analysis (quarterly) Crankshaft deflection readings for medium/slow speed diesel engines

Internal Combustion Engines

Machine condition monitoring of internal combustion engines must provide detailed engine analysis, in addition to the data required under the section *Submission requirements*. To that end, the following data should be recorded at least monthly, unless indicated otherwise (Table 12.1).

For machines for which variable or abnormal readings are noted, readings are to be recorded by the vessel's personnel more frequently, as appropriate to properly monitor the performance range or establish the trend.

Electrical Switch Gear and Power Distribution Panels

Condition monitoring plans for electrical equipment should include the examination of panels, switchboards, transformers and other essential electrical apparatus by infrared photographic thermography during each five-year survey cycle while the circuit is energised and under normal workloads. A report describing the results of the survey, as well as periodic insulation resistance records must be retained onboard for review by the attending Class approved Surveyor.

Permanently Installed Monitoring Equipment

Permanently installed electronic analysing equipment used for the condition monitoring programme must comply with the Class requirements regarding testing and certification of automatic and remote-control systems for use onboard ships.

Alternative Techniques

The application of techniques of condition monitoring, other than those discussed in this chapter, may be specially considered by Class where a request to do so is made in writing to the appropriate Class technical office. For example, condition monitoring based on semi-annual signatures may be deemed acceptable as an alternative technique for rotating machinery in lieu of quarterly overall vibration meter readings supplemented by an annual signature. The semi-annual signatures are to be taken and reviewed by a representative specialist of a Class Recognised Condition Monitoring Company. External checks, such as lube oil analysis, shaft position indicating and bearing temperatures are not affected and should continue to be monitored by the crew at least on a quarterly basis. The annual vessel owner's report is to clearly indicate that this alternative is being utilised and must include both semi-annual signatures for all of the monitored equipment. In addition, a summation and analysis of all unscheduled maintenance and/or breakdowns of the monitored equipment which were not identified by the semi-annual signatures must be included. Any reports submitted without the required statement of maintenance and/or summation will usually be returned pending remedial action.

Overhauls and Damage Repairs

Overhauls

In all cases a Class approved Surveyor is required to attend and report on representative overhauls of the main and auxiliary machinery. Following overhauls, new baseline data is to be recorded in the presence of a Class Recognised Condition Monitoring Company within six months of the overhaul and included in the Annual Report. Documentation on overhauls of items covered by the preventative maintenance programme is to be reported to and signed off by the chief engineer.

Damage Repairs

All damage to components/machinery is to be reported to the Class technical office. Repairs of such damaged components/machinery under the preventative maintenance programme are to be carried out to the satisfaction of the Class approved Surveyor in accordance with the guidance provided in the section, *Onboard documentation.* Any repair and corrective action regarding machinery under the preventative maintenance programme is to be recorded and the repair verified by the attending Class approved Surveyor at the Annual Confirmation Survey. In the case of overdue outstanding recommendations or a record of unrepaired damage which would adversely affect the preventative maintenance programme, the relevant items are to be kept out of the programme until the recommendation is fulfilled or the repair is carried out.

Annual Confirmation Surveys of Preventative Maintenance Programme

Simultaneously with each Annual Survey of Machinery, for vessels on a preventative maintenance programme, an Annual Confirmation Survey is to be performed by the attending Class approved Surveyor. The purpose of this survey is to verify that the programme is being correctly operated, and that the machinery has been functioning satisfactorily since the previous survey. The survey is to include a general examination of the items concerned. In doing so, the Class approved Surveyor is to review the vessel owner's annual report and examine the performance and maintenance records to verify that the machinery has functioned satisfactorily since the previous survey or action has been taken in response to machinery operating parameters exceeding acceptable tolerances and the overhaul intervals have been maintained. Any and all written details of breakdown or malfunction are to be made available for review. Furthermore, a description of repairs carried out is to be provided and examined by the Class approved Surveyor. Any machinery part, which has been replaced with a spare due to damage, is to be retained onboard, wherever possible, until examined by the Surveyor. Finally, at the discretion of the Class approved Surveyor, function tests, confirmatory surveys and random check readings, where condition monitoring equipment is in use, are to be carried out as far as practicable and reasonable. Upon satisfactory completion of the above requirements, the preventative maintenance programme may be accepted by Class for its continued use. The Class approved Surveyor may credit to the CMS any machines that were overhauled and tested in the presence of and to the satisfaction of the attending Class approved Surveyor. Additionally, any machinery that has been overhauled in accordance with the planned maintenance schedule may be credited to the CMS by the attending Class approved Surveyor after a satisfactory operational test. Any machinery that has acceptable operating conditions as per the condition monitoring programme may be credited to the CMS by the attending Class approved Surveyor after a satisfactory operational test.

Glossary

The following definitions are applied to the terms used throughout this book.

Baseline data. The baseline data refer to condition monitoring indications—usually vibration records on rotating equipment—established with the equipment item or component operating in good order when the unit first entered the Programme, or the first condition-monitoring data collected following an overhaul or repair procedure that invalidated the previous baseline data. The baseline data are the initial condition monitoring data to which subsequent periodical condition-monitoring data are compared.

CANopen network. CAN (Controller Area Network) is a standardised application for distributed automation systems based on transmitting time-critical process data, standardised data related to the system components and functional status.

CANbus. The data link layer of CANopen transmitting data between equipment, system controllers and data analysers.

Cause. Refer to "failure cause".

Class Recognised Condition Monitoring Company. This term refers to those companies which Class has approved as Service Suppliers.

Component. The hierarchical level below equipment items. This is the lowest level for which the component can be identified for its contribution to the overall functions of the functional group; can be identified for its failure modes; is the most convenient physical unit for which the preventative maintenance plan or the spares holding requirement can be specified.

Condition based maintenance (CBM). A maintenance plan, conducted on a frequent or real-time basis, which is based on the use of Condition Monitoring to determine when part replacement or other corrective action is required. This process involves establishing a baseline and operating parameters, then frequently monitoring the machine and comparing any changes in operating conditions to the baseline. Repairs or replacement of parts are carried out before the machinery fails based upon the use of the tools prescribed for CM.

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Condition monitoring (CM). Condition monitoring comprises scheduled diagnostic technologies used to monitor machine condition to detect a potential failure. Practitioners in some countries refer to this term as an "on-condition task" or "predictive maintenance".

Consequence. The way in which the effects of a failure mode matter. Consequence can be expressed as the number of people affected, property damaged, amount of oil spilled, area affected, outage time, mission delay, dollars lost, etc. Regardless of the measure chosen, the consequences are expressed "per event".

Data historian. A data historian is a type of database designed to archive automation and process data. They are designed to store high frequency data and data collecting on a regular basis. Historians are used to troubleshoot processes, optimise manufacturing, store data for regulatory compliance, etc. It does not store transactional or relational data.

Effects. Refer to "failure effects".

Equipment items. The hierarchical level below systems comprising various groups of components.

Failure cause. The failure cause is the basic equipment failure that results in the failure mode. For example, pump bearing seizure is one failure cause of the failure mode "pump fails off".

Failure characteristic. The failure characteristic is the failure pattern (i.e., wear-in, random, wear-out) exhibited by the failure mode.

Failure effects. Failure effects are the consequences that can result from a failure mode and its causes.

- *End effect.* The overall effect on the vessel that is typically related to the consequences of interest for the analysis (loss of propulsion, loss of manoeuvrability, etc.). For the purposes of this publication, the term "End effect" applies only to the total loss or degradation of the functions related to propulsion and directional control, including any of the following consequences: loss of containment, explosion/fire, reduction in safety occurring immediately after or a short time thereafter as a result of a failure mode. For offshore activities, these may be extended to include any functions related to drilling operations, position keeping, hydrocarbon production and processing, or import and export functions.
- *Local effect.* The initial change in the system operation that would occur if the postulated failure mode occurred.
- *Next higher effect.* The change in condition or operation of the next higher level of indenture caused by the postulated failure mode. This higher-level effect is typically related to the functional failure that could result.

Failure management strategy. A failure management strategy is a proactive strategy to manage failures and their effects to an acceptable level of risk. It consists of proactive maintenance tasks, run to failure for low risks, or one-time changes for high risks.

Failure mechanism. The failure mechanism describes how the failure mode may occur. One failure mode for a particular piece of equipment may have several failure mechanisms. The failure mechanism may vary during the life of the equipment as the failure rate pattern changes.

Failure mode. The failure mode describes how equipment can fail and potentially result in a functional failure. Failure mode can be described in terms of an equipment failure cause (i.e., pump bearing seizes), but is typically described in terms of an observed effect of the equipment failure (i.e., pump fails off).

Failure rate. The failure rate is the number of failures per unit time that can be expected to occur for the equipment.

FMECA. The acronym for "Failure mode effects and criticality analysis".

Frequency. The frequency of a potential undesirable event is expressed as events per unit time, usually per year. The frequency should be determined from historical data if a significant number of events have occurred in the past. Often, however, risk analyses focus on events with more severe consequences (and low frequencies) for which little historical data exist. In such cases, the event frequency is calculated using risk assessment models.

Function. A function is what the functional group, systems, equipment items, and components are designed to do. Each function should be documented as a function statement that contains a verb describing the function, an object on which the function acts, and performance standard(s).

- *Primary function.* A primary function is directly related to producing the primary output or product from a functional group/system/equipment item/component.
- *Secondary function.* A secondary function is not directly related to producing the primary output or product, but nonetheless is needed for the functional group/system/equipment item/component.

Functional failure. A functional failure is a description of how the equipment is unable to perform a specific function to a desired level of performance. Each functional failure should be documented in a functional failure statement that contains a verb, an object and the functional deviation.

Functional group. A hierarchical level addressing propulsion, manoeuvring, electrical, vessel service, and navigation and communications functions.

Indications (failure detection). Indications are alarms or conditions that the operator would sense to detect the failure mode.

Likelihood. See "frequency".

MODBUS. Is a common serial communications protocol for connecting industrial electronic devices such as sensors and programmable logic controllers (PLCs).

One time change. A maintenance strategy in which equipment or systems, which have been determined to present an unacceptable level of risk and have no potential mitigations, are replaced or significantly altered in order to provide an acceptable level of risk.

OPC server. OPC ("OLE" PC) (object linking and embedding for process control) is a software interface standard to allow Windows programmes to communicate with industrial hardware devices.

Operating context. The operating context of a functional group is the circumstances under which the functional group is expected to operate. It should describe the physical environment in which the functional group is operated, a precise description of the manner in which the functional group is operated and the specified performance capabilities of the functional group.

Preventative maintenance (PM) programme. A maintenance plan which uses time-based inspection, part replacement or overhauls in an effort to prevent equipment failures. Timing can be based on calendar days, cycles counter or equipment running hours. Such schedules are generally established by the machinery manufacturer and include lubrication servicing; filter, bearing and seal replacements; as well as major overhaul. This refers to the preventative maintenance programme requirements discussed in Chap. 12. The preventative maintenance programme should be based on IACS Unified Requirement Z20 (or as amended), although there are significant differences concerning equipment permitted to be enrolled.

P–F interval. The Potential Failure interval is the time interval between the point at which the onset of failure can be detected and the point at which functional failure occurs. A condition-monitoring task should be performed at less than half of this interval.

Planned maintenance. For the purposes of this publication, planned maintenance is a scheduled maintenance task that entails discarding a component at or before a specified age limit, regardless of its condition at the time. It also refers to a scheduled maintenance task that restores the capability of an item at or before a specified age limit, regardless of its condition at the time, to a level that provides an acceptable probability of survival to the end of another specified interval. These maintenance tasks are also referred to as “scheduled discard” and “scheduled restoration”, respectively.

Potential failure. A potential failure is an identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring.

Predictive maintenance. Refer to “condition monitoring”.

Preventative maintenance. Preventative maintenance consists of all the maintenance tasks identified as necessary to provide an acceptable probability of survival to the end of a specified interval for the machinery systems. In IACS UR Z20, this is referred to as a “planned maintenance scheme”.

Proactive maintenance task. A proactive maintenance task is implemented to prevent failures before they occur, detect the onset of failures or discover failures before they impact system performance.

PROFIBUS. PROFIBUS (process field bus) is a standard for fieldbus communication in automation technology.

Random failure. Random failure is dominated by chance failures caused by sudden stresses, extreme conditions, random human errors, etc. (i.e., failure is not predictable by time).

Reactive maintenance. A maintenance strategy in which equipment is run until failure before corrective action is taken. This is useful for items which are low risk, low-cost and have no impact on operational, environmental or safety concerns as a result of failure.

Reliability. The probability that an item will perform its intended function for a specified interval under stated conditions.

Reliability based maintenance (RBM). A maintenance strategy development model that will act as the foundation for applying selective reliability techniques, choosing and deploying a maintenance plan, and creating an effective reliability strategy to support an efficient maintenance environment.

Reliability centred maintenance (RCM). A process that is used to determine the most effective approach to maintenance. It involves identifying actions that when taken will reduce the probability of failure and which actions are most cost effective. A number of leading Classification Societies have developed maintenance programmes which use RCM analysis of installed equipment to develop a maintenance programme, a spare parts holdings list and includes a sustainment plan.

Risk. Risk is composed of two elements, frequency and consequence. Risk is defined as the product of the frequency with which an event is anticipated to occur and the severity of the consequence of the event's outcome.

Systems. The hierarchical level below functional group, comprising various groups of equipment items.

TCP/IP. TCP/IP (transmission control protocol and internet protocol) is the computer networking model and set of communications protocols used on the internet and similar computer networks.

Wear-in failure. Wear-in failure is dominated by "weak" members related to problems such as manufacturing defects and installation/maintenance/startup errors. It is also known as "burn in" or "infant mortality".

Wear-out failure. Wear-out failure is dominated by end-of-useful life issues for equipment.