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Condition monitoring and diagnostics of machines — Vibration condition monitoring —

Part 3: Guidelines for vibration diagnosis

Surveillance et diagnostic d'état des machines — Surveillance des vibrations —

Partie 3: Lignes directrices pour le diagnostic des vibrations

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

ISO 13373 consists of the following parts, under the general title *Condition monitoring and diagnostics of machines — Vibration condition monitoring*:

— *Part 1: General procedures*

— *Part 2: Processing, analysis and presentation of vibration data*

— *Part 3: Guidelines for vibration diagnosis*

— *Part 9: Diagnostic techniques for electric motors*

Introduction

This part of ISO 13373 has been developed as a set of guidelines for the general procedures to be considered when carrying out vibration diagnostics of machines. It is intended to be used by vibration practitioners, engineers and technicians and it provides them with useful diagnostic tools. These tools include diagnostic flowcharts, process tables and fault tables. The material contained herein presents a structured approach of the most basic, logical and intelligent steps to diagnose vibration problems associated with machines. However, this does not preclude the use of other diagnostic techniques.

ISO 13373-1 presents the basic procedures for vibration signal analysis. It includes: the types of transducers used, their ranges and their recommended locations on various types of machines, online and off-line vibration monitoring systems, and potential machinery problems.

ISO 13373-2 which leads to the diagnostics of machines includes: descriptions of the signal conditioning equipment that is required, time and frequency domain techniques, and the waveforms and signatures that represent the most common machinery operating phenomena or machinery faults that are encountered when performing vibration signature analysis.

The present part of ISO 13373 provides general guidelines for a range of machinery. Guidance for specific machines is provided in other parts of this International Standard (currently under development).

ISO 13373 does not define vibration limits; these are specified in ISO 7919 (all parts) for rotating shafts and ISO 10816 (all parts) for non-rotating parts.

Condition monitoring and diagnostics of machines — Vibration condition monitoring —

Part 3: Guidelines for vibration diagnosis

1 Scope

This part of ISO 13373 sets out guidelines for the general procedures to be considered when carrying out vibration diagnostics of rotating machines. It is intended to be used by vibration practitioners, engineers and technicians and provides a practical structured approach to fault diagnosis. In addition it gives examples of faults common to a wide range of machines.

NOTE Guidance for specific machines is provided in other parts of ISO 13373.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1925,[1)] *Mechanical vibration — Balancing — Vocabulary*

ISO 2041, *Mechanical vibration, shock and condition monitoring — Vocabulary*

ISO 7919-1, *Mechanical vibration of non-reciprocating machines — Measurements on rotating shafts and evaluation criteria — Part 1: General guidelines*

ISO 13372, *Condition monitoring and diagnostics of machines — Vocabulary*

ISO 13373-1, *Condition monitoring and diagnostics of machines — Vibration condition monitoring — Part 1: General procedures*

ISO 13373-2, *Condition monitoring and diagnostics of machines — Vibration condition monitoring — Part 2: Processing, analysis and presentation of vibration data*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 1925, ISO 2041 and ISO 13372 apply.

4 Measurements

4.1 Vibration measurements

Reliable measurement is the essential basis of using this part of ISO 13373 (see Reference [1]).

1) To become ISO 21940-2 when revised.

In general, there are three types of vibration measurements:

a) vibration measurements made on the non-rotating structure of the machine, such as the bearing housings, machine casings or machine base, using e.g. accelerometers or velocity transducers (see ISO 2954);

b) relative motion measurements between the rotor and the stationary bearings or housing, using e.g. proximity probes (see ISO 10817-1);

c) measurements of the absolute vibratory motion of the rotating elements, using e.g. shaft riders or by combining the outputs of the methods described in items a) and b) (see ISO 10817-1).

International Standards have been written to help assess the vibration severity for these types of measurements, especially ISO 7919 and ISO 10816.

It is important to recognize that the appropriate transducer and measurement system should be used for the diagnosis of faults considering specific situations and machine types. For example, by taking into account the machines' particular operational duty, the required frequency range and the resolution of measurement are determined.

Description of transducer and measurement systems as well as specification of techniques are given in ISO 13373-1 and ISO 13373-2, which shall be considered for appropriate selection.

4.2 Machine operational parameter measurements

Operational parameters can significantly affect the vibration signature and therefore should be acquired alongside the vibration data in order to allow correlation for a diagnosis process. Examples are rotational speed, load, pressure and temperature.

It is good practice to obtain baseline vibration characteristics under a range of operating conditions and configurations as a basis for comparison with future vibration events.

Additional guidelines on using operational parameters are given in ISO 17359.

5 Structured diagnostic approach

The tools used in this part of ISO 13373 to guide the diagnostic process are flowcharts, process tables and fault tables. The flowcharts and the process tables are essentially a step-by-step question and answer procedure that guides the user in the diagnosis process. The flowcharts are used for an overview of the vibration events and characterize the features, while the process tables are used for more in-depth analysis. The fault tables are used to illustrate common machinery events and how they manifest themselves.

Annex A specifies the systematic approach to the vibration analysis of machines:

a) A.1 is used to gather background information regarding the machine, nature and severity of the vibration.

b) A.2 is used to answer a set of questions aimed at arriving at a probable diagnosis of such common faults as unbalance, misalignment and rubs.

c) A.3 is used to set out certain considerations when recommending actions following a probable diagnosis.

In addition, approaches for faults common to a wide range of machines are shown in other annexes:

— Installation faults and examples are described in Annex B.

— Radial hydrodynamic fluid-film bearing faults and examples are described in Annex C.

— Rolling element bearing faults and examples are described in Annex D.

Guidance for specific machines is provided in other parts of ISO 13373.

This approach is considered to be good practice put together by experienced users, although it is acknowledged that other approaches can exist.

A word of caution to all users: in some cases the vibration diagnosis can point to several root causes. It is recommended to consult with the manufacturer under these circumstances.

6 Additional analysis and testing

6.1 General

After using the relevant flowcharts, process tables and fault tables, further testing can be necessary to establish the cause and effect mechanism. In some circumstances, with approval of the plant operator, a physical change to the machine can be required to observe an influence.

Typical tests and analysis techniques are described 6.2 to 6.4.

6.2 Not requiring changes to operating parameters

6.2.1 General

These tests can be carried during normal operation, i.e. no changes to the characteristics of the machine.

6.2.2 Trend analysis

The objective of trend analysis is to track changes in machine condition with time. This can be achieved through continuous or periodic measurements. Trending is done with operational parameters as well as vibration parameters. Vibration is trended as an overall value either peak or r.m.s. value in a certain frequency band, or as a filtered value in a number of smaller bands. More elaborate analysis can include regression analysis of trended data, as well as possible extrapolation.

6.2.3 Phase analysis

Phase is an important diagnostic tool for which a reference signal is required. For example, phase is a useful tool to distinguish between misalignment, resonance, rubs and unbalance.

6.2.4 Resonance test

In a resonance test, e.g. impact test, shaker test, the object is to find any natural frequencies or resonance speeds that can be excited by the machine. Usually, an impact test is conducted on the machine to determine the natural frequencies of stationary parts, while a resonance speed test is required to determine the natural frequencies of rotor/rotor train. An impact test is usually done while the machine is not running. However if resonance speed information is sought, then a run-up or coast-down test would be recommended (see 6.3.1).

6.2.5 Measurement of operational deflection shape

The operational deflection shape (ODS) measurement is an actual visualization of the machine behaviour, at any frequency (but usually at the running speed), under its normal operating conditions. It is important to measure not only the amplitude of vibration, but also the phase at all points on the machine. This allows the visualization of the actual relative deflection of the machine at its operating condition.

6.2.6 Long-time waveform capture

This technique is used to capture raw time data that would otherwise not be captured in conventional vibration measurement. The time period will be dependent upon the particular application. Usually multiple measurements are conducted simultaneously, including operating parameter measurement. This measurement can assist in capturing fast events or allow post-analysis of a raw signal.

6.3 Requiring changes to operating parameters

6.3.1 Changes to operating conditions

Changes to operating conditions should always be discussed with the plant operator. Operating conditions outside the manufacturer's recommended limits should be treated with special care and will need the acceptance of all parties.

The following are examples:

— change of machine speed, e.g. run up, run down;

— vibration measurements during variation of parameters, e.g. change of oil temperature, change of load.

6.3.2 Complete experimental modal analysis

Modal testing is a very powerful tool to obtain the machine and structure modal parameters, including natural frequencies, damping ratios and mode shapes. This is an expensive and time-consuming test that requires extensive instrumentation and experience, and should only be used when absolutely necessary. Normally the machine must be shut down for this test. The characteristics of the machine obtained from a test at rest can be different from the characteristics at operating speed, particularly for machines with hydrodynamic bearings.

6.4 Changes to the physical state of the machine

Changes to the physical state are recognized as being intrusive and can involve changing position, mass or stiffness characteristics. It is advisable to have a measurement before and after making any changes in the physical state of the machine and to carry out a risk assessment.

The following are examples of changes to physical state:

— unbalance test;

— 180° turning of coupling;

— running the machine uncoupled;

— additional measurements, e.g. alignment, rotor position in bearing, temperature of stator.

7 Additional diagnostic techniques

The main emphasis of this part of ISO 13373 is a logical framework based upon experience. However, other diagnostic techniques are available, such as the following:

— artificial intelligence;

— knowledge-based;

— pattern recognition;

— neural networks.

These techniques are identified in ISO 13379-1.

8 Considerations when recommending actions

A number of factors will influence remedial or corrective actions including the following:

— safety;

— commercial;

— incorrect design.

Clearly, the appropriate action(s) for a particular diagnosis will depend on individual circumstances and it is beyond the scope of this part of ISO 13373 to make specific recommendations. Nevertheless, it is important for the diagnostic engineer to consider possible actions resulting from their diagnosis and the implications of those actions.

Recommended actions will depend on the degree of confidence in the fault diagnosis (e.g. has the same diagnosis been made correctly before for this machine?), the fault type and severity as well as on safety and commercial considerations. It is neither possible nor the aim of this part of ISO 13373 to recommend actions for all circumstances. Nevertheless, there are several questions that should be considered when recommending actions, some of which are indicated in A.3.

Annex A
(normative)

Process tables for the systematic approach to vibration analysis of machines

A.1 Initial questions

Initial questions which comprise information gathering and verification are summarized in Table A.1.

Table A.1 — Initial questions

Step	Description	Details	Next step
1	What is the machine type?	Establish the machine elements (driver, driven, coupling, bearings, fixed or variable speed, etc.) Is the practitioner familiar with this type of machine? Is there any operating experience of this or similar design of machine/plant? Where is the plant and what is the unit number?	2
2	Is there a machine integrity concern?	Is the machine operating now? Is it advisable to continue to operate? Is it advisable to restart the machine? Has a risk analysis taken place to assess whether the integrity of the machine will be maintained during continued operation while the diagnostic process is carried out?	3
3	Is there a vibration anomaly?	Can vibration data be obtained? What is the normal operating vibration behaviour of this machine?	4
4	How was the anomaly found?	Is there a vibration alarm? Did online vibration data show a significant change? Is there a significant deviation from a previous vibration survey? Was there an uncharacteristic noise from the machine? Did visual inspection show a defect, e.g. a gas/oil/steam/water leak?	5

Table A.1 *(continued)*

Step	Description	Details	Next step
5	Is the indicated vibration valid?	Check signal time/spectral characteristics. Are they as expected? Do they show symptoms of signal faults (e.g. zero output, DC offset, erratic low-frequency components)? Is the transducer mounting correct? Is the cable integrity acceptable? Is the signal conditioning operating correctly? Consider taking hand-held independent measurements, e.g. pedestal mounted or shaft rider. Check whether non-vibration symptoms are evident (e.g. oil/bearing temperature changes, shaft position changes, unusual noises, etc.). Is the vibration anomaly isolated to one transducer (see step 6)?	6
6	Is the vibration anomaly isolated to one transducer?	Check orthogonal directions Check other axial positions Compare pedestal and shaft vibration Inspect transducer and measurement chain Consider swapping channels or components of measurement chain	7
7	Is there a vibration severity concern?	How do the overall (broadband) vibration values compare with appropriate standards e.g. ISO 7919 or ISO 10816 zones. If these values are excessive (e.g. are within zones C or D) and abnormal then consider rapid plant action (subject to steps 5 and 6). If not then proceed to step 8.	8
8	Vibration signal characteristics: what is the signal content?	Overall magnitude (broadband) Amplitude and phase of the 1x component Amplitude and phase of the 2x component Spectral content of the signal and amplitude of other components (e.g. blade pass, rotor bar pass, subsynchronous frequencies) as appropriate for machine type Shaft position/shaft centreline/shaft orbit	9
9	Has this type of anomaly been observed before?	What was the experience gained, e.g. how long did the anomaly last, was the cause determined, was there a failure?	10

Table A.1 *(continued)*

Step	Description	Details	Next step
10	What are the timescales for the anomaly?	When did the anomaly occur? How long has the anomaly been present? How long did the change take to propagate e.g. was there a step change (e.g. within a few seconds?), was there a gradual change (e.g. minutes or hours)? Are the vibration characteristics still changing?	11
11	What were/are the machine operating conditions?	What were the machine operating conditions when the anomaly was found? What are the operating conditions now? Were/are these operating conditions normal? Were/are these within the design envelope?	12
12	Were there any operational changes leading up to the anomaly?	Are these operational changes normal? When were similar operational changes last carried out? Trend back to previous "healthy" state prior to any recent maintenance activities or changes in operational conditions. Is the response normal for these operational changes?	13
13	Were there any operational changes in response to the anomaly?	What was the machine response? Was this consistent with previous experience?	14
14	Can any non-vibration or operational parameter be correlated with the anomaly?	Investigate whether non-vibration parameters are correlated, e.g. speed, load, temperature, pressure, flow, position (axial expansion, thrust)	15
15	Have there been any recent maintenance activities?	Do these correlate with the anomaly? When were similar activities previously done and what was the vibration response?	16
16	Go to A.2 (step 17)		

A.2 Diagnostic questions

Diagnostic questions are summarized in Table A.2.

Table A.2 — Diagnostic questions

Step	Description	Details	Next step
17	Can vibration and operational parameters be trended back to previous occurrence of similar operational conditions?	Check overall, 1x amplitude/phase, 2x amplitude/phase, non-synchronous, blade passing frequency, rotor bar passing frequency components, etc. as appropriate for machine type.	18
18	Is vibration principally 1x and 2x (within 10 %)?	Check spectra and orders if available. If Yes: when no new vibration components are present proceed to step 19. Else go to step 22.	Y-19 N-22
19	Is there a step 1x vector change uncorrelated with operational changes?	If Yes: investigate further (e.g. check for step changes at different axial positions, different directions, pedestal and shaft vibration). Suggests sudden balance change (e.g. rotor material loss), machine movement (e.g. coupling, winding, keyway) or instrument change (e.g. tachometer adjustment). Else go to step 20.	Y-28 N-20
20	Is there a significant 2x vector change?	If Yes: investigate further. Can suggest a cracked shaft (e.g. check for 1x/2x amplitude/phase changes with time, higher order changes, changes in run-up/run-down response at resonance speeds for 1x to 4x), angular misalignment (e.g. check for axial vibration in anti-phase on bearings either side of coupling) or parallel offset misalignment (e.g. check for radial vibration in anti-phase on bearings either side of coupling). Else go to step 21.	Y-28 N-21
21	If the answers to steps 19 and 20 are No, investigate further.	Gradual change in 1x vector could indicate machine thermal sensitivity (e.g. check history), misalignment (does not always lead to 2x changes noted under step 20), rub (e.g. check for cyclic 1x amplitude/phase behaviour, check spectra for sub/super synchronous harmonics, check for truncated time waveform and orbit shape), mechanical looseness (e.g. check for lost motion across machine mounting interfaces) or cracked shaft (e.g. check for amplitude/phase changes with time, higher order changes, changes in run-up/run-down response at resonance speeds for 1x to 4x).	28
22	Are there harmonics of 0,33x, 0,5x or 1x present?	If Yes: investigate further. Suggests nonlinearity such as rub (e.g. check for cyclic 1x amplitude/phase behaviour, check spectra for 0,5x or 0,33x harmonics for machines running above 2nd or 3rd resonance speeds respectively, check for truncated time waveform and orbit shape,), mechanical looseness (e.g. check for lost motion across machine mounting interfaces, check for loose bearing fit showing multiple harmonics and erratic phase), signal saturation (e.g. check spectra and time waveform, check alternative instrumentation) or cracked shaft (e.g. check for changes in 1x to 4x harmonics, check for changes in run-up/run-down response at resonance speeds for 1x to 4x). Else go to step 23.	Y-28 N-23

Table A.2 *(continued)*

Step	Description	Details	Next step
23	If data are available, does vibration track at 0,4x to 0,47x during run-up/run-down?	If Yes: investigate further. Suggests fluid whirl instability. Check for changes in shaft centreline position, check for changes in oil pressure/temperature conditions for hydrodynamic bearings. Assess machine design and any recent modifications for likely sources of instability (e.g. hydrodynamic bearing design, steam gland design). Consider changes to operating conditions (e.g. load, hydrodynamic bearing temperature changes), which can affect stability. Else go to step 24.	Y-28 N-24
24	Is there a single frequency component at a resonance speed or harmonic?	If Yes: investigate further. Establish machine resonance speeds. If data are available, check if component remains at fixed frequency during run-up/run-down at speeds above the resonance speed. If so this suggests fluid whip instability. Check for changes in shaft centreline position, check for changes in oil pressure/temperature conditions for hydrodynamic bearings. Assess machine design and any recent modifications for likely sources of instability (e.g. hydrodynamic bearing design, steam gland design). Consider changes to operating conditions (e.g. load, hydrodynamic bearing temperature changes), which can affect stability. An alternative possibility is a structural resonance whose frequency would typically not change during run-up/run-down even below the first resonance speed (this could be confused with fluid whip if resonance speeds are not known or well-defined). Else go to step 25.	Y-28 N-25
25	Is there evidence of low-frequency signal noise?	Check spectra and time waveforms. If Yes: this suggests a signal fault. Check transducer, cabling, signal conditioning equipment, etc. Else go to step 26.	Y-28 N-26
26	Is there evidence of high-frequency components for a pump (e.g. blade pass frequency or harmonics)?	If Yes: investigate further. If high-frequency components (e.g. blade pass frequency or harmonics) have changed without changes in operational conditions or maintenance activities, then this suggests possible impeller/diffuser wear or flow path obstruction (e.g. check for fall-off in hydraulic performance). If the machine has started to exhibit changes across a broad band of high frequency components then this suggests possible cavitation (e.g. check for presence of "growling" noise from pump). Else go to step 27.	Y-28 N-27
27	Is there evidence of high-frequency components for an electrical machine?	If Yes: investigate further. For example, for a squirrel-cage induction motor, take zoom spectra to establish presence of twice slip frequency sidebands about 1x, 2x, rotor bar pass frequency and also about twice supply frequency sidebands centred on the rotor bar pass frequency. Presence of twice slip frequency sidebands suggests possible rotor cage defects.	28
28	Go to A.3		

A.3 Considerations when recommending actions

This Clause is concerned with assessing the risk before recommending actions once a diagnosis has identified faults. Recommended actions will depend on the degree of confidence in the fault diagnosis (e.g. has the same diagnosis been made correctly before for this machine?), the fault type and severity as well as on safety and commercial considerations. It is neither possible nor the aim of this part of ISO 13373 to recommend actions for all circumstances. Nevertheless, there are several questions that should be considered when recommending actions, some of which are indicated below.

a) Instrument faults

   Can the instrument be repaired or replaced with the machine in service?

   Can alternative instrumentation be fitted?

   Can the machine condition be adequately determined from the valid signals that remain?

   Can repair/replacement wait until a scheduled outage or does the machine duty and any known operational risks require immediate intervention?

b) Less severe or undiagnosed machine faults

   Can an enhanced condition monitoring scheme be adopted to determine any further deterioration in condition while further investigations are being carried out?

c) More severe or diagnosed machine faults

   What is the machine's safety duty?

   What is the machine's commercial duty?

   What are the safety/commercial/environmental consequences of the machine failing in service?

   Is there machine redundancy?

   Are there spare machines available if failure occurs?

   Can effective operational changes be made (e.g. load, speed, temperature changes) to mitigate the fault effects?

   When is the next scheduled outage to repair/replace the machine?

   Is there previous experience of the same fault on the same machine type?

   Can an enhanced condition monitoring scheme be adopted to determine any further deterioration in condition?

   Can the machine be run to the next scheduled outage without unacceptable risk of the machine failing in service?

   Can the machine be taken out of service in a controlled way to avoid worsening the fault condition?

Annex B
(informative)

Installation faults common to all machines

B.1 Flowchart for vibration diagnostics of installation faults

This Annex describes the diagnosis process of installation faults. These faults are common to all machines. The flowchart in Figure B.1 is meant to be a guideline to the diagnosis process and is not meant to be comprehensive.

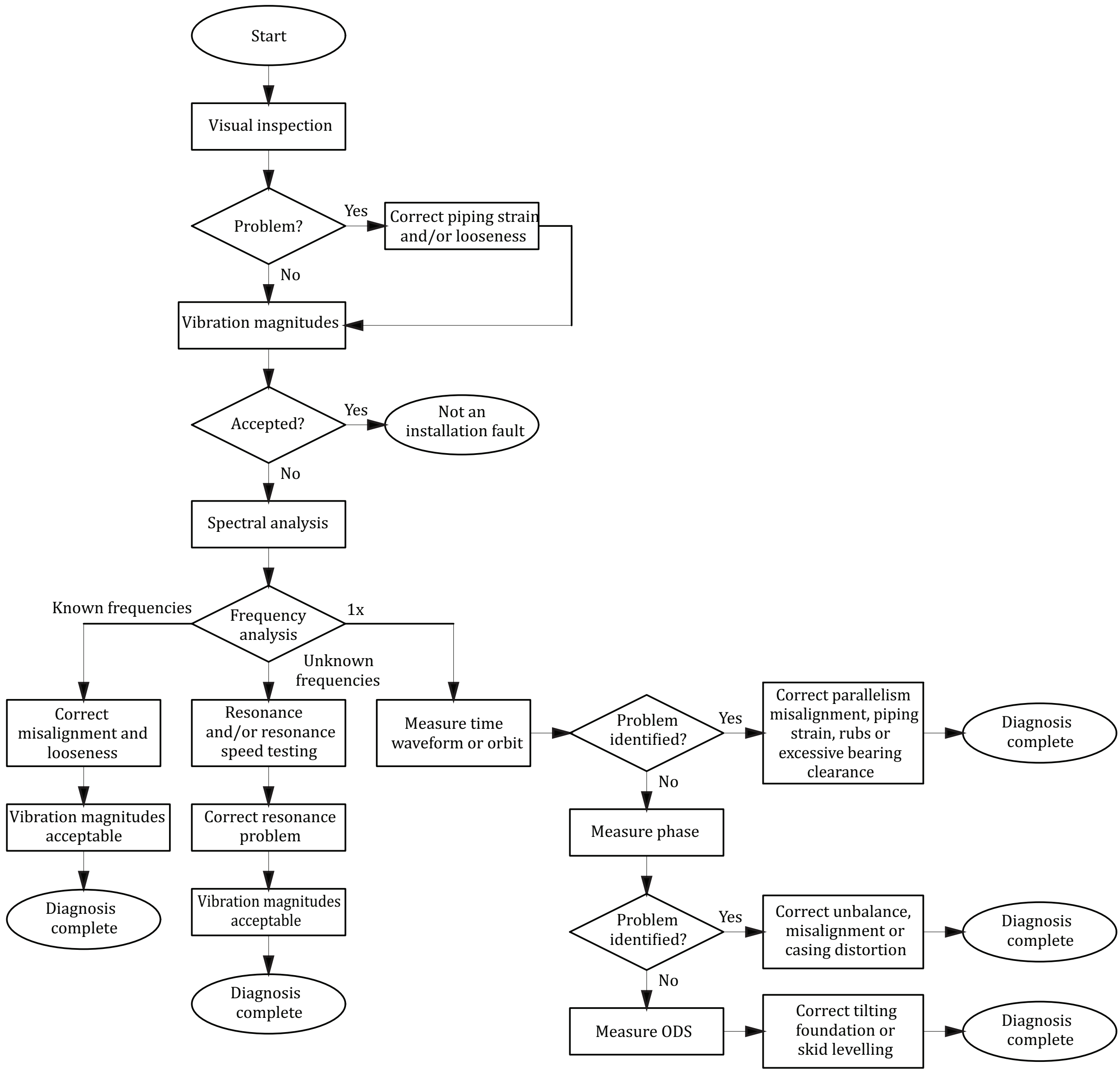


Figure B.1 — Flowchart for the diagnosis of installation faults

B.2 Methodology

B.2.1 General

The recommended methodology is illustrated in Figure B.1. It is recommended that the methodology for diagnosis of installation problems consists of visual inspection and spectral analysis[2] as the main components of the testing of the installed machine. In addition, resonance testing,[3] time waveform analysis, orbit analysis, phase analysis and operational deflection shape (ODS)[4] analysis are used if and when judged necessary.

B.2.2 Visual inspection

It is recommended that before any testing of installed machinery be performed, a visual inspection of the machine and the site be completed.

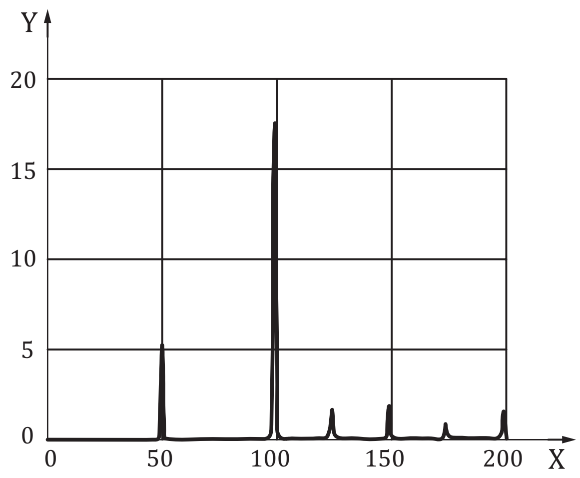
B.2.3 Vibration magnitudes

Vibration magnitudes should be measured and compared to appropriate International Standards. If the magnitudes are within limits, then this needs not to be an installation fault.

B.2.4 Spectral analysis

Order analysis over the entire operating range and spectral analysis are the core of the diagnosis of rotating machinery. However, this can be machine dependent. Spectral data are usually taken as velocity data, but also as acceleration data for high-speed machines and as displacement data for compressors and low-speed machines.

These spectral data should be measured on all bearings on the driver and driven machine, in all three directions, horizontal, vertical and axial, as appropriate. Complete knowledge of the machine should be available to identify characteristic frequencies. The purpose of the spectral analysis is to identify the frequencies causing the machine to vibrate. If all vibration amplitudes are within acceptable limits,[5] then the machine would be accepted as normal. However, if any of the spectral components has a high amplitude, then spectral analysis is used to correlate the frequency of the high-amplitude vibration to a machine frequency.



Key

X frequency in Hz

Y vibration velocity magnitude in vertical direction in mm/s

Figure B.2 — Misalignment in a pump [2]

The result of the spectral analysis of the high-amplitude vibration is one of three cases:

a) at 1x running speed frequency

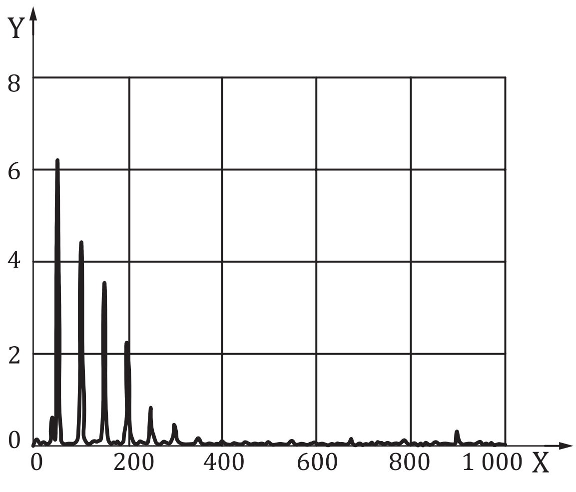
There are many machine-related problems that lead to high 1x vibration. Amongst these faults are rotor mechanical and thermal unbalance, piping strain and skid levelling. In this case, special vibration measurements have to be conducted on the machine to describe the nature of this 1x vibration, and to distinguish between the different 1x faults. These measurements include: time waveform measurement, phase measurement and measurement of the operational deflection shape (ODS).

b) at a frequency other than running speed (1x) that can be related to a known cause

Examples include misalignment which can be at pure 1x, or 1x and 2x (see Figure B.2), or even 3x. Another example is decreasing amplitude of harmonics of the running speed in the spectrum (see Figure B.3). This spectrum shape is usually correlated with looseness in the bearings or mounting skid.

c) at a frequency that cannot be related to commonly known machine defects

In such cases, additional testing is required to determine the source of these frequencies. This could include resonance testing (including impact test and transient testing), modal testing and flow characteristics testing, see Figure B.4 a) to d). The purpose of the resonance testing is to correlate the observed frequency to natural frequencies (stationary components) or resonance speeds (rotating components) of the machine. Modal testing is a more advanced form of resonance testing, where all the modal characteristics of the machine are determined, including natural frequencies, damping ratios, and mode shapes. Modal testing is rarely used in the field, as it is an elaborate testing method, and is usually time consuming and costly. However, when justified, it can be a very powerful tool to obtain the machine characteristics and identify clearly the observed frequency in the spectrum, and suggest a solution to the problem. As for the flow characteristics testing, it is always a good idea to make sure that the rotating machine is operating at or near the best efficiency point, otherwise higher vibration amplitudes are to be expected. This is the case for recirculation and cavitation in pumps, and stall in compressors, for example.



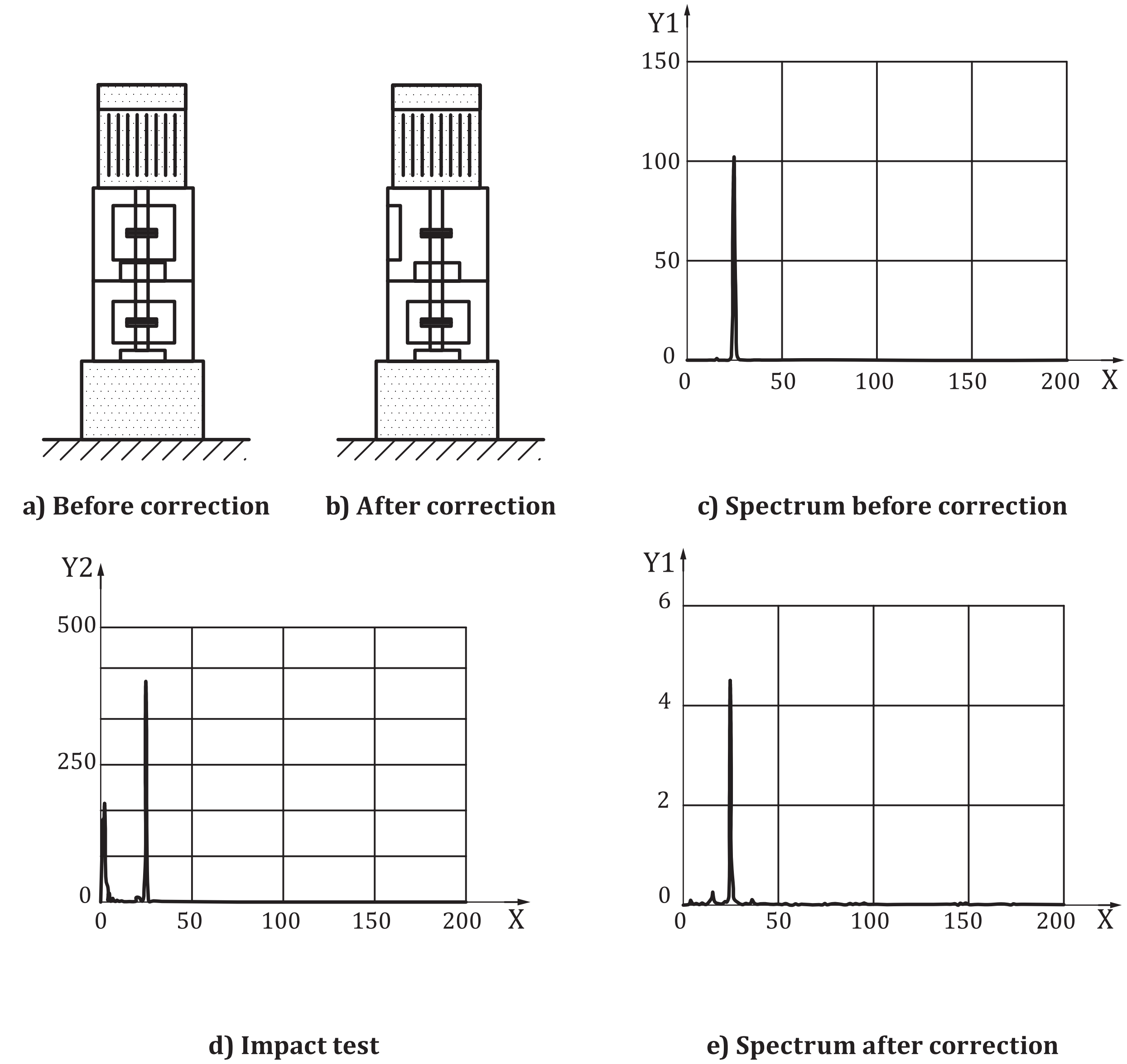
Key

X frequency in Hz

Y vibration velocity magnitude in horizontal direction in mm/s

Figure B.3 — Looseness in a motor bearing [2]

The most difficult case occurs when the spectral analysis reveals high 1x vibration. There are many faults, related to installation problems, that lead to high 1x vibration. Amongst these faults are unbalance, misalignment, casing distortion, tilted foundation, skid levelling, piping strain and excessive bearing clearance. In this case, special vibration measurements have to be conducted on the machine to describe the nature of this 1x vibration, and to distinguish between the different 1x faults. These measurements include: time waveform measurement, phase measurement, and measurement of ODS.



a) Before correction **b) After correction** **c) Spectrum before correction**

d) Impact test **e) Spectrum after correction**

Key

X frequency in Hz

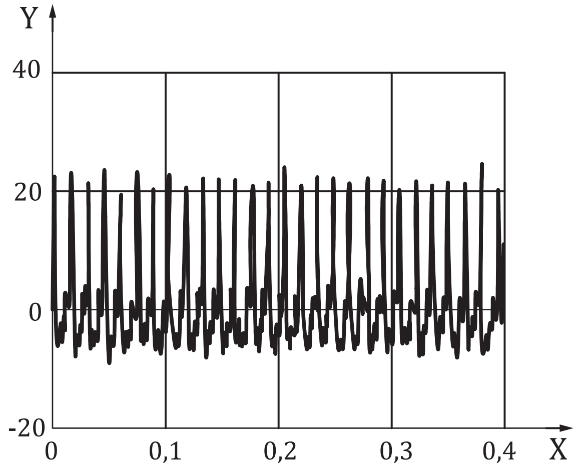
Y1 vibration velocity magnitude in vertical direction in mm/s

Y2 energy spectral density in nm/s

Figure B.4 — Resonance testing of a vertical pump

B.2.5 Time waveform analysis

The time-waveform measurement can be used to distinguish between misalignment (see Figure B.5), piping strain (see Figure B.6) and excessive bearing clearance (see Figure B.7). For piping strain, it is quite clear that the forcing on the machine is directional, usually in the horizontal direction, and this directional force is acting on the whole machine. Inappropriate bearing clearance also results in directional forces. However, this is localized at the bearing with the inappropriate clearance. This is particularly true for special geometry bearings, such as elliptical or multi-lobe bearings.

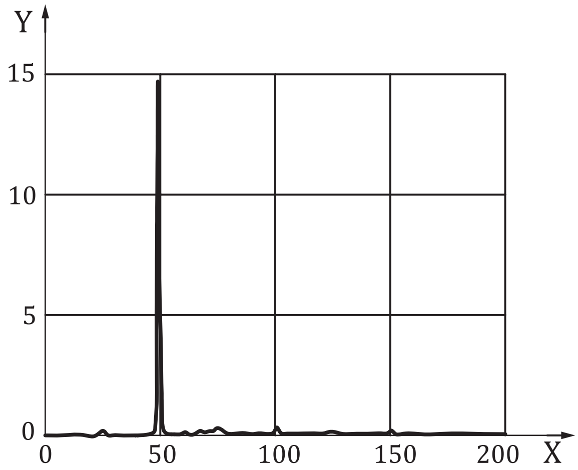


Key

X time in s

Y vibration displacement in horizontal direction in µm

Figure B.5 — Time waveform for misalignment [2]

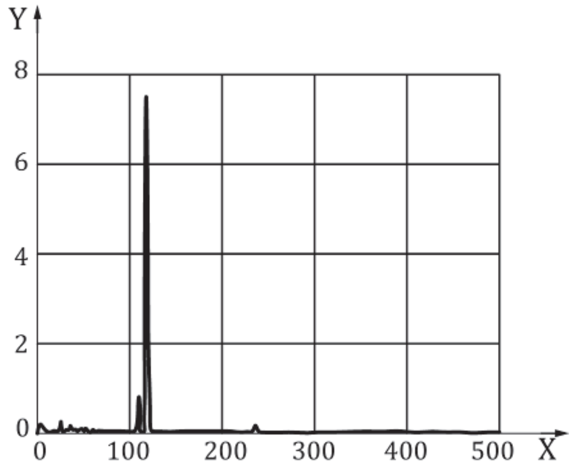


Key

X frequency in Hz

Y vibration velocity magnitude in vertical direction in mm/s

Figure B.6 — Directional spectrum of piping strain [2]



Key

X frequency in Hz

Y vibration velocity magnitude in vertical direction in mm/s

Figure B.7 — Inappropriate bearing clearance [2]

B.2.6 Phase analysis

The phase analysis is used to diagnose common installation anomalies like unbalance, misalignment, bent shaft and casing distortion. The following examples show the use of phase information for diagnosis.

a) If there is a 180° radial phase shift across the coupling, then usually the problem is misalignment. If no radial phase shift occurs across the coupling, then usually the problem is unbalance. However, in a few cases, if a node of the mode shape occurs at the coupling, then the interpretation of the radial phase information has to be re-evaluated. It should be noted that the 180° axial phase shift across the coupling is a good indicator of misalignment.

b) Casing distortion can be identified by 180° phase shift across the machine (side-to-side or end-to-end) in the horizontal, vertical and/or axial directions.

c) When a rotor has a resonance speed there will be theoretically a 180° phase shift when it runs through this (see Figure B.3). In reality, due to damping and other resonance speeds, the phase shift is less than 180°.

A cocked bearing can be identified by measuring phase around the bearing housing and noticing the phase shift due to the wobbly action of the cocked bearing. In many cases a coupled time-waveform-phase analysis is quite useful in visualizing the vibration pattern and identifying the problem.

B.2.7 ODS analysis

If the 1x vibration problem is still not solved after the time waveform and phase analysis, then an operational deflection shape (ODS) should be measured. The ODS is useful in identifying problems of tilted foundation (see Figure B.8), skid levelling (see Figure B.9), skid looseness, and shaft parallelism. In the ODS measurement, phase-referenced 1x vibration is measured at grid points on the machine structure or skid. This reveals the actual deflection shape of the machine under the operating load, and at the operating speed. Note that the ODS is not a mode shape of the machine or structure, unless the machine is in resonance, but it can be considered as a summation of the contributions of all of the modes of vibration. ODS analysis can be quite useful in identifying installation problems, as it provides a visualization of the actual vibration pattern of the machine and/or skid. In particular, if a machine skid exhibits a node in its ODS, then this is a clear indication of a tilted foundation or a levelling problem in the skid. Accurate measurement of skid and/or foundation levels would then be required to confirm the results of the ODS analysis.

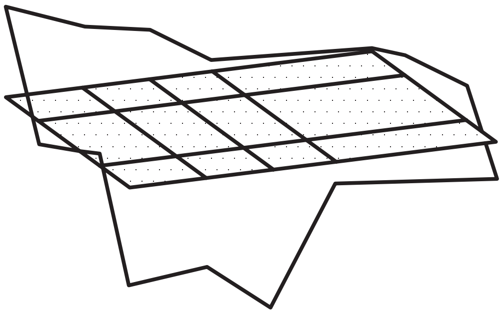


Figure B.8 — Tilted foundation [2]

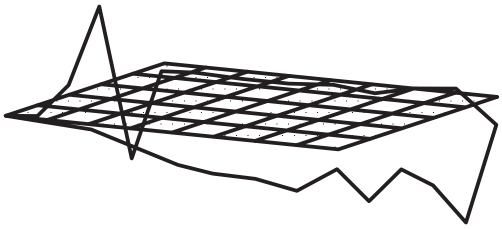


Figure B.9 — Skid levelling [2]

Table B.1 — Fault table for installation faults

Fault	Vibration characteristics	Other descriptors	Comments
Misalignment/ concentricity errors	1x or 1x and 2x, sometimes 3x	Directional force 180° phase shift across coupling	Align machine
Looseness	Usually decreasing harmonics of running speed	Looseness can be at bearings or skid, or anchor bolts. Use phase to discern position of looseness	Tighten machine bolts
Bearing clearance	1x, with small harmonics	Directional	Repair or replace bearing
Piping strain	1x	Directional, wave clipping in time waveform	Piping flanges should match without jacking
Soft foot	1x, plus 2x supply frequency	Soft foot test	Relieve soft foot
Rubbing	Clipping in time waveform, rotating vectors (spiral vibration)	Can produce backward whirl	Relieve rubbing
Unbalance	1x	0° phase shift across coupling	Balance machine
Bent shaft	1x particularly at low speed	Can cancel with unbalance at particular speeds	Call manufacturer
Casing distortion	1x, sometimes 2x	180° phase shift from end to end	Relieve distortion
Resonance	High vibration at a particular frequency	Resonance testing indicates natural frequency	Change speed, stiffen machine or add mass. Sometimes damping can be needed
Tilting foundation	ODS usually at 1x	Rocking motion in ODS	Need civil engineer to resolve issue
Skid levelling	ODS usually at 1x	Slight slope in ODS, can exhibit a node	Level skid

Annex C
(informative)

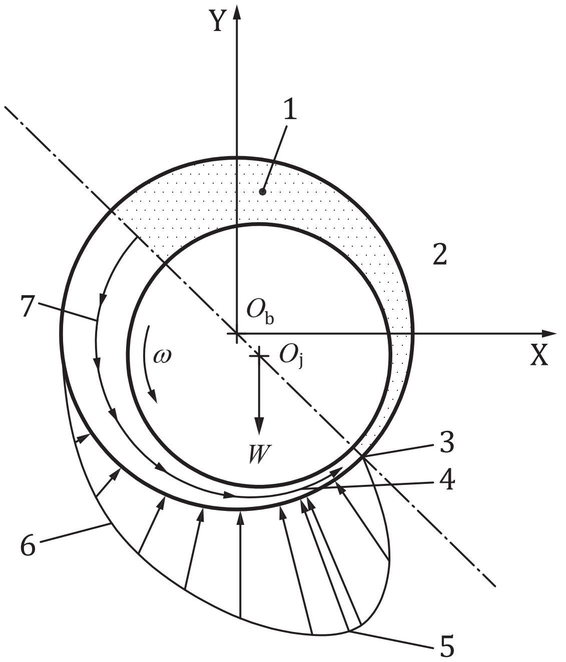
Diagnosis of radial hydrodynamic fluid-film bearings

C.1 Background

Bearings are part of the support system for a rotating element. Hydrodynamic fluid-film bearings support the journal on a cushion of fluid, usually oil, generated through the dynamic action of dragging the fluid through a wedge or wedges. Figure C.1 shows this oil wedge.

The bearings comprise only a portion of the machine but they are significant elements which provide significant stiffness and damping components. In some cases problems can appear due to bearing instability.

Hydrodynamic bearings provide support for both rigid and flexible rotors and for rotors operating above or below a natural frequency. The flexibility of the bearing's support (pedestal supporting the hydrodynamic bearing or flexibility of the foundation of the pedestal) can vary greatly depending upon machine design or deterioration with time.



Key

1	divergent cavitated film
2	bearing
3	minimum film thickness
4	maximum film temperature
5	maximum pressure
6	hydrodynamc pressure profile
7	converging oil wedge
O_b	origin of bearing
O_j	origin of journal
W	weight
ω	rotation

NOTE Equilibrium exists if $\Sigma F_x = 0$ and $\Sigma F_y = W$.

Figure C.1 — Oil wedge in a hydrodynamic bearing

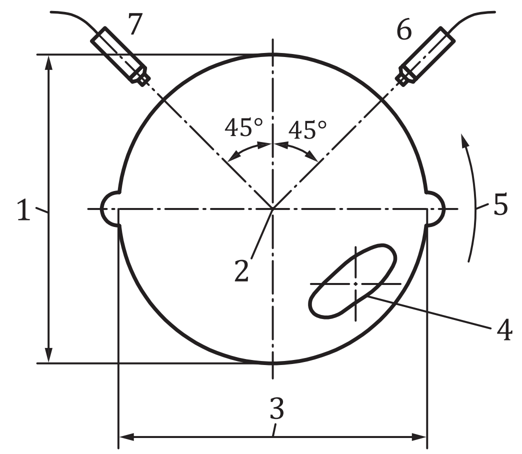
C.2 Important measurements

Two important measurements are the shaft centreline position and the orbit.

Measuring the position of the journal in the bearing requires two non-collinear shaft relative position measurements; usually this is accomplished using an orthogonal pairing of shaft relative transducers as in Figure C.2. The 45° off vertical positions shown in Figure C.2 are often preferred for practical reasons of assembly and disassembly, see ISO 10817-1.

The shaft centreline position measured within the bearing is a time-averaged position resulting from the DC components of the two signals from the shaft relative probes (see Figure C.3) while the orbit is essentially the plot of the AC components of the two signals (see also Figure C.3). In fact, Figure C.3 shows both the shaft centreline and the orbit within the clearance circle.

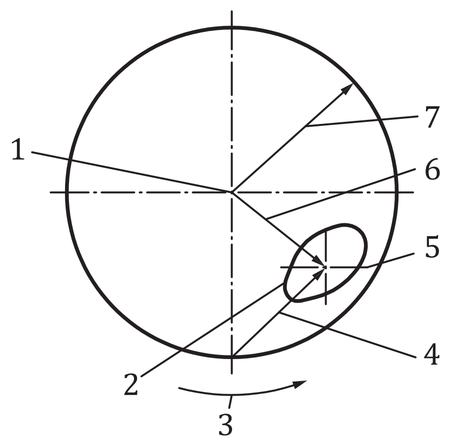
The position information includes the effects of shaft vibratory motion. For example, the orbit plot of a shaft exhibiting oil whirl at large amplitude can essentially fill the bearing clearance envelope resulting in an average position close to the bearing centre.



Key

1 vertical clearance
2 bearing centre
3 horizontal clearance
4 shaft orbit
5 counter-clockwise rotation
6 probe 2
7 probe 1

Figure C.2 — Measuring with orthogonal shaft relative probes



Key

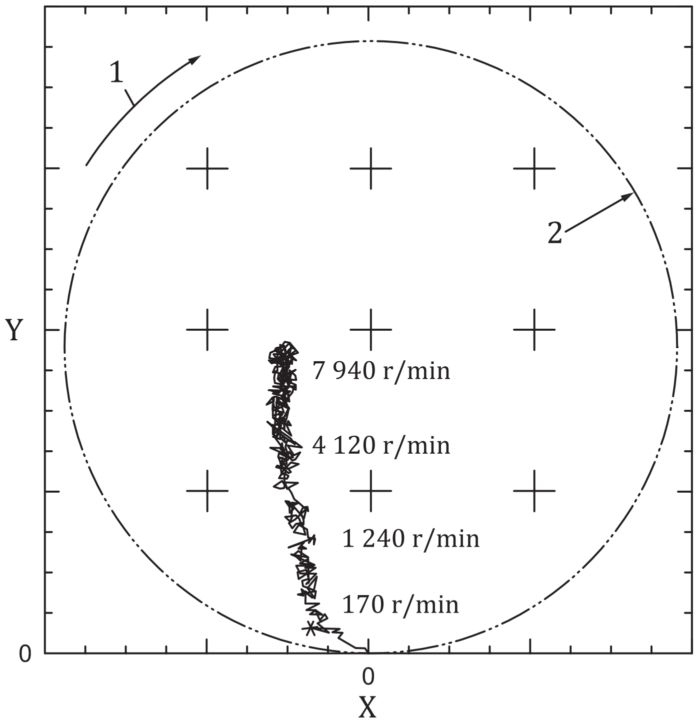
1 bearing centre
2 shaft orbit
3 counter-clockwise rotation
4 shaft centreline shift vector
5 shaft centreline position
6 eccentricity vector
7 bearing radial clearance

Figure C.3 — Characteristic vibration and position shift in a bearing

Figure C.4 depicts the change of the position of the shaft centreline with increasing speed. This is usually affected by the bearing loading. Operating in a position where the shaft centreline is close to the clearance circle (i.e. low speed, high eccentricity and/or high bearing loading) can result in rubbing, while operating with the shaft centreline close to the bearing centre (i.e. high speed, low eccentricity and/or low bearing loading) can result in unstable operation.

The loading can change due to forces inside the machine such as gear loads and pressures from the process fluid. Alignment changes also affect the loading on the bearings. Using shaft relative probes that can discern position as well as vibration provides a means to investigate issues resulting from or in changes to the bearing loading.

For vertical machines, due to the lack of gravity load on the bearing, the shaft centreline position is not uniquely defined, and the machine requires special attention, e.g. pre-loading of bearings.



Key

X horizontal position

Y vertical position

1 clockwise rotation

2 bearing clearance circle

Figure C.4 — Shaft centreline plot

Other important measurements are bearing temperature and casing vibration. Temperature detectors are often embedded in the bearing. Changes in load can be seen with these types of detectors. Ideally, the temperature detector(s) are installed near the point of expected maximum temperature; tilting pad bearings might use temperature detectors in multiple loaded pads. Wider bearings might have temperature measurements on either side of the bearing centreline. Given the location of these temperature detectors, redundant configurations can be appropriate.

Depending upon the type of machine and bearing support system, casing vibration measurements can be required to help investigate the problem. As with the shaft relative transducers, these can be part of the permanent instrumentation or can be added for testing purposes. While there are rules of thumb to suggest when to use these, the best way to determine the need is to take a sample of the vibration. For a test, even if it results in little casing motion, it can be prudent to capture these measurements. See ISO/TR 19201 for a discussion when to use casing vibration measurements.

C.3 Vibration in a fluid-film bearing

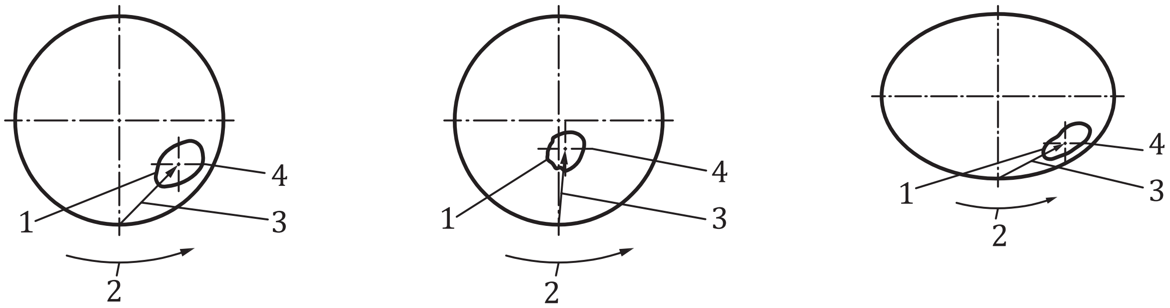
Figure C.5 shows typical expected vibration and position patterns for various bearings. The plain bearing and elliptical bearing are fixed arc bearings. The tilting pad bearing has pads that have either a sliding or rolling pivot.

NOTE Similar to this are the flex pivot bearings with a flexible element controlling the tilting of the pad.

Figure C.5 shows typical vibration, but actual vibration can vary from these drawings. In general elliptical bearings have lower horizontal stiffness, and one would expect a larger horizontal vibration compared to the plain journal bearing; however, support stiffness can alter this.

The tilting pad bearing is identified as a load-on-pad bearing. The plot shows some variation from a straight vertical rise for the shaft centreline position. This can result from not having a purely vertical force on the bearing due to gravity, or as research has shown sliding pivots (ball and socket type pivots) can generate this effect.

Of note, a load-on-pad tilting pad bearing will usually have greater asymmetry between the horizontal and vertical stiffness. Load-between-pad tilting pad bearings can have a more round orbit due to greater similarity in the horizontal and vertical stiffness of the bearings; support stiffness asymmetry can alter this greatly.



a) Plain journal bearing **b) Tilting pad bearing — Load on pad** **c) Elliptical bearing**

Key

1 shaft orbit

2 counter-clockwise rotation

3 shaft centreline shift vector

4 shaft centreline position

Figure C.5 — Typical patterns of vibration and position characteristics

The stationary support for the bearing reacts to forces transmitted by the oil film. The resulting vibration is measured generally using casing mounted transducers. A radial bearing support with no thrust bearing can vibrate in three orthogonal directions, and as such one might conduct a preliminary survey or as part of the test plan in three directions to determine this.

Torsional vibration can couple to lateral vibration particularly at a gear. Knowledge of torsional natural frequencies and excitations can help when analysing a machinery train with a gear element.

Other fault conditions are possible depending upon the machine. A list of possible fault conditions is given in Table C.1.

C.4 Diagnosis process for fluid-film bearings

C.4.1 General

Figure C.6 shows the diagnosis flowchart for rotors supported by fluid-film bearings, while Table C.1 shows the fault table for faults associated with fluid-film bearings.

C.4.2 Overall vibration

If an anomaly has been detected, the first step is to check the relative shaft vibration at the bearing as defined in ISO 7919-1. If vibration magnitudes are not high, then the shaft averaged centreline position needs to be checked. If not suitable then consider: cocked bearing, misalignment, thermal growth, bearing over/under load, or bearing wear.

C.4.3 1x vibration

Table C.1 includes the expected faults for high 1x vibration.

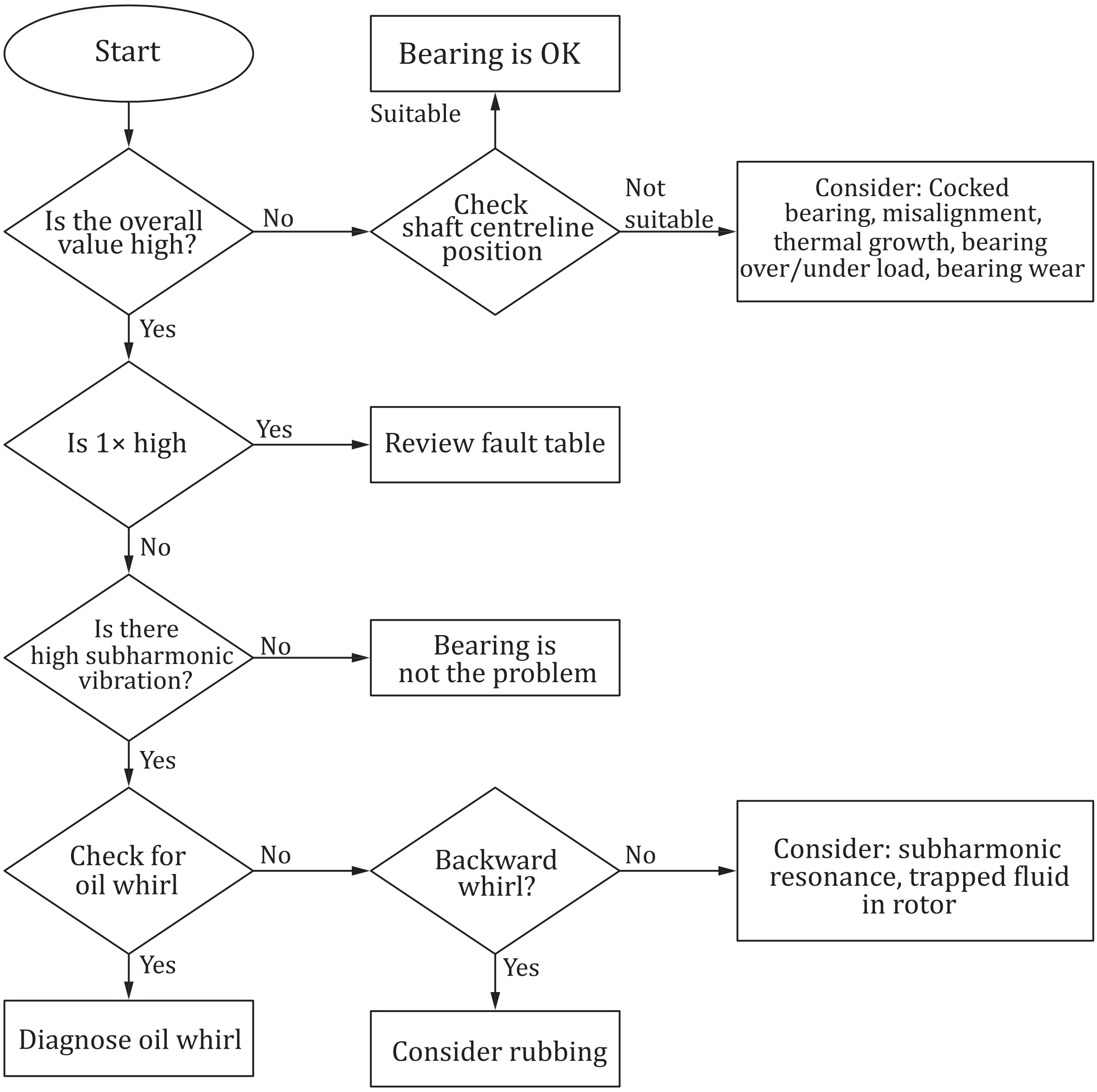


Figure C.6 — Fluid-film bearing diagnosis flowchart

Table C.1 — Fluid-film bearing fault table

Condition	Measurement conditions	Initial rate of change	Major frequency component of changed vibration magnitude	Subsequent behaviour of vibration with time	Effect on resonance speed	Repeatability	Comments
Clearance increase	Increase in 1x, if near resonance, could result in decrease in 1x	Gradual	Initially 1x amplitude and phase	If clearance opens greatly, harmonics or subharmonics can appear; instability (whirl or whip) is possible depending upon the rotor system	Lowers if perceptible	Yes, depending upon mechanism; clearance can open for a variety of reasons, even on turning gear	Generally, causes a decrease in stiffness, which affects vibration; effective damping can increase, might not notice
Loss of babbitt	Vibration or temperature can change	Depends upon the degree of loss	1x, but harmonics, subharmonics, or instability are possible	Increase in symptoms	Can reduce		Babbitt deterioration can interfere with oil flow and can lead to catastrophic failure of the bearing
Oil carbonization	Shaft relative	1x saw-tooth like behaviour over several weeks	1x	Cyclic		Repeatable	It can increase vibration due to rubbing of bearing seals
Bearing loose in housing	Shaft relative and shaft absolute measurements applicable	Probably results from installation or maintenance issues	1x or harmonics/subharmonics Can lead to instability or rubbing Directionality can be present		Response level significantly changed		Affects overall support dynamic stiffness, which can result in instability or rubbing
Cocked bearing	Vibration sensors, temperature	Results from installation or maintenance	Directionality can be present				Clearance is uneven across the bearing; can result in rubbing

Table C.1 *(continued)*

Condition	Measurement conditions	Initial rate of change	Major frequency component of changed vibration magnitude	Subsequent behaviour of vibration with time	Effect on resonance speed	Repeatability	Comments
Morton effect/ rubbing in bearing seals	Shaft relative, particularly also casing	Steady changes to 1x with eventual steady increase to 1x (produces circles in polar plot)	1x, 2x	Vibration can exceed set points	If above resonance, large response during coast-down with possibility of rubbing	Not always	Often thought of as a bearing issue, but the rotor system involved does affect this
Alignment	Shaft relative, temperature, shaft position, casing	1x, shaft centreline position or change of position while coming to thermal equilibrium Elongated or flattened orbit 2x, possibly other harmonics	1x	Temperature can trend across bearings in opposite directions as might shaft positions. Shaft can ride at an unusual attitude angle or eccentricity Can result in unloading bearing and instability	Can increase or decrease	Yes Operating conditions that affect component temperatures can correlate	Couplings and shaft asymmetric features like keyways can introduce 2x vibration. Non-linearities can result in 2x or other harmonics. Can take large misalignment Can lead to bearing failure
Bearing installed backwards	Vibration, temperature	Unusual vibration, could result in instability, 1x, or rubbing Pad operation in a tilting pad bearing can be impaired for offset pad designs Can run hot; oil flow can be disturbed					Mechanical design should eliminate this possibility but does not always Many bearings will not operate correctly if installed backwards or rotated from the correct orientation

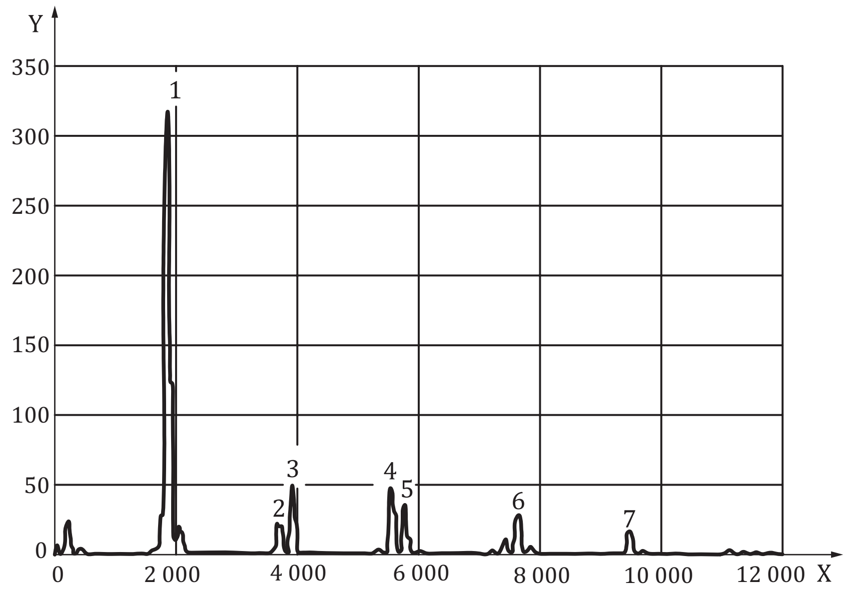
C.4.4 Subharmonic vibration

Subharmonic vibration can take the form of forward or backward whirling motions.

The most common forward subharmonic vibration problem is oil whirl/oil whip. The oil whirl is a self-excited vibration in the fluid-film bearing at a frequency less than 0,5x. This can be a benign vibration. During start-up an oil whirl component can appear and continue as the machine speed increases. The oil whirl usually disappears as the machine reaches its first resonance speed. Oil whirl can reappear after crossing the resonance speed. When the oil whirl frequency reaches the frequency value of the first resonance speed, oil whip occurs. Figure C.7 shows a typical oil whip spectrum.[5] This is the instability that results in the limit-cycle condition and would result in violent vibrations. If the machine speed increases further, the oil whip frequency will remain at the first resonance speed frequency.

Other possible causes of forward subharmonic vibration include trapped fluid in hollow shafts or couplings which can occur at a frequency between 0,6x to 0,95x, and a subharmonic resonance can occur if a subharmonic frequency coincides with a natural frequency.

In addition backward subharmonic vibration can occur, which usually relates to external loops in the orbit; in this case, rubbing should be considered.



Key

X frequency in cycles per minute
Y peak-to-peak vibration displacement in µm
1 1x oil whip component (locked at first resonance speed)
2 second resonance speed
3 2x oil whip component
4 3x oil whip component
5 service speed 5 800 r/min
6 4x oil whip component
7 5x oil whip component

NOTE After Reference [5].

Figure C.7 — Typical oil whip spectrum

Annex D
(informative)

Diagnosis of rolling element bearings

D.1 General

Rolling element bearings are one of the most common support components of rotating machinery. Rolling element bearings consist of an inner race, an outer race, and a number of rolling elements that are guided by a cage.

Bearing faults can be detected by vibration analysis followed by diagnosis performed by spectrum analysis identifying the bearing fault frequencies, which are

a) ball pass frequency of the outer race (BPFO), which appears when all the rolling elements pass on a defect on the outer race,

b) ball pass frequency of the inner race (BPFI), which appears when all the rolling elements pass on a defect on the inner race,

c) ball spin frequency (BSF), which is the circular frequency of each rolling element as it spins, and

d) fundamental train frequency (FTF), which is the frequency of the cage.

These frequencies can be calculated as follows:

$$\mathrm{BPFO} = \frac{N}{2}\left| f_{\mathrm{o}} - f_{\mathrm{i}} \right| \left(1 - \frac{B}{P}\cos\phi \right) \tag{D.1}$$

$$\mathrm{BPFI} = \frac{N}{2}\left| f_{\mathrm{o}} - f_{\mathrm{i}} \right| \left(1 + \frac{B}{P}\cos\phi \right) \tag{D.2}$$

$$\mathrm{BSF} = \frac{P}{2B}\left| f_{\mathrm{o}} - f_{\mathrm{i}} \right| \left[1 - \left(\frac{B}{P}\right)^2 \cos^2\phi \right] \tag{D.3}$$

$$\mathrm{FTF} = \frac{f_{\mathrm{o}}}{2}\left(1 + \frac{B}{P}\cos\phi \right) + \frac{f_{\mathrm{i}}}{2}\left(1 - \frac{B}{P}\cos\phi \right) \tag{D.4}$$

where

f_{o} is the outer race rotational frequency (Hz) or rotational speed (r/min);

f_{i} is the inner race rotational frequency (Hz) or rotational speed (r/min);

N is the number of balls or rollers;

B is the diameter of ball or roller;

P is the pitch diameter of rollers or balls;

ϕ is the contact angle.

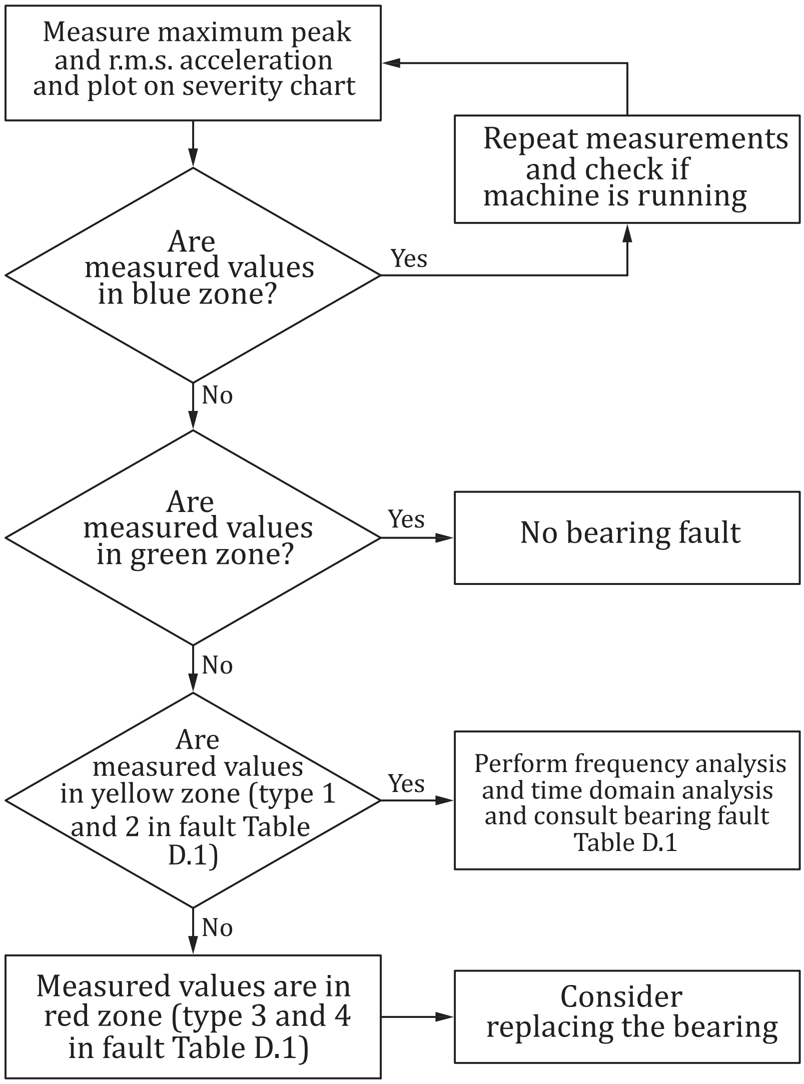
D.2 Diagnosis methodology

D.2.1 General

The methodology consists of detecting bearing faults by using acceleration measurements in the 10 Hz to 10 kHz band (see flowchart Figure D.1 and severity chart Figure D.2). This process is to guide the decision-making regarding the bearing condition. The measurement of 4 kHz and 8 kHz octave bands are referred to in the fault Table D.1. Also, other techniques requiring high-frequency measurements up to 40 kHz, and even higher, are used to obtain the amplitude-demodulated spectrum referred to in Table D.1.

D.2.2 Diagnostic flowchart

Figure D.1 shows the flowchart for rolling element bearing diagnostics. The maximum peak acceleration detects shock-related defects while the r.m.s. acceleration detects friction-related defects.



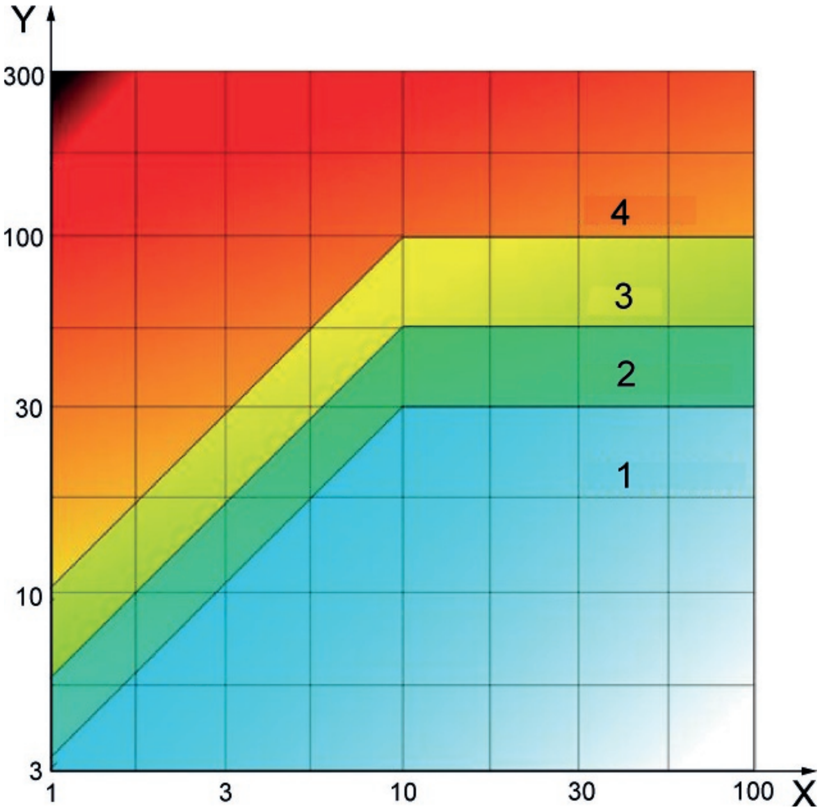
NOTE The coloured zones are defined in the severity chart in Figure D.2.

Figure D.1 — Rolling element bearing diagnostic flowchart

D.2.3 Severity chart

On the severity chart in Figure D.2, when the maximum peak and r.m.s. acceleration are too high, the rolling element bearing is in bad condition (red zone), when the maximum peak and r.m.s. acceleration are low (green zone) the rolling element bearing is in good condition. When in the yellow zone, the condition of the rolling element bearing is doubtful. The blue zone indicates possible measurement errors, so a repetition of the measurement is recommended.

This severity chart is not recommended on gearbox-driven machines or other machines where strong background noise is usually present.



Key

X r.m.s. acceleration (total value from 10 Hz to 10 kHz) in m/s^2

Y maximum peak acceleration in m/s^2

1 Unrealistically low[a]

2 Normal

3 Alert

4 Alarm

[a] Repetition of measurement recommended.

Figure D.2 — Rolling element bearing severity chart

Table D.1 — Fault table

Fault	Type of fault	Recommended measurement technique(s)	Symptom(s) in the vibration signal	Fault severity	Explanation (causes, origin, prognosis)
		Type 0 faults			
Misalignment of inner and outer race	Installation, improper loading	Baseband spectrum, amplitude demodulated spectrum of friction forces	Narrow-band spectrum 2x RPM random friction forces modulated by 2x RPM increase in axial direction	Low	Misalignment of the races
Excessive radial load	Improper loading	Baseband spectrum, amplitude demodulated spectrum of friction forces	Narrow-band spectrum 1x RPM random friction forces modulated by 1x RPM	Low	Unbalance, misalignment
Slip of inner race	Installation, manufactur-ing, improper loading	Amplitude demodulated spectrum of friction forces	Random friction forces modulated by 1x RPM and harmonics	High	This can cause excessive heat and lead to rapidly to breakdown
Insufficient clearance and overexpansion of the rolling elements	Installation, improper loading, improper operating conditions Environmental	Baseband spectrum, amplitude demodulated spectrum	2x BSF in the baseband spectrum and in the friction spectrum	High	Bearing can overheat
Lubrication defect	Insufficient or overgreasing	Broadband measurement	Increase in friction forces in the high frequency region (mostly 8 kHz octave band)	High	Can cause an increase in bearing temperature
Contamination	Foreign material (liquid or solid particles)	Broadband measurement	Increase in friction forces in the high frequency region (mostly 8 kHz octave band)	High	Can cause abrasion of the surfaces or improper operation inside the bearing
Poorly shaped (or looseness) of the bearing housing	Installation, manufacturing	Time domain, time-frequency domain, baseband spectrum, amplitude demodulated spectrum	Will generate shocks at 1x RPM and a few harmon-ics or BSFs and harmonics in the friction spectrum. Can also generate spurious friction bursts	Low, medium	Could be caused by geometric errors or looseness (improper dimensioning), also excessive loads
RPM is the rotational speed, BSF is the ball spin frequency Fault type 0: No bearing degradation (stage 0) Fault type 1: Slight bearing degradation (stage 1) Fault type 2: Medium bearing degradation (stage 2) Fault type 3: Severe bearing degradation (stage 3) Fault type 4: Extremely severe bearing degradation (stage 4) Fault type 5: Bearing has failed (stage 5)					

Table D.1 *(continued)*

Fault	Type of fault	Recommended measurement technique(s)	Symptom(s) in the vibration signal	Fault severity	Explanation (causes, origin, prognosis)
Dynamic instability	Improper loading, excessive clearances	Time domain, time-frequency domain, baseband spectrum, amplitude demodulated spectrum	Shocks at 1x RPM and harmonics, BPFO and FTF	Low, medium, high	Usually caused by inadequate loading
Type 1 faults					
Slight wear on outer race	Degradation stage 1	Amplitude demodulated spectrum of friction forces	Appearance of 1x BPFO modulation in friction forces spectrum	Low, medium	Usually fatigued-induced in the load zone
Slight wear on inner race	Degradation stage 1	Amplitude demodulated spectrum of friction forces	Appearance of 1x RPM modulation in friction forces	Medium	Usually fatigued-induced in the load zone
Fault	Type of fault	Recommended measurement technique(s)	Symptom(s) in the vibration signal	Fault severity	Explanation (causes, origin, prognosis)
Type 2 faults					
Spallings or cavities on outer race	Bearing degradation stage 2	Baseband spectrum, amplitude demodulated spectrum	Shocks, modulation of friction forces at 1x BPFO and harmonics	Medium	Common scenario, usually occurs in the load zone
Spallings or cavities on inner race	Bearing degradation stage 2	Time domain, time-frequency domain, baseband spectrum, amplitude demodulated spectrum	Shocks, modulation of friction forces at 1x BPFI and harmonics, modulation at 1x RPM	Medium, high	Usually develops after outer race faults; if before, could be caused by improper heat treatment during manufacturing
Worn-out cage	Bearing degradation stage 2	Time domain, time-frequency domain, baseband spectrum, amplitude demodulated spectrum	Modulation of friction forces at FTF	Medium, high	Precursor to a broken cage, generally indicate improper loading or internal operation of the bearing
RPM is the rotational speed, BSF is the ball spin frequency Fault type 0: No bearing degradation (stage 0) Fault type 1: Slight bearing degradation (stage 1) Fault type 2: Medium bearing degradation (stage 2) Fault type 3: Severe bearing degradation (stage 3) Fault type 4: Extremely severe bearing degradation (stage 4) Fault type 5: Bearing has failed (stage 5)					

Table D.1 *(continued)*

Fault	Type of fault	Recommended measurement technique(s)	Symptom(s) in the vibration signal	Fault severity	Explanation (causes, origin, prognosis)
Type 3 faults					
Broken cage	Bearing degradation stage 3	Time domain, time-frequency domain, baseband spectrum, amplitude demodulated spectrum	Shocks at FTF and/or harmonics, modulation of friction forces at FTF and/or harmonics	High	Can have serious effect on internal bearing operation and lead to catalectic breakdown
Cracked inner race	Bearing degradation stage 3	Time domain, time-frequency domain, baseband spectrum, amplitude demodulated spectrum	Shocks, modulation of friction forces at 1x BPFI and harmonics, modulation at 1x RPM	High	Often occurs rapidly on start-up because of too much heat
Damaged rolling elements	Bearing degradation stage 3	Time domain, time-frequency domain, baseband spectrum, amplitude demodulated spectrum	Shocks at 2x BSF, modulation of friction forces at 2x BSF and harmonics, modulation at FTF frequency Sometimes 1x BSF also appears	High	Rolling elements are degraded; from now, incipient failure can accelerate more rapidly
Brinelling	Bearing degradation stage 3	Time domain, time-frequency domain, baseband spectrum, amplitude demodulated spectrum	Shocks at regular intervals (characteristic frequencies) depending on location of damage	High	Often caused by transport, storage, idling too long (ambient vibration)
Fluting	Bearing degradation stage 3	Time domain, time-frequency domain, baseband spectrum, amplitude demodulated spectrum	Shocks at regular intervals (characteristic frequencies) and very high harmonics	High	Generally due to electro-static discharge inside bearing
Type 4 faults					
Most rolling contact surfaces severely damaged	Bearing degradation stage 4	Broadband measurement preferably with extraneous noise removal	Signal becomes completely random with level increase more than 20 dB (i.e. 10 times)	Very high	Final stage of bearing fault before breakdown. Must replace bearing

RPM is the rotational speed, BSF is the ball spin frequency

Fault type 0: No bearing degradation (stage 0)

Fault type 1: Slight bearing degradation (stage 1)

Fault type 2: Medium bearing degradation (stage 2)

Fault type 3: Severe bearing degradation (stage 3)

Fault type 4: Extremely severe bearing degradation (stage 4)

Fault type 5: Bearing has failed (stage 5)

Table D.1 *(continued)*

Fault	Type of fault	Recommended measurement technique(s)	Symptom(s) in the vibration signal	Fault severity	Explanation (causes, origin, prognosis)
Type 5 faults					
Destroyed bearing	Breakdown stage 5	Very low level random vibration	Very low level hiss sound	Very high	After the bearing is destroyed, the shaft just turns on the journal or catalectic failure occurs
RPM is the rotational speed, BSF is the ball spin frequency Fault type 0: No bearing degradation (stage 0) Fault type 1: Slight bearing degradation (stage 1) Fault type 2: Medium bearing degradation (stage 2) Fault type 3: Severe bearing degradation (stage 3) Fault type 4: Extremely severe bearing degradation (stage 4) Fault type 5: Bearing has failed (stage 5)					

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[8] ISO 10816 (all parts), *Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts*

[9] ISO 10817-1, *Rotating shaft vibration measuring systems — Part 1: Relative and absolute sensing of radial vibration*

[10] ISO 13379-1, *Condition monitoring and diagnostics of machines — Data interpretation and diagnostics techniques — Part 1: General guidelines*

[11] ISO 17359, *Condition monitoring and diagnostics of machines — General guidelines*

[12] ISO/TR 19201, *Mechanical vibration — Methodology for selecting appropriate machinery vibration standards*

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