



Machine Condition Monitoring and Fault Diagnostics

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Current Topic

- Introduction to Machine Condition Monitoring and Condition Based Maintenance
- Basics of Mechanical Vibrations
- Vibration Transducers
- Vibration Signal Measurement and Display
- Machine Vibration Standards and Acceptance Limits (Condition Monitoring)
- Vibration Signal Frequency Analysis (FFT)

Vibration Standards and Acceptance Limits

Standards are documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions of characteristics, to ensure that materials, products, processes and services are fit for their purpose.



Vibration Standards and Acceptance Limits

A good standard...

- represents consensus of opinion
- is easy to understand and use
- contains no ambiguities or loopholes



Vibration Standards and Acceptance Limits

Standard are intended:

To setup criteria for rating or classifying the performance of equipment or material

To provide a basis for comparison of the maintenance qualities of pieces of equipment of the same type

To test equipment whose continuous operation in necessary for industrial or public safety

To provide a basis for the selection of equipment or material

To setup a procedure for the calibration of equipment

Vibration Standards and Acceptance Limits

ISO Standards are developed according to the principles of ...

- Consensus amongst participants
- Industry-wide participation
- Voluntary participation



Vibration Standards and Acceptance Limits

IEC - International Electrical Commission (product oriented)

ANSI - American National Standards Institute (non-government)

NEMA – National Electric Manufacturing Association

API - American Petroleum Institute

Domestic Government Agencies

Defence Departments



Vibration Standards and Acceptance Limits

ISO - Organization for International Standardization

- Technology Oriented
- National Standards bodies from 130 countries
(Standards Council of Canada)

TC (Technical Committee) 108 – Mechanical
Vibration and Shock

SC (Sub-Committee) 5 - Condition Monitoring and
Diagnostics of Machines

Vibration Standards and Acceptance Limits

ISO TC 108 – Mechanical Vibration and Shock

SC 1 - Balancing

SC 2 - Measurement and Evaluation

SC 3 - Measuring Instruments

SC 4 - Human exposure

SC 5 - Condition Monitoring

SC 6 - Vibration Generating Systems



Vibration Standards and Acceptance Limits

ISO TC 108 – Mechanical Vibration and Shock

Scope (general):

Standardization in the field of mechanical vibration and shock, and condition monitoring and diagnostics of machines.

Vibration Standards and Acceptance Limits

ISO TC 108 – Mechanical Vibration and Shock

Scope (detail):

- terminology
- excitation
- vibration control
- human exposure
- measurement and calibration
- test methods
- condition monitoring & diagnostics

Vibration Standards and Acceptance Limits

ISO TC 108 SC 5

WG1 Terminology

WG2 Data Interpretation and Diagnostic
Techniques

WG3 Performance Monitoring and Diagnostics

WG4 Tribology

WG5 Prognostics

WG6 Formats and Methods for Presenting Data

WG7 Training and Certification

WG 8 M&D of machines

WG10 M&D of electrical equipment

WG11 Thermal Imaging

Condition monitoring and diagnostics of machines.

Standards in progress

Overview

ISO 17359
CM Guidelines

AWI 22349
CM Optimisation

ISO/CD 13372
Terminology

Equipment Specific

TR 19035
CM AC Rotating M/C

Techniques

ISO 13373
Vibration CM

ISO 13380
CM Using Performance

ISO/DIS 14830-1.2
CM Lubrication & Tribology

AWI 14830-2
CM Lubricant Sampling

ISO/WD 18434
CM Thermal Imaging

PWI xxxx
CM Acoustic techniques

PWI xxxx
CM other techniques

Training & Certification

ISO/FDIS 18436-2
Vibration CM Trg & Cert

PWI 18436-7 CM Specialist
CM Training & Certification

PWI 18436-4 Lubrication
CM Training & Certification

PWI 18436-5 Thermography
CM Training & Certification

PWI Acoustic techniques
CM Training & Certification

PWI Other techniques
CM Training & Certification

ISO/DIS 18436-1.2
Req for Cert Bodies
CM Training & Certification

PWI 18436-3
Req for Trg Bodies
CM Training & Certification

PWI 18436-6
Diagnostics & Prognostics
CM Training & Certification

Data Management

ISO/FDIS 13374-1
CM Data Processing
& analysis

PWI 13374-2
CM Data Communication
Formats

PWI 13374-3
CM Data Presentation
Formats

Diagnostics & Prognostics

ISO/FDIS 13379
CM Diagnostics

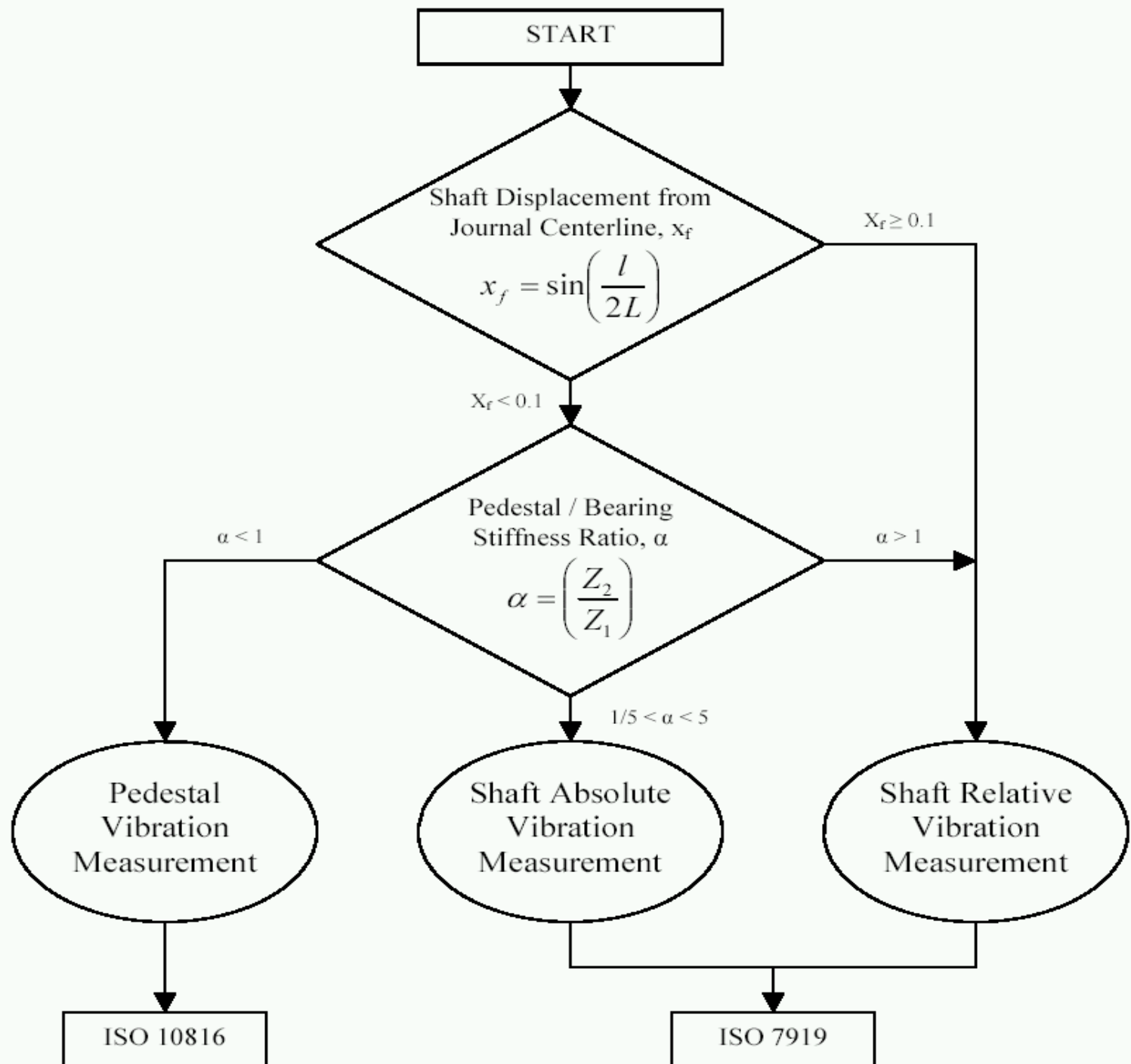
ISO/CD 13381-1
CM Prognostics

Vibration Standards and Acceptance Limits

ISO 7919 Series	Mechanical vibration of non-reciprocating machines - Measurement on rotating shafts and evaluation criteria
7919-1:1996	Part 1: General Guidelines
7919-2: 2001	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
7919-3: 1996	Part 3: Coupled industrial machines
7919-4: 1996	Part 4: Gas turbine sets
7919-5: 1997	Part 5: Machines set in hydraulic power generating and pumping plants

Vibration Standards and Acceptance Limits

ISO 10816 Series		Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts
10816-1: 1995		Part 1: General Guidelines
10816-2: 2001		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
10816-3: 1998		Part 3: Industrial machines with normal power above 15kW and nominal speeds between 120 r/min and 15000 r/min when measured in situ
10816-4: 1998		Part 4: Gas turbine sets excluding aircraft derivatives
10816-5: 2000		Part 5: Machines set in hydraulic power generating and pumping plants
10816-6: 1995		Part 6: Reciprocating machines with power ratings above 100 kW
10816-7 [‡]		Part 7: Rotodynamic pumps for industrial application



Vibration Standards and Acceptance Limits

Standards Based on Type of Machinery

1. Reciprocating Machinery

- both rotating & reciprocating components
- engines, compressors, pumps

2. Rotating Machinery - Rigid Rotors

- electric motors, single stage pumps, slow speed pumps
- measure vibration from housing, vibration transmitted well through housing

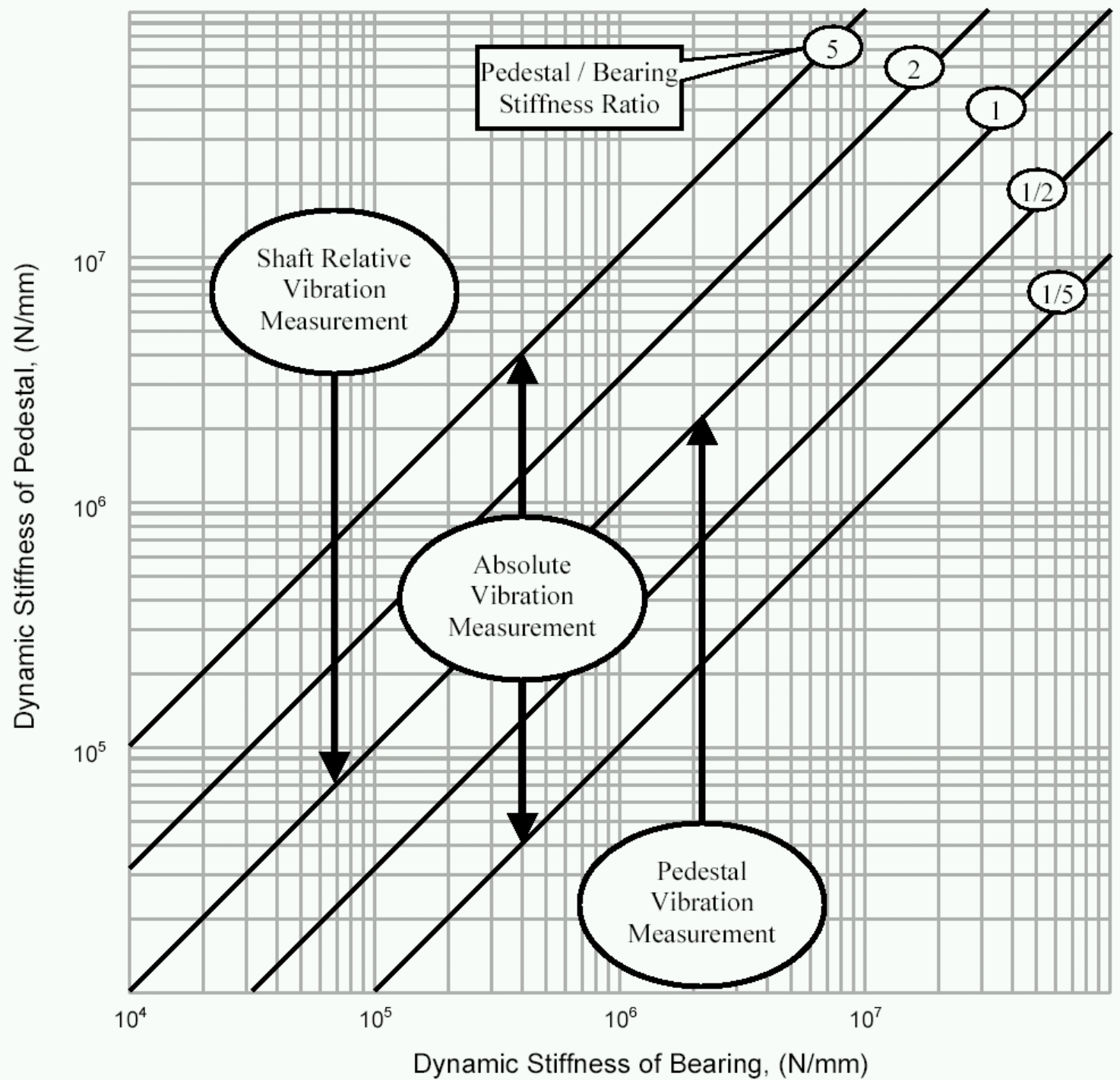
Standards Based on Machinery Type

3. Rotating Machinery - Flexible Rotors

- large steam turbines, multistage pumps, compressors
- critical speeds
- different modes of vibration at different speeds
- vibration not transmitted well through bearings
- must measure vibration of shaft directly

4. Rotating Machinery - Quasi-rigid Rotors

- low pressure steam turbines, axial flow compressors, fans
- some vibration gets through bearings



Vibration Standards and Acceptance Limits

Machine	Dynamic Stiffness Ratio, α	ISO 10816 (pedestal)	ISO 7919 (shaft)
High Pressure Turbine	5	Moderate	Good
Low Pressure Turbine	1.5	Moderate	Good
Large Generator	1.5	Moderate	Good
High Pressure Centrifugal Compressor	5	Not Good	Good
Large Fan	2/3	Good	Moderate
Small Fan & Pump	1/3	Good	Moderate
Vertical Pump	1/10	Good	Not Good
Large Steam Turbine Generator Set	1.5 to 3	Moderate	Good

Vibration Standards and Acceptance Limits

Standards Based on Vibration Severity

Standards depend on:

- frequency range of vibration (speed of machinery)
- type & size of machine
- service expected
- mounting system
- effect of machinery vibration on surroundings

Vibration Standards and Acceptance Limits

Standards Based on Vibration Severity

Standards depend on:

The highest value of the broad-band, root mean square value of the velocity amplitude in the frequency range from 10 to 1000 Hz as evaluated on the structure at prescribed points.

For rotating machinery whose rotational speed is in the range of 600 to 1200 rpm, the rms value of the velocity amplitudes corresponds most closely with vibration severity.

Standards Based on Machinery Type

Vibration Severity Criteria (ISO 2372)

RMS velocity ranges Of vibration severity		Vibration severity* for separate classes of machines			
mm/sec	in/sec	Class 1	Class 2	Class 3	Class 4
0.28	0.01	A	A	A	A
0.45	0.02				
0.71	0.03				
1.12	0.04	B	B	B	B
1.8	0.07				
2.8	0.11	C	C	C	C
4.5	0.18				
7.1	0.28	D	D	D	D
11.2	0.44				
18	0.71				
28	1.10				
45	1.77				

A – good, B – Acceptable, C – Monitor closely, D - Unacceptable

Vibration Standards and Acceptance Limits

Class I – individual components, integrally connected with complete machine (electric motors up to 15 kiloWatts)

Class II – Medium sized machines (15 – 75 kiloWatt electric motors)

Class III – Large prime movers on heavy, rigid foundations

Class IV – Large prime movers on relatively soft, light-weight foundations

Vibration Standards and Acceptance Limits

R.m.s. vibration velocity mm/sec	up to 15 kW Class I	15 to 75 kW Class II	> 75 kW (rigid) Class III	> 75 kW (soft) Class IV
0,28	A	A	A	A
0,45				
0,71				
1,12	B	B	B	B
1,8				
2,8	C	C	C	C
4,5				
7,1	D	D	D	D
11,2				
18				
28				
45				

Standards Based on Machinery Type

Quality Judgment of Vibration Severity (**ISO 3945**)

rms velocity vibration severity		Support Classification	
mm/sec	in./sec	Rigid supports	Flexible supports
0.46	0.018	Good	Good
0.71	0.028		
1.12	0.044		
1.8	0.071		
2.8	0.11	Satisfactory	Satisfactory
4.6	0.18		
7.1	0.28	Unsatisfactory	Unsatisfactory
11.2	0.44		
18.0	0.71	Unacceptable	Unacceptable
28.0	1.10		
26.0	1.80		
71.0	2.80		

Standards Based on Vibration Severity

Small - medium sized machines

- 600 - 12,000 r.p.m. shaft speeds
- rigid rotors
- velocity amplitudes
- highest broad-band root-mean-square value in frequency range 10-1000 Hz.
- triaxial bearing cap vibration measurements

Standards Based on Vibration Severity

Large sized machines

- 600 - 1,200 r.p.m. shaft speeds
- rigid support - machine fundamental resonant frequency is above main excitation frequency
- flexible support - machine fundamental resonant frequency is below main excitation frequency

Standards Based on Vibration Severity

Electric Motors – ISO standard 2373

- size dependent
- measured at no load

Standards Based on Vibration Severity

ISO standard 2373 is a special adaptation of ISO 2372 for electrical motors

Implies for three phase ac and dc motors with shaft height (the vertical distance from the base of the motor to the centerline of the shaft) between 80 and 400 mm

The criterion for vibration severity is given in terms of the rms value of velocity amplitude in the frequency range from 10 to 1000 Hz when measured with instrumentation which meets the requirements of ISO 2954

Standards Based on Vibration Severity

ISO Standard 2373

Measurements are made on the machine installed on a free suspension

The motor is operated at rated voltage and nominal frequency (for ac motors) and at its nominal speed (for machines with several speeds)

Measurements of vibration should be carried out under no load operation at the temperature reached by the motor after a sufficient period of no load operation

Standards Based on Machinery Type

Recommended Limits Of Vibration Severity For Electric Motors (ISO IS 2373)

Velocity amplitude (maximum rms values) for the
following shaft height h , in mm

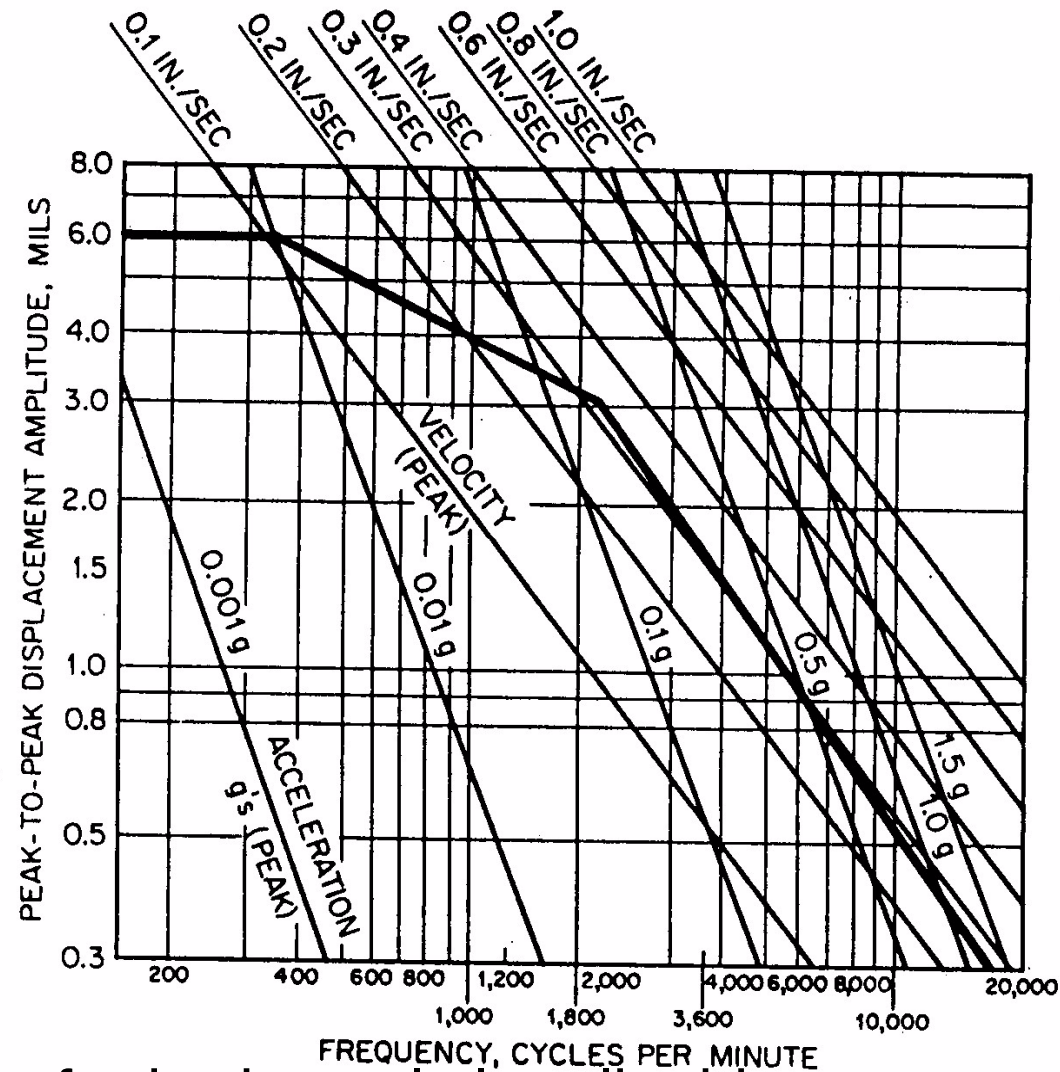
		80<h<132		132<h<225		225<h<400	
Quality grade	Speed (rpm)	mm/sec	in./sec	mm/sec	in./sec	mm/sec	in./sec
N (normal)	600 to 3600	1.8	0.071	2.8	0.110	4.5	0.177
R (reduced)	600 to 1800	0.71	0.028	1.12	0.028	1.8	0.071
	>1800 to 3600	1.12	0.044	1.8	0.071	2.8	0.110
S (special)	600 to 1800	0.45	0.018	0.71	0.028	1.12	0.044
	>1800 to 3600	0.71	0.028	1.12	0.044	1.8	0.071

Standards Based on Vibration Severity

Pumps

- operating in non-cavitating mode
- Suction piping must be arranged so as provide a straight uniform flow to the pump
- Piping must be connected in such a way so as to avoid undue strain on the pump
- Shaft coupling must be aligned to within the manufacturers recommendations

Standards Based on Machinery Type



Vibration Limits for horizontal clear liquid pumps, measured on bearing housing – Hydraulics Institute

Standards Based on Vibration Severity

Reciprocating Machinery

- type & size dependant
- load & mounting dependant
- < 3000 rpm
- frequency 2 - 300 Hz

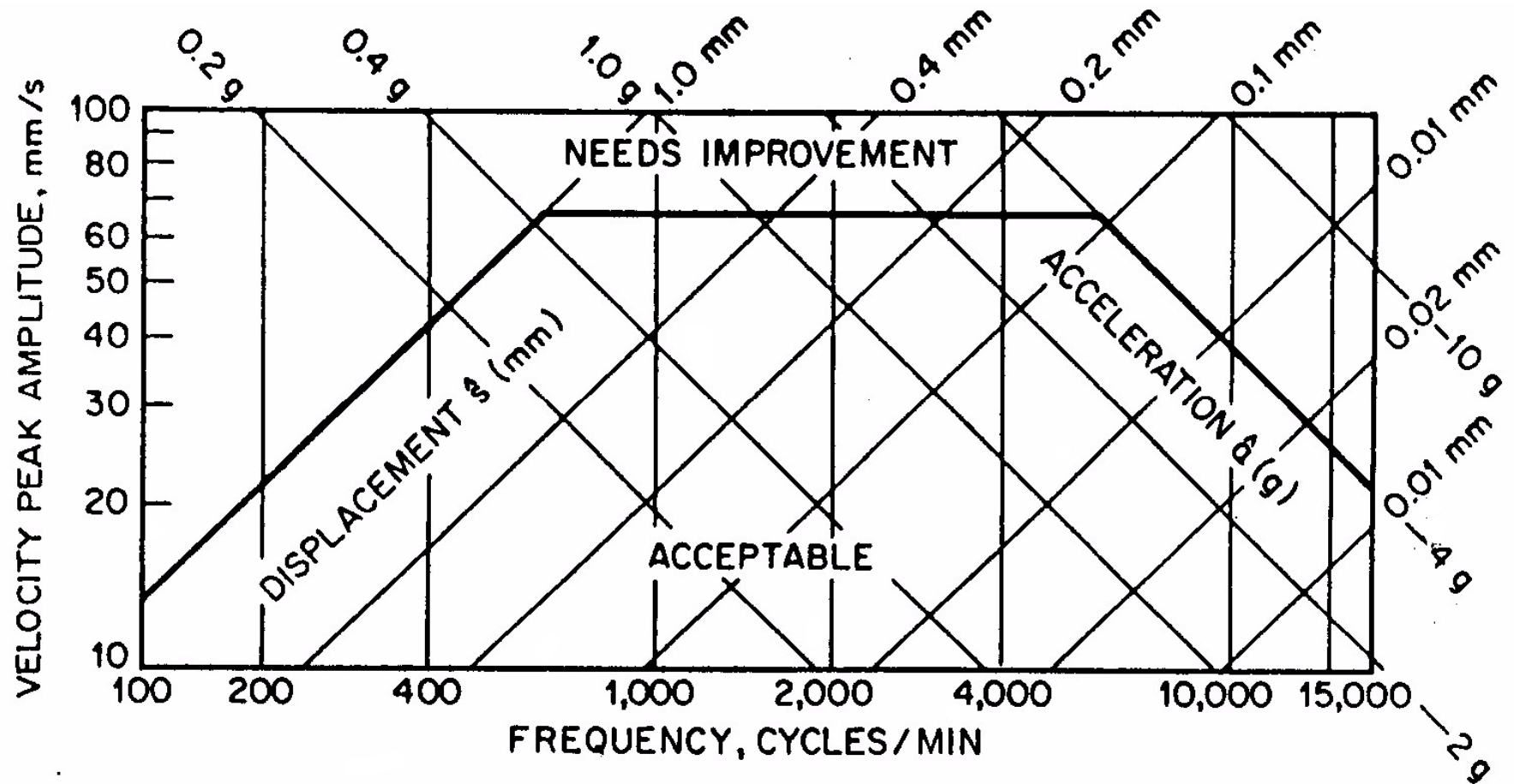
Steam Turbine Generator Sets

Industrial Turbo Machinery (High Speed)

Centrifugal Compressors

Gear Units

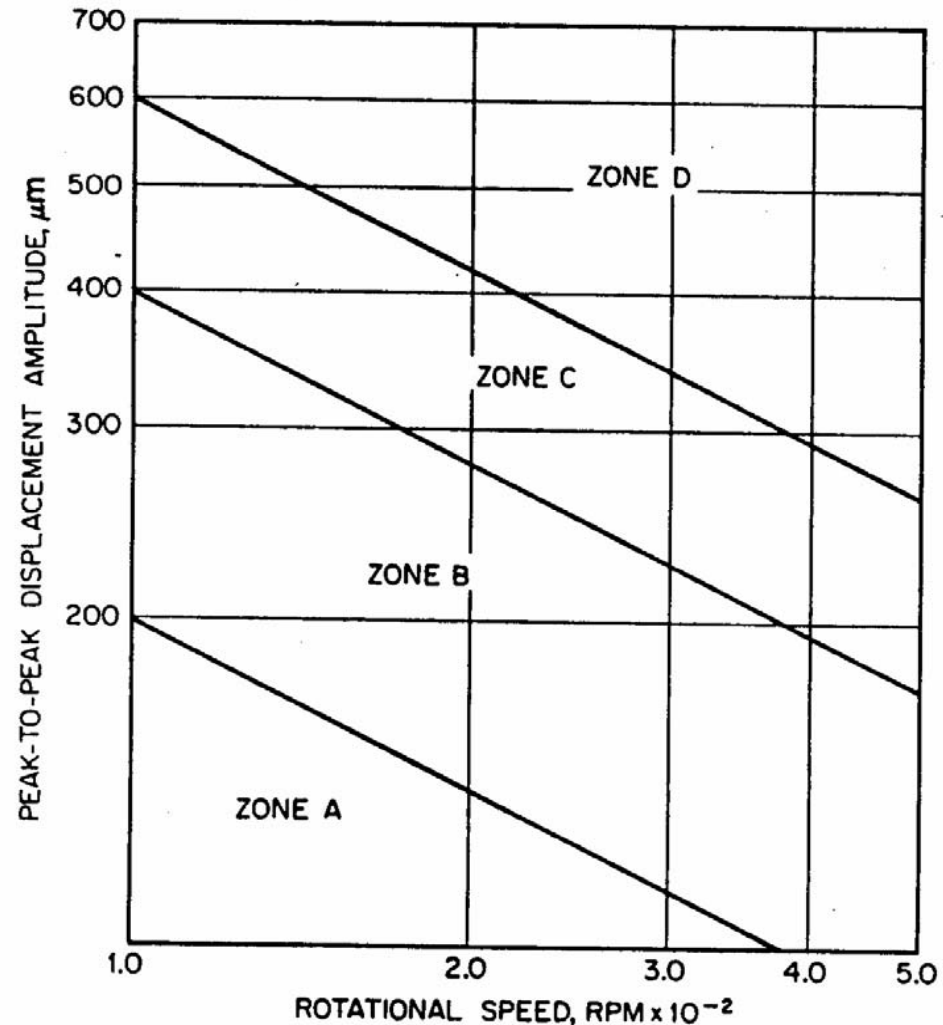
Standards Based on Machinery Type



Vibration severity limits for reciprocating machines

Standards Based on Machinery Type

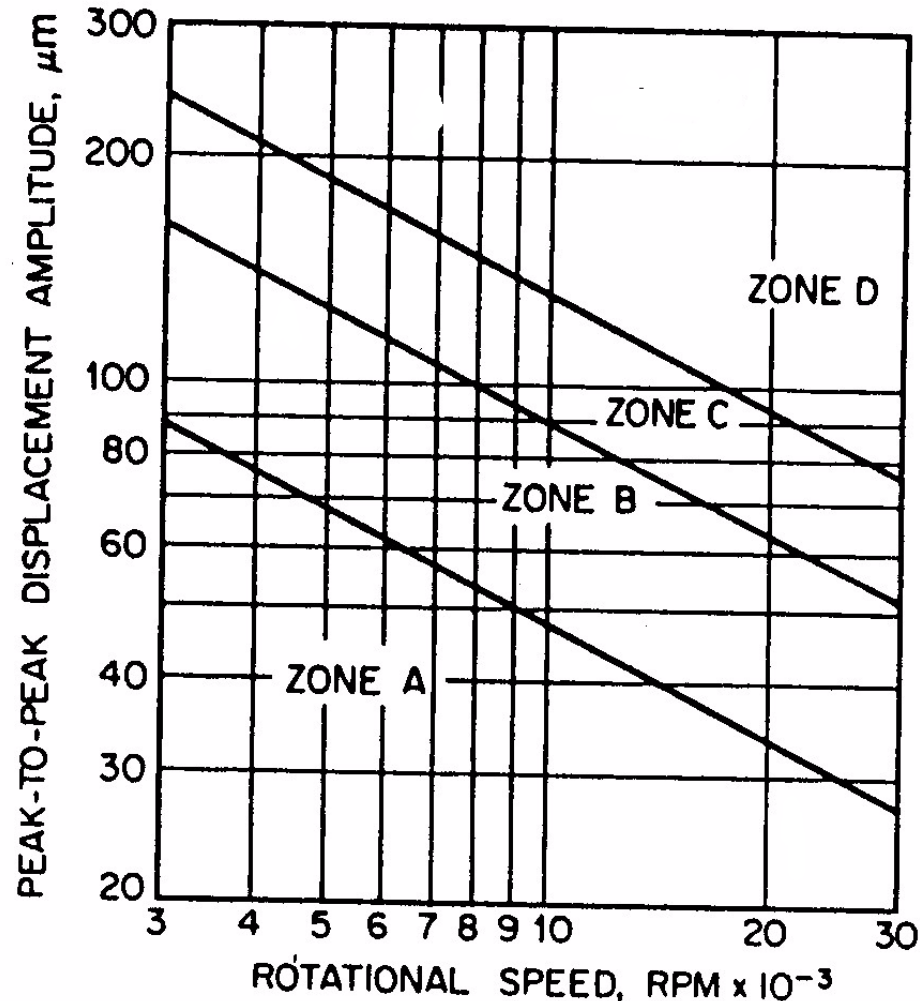
- A – good
- B – Acceptable
- C – Monitor closely
- D - Unacceptable



Vibration severity limits for large turbine generator machinery,
absolute shaft displacement - ISO IS 7919 (part 2)

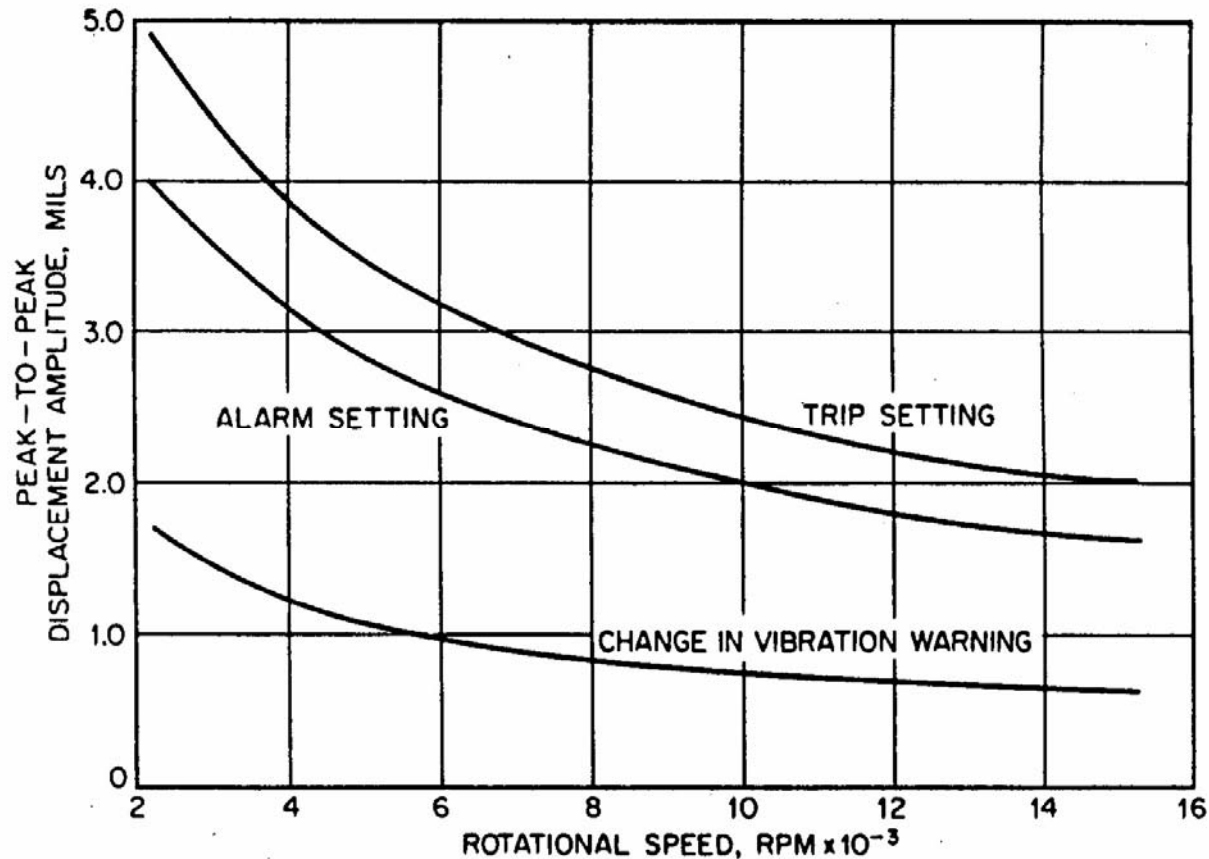
Standards Based on Machinery Type

- A – good
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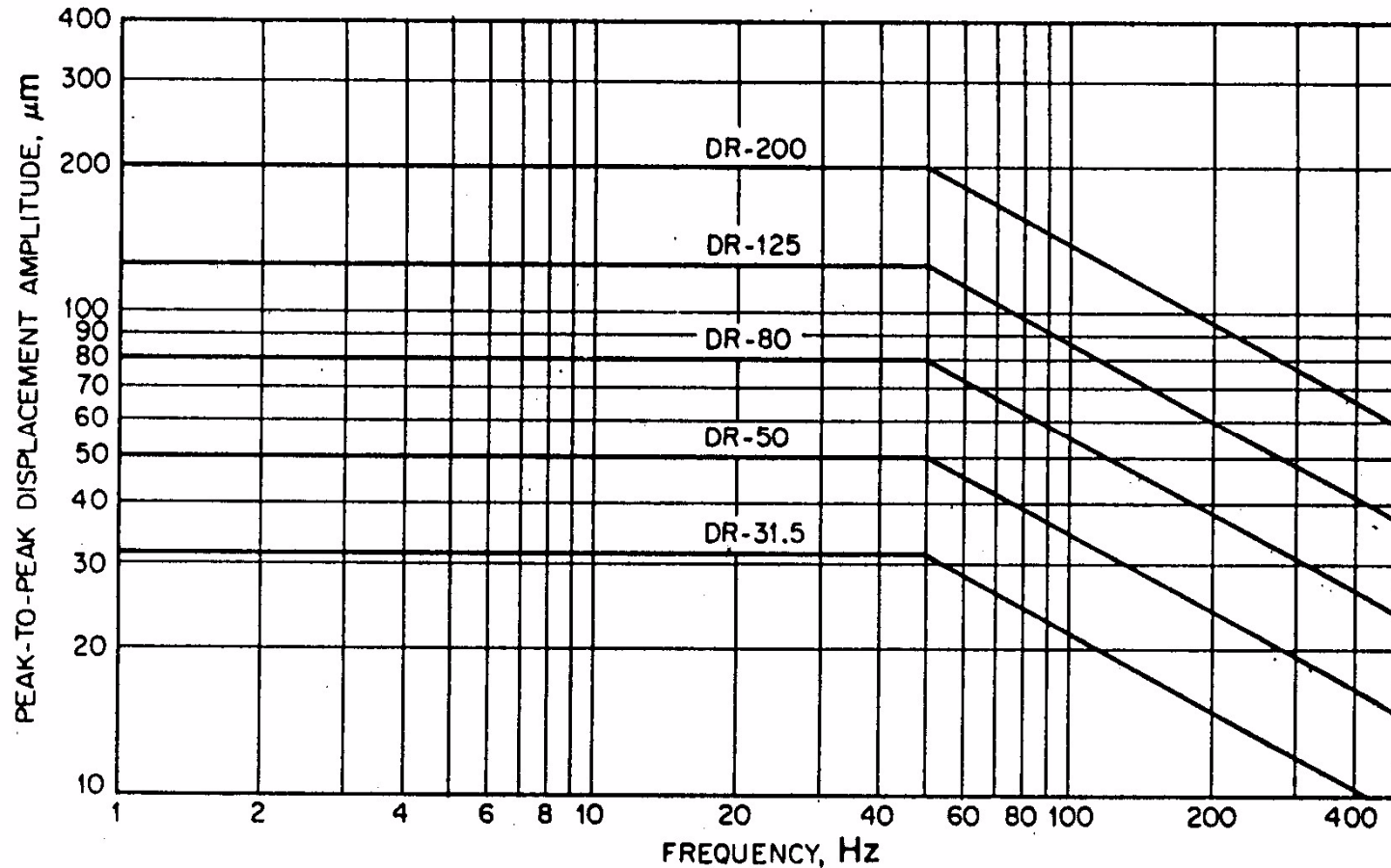
Vibration severity limits for industrial turbo-machinery,
shaft displacement relative to bearings - ISO IS 7919 (part 3)

Standards Based on Machinery Type



In-service vibration severity criteria for centrifugal compressors as a function of shaft speed – Compressed Air and Gas Institute

Standards Based on Machinery Type



Gear shaft vibration (displacement amplitude) vs. frequency
ISO draft standard

Vibration severity grade	Maximum values of overall vibration measured on the machine structure			Machine vibration classification number						
	Displacement μm (r.m.s.)	Velocity mm/s (r.m.s.)	Acceleration m/s ² (r.m.s.)	1	2	3	4	5	6	7
				Evaluation zones						
1,1	17,8	1,12	1,76	A/B	A/B	A/B	A/B	A/B	A/B	A/B
1,8										
2,8										
4,5										
7,1	71,0	4,46	7,01	C	C	C	C	C	C	C
11	113	7,07	11,1							
18	178	11,2	17,6							
28	283	17,8	27,9							
45	448	28,2	44,2	D	D	D	D	D	D	D
71	710	44,6	70,1							
112	1125	70,7	111							
180	1784	112	176							
Key to zones										
A: The vibration of newly commissioned machines would normally fall within this zone										
B: Machines with vibration within this zone are normally considered acceptable for long-term operation										
C: Machines with vibration within this zone are normally considered unsatisfactory for long-term continuous operation. Generally, the machine may be operated for a limited period in this condition until a suitable opportunity arises for remedial action.										
D: Vibration values within this zone are normally considered to be of sufficient severity to cause damage to the machine.										

Table 2.8 Vibration classification numbers and guide values for reciprocating machines.
(ISO 10816-6)

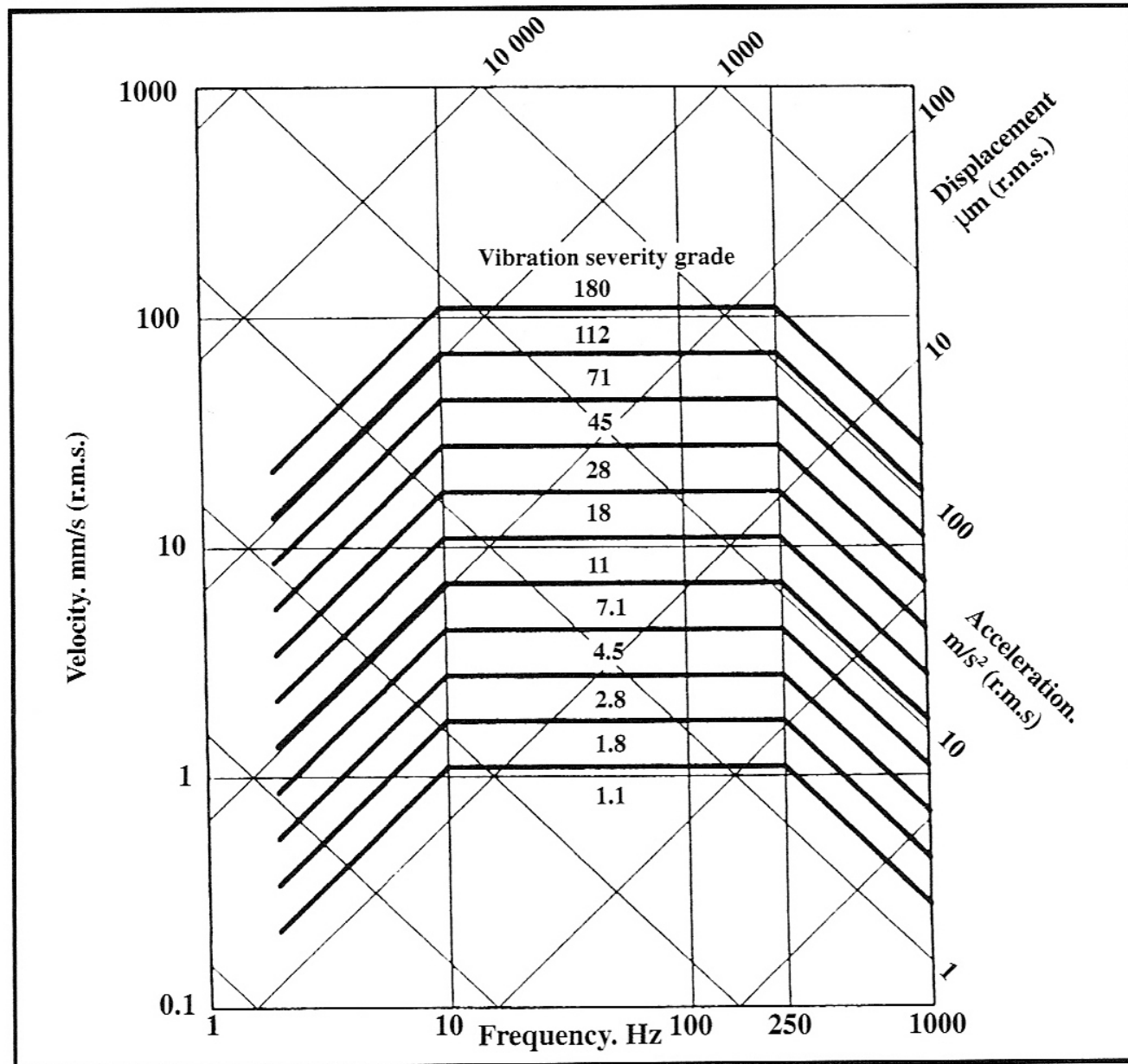
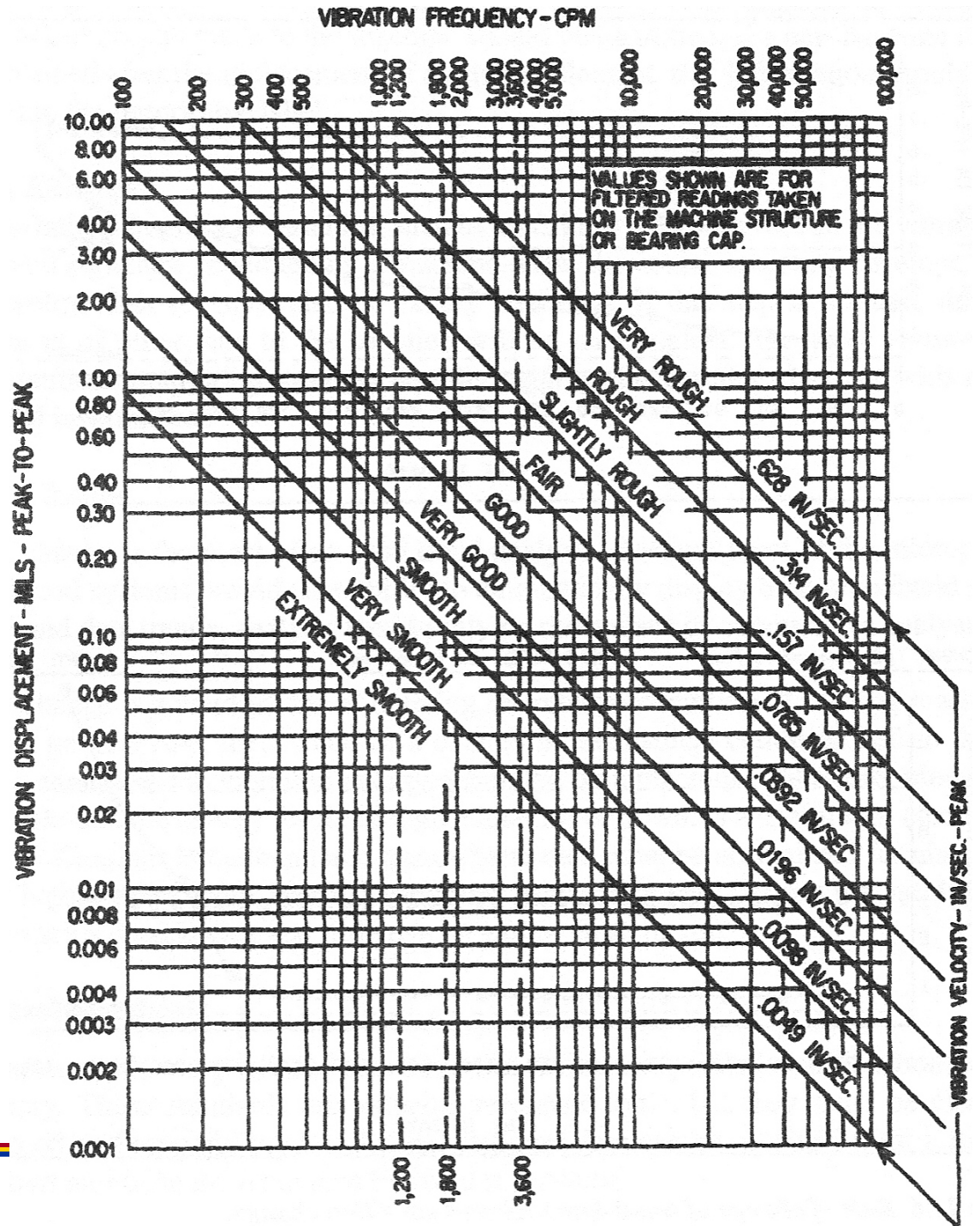


Figure 2.19 Vibration severity grade nomograph [ISO 10816-6]

Rathbone Chart showing Unbalance Severity



ISO Standards

ISO Condition Monitoring Standards

ISO Reference	Title
18431-1	Mechanical Vibration and Shock – Signal Processing – Part 1: General Introduction
18434-1	Condition Monitoring and Diagnostics of Machines – Thermal Imaging
18436-1	Condition Monitoring and Diagnostics of Machines – Requirements for Training and Certification of Personnel – Part 1: Requirements for Certifying Bodies and the Certification Process
18436-2	Condition Monitoring and Diagnostics of Machines – Part 2: Vibration Condition Monitoring and Diagnosis

ISO Standards

ISO Condition Monitoring Standards

ISO Reference	Title
18436-3	Condition Monitoring and Diagnostics of Machines – Accreditation of Organisation and Training Specialists - Part 3: Accreditation of Certification Bodies
18436-4	Condition Monitoring and Diagnostics of Machines – Part 4: Lubrication Management and Analysis
18436-5	Condition Monitoring and Diagnostics of Machines – Part 5: Thermography
18436-6	Condition Monitoring and Diagnostics of Machines – Part 6: Diagnostics and Prognostics
18436-7	Condition Monitoring and Diagnostics of Machines – Part 7: Condition Monitoring Specialists

ISO Standards

ISO Condition Monitoring Standards

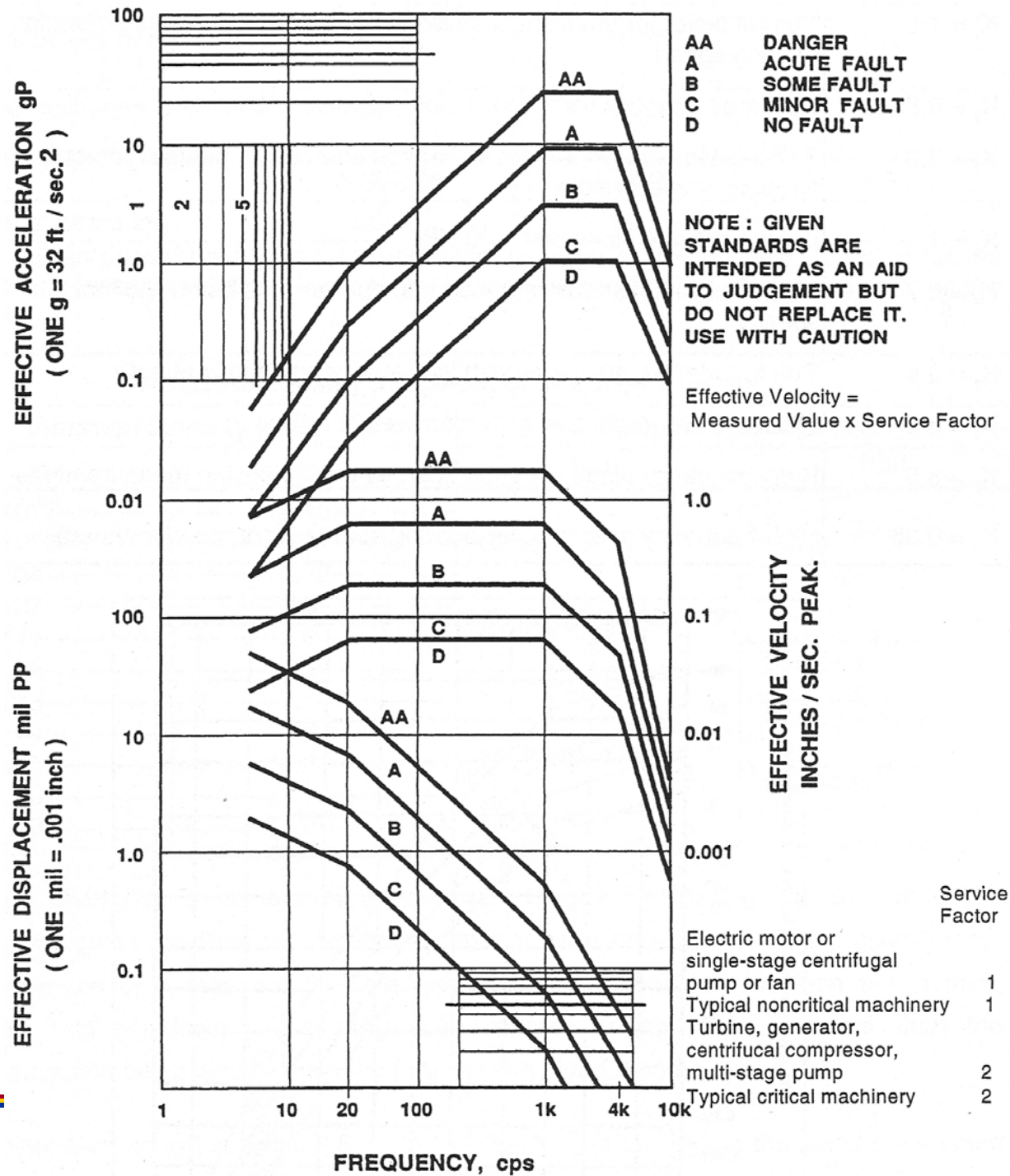
ISO Reference	Title
14830-1	Condition Monitoring and Diagnostics of Machines – Tribology Based Monitoring of Machines – Part 1: General Guidelines
14830-2	Condition Monitoring and Diagnostics of Machines – Tribology Based Monitoring of Machines – Part 2: Lubricant Sampling
13372	Condition Monitoring and Diagnostics of Machines – Vocabulary
13372-1	Condition Monitoring and Diagnostics of Machines – Vibration Condition Monitoring: General Procedures
13374-1	Condition Monitoring and Diagnostics of Machines – Data Processing, Communication and Presentation – Part 1: General Guidelines

ISO Standards

ISO Condition Monitoring Standards

ISO Reference	Title
13374-2	Condition Monitoring and Diagnostics of Machines – Data Processing, Communication and Presentation – Part 2: General Data Processing and Analysis Procedures
17359	Condition Monitoring and Diagnostics of Machines – General Guidelines
22349	Condition Monitoring and Diagnostics of Machines – Condition Based Maintenance Optimization – Part 1: General Guidelines
13379	Condition Monitoring and Diagnostics of Machines – Data Interpretation and Diagnostic Techniques – General Guidelines

Blake Chart



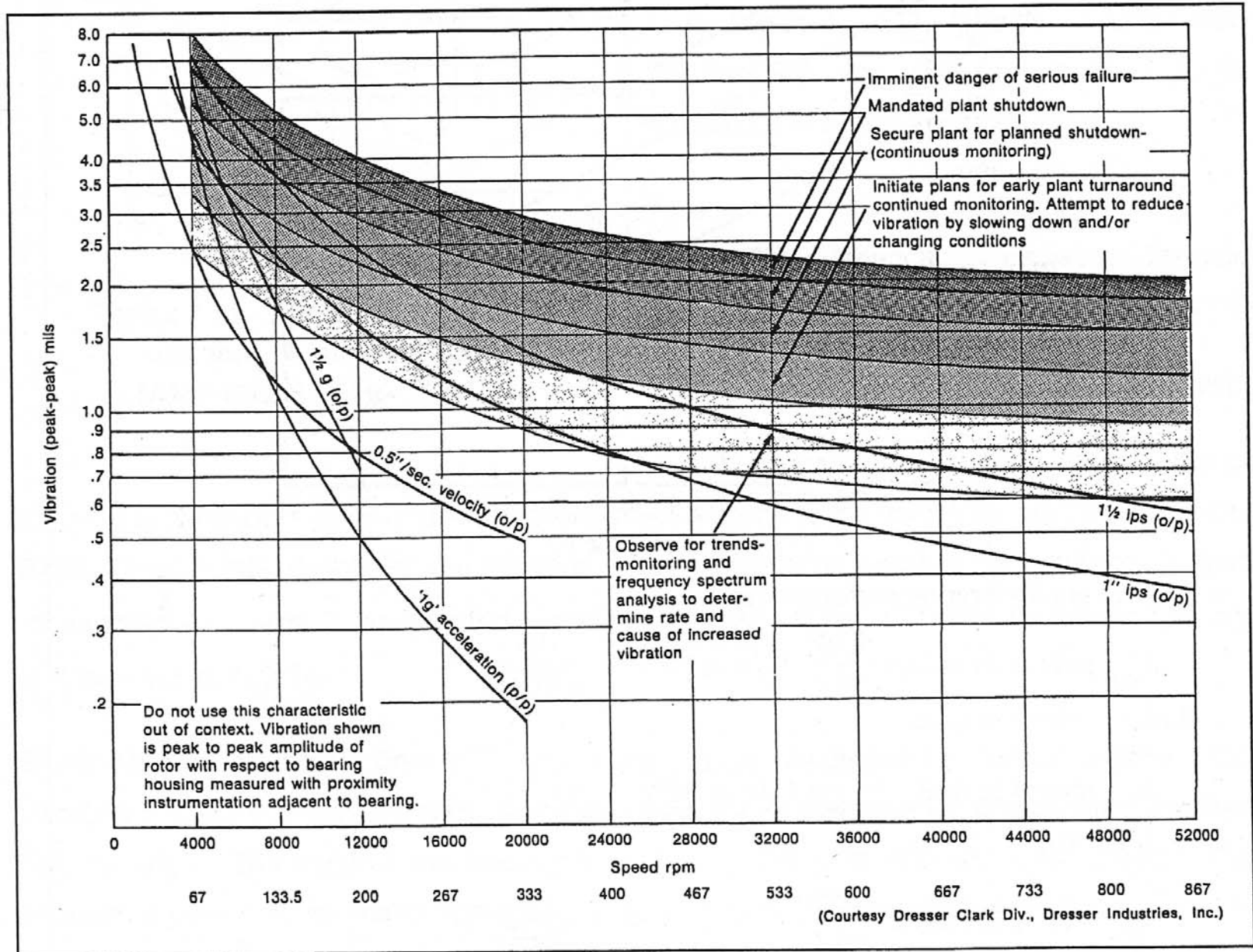


Figure 7.14. Dresser-Clark-Jackson Chart for Proximity Shaft Vibration Measurement on Certain Centrifugal Compressors^{7.22}

Training and Certification

FINAL
DRAFT

INTERNATIONAL
STANDARD

ISO/FDIS
18436-2

ISO/TC 108/SC 5

Secretariat: ANSI

Voting begins on:
2003-06-05

Voting terminates on:
2003-08-05

**Condition monitoring and diagnostics of
machines — Requirements for training
and certification of personnel —**

**Part 2:
Vibration condition monitoring and
diagnostics**

*Surveillance et diagnostic d'état des machines — Exigences relatives à
la formation et à la certification du personnel —*

Partie 2: Surveillance des vibrations et diagnostic d'état des machines

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Reference number
ISO/FDIS 18436-2:2003(E)

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Training and Certification

ISO 18436 consists of the following parts, under the general title *Condition monitoring and diagnostics of machines — Requirements for training and certification of personnel*:

- *Part 1: Requirements for certifying bodies and the certification process*
- *Part 2: Vibration condition monitoring and diagnostics*

The following parts are under preparation:

- *Part 3: Requirements for training bodies*
- *Part 4: Lubrication management and analysis*
- *Part 5: Thermography*
- *Part 6: Diagnostics and prognostics*
- *Part 7: Condition monitoring specialists*

Training and Certification

Table 1 — Recommended minimum duration of cumulative training (hours)

Category I	Category II	Category III	Category IV
32	70	110	174

Table 2 — Recommended minimum duration of cumulative experience (months)

Category I	Category II	Category III	Category IV
6	18	36	60

NOTE The months shown represent cumulative totals of months of experience for each classification. Work experience in months is based on a nominal 40 h week (175 h per month).

Training and Certification

Table 3 — Example of examination details

Classification	Number of questions	Time h	Pass rate %
Category I	50	2	75
Category II	100	3	75
Category III	100	4	75
Category IV	60	5	75



Training and Certification

Table A.1 — Overview

Subject	Hours of training			
	Category			
	I	II	III	IV
1. Principles of vibration	6	4	2	4
2. Data acquisition	8	4	2	2
3. Signal processing	2	4	3	8
4. Condition monitoring	2	4	3	1
5. Fault analysis	2	4	8	6
6. Corrective action	2	4	6	16
7. Equipment knowledge	8	4	4	—
8. Acceptance testing	2	2	2	—
9. Equipment testing and diagnostics	—	2	3	4
10. Reference standards	—	2	2	2
11. Reporting and documentation	—	2	2	4
12. Fault severity determination	—	2	3	3
13. Rotor/bearing dynamics	—	—	—	14
Total hours per category of training	32	38	40	64

ISO Standards

ISO 6954 - 1984

Mechanical Vibration and Shock – Guidelines for the overall evaluation of vibration in merchant ships

ISO 8528/9-1995

Reciprocating Internal Combustion Engine driven alternating current generating sets – Part 9: Measurement and evaluation of mechanical vibrations

ISO Standards

ISO 1940/1-2002

Mechanical vibration — Balance quality requirements of rigid rotors — Part 1: Specification and verification of balance tolerances

Acceptance Limits

Judging Overall Condition

- recognising changing machinery condition - time trends
- development and use of acceptance limits
- close to normal operating values to detect changes in condition
- tolerate normal operating variations without false alarms

Acceptance Limits

Two types of limits:

1. Absolute

- conditions could result in catastrophic failure
- physical constraints, allowable movement before contact

2. Change limits

- provide early warning well in advance of absolute limit
- machine vibration limits based on standards and experience
- overall vibration levels

Acceptance Limits

Note:

- the key to failure prevention is early discovery of deterioration
- rates of change are also important
- expected time until limits are exceeded

In General:

- high but stable vibration levels are of less concern than low but rapidly increasing levels.
- small % changes at high vib. levels are more significant than large % changes at low levels

Acceptance Limits

Example: rolling element bearings

- distinctive defect characteristics
- typically slow progressive failure
- trend levels to achieve maximum useful life, failure avoidance

However, rapid deterioration may occur due to:

- loss of lubrication
- lubrication contamination
- sudden overload

Acceptance Limits

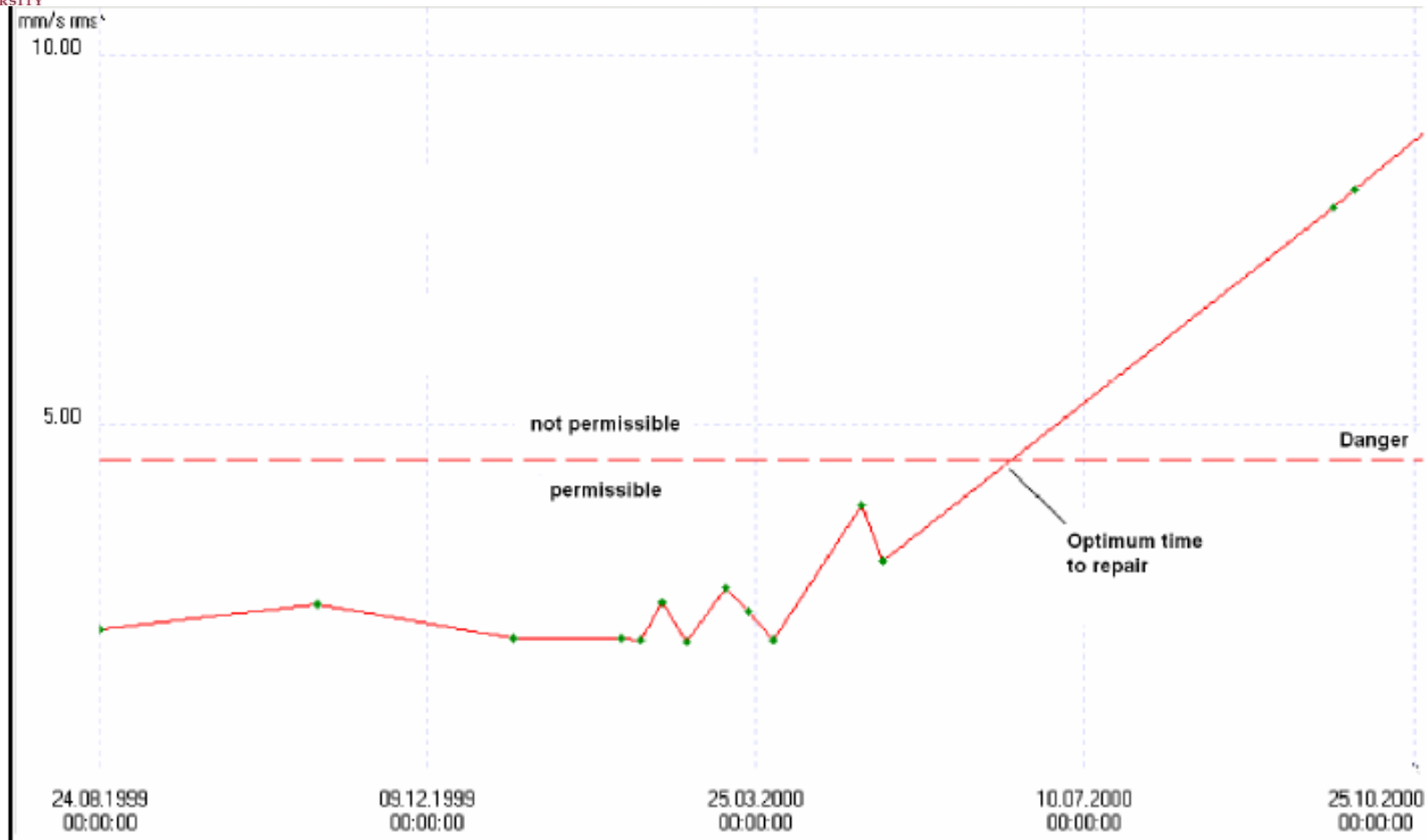
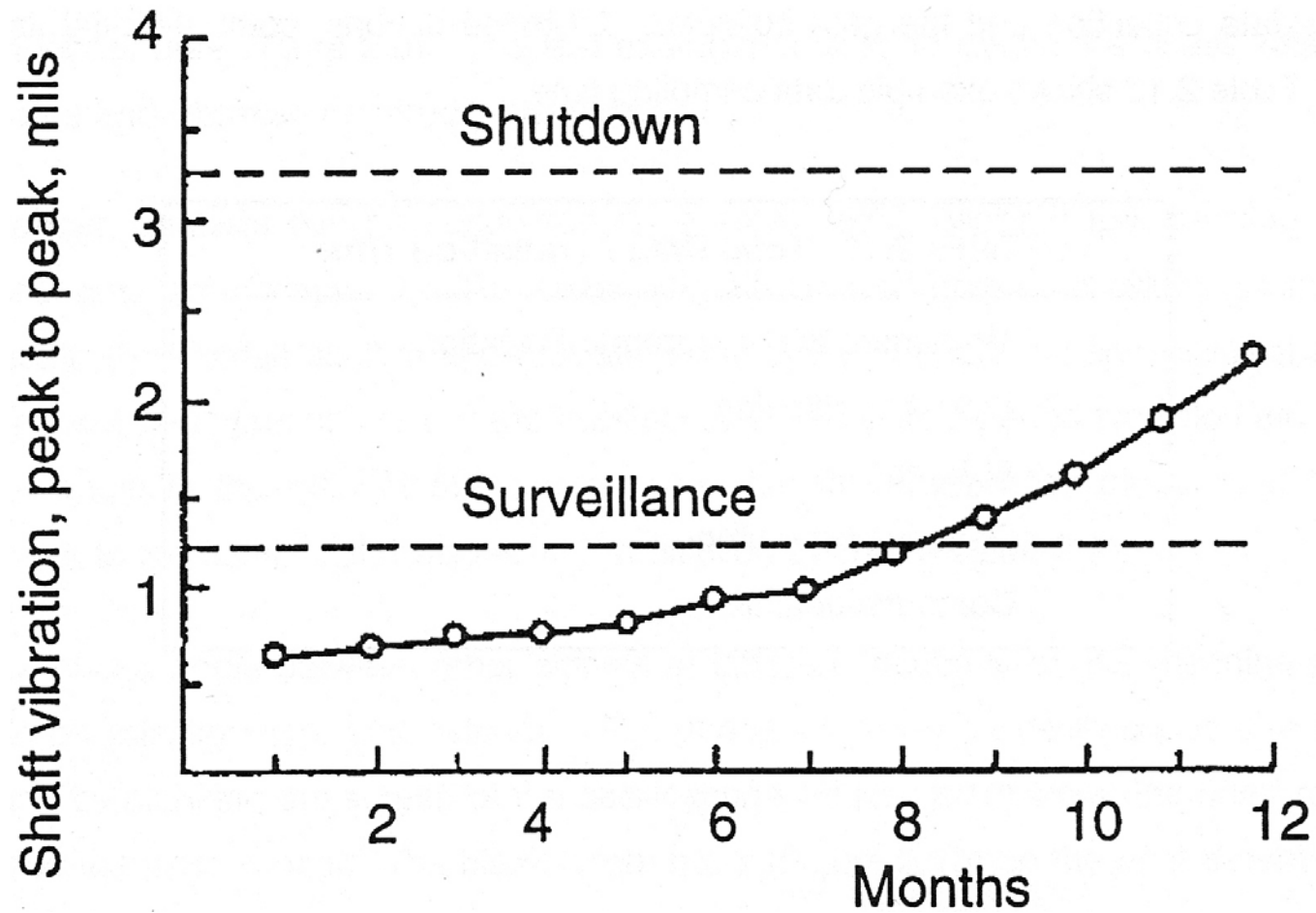


Figure 10.6: Machine condition assessment by comparison of the measured value with a recommended limit value

Acceptance Limits



Acceptance Limits

Note:

- changes in operating conditions can invalidate time trends
- speed or load changes may alter trends
- comparisons must take this into consideration

Standards Based on Vibration Severity

Statistical Limits

- take as many vibration readings as possible
- average the overall level or some other parameter
- alert or warning levels set at 2.5 standard deviations
- provides optimum sensitivity to small changes
- maximum immunity to false alarms
- settings based on actual conditions
 - accommodates normal variations
- takes into account the initial condition of machine

Standards Based on Vibration Severity

Judging Vibration Characteristics within the Frequency Spectra

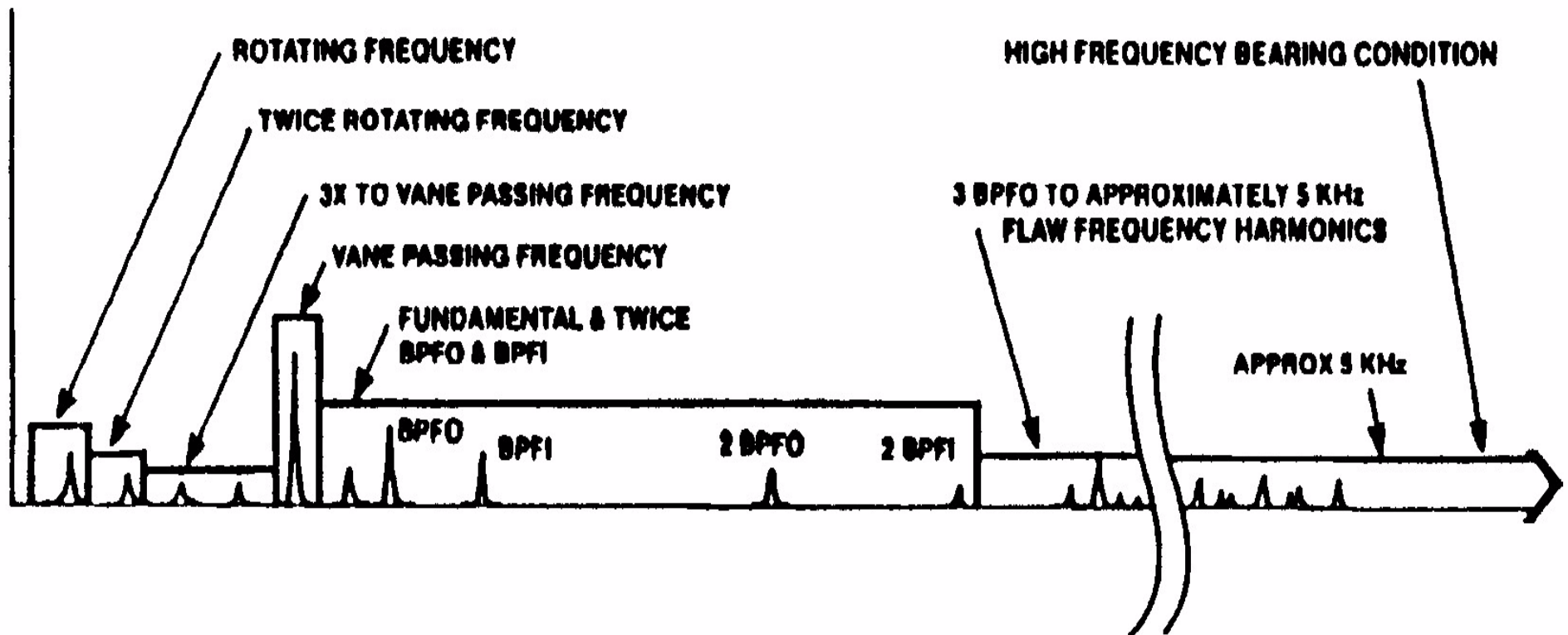
- spectral components are directly linked to forcing functions
- more accurate for trending and diagnostics
- early detection of specific faults
- frequency domain analysis

Standards Based on Vibration Severity

Limited Band Monitoring

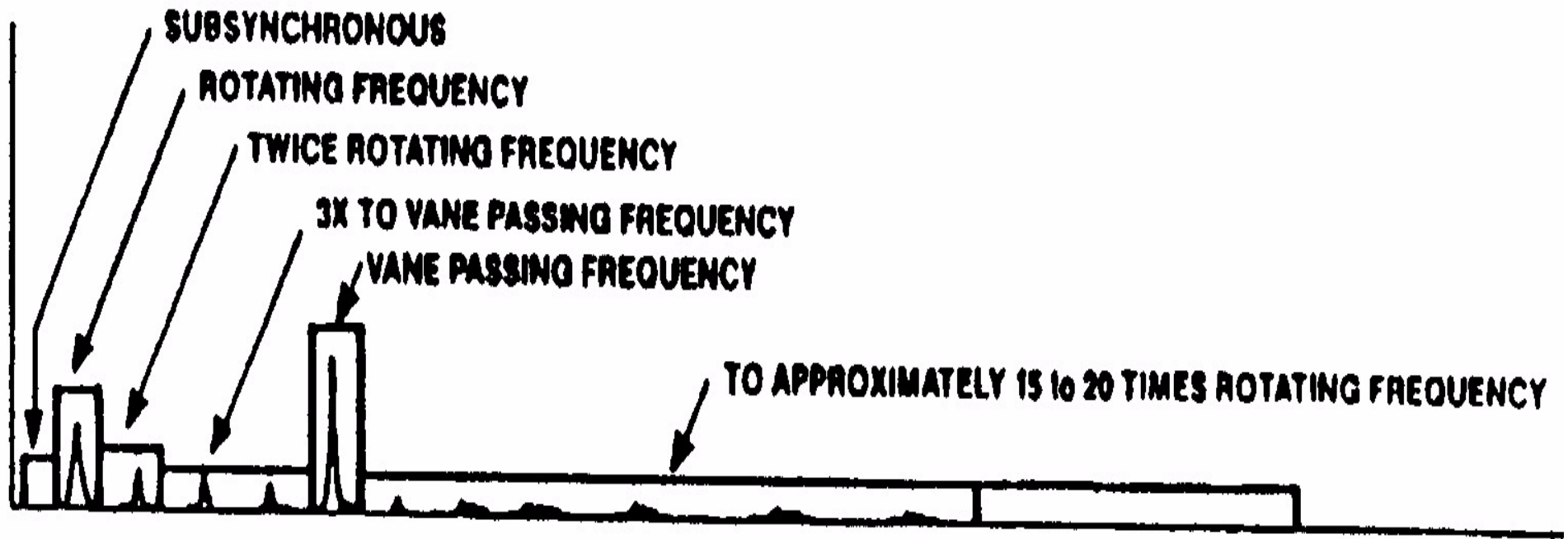
- spectrum is divided into frequency bands
- total energy or highest amplitude trended within each band
- each band has its own limits based on experience
- 10 bands or fewer
- shows small changes in component specific frequency ranges
- band widths and limits must be machine & sensor type/location specific

Standards Based on Vibration Severity



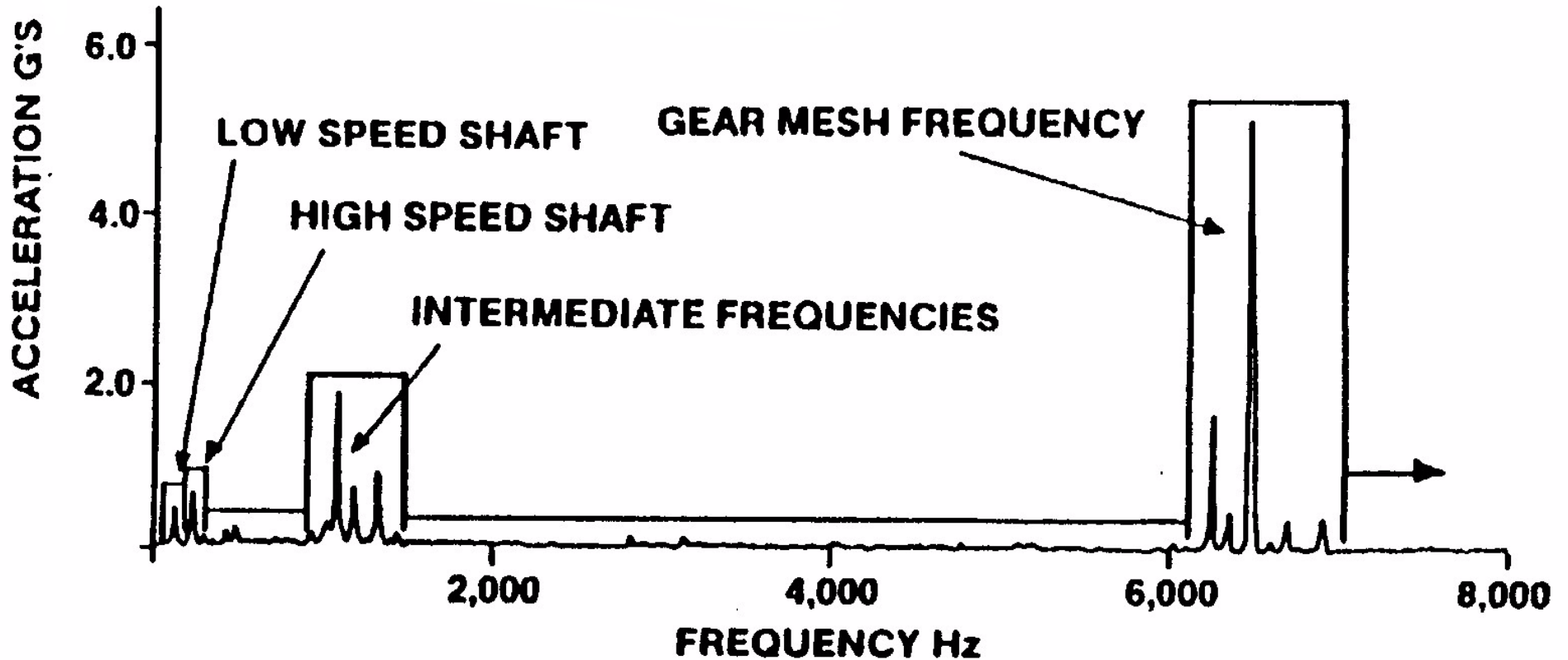
Rolling Element Bearing Spectrum

Standards Based on Vibration Severity



Fluid Film Bearing Spectrum

Standards Based on Vibration Severity



Gear Spectrum

Standards Based on Vibration Severity

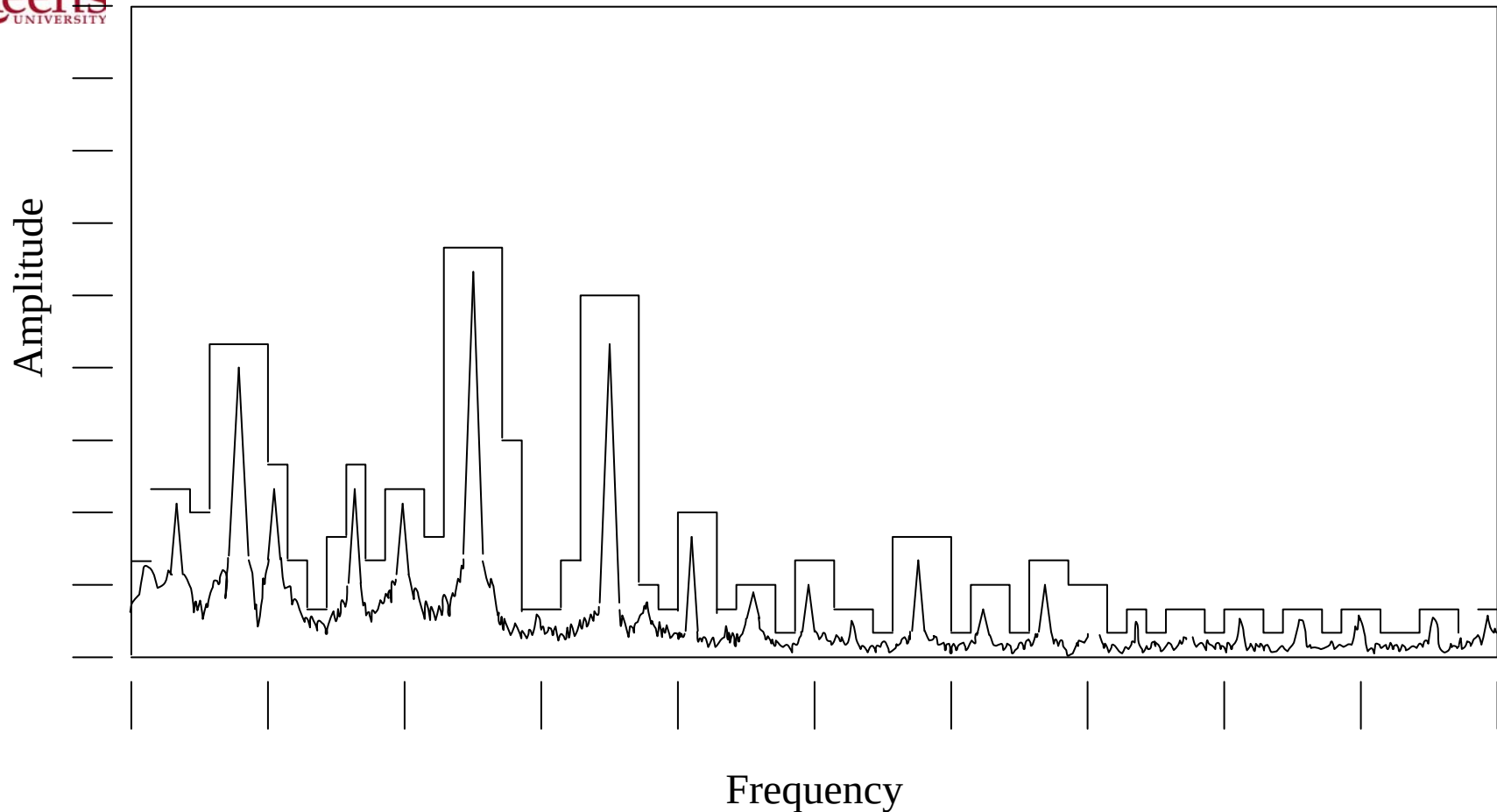
Narrow Band Monitoring

- same as limited band but with finer definition of bands

Constant Band Width

- bands have same width at high and low frequencies
- constant speed machines

Standards Based on Vibration Severity



Constant Band Width

Standards Based on Vibration Severity

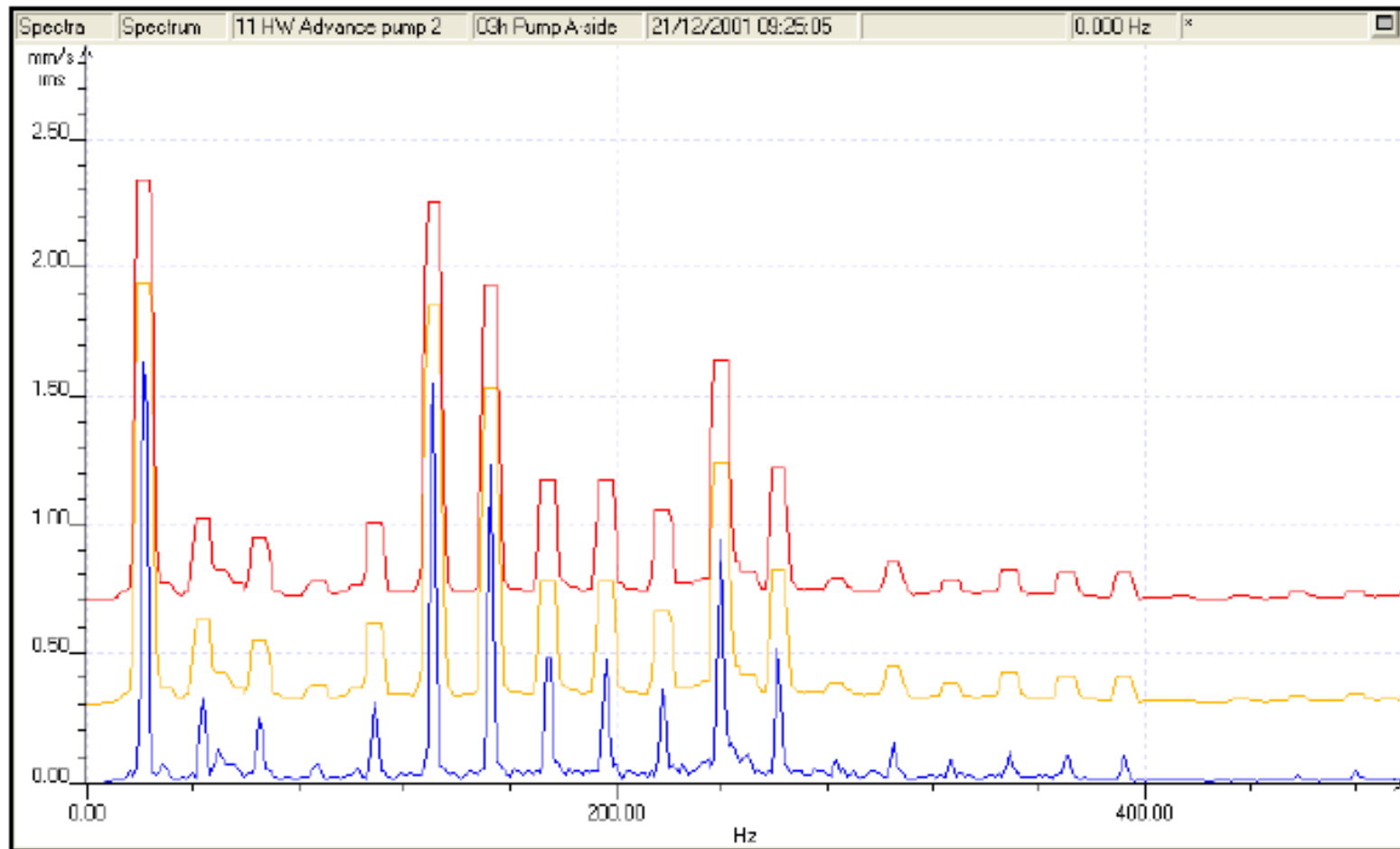


Figure 8.6: A spectrum showing the calculated alert and danger envelope alarms

Standards Based on Vibration Severity

Constant Percentage Band width

- band width remains a constant percentage of the frequency being monitored
- allows for small variations in speed



Standards Based on Vibration Severity

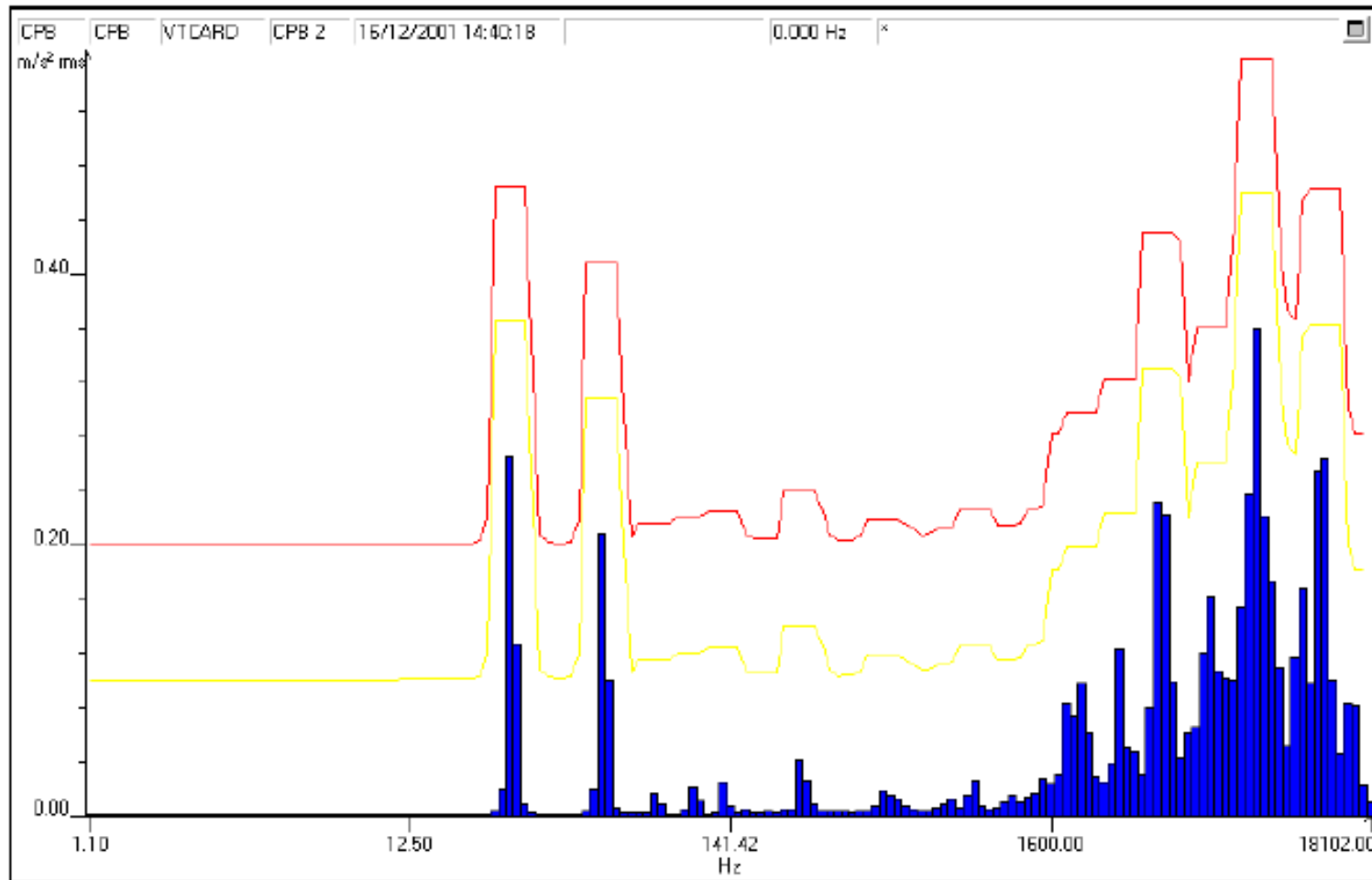


Figure 6.8: A CPB-spectrum with superimposed contour curves for an alert and danger alarm

Standards Based on Vibration Severity

Establishing a Reference Spectrum

1. Spectra from one good machine represents best condition for population.
2. Composite reference using vibration signals from all machines averaged together.
3. Each individual machine has its own reference (may be statistically derived if enough data is available).
 - all samples must represent machine in good condition
 - samples must be taken under normal operating conditions

Standards Based on Vibration Severity

Minimum Threshold Values for Trends

- we are looking for trends and levels
- low levels will have a wide % variation
- set a minimum level below which variation is ignored
- this requires knowledge of machine & operating conditions
- best used together (trends and levels)

Next Time

- Introduction to Machine Condition Monitoring and Condition Based Maintenance
- Basics of Mechanical Vibrations
- Vibration Transducers
- Vibration Signal Measurement and Display
- Machine Vibration Standards and Acceptance Limits (Condition Monitoring)
- Vibration Signal Frequency Analysis (FFT)