ISO standards for Machine vibration and balancing – Focus on large turbines and generators.

Energiforsk Vibrations in nuclear application 2018-11-13

Anders Nöremark

ISO standards for Machine vibration and balancing – Focus on large turbines and generators.

1. Introduction
2. What is ISO ,TC 108, SC2 WG1,WG31 and SIS
3. Vibration standards
   - Introduction
   - New numbering of vibration standards and what is new.
   - Most important for large steam turbines and generators ISO 20816-2
   - Information about other relevant standards for power plants
4. Balancing and balancing standards.
   - Introduction
   - New numbering of balancing standards and what is new.
   - Most important for large steam turbines and generators ISO 21940-11 Rigid rotors and 21940-12 Flexible rotors
   - Information about other relevant standards

Do we need standards?

Vibration standards

- Easier to share experiences with others.

- Easier to compare measurement values with other

- Simplifies contract writing

- Facilitates acceptance test

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Do we need standards ?

Balancing standards

- Makes it easier (possible) to build a complete machine from components from different manufacturer e.g. turbine-generator, motor-gearbox-compressor, motor-coupling-pump.

- Facilitate discussion between customer and manufacturer
  - facilitate writing of specifications(for customer)
  - makes it easier for a manufacturer to explain balancing procedure and criteria
  - facilitate customer control of balancing

- Good balancing standards will result in an improved quality of balancing and that will result in improved vibration behaviour of machines in situ

ISO Organization and general information.

- International Organization for Standardization develop and publish International Standards.

- ISO standards respond to a need in the market

- ISO standards are based on global expert opinion

- ISO standards are based on a consensus

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ISO history

- 1947 the new organization, ISO, officially began operations

- ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, 1956?

- Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*. 1963

- ISO 1940 Rigid rotors Published 1973 (SC 1)

- ISO 2372 Mechanical vibration of machines with operating speeds from 10 to 200 rev/s Published 1974

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SIS, Swedish Standards Institute

SIS, Swedish Standards Institute

Box 45443, 104 31 Stockholm

08-555 520 00

info@sis.se

SIS/TK 111 AG2

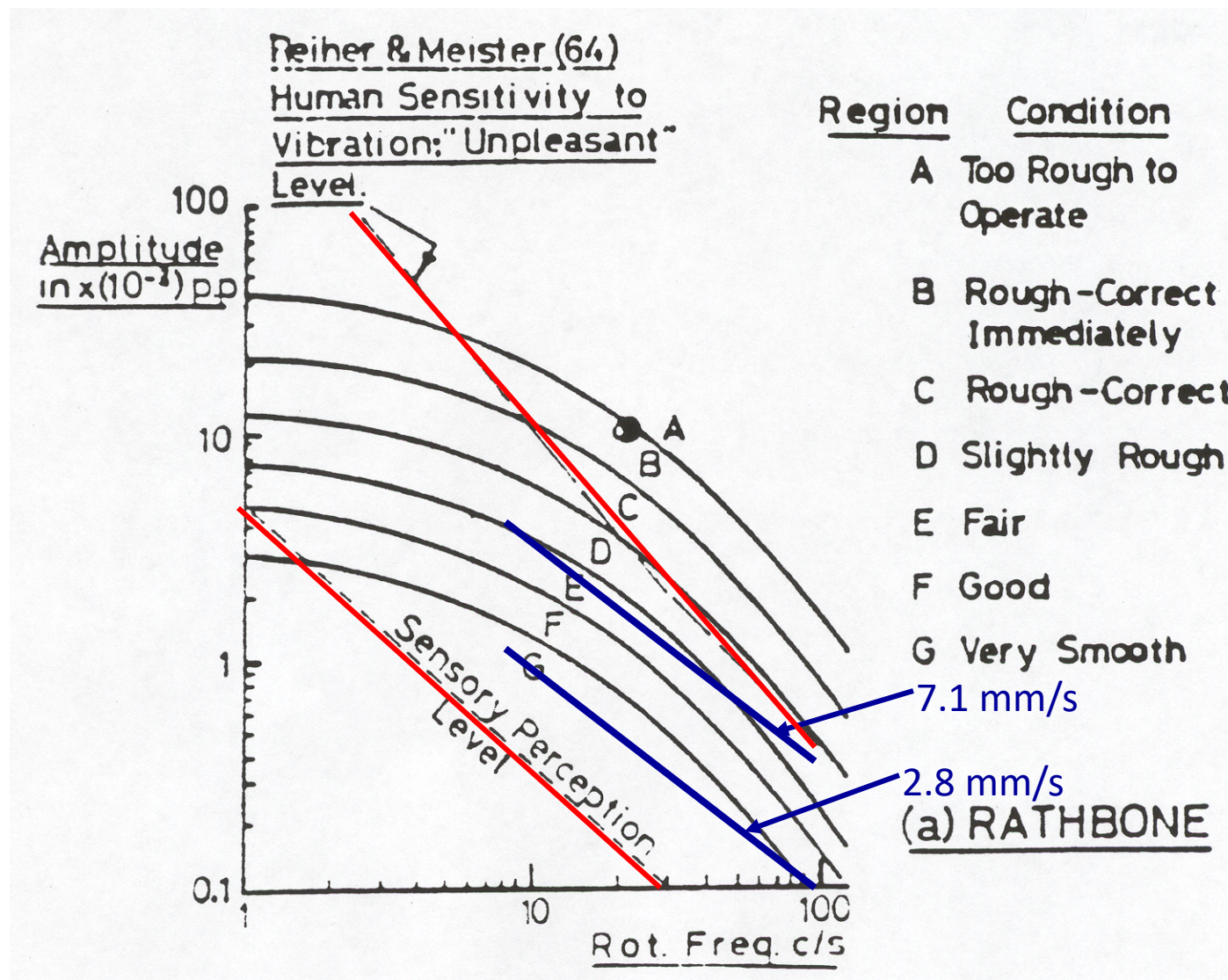Project manager Lisa Almkvist 08-55552115
lisa.almkvist@sis.se

Chairman Björn Larsson Siemens, Finspång

Vibration Standards history

- Rathbone 1939

- DIN VDI 2056 Bearing vibration 1957

- DIN VDI 2059 Shaft vibration 1972

- ISO 2372 Bearing vibration 1974

- ISO 3545 Bearing vibration Large machines 1977

- ISO 7919 Shaft vibration 1986

- ISO 10816 Bearing vibration 1995 (replaced 2372 and 3945) Many parts

- ISO 20816 Bearing and Shaft Vibration 2016 (merge of 7919 and 10816)

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"Standard" Rathbone 1939

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ISO Vibration standards today

- ISO 10816- Bearing vibration
- ISO 7919- Shaft vibration

- ISO 20816- New series bearing and shaft vibration. Merge of 10816 and 7919 to 20816.

Important for power plants.

- ISO 20816 -2 *Land-based gas turbines, steam turbines and generators in excess of 40 MW*, with fluid-film bearings and rated speeds of 1 500 r/min, 1800 r/min, 3 000 r/min and 3 600 r/min.

ISO Vibration standards Change numbering

- The old series ISO10816(bearing vibration) and ISO7919(shaft vibration) have or will be changed to ISO 20816(bearing and shaft vibration)

What is new in 20816-2 and 20816-4

- ISO 20816-2 includes gas turbines over 40 MW.

- ISO 10816-4 includes gas turbines between 3MW and 40 MW and gas turbines with operating speeds other than 1500,1800,3000 and 3600 RPM

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ISO Vibration standards Status today

- 20816-1 General guidelines (Published 2016)

- 20816-2: Land-based *gas turbines, steam turbines and generators in excess of 40 MW,* with fluid-film bearings and rated speeds of *1 500 r/min, 1 800 r/min, 3 000 r/min and 3 600 r/min* (2017)

- 10816-3 *Industrial machines* with nominal power above 15 kW and nominal speeds between *120 r/min and 15 000 r/min* when measured in situ (Published 2009) Will be revised

- 7919-3 Mechanical vibration — Evaluation of machine vibration by measurements on rotating shafts — Coupled *industrial machines* (Published2009) Will be revised

- 20816-4 *Gas turbines in excess of 3 MW*, with fluid-film bearings (Published 2018)

ISO Vibration standards Status today

- ISO 20816- 5: Machine sets in *hydraulic power* generating and pumping plants (2018)

- ISO 10816-6: *Reciprocating* machines with power ratings above 100 kW (1995)

- Part 7: *Rotodynamic pumps* for industrial applications, including measurements on rotating shafts (2009)

- Part 8: Reciprocating compressors 2014

20816-1 General guidelines

From Scope

- This document establishes general conditions and procedures for the measurement and evaluation of vibration using measurements made on rotating, non-rotating and non-reciprocating part of complete machines

Example of contents

- Following measurement quantities can be used:

- a) vibration displacement, measured in micrometres;
  b) vibration velocity, measured in millimetres per second;
  c) vibration acceleration, measured in metres per square second.

- No vibration limits are presented in Part -1

20816-1 General guidelines

From Scope

- a) structural vibration at all main bearing housings or pedestals measured radial (i.e. transverse) to the shaft axis;

- b) structural vibration at thrust bearing housings measured in the axial direction;

- c) vibration of rotating shafts radial (i.e. transverse) to the shaft axis at, or close to, the main bearings.

- These are in terms of the following:

- — vibration under normal steady-state operating conditions;

- — vibration during other (non-steady-state) conditions when transient changes are taking place, including run up or run down, initial loading and load changes;

- — changes in vibration which can occur during normal steady-state operation.

20816-1 Positions for measurements on rotating shafts
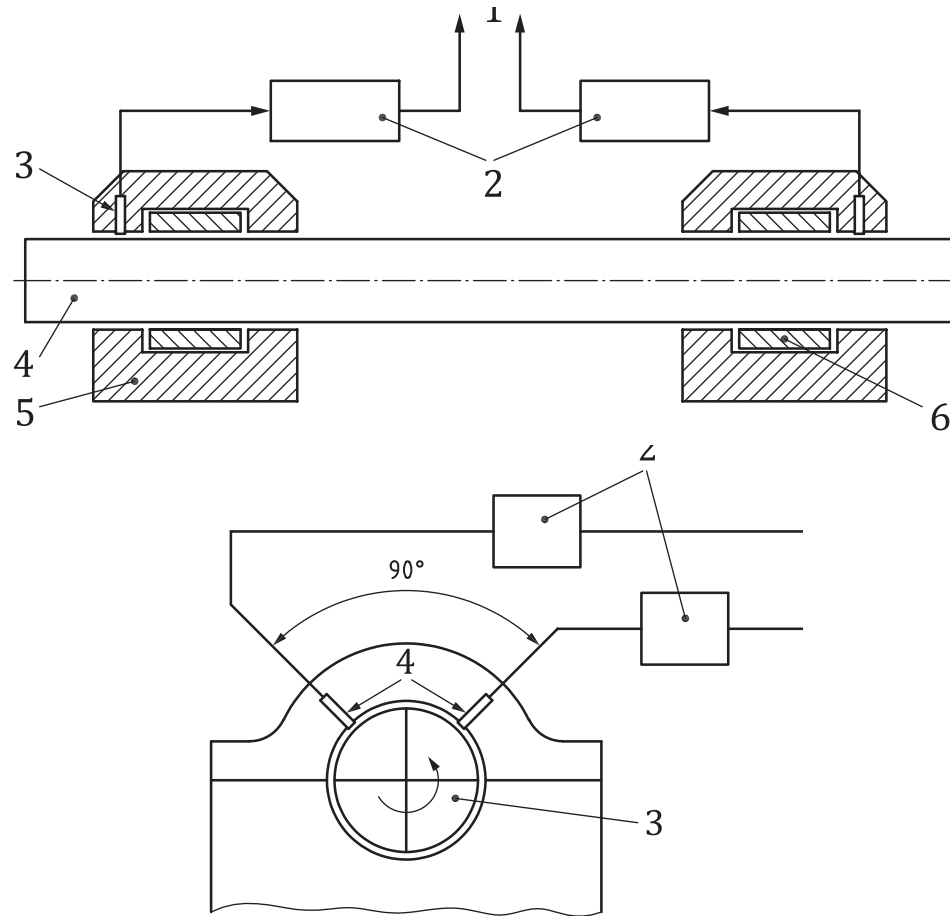
ISO 20816-1 Evaluation zones

- The following evaluation zones are defined to permit a qualitative assessment of the vibration on a given machine under steady-state conditions at normal operating speed and to provide guidelines on possible actions. Different categorization and number of zones may apply for specific machine types. These are provided in additional parts of ISO 20816.

ISO 20816-1 Evaluation zones

- **Zone A**: The vibration of newly commissioned machines normally falls within this zone.
  NOTE The effort required to achieve vibration within zone A *can be disproportionate and unnecessary.*

- **Zone B**: Machines with vibration within this zone are normally *considered acceptable for unrestricted long-term operation.*

ISO 20816-1 Evaluation zones

- **Zone 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.

- **Zone D**: Vibration values within this zone are normally considered to be of *sufficient severity to cause damage to* the machine.

ISO 20816-2 Land-based gas turbines, steam turbines and generators in excess of 40 MW

Title

Part 2:

INTERNATIONAL STANDARD ISO 20816-2:2017(E)

Mechanical vibration — Measurement and evaluation of machine vibration —

Land-based *gas turbines, steam turbines and generators in excess of 40 MW,* with fluid-film bearings and rated speeds of 1 500 r/min, 1 800 r/min, 3 000 r/min and 3 600 r/min

ISO 20816-2 Land-based gas turbines, steam turbines and generators in excess of 40 MW

From Scope

- This document is applicable to *land-based gas turbines, steam turbines and generators* (whether coupled with gas and/or steam turbines) with power outputs greater than 40 MW, fluid-film bearings and rated speeds of 1 500 r/min, 1 800 r/min, 3 000 r/min or 3 600 r/min.

ISO 20816-2 Frequency range

- The measurement system shall for structural vibration be capable of measuring broad-band vibration over a frequency range from 10 Hz to at least 500 Hz and for shaft vibration 1Hz to at least three times the maximum normal operating frequency or 125 Hz, whichever is greater .

ISO 20816-2 Typical measuring points and direction steam turbine bearing

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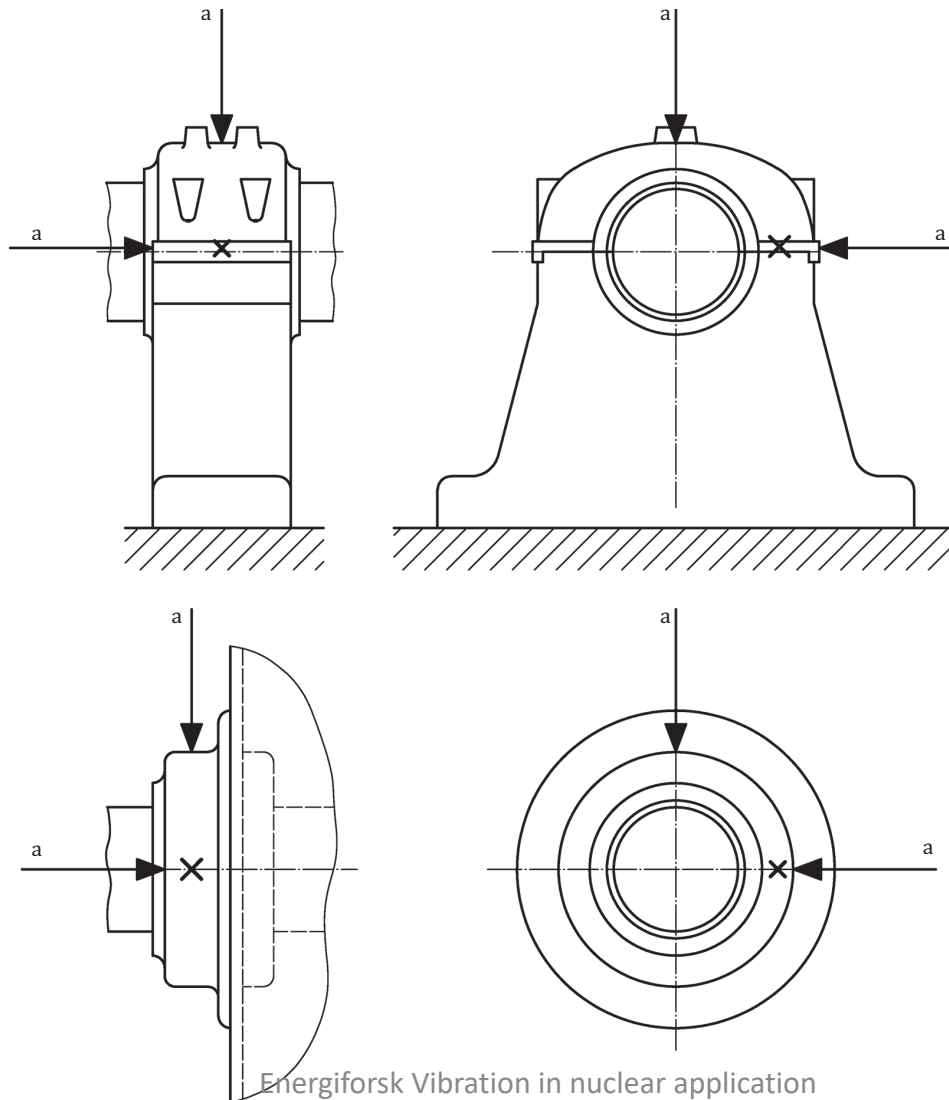
ISO 20816-2 Typical measuring points and direction a gasturbine bearing
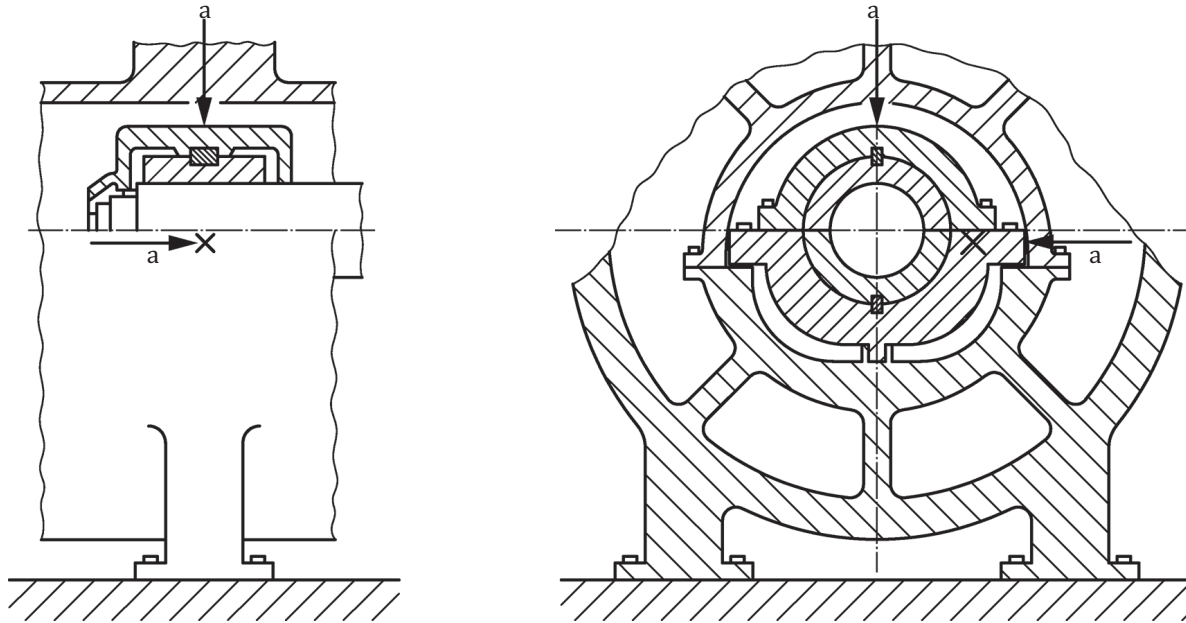
^a   Direction of measurement.

NOTE   The evaluation criteria in this document are applicable to radial vibration on all main bearings and to axial vibration on thrust bearings.

Figure 2 — Typical measuring points and directions on a gas turbine bearing

ISO 20816-2 Evaluation zone boundaries for vibration of non-rotating parts

Table A.1 — Values for bearing housing or pedestal r.m.s. vibration velocity at zone boundaries

	Shaft rotational speed r/min	Bearing housing or pedestal r.m.s. vibration velocity at zone boundaries mm/s		
		Zone boundary		
		A/B	B/C	C/D
Steam turbine and generator	1 500 or 1 800	2,8	5,3	8,5
	3 000 or 3 600	3,8	7,5	11,8
Gas turbine	3 000 or 3 600	4,5	9,3	14,7
NOTE Since it is not common practice to run gas turbines at 1 500 r/min or 1 800 r/min, no values are given.				

Zone A: The vibration of newly commissioned machines normally falls within this zone

— **Zone C**: Unsatisfactory for long- term continuous operation.

Zone B: Acceptable for unrestricted long-term operation.

•**Zone D**: sufficient severity to cause damage to the machine.

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ISO 20816-2 Evaluation zone boundaries for vibration of rotating shafts

Table B.1 — Values for shaft relative vibration peak-to-peak displacement at zone boundaries

	Shaft rotational speed r/min	Shaft *relative* vibration peak-to-peak displacement at zone boundaries μm		
		Zone boundary		
		A/B	B/C	C/D
Steam turbine and generator	1 500	100	200	320
	1 800	95	185	290
	3 000	90	165	240
	3 600	80	150	220
Gas turbine	3 000	90	165	240
	3 600	80	150	220
NOTE Since it is not common practice to run gas turbines at 1 500 r/min or 1 800 r/min, no values are given.				

Zone A: The vibration of newly commissioned machines normally falls within this zone

Zone B: Acceptable for unrestricted long-term operation.

— **Zone C**: Unsatisfactory for long- term continuous operation

•**Zone D**: Vibration values within this zone are normally considered to be of sufficient severity to cause damage to the machine.

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ISO 20816-2 Alarm limit during run up, run down and overspeed

Table 1 — ALARM limit during run up, run down or overspeed

Speed range (in relation to rated speed)	Vibration of non-rotating parts (see Table A.1)	Shaft relative and shaft absolute vibration (see Tables B.1 and B.2)
<20 %	n/a (see Note)	1,5 × C/D boundary
20 % to 90 %	1,0 × C/D boundary	1,5 × C/D boundary
>90 %	1,0 × C/D boundary	1,0 × C/D boundary
NOTE The ratio of vibration displacement to velocity is inversely proportional to frequency; hence, for measurements made on non-rotating parts, there are drawbacks in using a constant velocity criterion at speeds below 20 % of rated speed (see Annex D).		

ISO 20816-2 Acceptance criteria

- Acceptance criteria should always be subject to *agreement between the machine supplier and purchaser*

- The evaluation *zones provide a basis for defining acceptance criteria* but the numerical are not intended to serve as acceptance specifications.

- Historically, for new machines, acceptance criteria have been specified in *zone A or zone B*, but would *normally not exceed 1,25 times the zone A/B boundary*.

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ISO 20816-2 Setting of ALARMS

- The ALARM limits can vary for individual machines. It is recommended that the values chosen *should normally be set relative to baseline* values determined from experience for the measurement position or direction for that particular machine.

- It is recommended that the ALARM limit be set higher than the baseline by an amount equal to 25 % of the zone boundary B/C. The ALARM limit should *not normally exceed 1,25 times the zone boundary B/C*.

ISO 20816-2 Setting of TRIPS

- The TRIP limits *generally relate to the mechanical integrity of the machine* and are dependent on any specific design features which have been introduced to enable the machine to withstand abnormal dynamic forces.

ISO 20816-2 Setting of TRIPS

- It is not possible to give more precise guidelines for absolute TRIP limits. In general, the TRIP limit is within zone C or D, but it is recommended that it not exceed 1,25 times the zone boundary C/D.

ISO 10816-3 Industrial machines measurements on non-rotating parts

- Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15 000 r/min when measured in situ

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ISO 10816-3 Industrial machines measurements on non-rotating parts

- The machine sets covered by this part of ISO 10816 include:
- – steam turbines with power up to ~~50~~ 40 MW;
- – steam turbine sets with power greater than ~~50~~ 40MW and speeds below 1 500 r/min or above 3 600 r/min (not included in ISO 10816-2);
- – rotary compressors;
- – industrial gas turbines with power up to 3 MW;
- – generators;
- – electrical motors of any type;
- – blowers or fans.

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ISO 10816-3 Industrial machines measurements on non-rotating parts

Table A.1 — Classification of vibration severity zones for machines of Group 1: Large machines with rated power above 300 kW and not more than 50 MW; electrical machines with shaft height $H \geqslant$ 315 mm

Support class	Zone boundary	r.m.s. displacement μm	r.m.s. velocity mm/s
Rigid	A/B	29	2,3
	B/C	57	4,5
	C/D	90	7,1
Flexible	A/B	45	3,5
	B/C	90	7,1
	C/D	140	11,0

ISO 7919-3 Coupled industrial machines

- This part of ISO 7919 applies to coupled industrial machines with fluid-film bearings, having maximum continuous rated speeds in the range 1 000 r/min to 30 000 r/min and not limited by size and power, comprising
- Comprising (almost) the same machines as 10816-3

20816-4 Gas turbines in excess of 3 MW, with fluid-film bearings

- This document is applicable to land-based gas turbines with fluid-film bearings and power outputs *greater than 3 MW and an operating speed under load between 3 000 r/min and 30 000 r/min.*

20816-4 Gas turbines in excess of 3 MW, with fluid-film bearings

- <u>Not applicable to the following</u>
- gas turbines with power outputs greater than 40 MW at rated speeds of 1 500 r/min, 1 800 r/min, 3 000 r/min or 3 600 r/min (see ISO 20816-2);
- aero-derivative gas turbines (including gas turbines with dynamic properties similar to those of aero-derivative

20816-4 Evaluation zone boundaries for vibration of non-rotating parts

- ## Same limits as in ISO 20816-2

Values for bearing housing or pedestal RMS vibration velocity at zone boundaries

Zone boundary	RMS vibration velocity at zone boundaries mm/s
A/B	4,5
B/C	9,3
C/D	14,7

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20816-4 Evaluation zone boundaries for vibration of rotating shafts

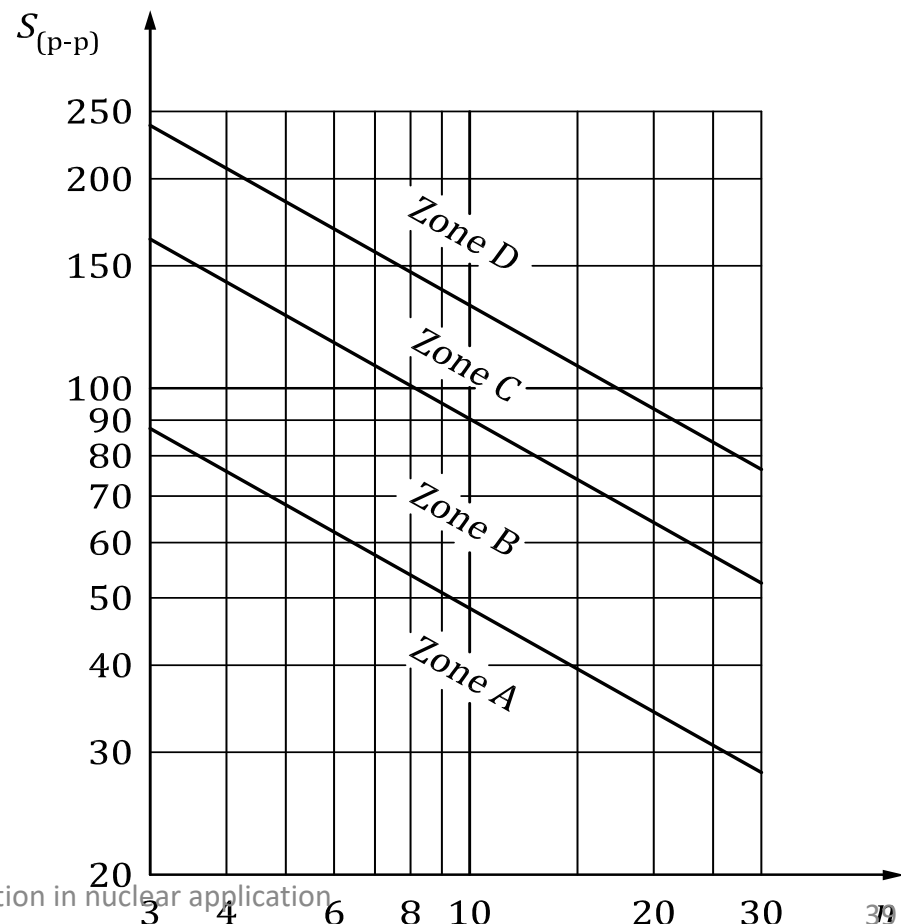- Same limits as ISO 7919-4

Zone boundary A/B

$$S_{(p-p)} = \frac{4\ 800}{\sqrt{n}}$$

Zone boundary B/C

$$S_{(p-p)} = \frac{9\ 000}{\sqrt{n}}$$

Zone boundary C/D

$$S_{(p-p)} = \frac{13\ 200}{\sqrt{n}}$$

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Balancing standards

- Introduction to balancing
- Balancing standards

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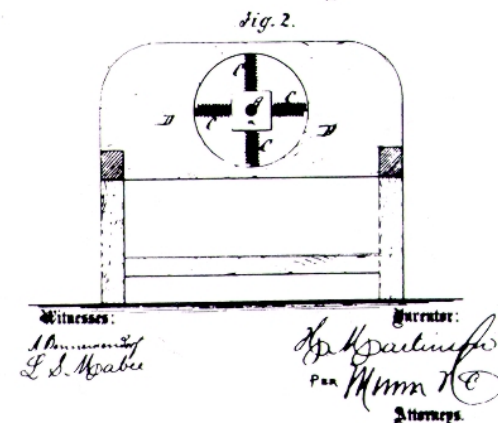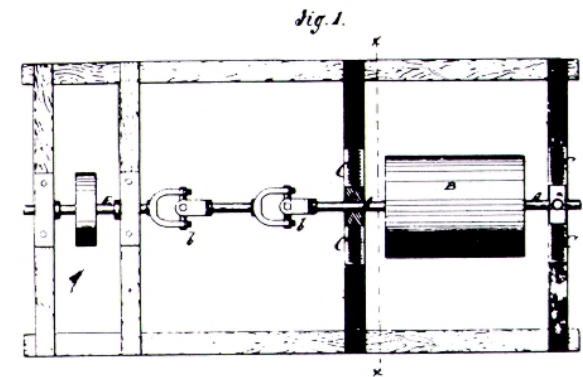2018, ISO-standards Anders Nöremark

Introduction to balancing

- The *aim* of balancing any rotor is to achieve *satisfactory running* when installed on site
- *For nearly all rotors, balancing is regarded today as absolutely necessary*, whether it is to increase the time between overhauls, improve performance, or obtain smoth vibration-free operation.
- Most rotors are balanced in workshop prior to machine assembly because afterwards, for example, there may be only limited access to the rotor.
- Furthermore, balancing of the rotor is often the stage at which a rotor is approved by the purchaser.

Introduction to balancing

- Thus, while satisfactory running on site is the aim, the balance quality of the rotor is usually initially assessed in a balancing facility.

- The first patent which referred to a balancing machine was filed in the year 1870(four years after the invention of the dynamo by *Siemens)*

Introduction to balancing

- Rotor unbalance may be caused by design, material, manufacturing and assembly.
- Every rotor, even in series production, has an individual unbalance distribution along its length.
- In reality this unbalance is an infinite number of unbalance vectors, distributed the rotor.
- For "rigid" rotors the unbalance can always be represented in two arbitrary planes.
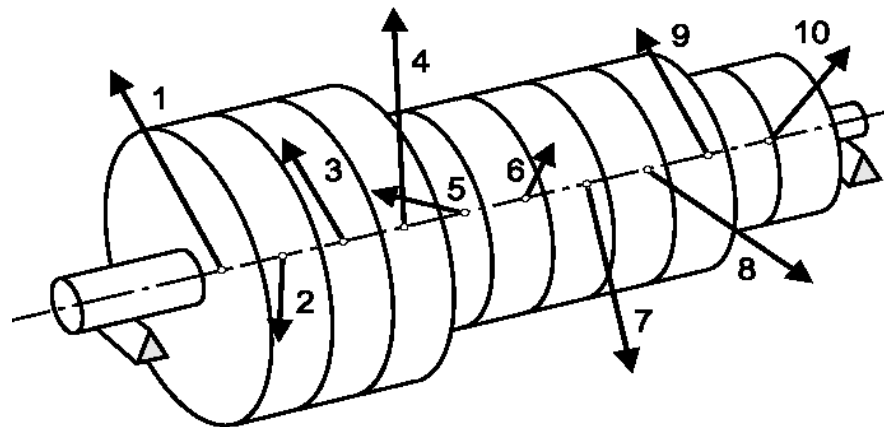
Balancing standards

- The aim of balancing any rotor is to achieve satisfactory running when installed *in-situ*.

- The balancing machines available today enable residual unbalances to be reduced to very low limits. Therefore, it is necessary to specify an unbalance quality requirement for a balancing task, as *in most cases it would not be cost-effective to reduce the unbalance to the limits of the balancing machine.*

Status of published balancing standards

5. Status of published standards and project progress

Part	ISO 21940 Mechanical vibration – Rotor balancing
1	ISO/WD 21940-1 Mechanical vibration — Rotor balancing — Part 1: Introduction: CD
2	ISO/WD 21940-2 Mechanical vibration — Rotor balancing — Part 2: Vocabulary: Published May 2017
11	2nd ISO/CD 21940-11:2014 Mechanical vibration — Rotor balancing — Part 11: Procedures and tolerances for rotors with rigid behaviour: Published November 2017
12	ISO/CD 21940-12:2014 Mechanical vibration — Rotor balancing — Part 12: Procedures and tolerances for rotors with flexible behaviour Published April 2016
13	ISO 21940-13:2012 Mechanical vibration — Rotor balancing — Part 13: Criteria and safeguards for the in-situ balancing of medium and large rotors. Published March 2012, Review June 2017
14	ISO 21940-14:2012 Mechanical vibration — Rotor balancing — Part 14: Procedures for assessing balance errors. Published March 2012, Review September 2017
21	ISO 21940-21:2012 Mechanical vibration — Rotor balancing — Part 21: Description and evaluation of balancing machines. Published July 2012, Under revision
22	ISO 3719:1994 Mechanical vibration — Symbols for balancing machines and associated instrumentation Withdrawn July 2012 without successor
23	ISO 21940-23:2012 Mechanical vibration — Rotor balancing — Part 23: Enclosures and other protective measures for the measuring station of balancing machines. Published June 2012, Review September 2017
31	ISO 21940-31:2013 Mechanical vibration — Rotor balancing — Part 31: Susceptibility and sensitivity of machines to unbalance. Published August 2013,
32	ISO 21940-32:2012 Mechanical vibration — Rotor balancing — Part 32: Shaft and fitment key convention. Published March 2012, Review June 2017

- 1 Introduction
- 2 Vocabulary
- 11 Rigid rotors
- 12 Flexible rotors
- 13 In-situ balancing
- 14 Errors
- 21 Balancing machines
- 22 Symbols for balancing machines
- 23 Enclosure
- 31 Susceptibility
- 32 Shaft key

Status of published balancing standards and project progress + (new numbers and old numbers)

- ISO/WD *21940-1* Mechanical vibration — Rotor balancing — Part 1: Introduction:
  CD (old number *19499*)

- ISO/WD *21940-2* Mechanical vibration — Rotor balancing — Part 2: Vocabulary:
  Published May 2017(old number *1925*)

- ISO/*21940-11*:2014 Mechanical vibration — Rotor balancing — Part 11: Procedures and tolerances for rotors with *rigid* behaviour:
  Published November 2017 (old number *1940-1*)

- ISO/CD *21940-12*:2014 Mechanical vibration — Rotor balancing — Part 12: Procedures and tolerances for rotors with *flexible* behaviour Published April 2016 (old number *11342)*

Status of published balancing standards and project progress + (new numbers and old numbers)

- ISO *21940-13*:2012 Mechanical vibration — Rotor balancing — Part 13: Criteria and safeguards for the *in-situ* balancing of medium and large rotors. (old number *20806*)Published March 2012, Review June 2017

- ISO *21940-14:*2012 Mechanical vibration — Rotor balancing — Part 14: Procedures for assessing balance errors.Published March 2012, Review September 2017 (old number *1940-2*)

- ISO *21940-21*:2012 Mechanical vibration — Rotor balancing — Description and evaluation of balancing machines.Published July 2012, Under revision (old number *2953*)

Status of published balancing standards and project progress + (new numbers and old numbers)

- ISO *21940-23*:2012 Mechanical vibration — Rotor balancing — Enclosures and other protective measures for the measuring station of balancing machines.Published June 2012, Review September 2017 (old number *7475*)

- ISO *21940-31*:2013 Mechanical vibration — Rotor balancing — Susceptibility and sensitivity of machines to unbalance.Published August 2013, (old number 10814)

- ISO *21940*-32:2012 Mechanical vibration — Rotor balancing — Shaft and fitment key convention.Published March 2012, Review June 2017 (old number *8821*)

ISO 21940-11

Title

Mechanical vibration – Rotor balancing

Part 11:

Procedures and tolerances for rotors with rigid behaviour

- **Changed number from 1940-1 to 21940-11**

Definition of rigid behaviour

From ISO 21940-2 Vocabulary:

- Rigid behaviour
  rotor where the flexure caused by its *unbalance* distribution can be neglected with respect to the agreed *unbalance tolerance* at any speed up to the maximum *service speed* .

From API 616

- Rotors with rigid behavior shall be balanced at low speed in two planes per ISO1940-1.If the first flexural critical speed exceeds the maximum operating speed by at least 50 %, then the rotor can normally be considered rigid for balancing purposes.

ISO STANDARD 21940-11 Procedures and tolerances for rotors with rigid behaviour

From Scope

- This document establishes *procedures and unbalance tolerances for balancing rotors with rigid behaviour*. It specifies
- a) the magnitude of the permissible residual unbalance,
- b) the necessary number of correction planes,
- c) the allocation of the permissible residual unbalance to the tolerance planes, and
- d) how to account for errors in the balancing process.

ISO 21940-11 Derivation of the unbalance tolerances

The magnitude of permissible residual unbalance can be determined by five different methods. The methods are based on

- a) balance *quality grades,* derived from long-term practical experience with a large number of different rotors

- b) experimental evaluation of permissible residual unbalances

- c) limited bearing forces due to unbalance

- d limited vibrations due to unbalance

- e) established experience with unbalance tolerances

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ISO 21940-11 Balance quality grade G

- On the basis of worldwide experience and similarity considerations balance quality grades G have been established which permit a classification of the balance quality requirements for typical machinery types. *These balance quality grades enable the calculation of permissible residual unbalances .*

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ISO 21940-11 Guidance for balance quality grades for rotors with rigid behaviour
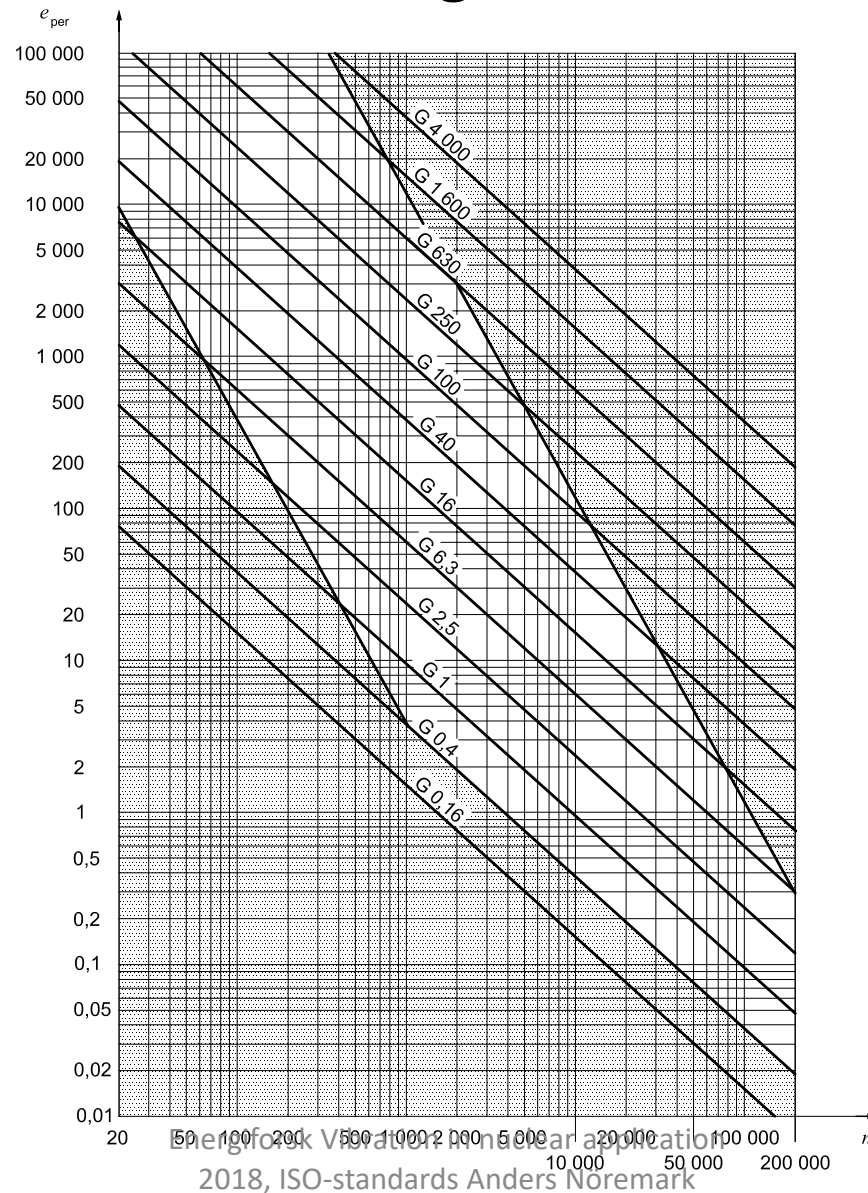
Table 1 — Guidance for balance quality grades for rotors with rigid behaviour

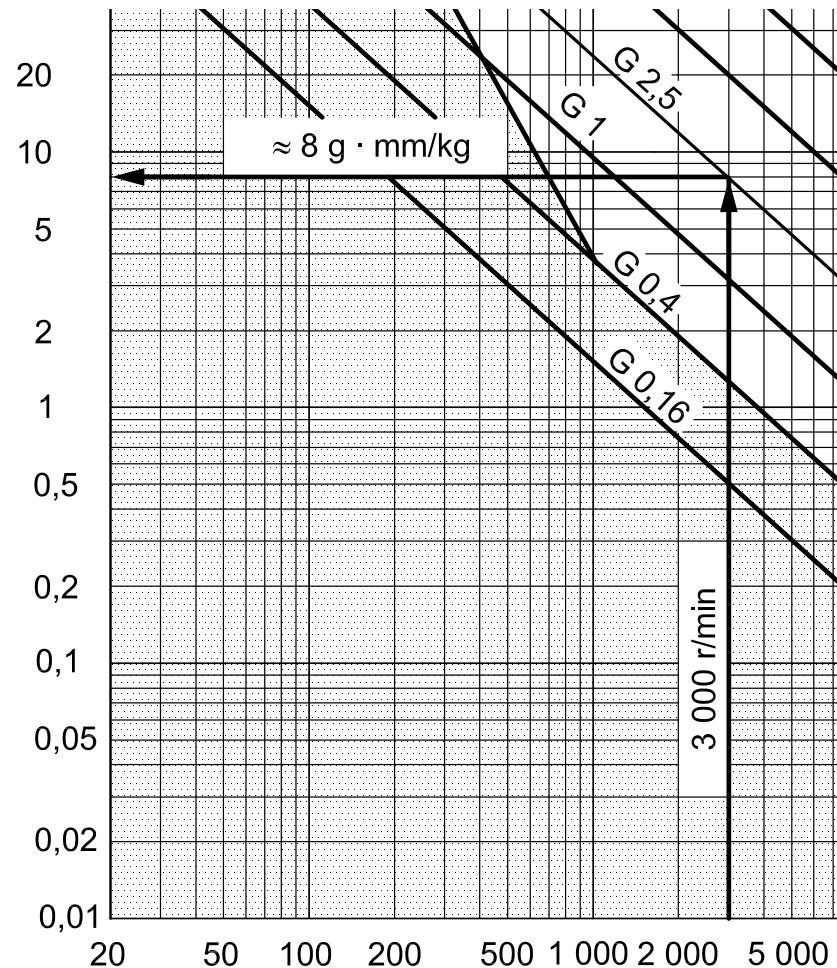| Machinery types: General examples	Balance quality grade G	Magnitude $e_{per}\,\Omega$ mm/s
Crankshaft drives for large, slow marine diesel engines (piston speed below 9 m/s), inherently unbalanced	G 4000	4 000
Crankshaft drives for large, slow marine diesel engines (piston speed below 9 m/s), inherently balanced	G 1600	1 600
Crankshaft drives, inherently unbalanced, elastically mounted	G 630	630
Crankshaft drives, inherently unbalanced, rigidly mounted	G 250	250
Complete reciprocating engines for cars, trucks and locomotives	G 100	100
Cars: wheels, wheel rims, wheel sets, drive shafts Crankshaft drives, inherently balanced, elastically mounted	G 40	40
Agricultural machinery Crankshaft drives, inherently balanced, rigidly mounted Crushing machines Drive shafts (cardan shafts, propeller shafts)	G 16	16
Aircraft gas turbines Centrifuges (separators, decanters) Electric motors and generators (of at least 80 mm shaft height), of maximum rated speeds up to 950 r/min Electric motors of shaft heights smaller than 80 mm Fans Gears Machinery, general Machine tools Paper machines Process plant machines Pumps Turbo chargers Water turbines	G 6,3	6,3
Compressors Computer drives Electric motors and generators (of at least 80 mm shaft height), of maximum rated speeds above 950 r/min Gas turbines and steam turbines Machine-tool drives Textile machines	G 2,5	2,5
Audio and video drives Grinding machine drives	G 1	1
Gyroscopes Spindles and drives of high-precision systems	G 0,4	0,4

ISO 21940-11Guidance for balance quality grades for rotors with rigid behaviour

Compressors Computer drives Electric motors and generators (of at least 80 mm shaft height), of maximum rated speeds above 950 r/min Gas turbines and steam turbines Machine-tool drives Textile machines	G 2,5

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ISO 21940-11 Guidance for balance quality grades for rotors with rigid behaviour

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ISO 21940-11 Guidance for balance quality grades for rotors with rigid behaviour

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ISO 21940-11 Experimental evaluation of the balance quality limit

- Experimental evaluation of the balance quality tolerances is often carried out *for mass production applications*. Tests are commonly performed *in situ*.

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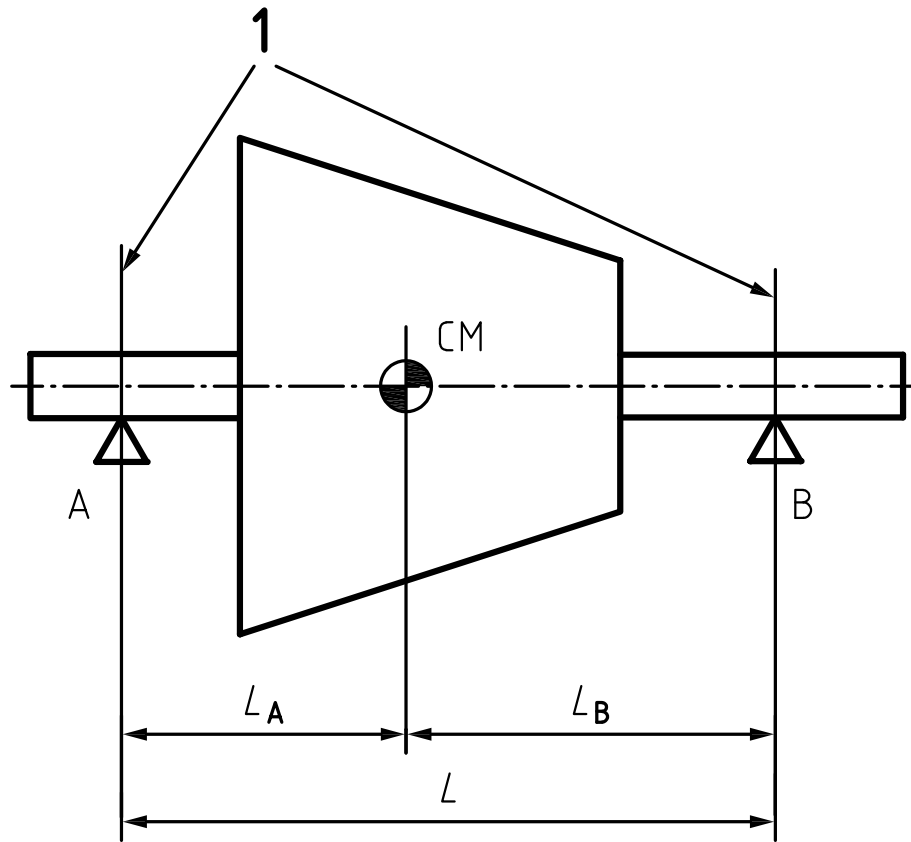
ISO 21940-11 Balance quality limit based on experience

- If a company has gained sufficient established experience to assess systematically the balance quality it may make full use of this.

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ISO 21940-11 Allocation of permissible residual unbalance to tolerance planes (normally bearing planes)

- The permissible residual unbalance, Uper is allocated in proportion to the distances from the centre of mass to the opposite tolerance plane.

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ISO 21940-11Allocation of permissible residual unbalance to tolerance planes

$$U_{\text{per A}} = U_{\text{per}} \frac{L_{\text{B}}}{L}$$

$$U_{\text{per B}} = U_{\text{per}} \frac{L_{\text{A}}}{L}$$

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ISO 21940-11 Allocation of unbalance tolerances to correction planes

- Many of today's balancing processes still apply unbalance tolerances at the correction planes.

- Since correction planes are selected in accordance with the correction process, they might not be ideal for unbalance tolerances .

- Thus, using unbalance tolerances in correction planes, many rotors are balanced to smaller unbalance values than necessary.

ISO 21940-11 Accounting for errors in the verification of permissible residual unbalances

Combined error

- After systematic errors in the unbalance readings have been corrected, ΔU is the remaining combined error which has to be allocated to the tolerance plane

- the combined error in plane A, ΔUA, and

- the combined error in plane B, ΔUB.

- However,if ΔUA is *found to be less than10%* of UperA or ΔUB is less than10% of UperB *,it may be disregarded*.

- if ΔUA is found to be more than10% of UperA or ΔUB is more than 10% of UperB see ISO 21940-14

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ISO 21940-12

Title

Mechanical vibration — Rotor balancing —

Part 12:

Procedures and tolerances for rotors with flexible behaviour

ISO 21940-12 Definition of flexible behaviour

- **Flexible behaviour**
  Rotor where the flexure caused by its *unbalance* distribution cannot be neglected with respect to the agreed *unbalance tolerance* at any speed up to the maximum *service speed*

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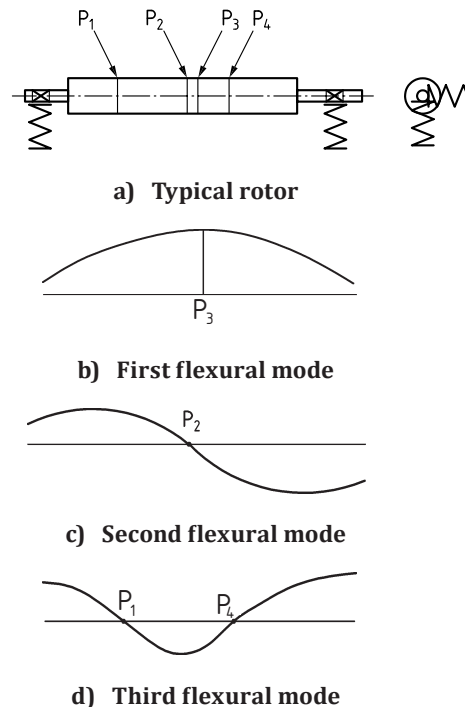
ISO 21940-12

From Scope

- This part of ISO 21940 presents typical of rotors with flexible behaviour.

- Describes balancing procedures, specifies methods of assessment of the final state of balance, and establishes guidelines for balance quality criteria.

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ISO 21940-12 Fundamentals of dynamics and balancing of rotors with flexible behaviour

- Rotors with flexible behaviour normally require multiplane balancing at high speed.

- Nevertheless, some rotors with flexible behaviour can also be balanced at low speed.

ISO 21940-12 Rotors with flexible behaviour

Simplified mode shapes for rotors with

flexible behaviour on flexible supports

a) Typical rotor

b) First flexural mode

c) Second flexural mode

d) Third flexural mode

Key

P_1, P_2, P_4 nodes

P_3 antinode

Figure 1 — Simplified mode shapes for rotors with flexible behaviour on flexible supports

ISO 21940-12 Fundamentals of dynamics and balancing of rotors with flexible behaviour
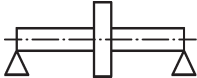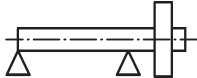
- Generally if the speed of the rotor is influenced by *n* flexural resonance speeds, then *n* + 2 correction planes are often needed. If the rotor is influenced by more than one plane it is often possible to use less than n+2 correction plane.

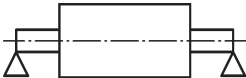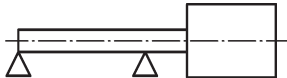- An adequate number of correction planes at suitable axial positions shall be included at the design stage.

ISO 21940-12 Balancing procedures

Table 2 — Balancing procedures

Procedure	Description	Subclause
Low-speed balancing		
A	Single-plane balancing	6.5.1
B	Two-plane balancing	6.5.2
C	Individual component balancing prior to assembly	6.5.3
D	Balancing subsequent to controlling initial unbalance	6.5.4
E	Balancing in stages during assembly	6.5.5
F	Balancing in optimum planes	6.5.6
High-speed balancing		
G	Multiple speed balancing	7.3
H	Service speed balancing	7.4
I	Fixed speed balancing	7.5

ISO 21940-12Low speed balancing of rotors with flexible behaviour (examples)

Configuration	Rotor characteristics	Recommended balancing procedure[a]
1.1 Discs	**Elastic shaft without unbalance, rigid disc(s)**	
	Single disc — perpendicular to shaft axis — with axial runout	A; C B; C

1.2 Rigid sections	**Elastic shafts without unbalances, rigid sections**	
	Single rigid section — removable — integral	B; C; E B

ISO 21940-12 Multiple speed balancing

- The rotor is balanced at a series of balancing speeds , which are selected so that there is a balancing speed close to each resonance speed within the service speed range.

- Experience has shown that it is often advantageous to also carry out balancing at low speed. This is particularly advantageous for rotors significantly affected by only the first flexural resonance speed.

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ISO 21940-12 Evaluation criteria

Choice of criteria

- One practice when evaluating the balance quality of a rotor with flexible behaviour in the factory is to consider *the once-per-revolution vibration.*

- Another practice is to evaluate the balance quality by considering the *residual unbalance*.

- Evaluation criteria are, therefore, established either in terms of vibration limits or permissible residual unbalances.

ISO 21940-12 Vibration limits in the balancing machine

- If the final state of unbalance is to be evaluated in terms of vibration criteria in the balancing machine, then these shall be chosen to ensure that the relevant *vibration limits are satisfied on site.*

ISO 21940-12 Vibration limits in the balancing machine

- There is a complex relationship between vibrations measured in the balancing machine and those obtained in the fully assembled machine on site, which is dependent on a number of factors. *Where experience exists, it should be used* as the basis for defining the permissible vibration in the balancing machine.

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ISO 21940-12 Vibration limits in the balancing machine

- There can, however, be cases where such in balancing machine experience does not exist, and some advice,are given, how to calculate vibration limits in the balancing machine, based on vibration limits in situ.

- $y = x K0 \, K1 \, K2$ y=permissible vibration in balancing machine x=permissible vibration in situ

- Very complicated (or impossible) to use.

ISO 21940-12Residual unbalance tolerances For rotors with flexible behaviour

- For rotors with flexible behaviour balanced at low speed, permissible residual unbalances in specified correction planes (ISO 21940-11) are used to state the balance quality.

- For rotors balanced at high speed, permissible residual modal unbalances are applied. The residual unbalance tolerances are based on those recommended in ISO 21940-11 for rotors with rigid behaviour and percentages of these values for the bending modes of rotors with shaft-elastic behaviour.

ISO 21940-12 Definition of equivalent *n*th modal unbalance

- ## equivalent *n*th modal unbalance

- minimum single *unbalance* equivalent to the *n*th *modal unbalance* in its effect on the *n*th *flexural mode.*
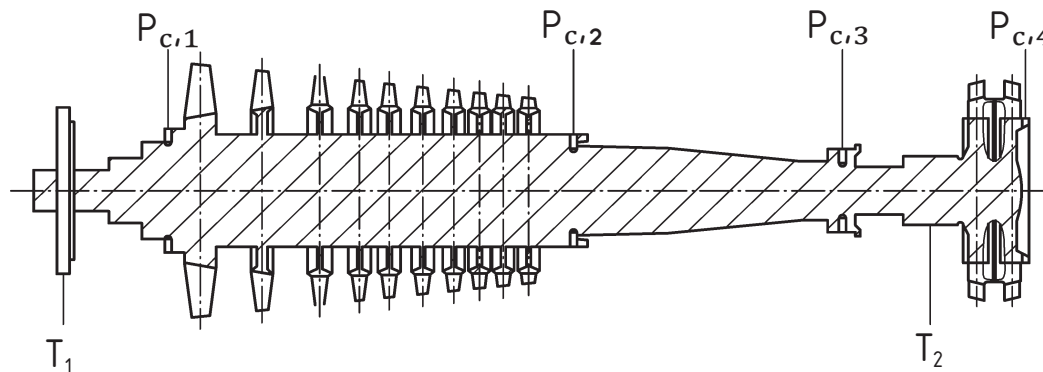
ISO 21940-12 Residual unbalance tolerances

- First and second bending modes
- a) the equivalent first modal residual unbalance shall not exceed 60 %; (of rek. in 21940-11)
- b) the equivalent second modal residual unbalance shall not exceed 60 %;
- c) if low-speed balancing is carried out , the total residual unbalance as a rigid body shall not exceed 100%.
- In cases when one of the modes is less significant than the other, the corresponding limit can be relaxed, but shall not exceed 100 %.

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ISO 21940-12 Example calculation of equivalent residual modal unbalances

D.1 Residual unbalance calculation

The principles of residual unbalance calculation are shown in the following example. A recommended procedure is outlined in 9.2.3.

The rotor is a gas turbine rotor with four correction planes $P_{c,1}$ to $P_{c,4}$ (see Figure D.1). The balancing calculations are based on vibration measurements at the two bearings (transducers T_1 and T_2).

Key

$P_{c,1}$, $P_{c,2}$, $P_{c,3}$, $P_{c,4}$ correction planes
T_1, T_2 transducers

Figure D.1 — Example gas turbine rotor

ISO 21940-12 Example calculation of equivalent residual modal unbalances

The service speed of the rotor is 10 125 r/min.

The rotor mass is 1 625 kg.

The permissible total unbalance for an equivalent rigid body according to balance quality grade G 2,5 is taken from ISO 21940-11 to be 2,37 g·mm/kg.

The total residual unbalance for an equivalent rigid body is therefore

$$2{,}37 \; \frac{\text{g} \cdot \text{mm}}{\text{kg}} \times 1\,625 \text{ kg} = 3\,850 \text{ g} \cdot \text{mm} \tag{D.1}$$

The permissible equivalent first modal unbalance (60 % thereof, see 8.3.4.2) is 2 311 g·mm.
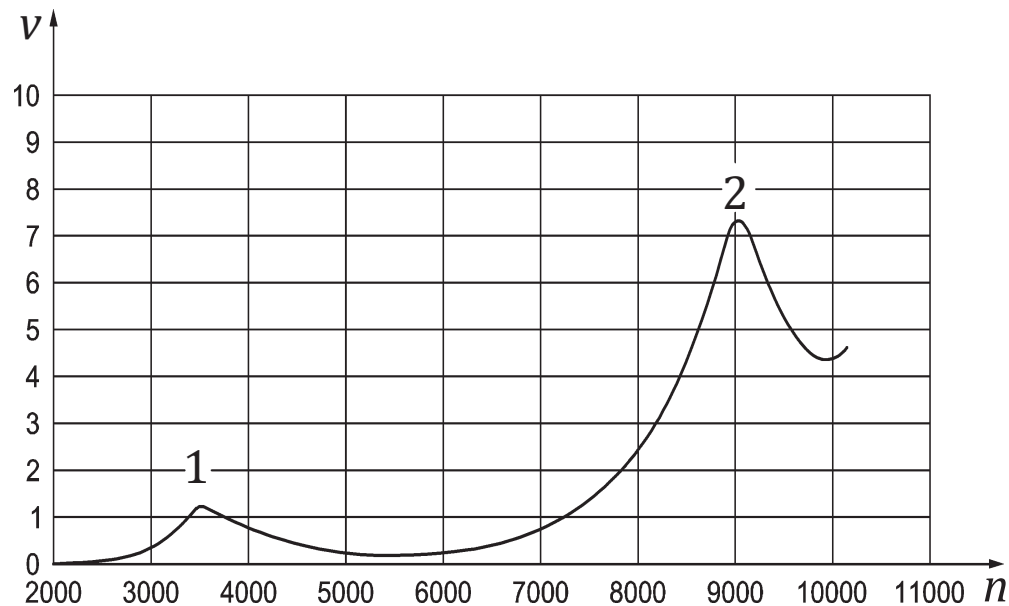
The permissible equivalent second modal unbalance (60 %) is 2 311 g·mm.

ISO 21940-12 Balancing speeds

D.2   Influence coefficients

The balancing speeds for this rotor are the following (see [Figure D.2](#)):

— 1 000 r/min (low speed);

— 3 400 r/min (just below rotor resonance 1);

— 9 000 r/min (just below rotor resonance 2).

ISO 21940-12 Influence coefficients

Table D.1 — Influence coefficients

Measurement point	Correction plane				Speed r/min
	$P_{c,1}$	$P_{c,2}$	$P_{c,3}$	$P_{c,4}$	
Transducer 1	0,059 4/3° [a]	0,033 0/1°	0,009 12/333° [a]	0,004 90/233°	1 000
Transducer 2	0,002 16/35° [a]	0,022 7/14°	0,033 4/11° [a]	0,042 5/9°	
Transducer 1	0,249/82°	0,343/94°	0,055/222°	0,360/265° [a]	3 400
Transducer 2	0,087/107°	0,157/87°	0,102/34°	0,224/6° [a]	
Transducer 1	1,99/146°	2,29/285° [a]	1,56/293°	2,07/176°	9 000
Transducer 2	1,92/353°	1,99/134° [a]	1,16/109°	0,595/281°	
[a] Influence coefficients used for residual unbalance calculation.					

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ISO 21940-12 Final vibration readings and residual unbalance

Table D.2 — Final vibration readings

Speed	Transducer		Unit
r/min	T_1	T_2	
1 000	0,01/237°	0,022/147°	mm/s
3 400	0,55/52°	0,22/125°	mm/s
9 000	2,35/305°	1,44/139°	mm/s

Table D.3 — Residual unbalance at 1 000 r/min

Plane	Calculated	Permissible
	g·mm	g·mm
$P_{c,1}$	246	1 925
$P_{c,3}$	671	1 925

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Final vibration readings and residual unbalance

Table D.4 — Residual unbalance at 3 400 r/min

Transducer	Calculated	Permissible g·mm
T_1	(0,55/0,36) 1 000 = 1 530 g·mm	2 311
T_2	(0,22/0,224) 1 000 = 982 g·mm	2 311

Table D.5 — Residual unbalance at 9 000 r/min

Transducer	Calculated	Permissible g·mm
T_1	(2,35/2,29) 1 000 = 1 026 g·mm	2 311
T_2	(1,44/1,99) 1 000 = 723 g·mm	2 311

ISO 21940- What is new in -11 and 12?

- ## ISO 21940-11 Rigid rotors.

- Small changes.
- Accounting for errors in the verification of permissible residual unbalances. If ΔU_A is found to be less than10% of U_{perA} or ΔU_B is less than10% of U_{perB} ,it may be disregarded.

- ## ISO 21940-12 Flexible rotors.

- Very small changes.
- The corrigendum from 2000 has been implemented in the main document

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