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Mechanical vibration — Rotor balancing —

Part 11:
Procedures and tolerances for rotors with rigid behaviour

Vibrations mécaniques — Équilibrage des rotors —

Partie 11: Modes opératoires et tolérances pour rotors à comportement rigide

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Foreword

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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).

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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 World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

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*.

This first edition cancels and replaces ISO 1940-1:2003, which has been technically revised. The main changes are deletion of the terms and definitions which were transferred to ISO 21940-2 and a more pronounced explanation of the application of permissible residual unbalances for the processes of balancing a rotor and verifying its residual unbalance. Information on specification of unbalance tolerances based on vibration limits has been removed.

It also incorporates the Technical Corrigendum ISO 1940-1:2003/Cor 1:2005.

A list of parts in the ISO 21940 series can be found on the ISO website.

Introduction

Rotor balancing is a procedure by which the mass distribution of a rotor (or part or module) is checked and, if necessary, adjusted to ensure the unbalance tolerance is met. This document covers the balancing of rotors with rigid behaviour. A rotor is said to be rigid when the flexure of the rotor caused by its unbalance distribution can be neglected with respect to the agreed unbalance tolerance at any speed up to the maximum service speed. For these rotors, the resultant unbalance, and often moment unbalance, are of interest, which when combined are expressed as a dynamic unbalance of the rotor.

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.

In addition to specifying an unbalance tolerance, it is necessary to consider the errors introduced by the balancing process. This document takes into account the influence of these errors to distinguish clearly between the specified permissible residual unbalance and the reduced residual unbalance values to be achieved during the balancing process.

Mechanical vibration — Rotor balancing —

Part 11:
Procedures and tolerances for rotors with rigid behaviour

1 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.

NOTE In ISO 21940-14, the assessment of balancing errors is considered in detail. Fundamentals of rotor balancing are contained in ISO 19499 which gives an introduction to balancing.

This document does not cover the balancing of rotors with flexible behaviour. Procedures and tolerances for rotors with flexible behaviour are dealt with in ISO 21940-12.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 21940-2 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

4 Pertinent aspects of balancing

4.1 General

Rotor balancing is a procedure by which the mass distribution of a rotor is examined and, if necessary, adjusted to ensure that the residual unbalance or vibration in service is within specified limits. It should be noted that the vibration in service can originate from sources other than unbalance.

Rotor unbalance can be caused by design, material, manufacturing and assembly. Every rotor has an individual unbalance distribution along its length, even in series production.

4.2 Representation of the unbalance

For a rotor with rigid behaviour, different vectorial quantities can be used to represent the same unbalance as shown in Figure 1.

Figure 1 a) to c) shows different representations in terms of resultant unbalance and resultant couple unbalance, whereas Figure 1 d) to f) shows different representations in terms of a dynamic unbalance in two planes.

NOTE 1 The resultant unbalance vector can be located in any radial plane (without changing magnitude and angle), but the associated resultant couple unbalance is dependent on the location of the resultant unbalance vector.

NOTE 2 The centre of unbalance is that location on the shaft axis for the resultant unbalance, where the resultant couple unbalance is a minimum.

If single-plane balancing is sufficient (see 4.5.2) or when considerations are made in terms of resultant unbalance and resultant couple unbalance (see 4.5.4), the representation in Figure 1 a) to c) is preferable.

In the case of typical two-plane considerations, the representation in Figure 1 d) to f) is advantageous.

4.3 Unbalance effects

Resultant unbalance and resultant moment unbalance (the latter can also be expressed as resultant couple unbalance) have different effects on forces on the bearings and on the vibration of the machine. In practice, therefore, both unbalances are often considered separately. Even if the unbalance is stated as a dynamic unbalance in two planes, it should be noted that in most cases there is a difference in effects if the unbalances predominantly form either a resultant unbalance or a resultant moment unbalance.

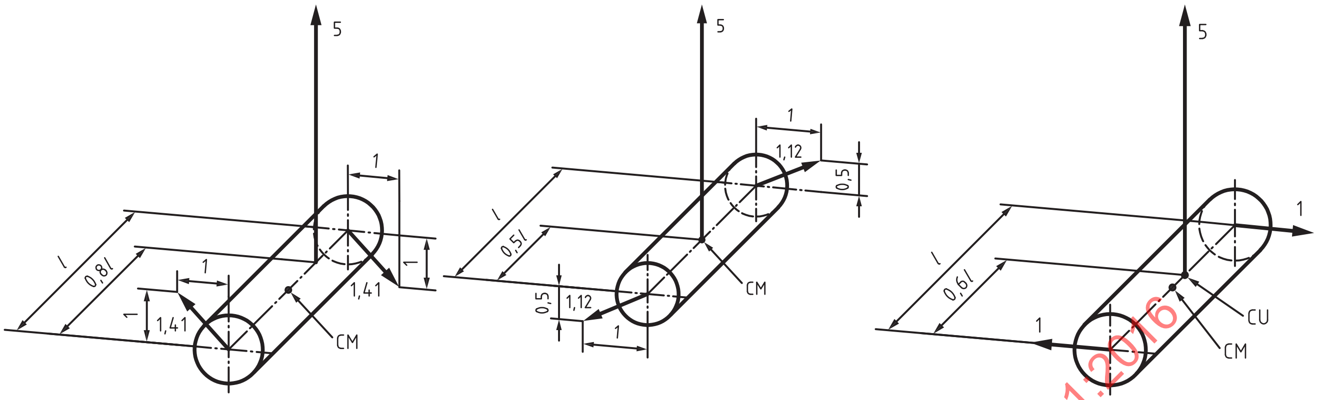
4.4 Reference planes for unbalance tolerances

It is recommended to use reference planes to state the unbalance tolerances. For these planes, only the magnitude of each residual unbalance needs to stay within the respective balance tolerance whatever the angular position may be.

The aim of balancing is usually to reduce vibrations and forces transmitted through the bearings to the environment. For the purposes of this document, the reference planes for unbalance tolerances are taken to be the bearing planes. However, this use of bearing planes does not always apply.

NOTE For a component without a shaft (e.g. a disc shaped element), but where the final bearing positions are known (or can be estimated), these planes can be used.

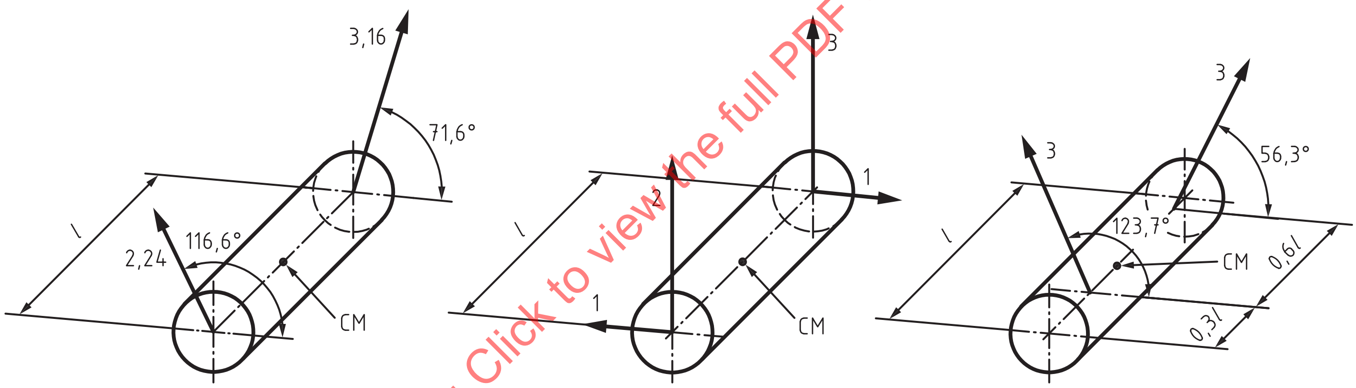
Unbalances in gram millimetres



a) Resultant unbalance vector together with an associated couple unbalance in the end planes

b) Special case of a), namely resultant unbalance vector located at centre of mass CM (static unbalance), together with an associated couple unbalance in the end planes

c) Special case of a), namely resultant unbalance vector located at the centre of unbalance CU



d) Unbalance vector in each of the end planes

e) Two 90° unbalance components in each of the end planes

f) Unbalance vector in each of any two other planes

Key

CM	centre of mass
CU	centre of unbalance
l	rotor length

NOTE For Figure 1 c), the associated couple unbalance is a minimum and lays in a plane orthogonal to the resultant unbalance vector.

Figure 1 — Different representations of the same unbalance of a rotor with rigid behaviour

4.5 Correction planes

4.5.1 General

Rotors that are out of unbalance tolerance need correction. These unbalance corrections often cannot be performed in the planes where the unbalance tolerances were set, but need to be performed where material can be added, removed or relocated.

The number of necessary correction planes depends on the magnitude and distribution of the initial unbalance, as well as on the design of the rotor, e.g. the shape of the correction planes and their location relative to the tolerance planes.

4.5.2 Rotors which need one correction plane only

For some rotors, only the resultant unbalance is out of tolerance but the resultant moment unbalance is in tolerance. This typically happens with rotors having a single disc, provided that

a) the bearing distance is sufficiently large,

b) the disc rotates with sufficiently small axial runout, and

c) the correction plane for the resultant unbalance is properly chosen.

After single-plane balancing has been carried out on a sufficient number of rotors, the largest residual moment unbalance is determined and divided by the bearing distance, yielding a couple unbalance.

If, even in the worst case, the couple unbalance found this way is acceptable, it can be expected that single-plane balancing is sufficient.

For single-plane balancing, the rotor does not need to rotate but, for sensitivity and accuracy reasons, in most cases, rotational balancing machines are used.

4.5.3 Rotors which need two correction planes

If a rotor with rigid behaviour does not comply with the conditions specified in 4.5.2, the moment unbalance needs to be reduced as well. In most cases, resultant unbalance and resultant moment unbalance are assembled into a dynamic unbalance: two unbalance vectors in two planes; see Figure 1 d).

For two-plane balancing, it is necessary for the rotor to rotate, since otherwise the moment unbalance would remain undetected.

4.5.4 Rotors with more than two correction planes

Although all rotors with rigid behaviour theoretically can be balanced in two planes, sometimes more than two correction planes are used, e.g.

a) in the case of separate corrections of resultant unbalance and couple unbalance, if the correction of the resultant unbalance is not performed in one (or both) of the couple planes, and

b) if the correction is spread along the rotor.

In special cases, spreading the correction along the rotor can be necessary due to restrictions in the correction planes (e.g. correction of crankshafts by drilling into the counterweights) or advisable in order to keep the function and component strength.

4.6 Permissible residual unbalance

In the simple case of an inboard rotor for which the couple unbalance may be ignored (see 4.5.2), its unbalance state can then be described as a single vectorial quantity, the unbalance, U.

To obtain a satisfactory running of the rotor, the magnitude of this unbalance, i.e. the residual unbalance, U_{res}, shall not be higher than a permissible value, U_{per}:

$$U_{res} \leq U_{per} \tag{1}$$

More generally, the same applies to any type of a rotor with rigid behaviour, but then U_{per} covers the resultant unbalance and the resultant moment unbalance, see also 5.2.

NOTE The SI unit for U_{per} is kg·m (kilogram metres), but for balancing purposes, more practical units are g·mm (gram millimetres), kg·mm (kilogram millimetres) or mg·mm (milligram millimetres).

U_{per} is defined as the total tolerance in the plane of the centre of mass. In the case of two-plane balancing, this tolerance shall be allocated to the tolerance planes (see Clause 7).

5 Similarity considerations

5.1 General

Some considerations on similarity can help in the understanding and calculation of the influences of rotor mass and service speed on the permissible residual unbalance.

5.2 Permissible residual unbalance and rotor mass

In general, for rotors of the same type, the permissible residual unbalance, U_{per}, is proportional to the rotor mass, m, as given in Formula (2):

$$U_{per} \sim m \tag{2}$$

The ratio of U_{per} to the rotor mass, m, is the permissible residual specific unbalance, e_{per}, as given in Formula (3):

$$e_{per} = U_{per}/m \tag{3}$$

NOTE 1 The SI unit for U_{per}/m is kg·m/kg (kilogram metres per kilogram) or m (metres), but a more practical unit is g·mm/kg (gram millimetres per kilogram), which corresponds to µm (micrometres) because many permissible residual specific unbalances are between 0,1 µm and 10 µm.

NOTE 2 The term e_{per} is useful especially if geometric tolerances (e.g. runout, play) are related to unbalance tolerances.

NOTE 3 In the case of a rotor with only a resultant unbalance (see 4.5.2), e_{per} is the distance of the centre of mass from the shaft axis. However, in the case of a general rotor with both resultant unbalance and resultant moment unbalance present, e_{per} is an artificial quantity containing the effects of the resultant unbalance as well as of the resultant moment unbalance.

NOTE 4 There are limits for achievable residual specific unbalance, e_{per}, depending on the setup conditions in the balancing machine (e.g. centring, bearings and drive).

NOTE 5 Small values of e_{per} can only be achieved in practice if the accuracy of shaft journals (roundness, straightness, etc.) is adequate. In some cases, it can be necessary to balance the rotor in its own service bearings, using belt-, air- or self-drive. In other cases, balancing needs to be carried out with the rotor completely assembled in its own housing with bearings and self-drive, under service condition and temperature.

5.3 Permissible residual specific unbalance and service speed

For rotors of the same type, experience shows that, in general, the permissible residual specific unbalance value, e_{per}, varies inversely with the service speed, n, of the rotor:

$$e_{per} \sim 1/n \tag{4}$$

Differently expressed, this relationship is given in Formula (5):

$$e_{per}\,\Omega = c \tag{5}$$

where

Ω is the angular velocity of the service speed, in rad/s (radians per second), with $\Omega = 2\pi\, n/(60\ \text{s/min})$ and the service speed, n, in r/min (revolutions per minute);

c is a constant.

This relationship follows also from the fact that for geometrically similar rotors running at equal peripheral velocities, the stresses in the rotors and the bearing specific loads (due to centrifugal forces) are the same. The balance quality grade G (see 6.3) is based on this relationship.

6 Specification of unbalance tolerances

6.1 General

The first step in the balancing process is to establish the magnitude of permissible residual unbalance of the rotor and to allocate it to the tolerance plane(s). In order to meet these unbalance tolerances reliably, reduced residual unbalance tolerances shall take account of errors as detailed in Clause 10.

NOTE 1 The ideal target value of the unbalance typically is zero (i.e. in a vector diagram, the unbalance tolerance is the radius of the circular tolerance region around the origin).

NOTE 2 Sometimes the target unbalance has a specified quantity, given by amount and angle (e.g. removed keys, asymmetric crank shafts, compensating shafts or rotational vibration exciter). In these cases, the unbalance tolerance is the radius of a circle around the specified target unbalance vector.

6.2 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 (see 6.3),

b) experimental evaluation of permissible residual unbalances (see 6.4),

c) limited bearing forces due to unbalance (see 6.5.1),

d) limited vibrations due to unbalance (see 6.5.2), and

e) established experience with unbalance tolerances (see 6.6).

Both the choice of method and the permissible unbalance tolerance are recommended to be part of the agreement between the manufacturer and customer.

6.3 Balance quality grade G

6.3.1 Classification

On the basis of worldwide experience and similarity considerations (see Clause 5), balance quality grades G have been established which permit a classification of the balance quality requirements for typical machinery types (see Table 1). These balance quality grades enable the calculation of permissible residual unbalances (see 6.3.3). Experience has shown that this will generally result in satisfactory operation of the rotor in service.

The balance quality grade G is designated according to the magnitude of the product $e_{per}\ \Omega$, expressed in mm/s (millimetres per second).

EXAMPLE If $e_{per}\ \Omega$ = 6,3 mm/s, the balance quality grade is designated G 6,3.

Balance quality grades are separated from each other by a factor of 2,5. A finer grading can be necessary in some cases, especially when high-precision balancing is required, but it should not be less than a factor of 1,6.

The values of e_{per} (= U_{per}/m) are plotted against the maximum service speed, n, in Figure 2, which contains additional information on the range of rotational speed and balance quality grade G commonly experienced.

6.3.2 Special designs

The balance quality grades are based on typical machine design, where the rotor mass is a certain fraction of the mass of the complete machine. In special cases, modifications are needed.

EXAMPLE Electric motors with shaft heights smaller than 80 mm are grouped to G 6,3 and the permissible residual unbalance is derived from this group (see 6.3.3). This permissible residual unbalance value is applicable as long as the rotor mass is a typical percentage of the machine mass (e.g. 30 %). However,

a) in the case of lightweight rotors (e.g. iron-less armatures), the rotor mass can be only 10 % of the total mass. As a result, three times the permissible residual unbalance may be allowed;

b) on the contrary, if the rotor mass is extremely high (e.g. external-rotor motors), the rotor mass can be above 90 % of the total mass. In such cases, the permissible residual unbalance might need to be reduced by a factor of three.

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

NOTE 1 Typically, completely assembled rotors are classified here. Depending on the particular application, the next higher or lower grade may be used instead. For components, see Clause 9.

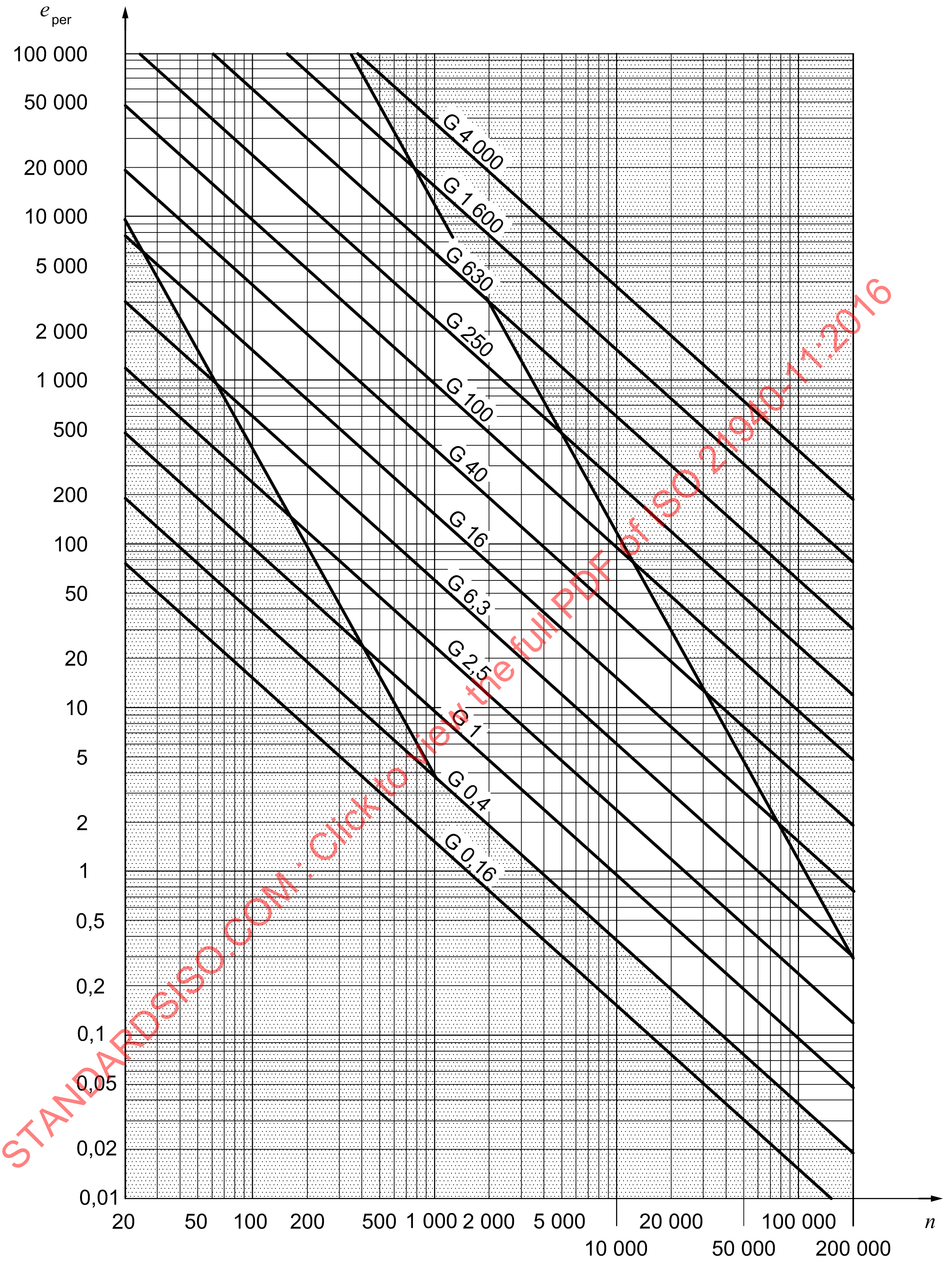
NOTE 2 All items are rotating if not otherwise mentioned (reciprocating) or self-evident (e.g. crankshaft drives).

NOTE 3 For some additional information on the chosen balance quality grade, see Figure 2 which contains generally used areas (service speed and balance quality grade G) based on common experience.

NOTE 4 For some machines, specific International Standards stating unbalance tolerances exist.

NOTE 5 The selection of a balance quality grade G for a machine type requires due consideration of the expected duty of the rotor when installed *in situ* which typically reduces the grade to a lower level if lower vibration magnitudes are required in service.

NOTE 6 The shaft height of a machine without feet, or a machine with raised feet, or any vertical machine, is to be taken as the shaft height of a machine in the same basic frame, but of the horizontal shaft foot-mounting type. When the frame is unknown, half of the machine diameter should be used.



Key

e_{per} permissible residual specific unbalance, in g·mm/kg

n service speed, in r/min

NOTE The white area marks the field of common experience.

Figure 2 — Permissible residual specific unbalance based on balance quality grade G and service speed, *n*, (see 6.3)

6.3.3 Permissible residual unbalance

The permissible residual unbalance, U_{per}, expressed in g·mm (gram millimetres), can be derived on the basis of a selected balance quality grade G in mm/s (millimetres per second) by using Formula (6) based on Ω or Formula (7) based on n:

$$U_{per} = 1\,000\ \mathrm{G}\ m/\Omega \tag{6}$$

or

$$U_{per} = 9\,549\ \mathrm{G}\ m/n \tag{7}$$

where

m	is the rotor mass in kg (kilograms);
n	is the service speed in r/min (revolutions per minute);
$\Omega = 2\pi\, n/(60\ \mathrm{s/min})$	is the angular velocity of the service speed in rad/s (radians per second).

As an alternative, Figure 2 may be used to derive U_{per} then:

$$U_{per} = e_{per}\, m \tag{8}$$

For the permissible residual unbalance, U_{per}, the balance quality grade, $e_{per}\,\Omega$, and the permissible residual specific unbalance, e_{per}, the SI units are used here with prefixes, so special care is needed to apply Formulae (6), (7) and (8). An example calculation is given in Annex A.

U_{per} is the total tolerance in the plane of the centre of mass. In the case of two-plane balancing, this tolerance shall be allocated to the tolerance planes (see Clause 7).

NOTE Different systems quote permissible residual unbalance in terms of the expression W/N, where W is the rotor mass and N is the maximum service speed.

6.4 Experimental evaluation

Experimental evaluation of the balance quality tolerances is often carried out for mass production applications. Tests are commonly performed *in situ*. The permissible residual unbalance is determined by introducing various test unbalances successively in each correction plane based on the most representative criterion (e.g. vibration, force, noise caused by unbalance).

In two-plane balancing, the different effects of unbalances with the same phase angle and of those 180° apart shall be taken into account.

6.5 Unbalance tolerances based on bearing forces or vibrations

6.5.1 Bearing forces

The main objective in this case is to limit the bearing forces caused by unbalances. The limits are stated first in terms of bearing forces, but then need transformation into unbalances. In the case of a sufficiently steady (not moving) bearing housing, this transformation simply uses the formula for the centrifugal force (see Annex B).

In all other cases, the dynamic behaviour of the structure under service condition shall be considered. There are no simple rules available for these cases.

6.5.2 Vibrations

The main objective in this case is to limit vibrations in certain planes. Balance quality tolerances can be derived from these limits.

6.6 Methods based on established experience

If a company has gained sufficient established experience to assess systematically the balance quality tolerances of its products, it may make full use of this. Annex C gives some guidance.

7 Allocation of permissible residual unbalance to tolerance planes

7.1 Single plane

In the case of single-plane correction (see 4.5.2), U_{per} is used entirely for this plane. In all other cases, U_{per} shall be allocated to the two tolerance planes.

7.2 Two planes

7.2.1 General

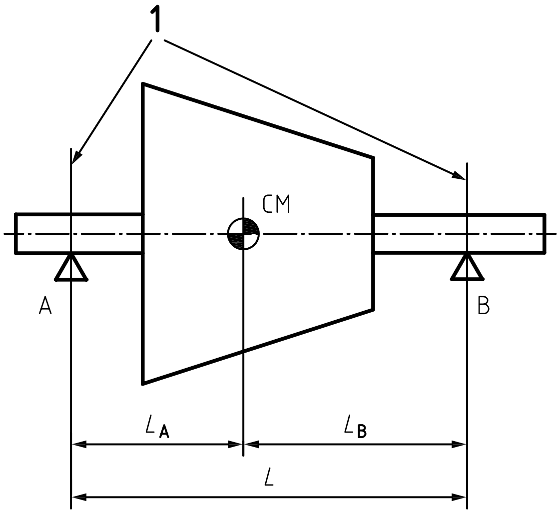
The permissible residual unbalance, U_{per}, is allocated in proportion to the distances from the centre of mass to the opposite tolerance plane (see Figures 3 and 4). If the tolerance planes are the bearing planes A and B, the Formulae (8) and (9) apply:

$$U_{per\,A} = U_{per} \frac{L_B}{L} \tag{8}$$

$$U_{per\,B} = U_{per} \frac{L_A}{L} \tag{9}$$

where

- $U_{per\,A}$ is the permissible residual unbalance in bearing plane A;
- $U_{per\,B}$ is the permissible residual unbalance in bearing plane B;
- U_{per} is the (total) permissible residual unbalance (in the plane of the centre of mass);
- L_A is the distance from the plane of the centre of mass to bearing plane A;
- L_B is the distance from the plane of the centre of mass to bearing plane B;
- L is the bearing distance.



Key

1	tolerance planes (= bearing planes)
A, B	bearings
CM	centre of mass
L	bearing distance
L_A	distance from the plane of the centre of mass to bearing plane A
L_B	distance from the plane of the centre of mass to bearing plane B

Figure 3 — Inboard rotor with centre of mass in an asymmetric position

7.2.2 Limitations for inboard rotors

For general outlines, see Figure 3. If the centre of mass is close to one bearing, the calculated tolerance for this bearing becomes very large, close to the value of U_{per}, and the value for the remote bearing becomes very small, close to zero. To avoid extreme tolerance conditions, it is stipulated that

a) the larger value shall not be greater than 0,7 U_{per}, and

b) the smaller value shall not be less than 0,3 U_{per}.

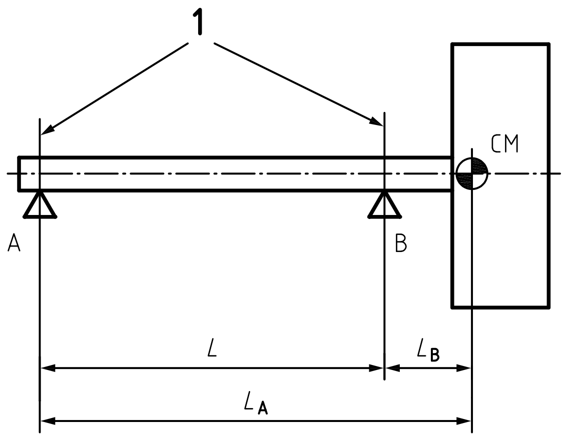
7.2.3 Limitations for outboard rotors

For general outlines, see Figure 4. The permissible residual unbalance tolerances are calculated according to Formulae (8) and (9). However, to avoid extreme tolerance conditions, it is stipulated that

a) the larger value shall not be greater than 1,3 U_{per};

b) the smaller value shall not be less than 0,3 U_{per}.

The upper unbalance limit is different from that of an inboard rotor. This assumes that bearing B and the supporting structure are designed to take the static load exerted by the overhung mass. Thus, it also supports a proportionately higher load caused by unbalances. If this is not the case, the limitations for inboard rotors have to be applied.



Key

1 tolerance planes (= bearing planes)

A, B bearings

CM centre of mass

L bearing distance

L_A distance from the plane of the centre of mass to bearing plane A

L_B distance from the plane of the centre of mass to bearing plane B

Figure 4 — Outboard rotor with centre of mass in an overhung position

8 Allocation of unbalance tolerances to correction planes

8.1 General

In contradiction to 4.4, 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 (see 4.4). If tolerances have to be allocated to the correction planes, note the following two points.

a) Both the magnitude of the residual unbalances and their relative angular position have an influence on the state of unbalance. Nevertheless, even in these cases, tolerances are usually defined only in terms of magnitude, not of angular relationship.

b) Any allocation rule is therefore a compromise. Such a rule has to take account of the worst case of angular relationship between the residual unbalances in both correction planes. For all other conditions, the same residual unbalance creates smaller effects on the rotor.

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

The unbalance tolerances can be derived by the methods described in Clause 6 noting the following.

— In the case of experimental determination (see 6.4), the permissible residual unbalance is generally derived for each correction plane: no further allocation is required.

— Whenever tolerance planes are used [e.g. based on balance quality grades (see 6.3), on special aims such like forces or vibrations (see 6.5) or on established experience (see 6.6)], a subsequent allocation to the correction planes may be needed.

8.2 Single plane

For rotors which need one correction plane only, the permissible residual unbalance, U_{per}, in this plane is equal to the total unbalance tolerance specified.

NOTE When applying balance quality grades (see 6.3) to determine U_{per}, the allocation to two tolerance planes (see Clause 7) is omitted.

8.3 Two planes

If correction planes I and II are close to the tolerance planes A and B, the tolerances may be transferred with a factor of 1, i.e. use the tolerance value of the adjacent tolerance plane. For more details and other conditions, see Annex D.

9 Assembled rotors

9.1 General

Assembled rotors may be balanced as a complete unit or as individual components. For each assembly, the unbalances of the components superimpose and assembly errors create additional unbalances, e.g. because of runout and play (see ISO 21940-14 for details).

NOTE If assembly errors are not significant, the choice of the balancing process can be governed by the availability of balancing machines.

9.2 Balanced as a unit

The best way to account for all unbalances in the rotor and all related assembly errors in one step is to balance the rotor as a fully assembled unit.

If a rotor is balanced as an assembly, but needs to be disassembled afterwards (e.g. for mounting into the housing), it is recommended that the angle of each component be marked to ensure identical angular positions during reassembly.

NOTE Even with these precautions in disassembling and assembling, problems with runout and play (see 9.1) can still exist.

9.3 Balanced on component level

If individual components are balanced separately, these aspects are important.

a) If combined errors (see ISO 21940-14) can be disregarded, the components shall be balanced to the same specific residual unbalance as the complete rotor.

b) If combined errors (mainly assembly errors, see ISO 21940-14) cannot be disregarded, the components shall be balanced to a lower specific residual unbalance than the complete rotor.

   If this causes problems (e.g. with a light fan or pulley on a heavy armature), any distribution rule is allowed, provided that the total unbalance of the assembly is kept within tolerance.

c) If connecting elements between rotor components are required (e.g. keys, see ISO 21940-32), their influence on the balance shall be taken into account.

If the unbalance tolerance for an assembly cannot be achieved by balancing each component separately, the assembly shall be balanced as a unit. In such cases, it is recommended that the necessity for balancing at component level be reconsidered. However, even with balancing of the final assembly, if the initial individual component unbalance is high or the unbalance correction is easier on the component, pre-balancing of the components may still be recommended. In this case, the components may be balanced to a coarser specific residual unbalance than the complete rotor.

10 Accounting for errors in the verification of permissible residual unbalances

10.1 General

The process of balancing requires the quantity "unbalance" to be measured, which includes the magnitude and the angle of the unbalance vector. As with all measured values, magnitude and angle need to be supplemented by a specification of the measurement error; see ISO 21940-14.

In addition, due to process requirements or limitations of the balancing equipment available, it might be necessary to deviate from the rotor configuration for which the permissible residual unbalance is specified, e.g. dismounted bearings, fans, couplings or blades. The uncertainty of unbalance introduced by these deviations shall be added to the error of measurement. The term "combined error" of ISO 21940-14 is extended here to include these deviations.

10.2 Unbalance tolerance

For balancing a rotor, a permissible residual unbalance, U_{per}, as defined in Clause 6 shall be specified. This value is allocated to the tolerance planes A and B as outlined in Clause 7.

The values used for the processes of balancing a rotor and verifying its residual unbalance shall, in addition, take into account their respective combined errors.

10.3 Combined error of unbalance measurements

After systematic errors in the unbalance readings have been corrected, ΔU is the remaining combined error (see 10.1) which has to be allocated to the tolerance planes A and B resulting in

a) the combined error in plane A, ΔU_A, and

b) the combined error in plane B, ΔU_B.

However, if ΔU_A is found to be less than 10 % of $U_{per\ A}$ or ΔU_B is less than 10 % of $U_{per\ B}$, it may be disregarded.

The magnitude of the combined error ΔU (and therefore also ΔU_A and ΔU_B) is usually different on different balancing machines. But even on the same balancing machine, the combined error depends on the machine setup.

NOTE Typical reasons for combined errors are balance machine accuracy and setup, tooling, drive shafts, 180° indexing procedure, process repeatability and reproducibility.

10.4 Verification of the permissible residual unbalance

10.4.1 General

As the final step of balancing or as an agreed part of the delivery procedure, it has to be verified that the rotor meets the unbalance tolerance. The combined error of an unbalance measurement has to be taken into account when checking the unbalance readings $U_{reading\ A}$ in plane A and $U_{reading\ B}$ in plane B against the specified tolerances $U_{per\ A}$ and $U_{per\ B}$, respectively.

10.4.2 Unbalance readings within tolerance

The unbalance is clearly within tolerance, i.e. does not exceed the specified tolerance U_{per}, if for the unbalance readings $U_{reading\ A}$ and $U_{reading\ B}$ both Formulae (10) and (11) hold true:

$$U_{reading\ A} \leq U_{per\ A} - \Delta U_A \tag{10}$$

$$U_{reading\ B} \leq U_{per\ B} - \Delta U_B \tag{11}$$

From these relations, it is evident that ΔU needs to be limited in size. The balancing process and the equipment used shall be chosen appropriately, otherwise $U_{per\ A} - \Delta U_A$ and $U_{per\ B} - \Delta U_B$ would become very small or even negative.

10.4.3 Unbalance readings out of tolerance

On the other hand, the residual unbalance is clearly out of tolerance if for the unbalance readings $U_{reading\ A}$ in plane A and $U_{reading\ B}$ in plane B at least one of the Formulae (12) or (13) holds true:

$$U_{reading\ A} > U_{per\ A} + \Delta U_A \tag{12}$$

$$U_{reading\ B} > U_{per\ B} + \Delta U_B \tag{13}$$

10.4.4 Region of uncertainly

The area between within tolerance and out of tolerance is the region of uncertainty.

In order to minimize the remaining regions of uncertainty given by Formulae (14) and (15):

$$U_{per\ A} - \Delta U_A < U_{reading\ A} \leq U_{per\ A} + \Delta U_A \tag{14}$$

$$U_{per\ B} - \Delta U_B < U_{reading\ B} \leq U_{per\ B} + \Delta U_B \tag{15}$$

the combined errors ΔU_A and ΔU_B shall be within tight limits. This requires adequate measuring equipment (see ISO 21940-21) with careful calibration and well-trained personnel.

Annex A
(informative)

Example of the specification of permissible residual unbalance based on balance quality grade G and allocation to the tolerance planes

A.1 Rotor data

Consider a turbine rotor with the following data (see Figure A.1):

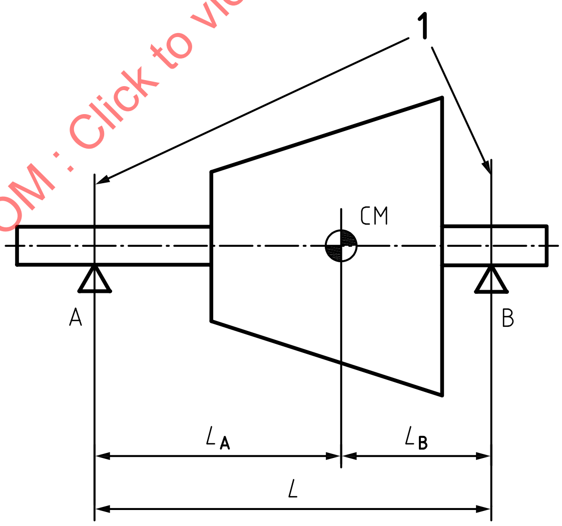
rotor mass: m = 3 600 kg

service speed: n = 3 000 r/min

distances: L_A = 1 500 mm

L_B = 900 mm

L = 2 400 mm



Key

1 tolerance planes (= bearing planes)

A, B bearings

CM centre of mass

L bearing distance

L_A distance from the plane of the centre of mass to bearing plane A

L_B distance from the plane of the centre of mass to bearing plane B

Figure A.1 — Rotor dimensions

Select the balance quality grade G from Table 1 for the machinery type “Gas turbines and steam turbines”: G 2,5.

Calculate the angular velocity, Ω, of the service speed, n, in rad/s (radians per second):

$$\Omega = 2\pi\, n/60 = 3\,000\,\pi/30 = 314{,}2 \text{ rad/s} \tag{A.1}$$

A.2 Specification of U_{per} based on Formula (6)

From Formula (6), the permissible residual unbalance, U_{per}, expressed in g·mm (gram millimetres), is given by Formula (A.2):

$$U_{per} = 1\,000\text{ G } m/\Omega = 1\,000 \times 2{,}5 \times 3\,600/314{,}2 = 28{,}6 \times 10^3 \text{ g·mm} \tag{A.2}$$

where

G is the selected balance quality grade;

m is the rotor mass, in kg (kilograms);

Ω is the calculated angular velocity of the service speed, in rad/s (radians per second).

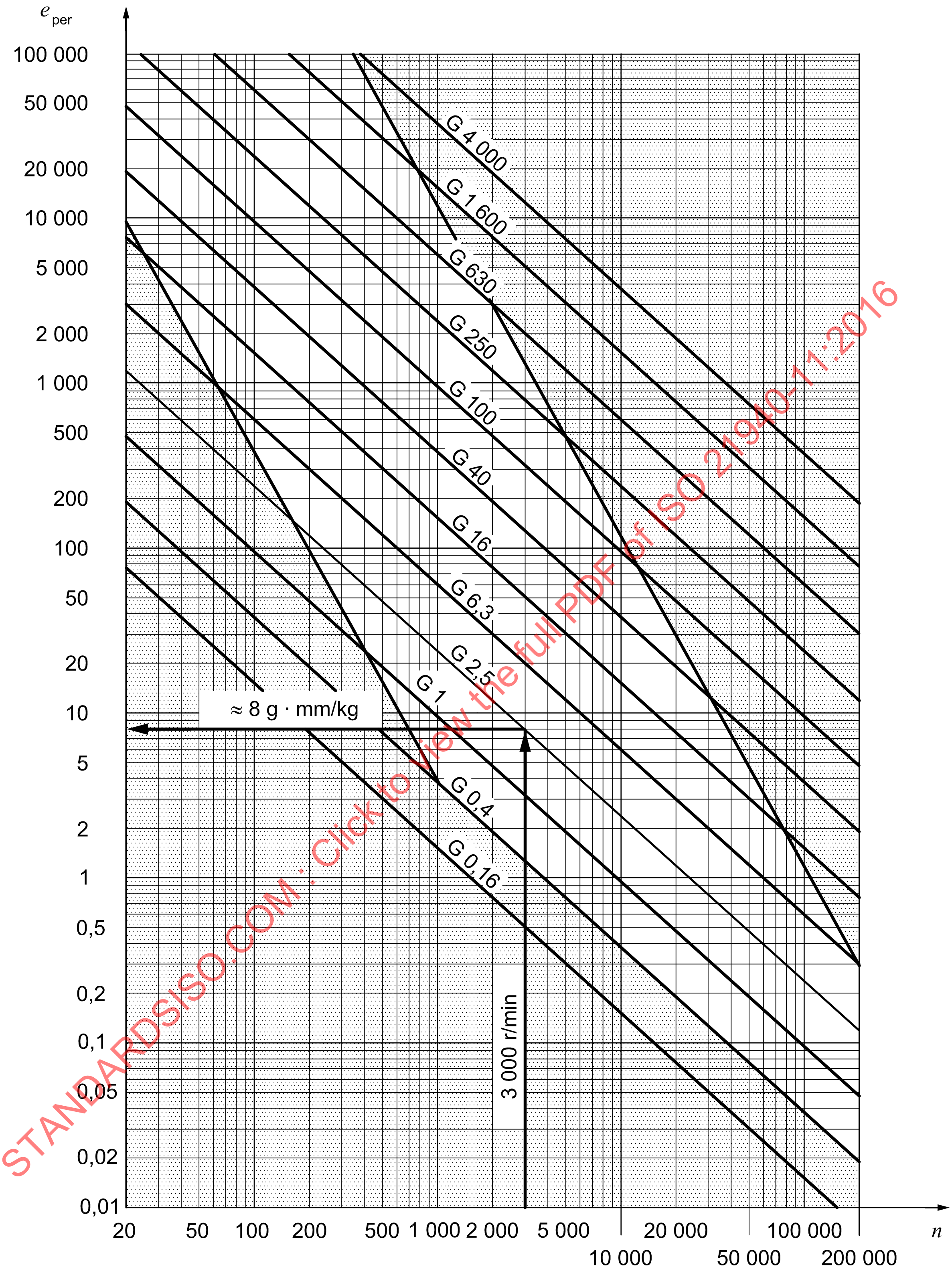
A.3 Specification of U_{per} based on Figure 2

For the given service speed n = 3 000 r/min and the selected balance quality grade G 2,5, e_{per} follows from Figure A.2 to be approximately:

$$e_{per} \approx 8 \text{ g·mm/kg} \tag{A.3}$$

Multiplied by the rotor mass, m, the permissible residual unbalance, U_{per} is [see Formula (7)]:

$$U_{per} \approx 8 \times 3\,600 = 28{,}8 \times 10^3 \text{ g·mm} \tag{A.4}$$



Key

e_{per} permissible residual specific unbalance, in g·mm/kg

n service speed, in r/min

Figure A.2 — Example of determination of e_{per} using Figure 2

A.4 Allocation to tolerance planes (bearing planes)

According to 7.2, the permissible residual unbalance, U_{per}, as calculated in A.2 (or estimated in A.3) can be allocated to the bearing planes A and B as follows:

$$U_{per\,A} = U_{per} \frac{L_B}{L} = 28{,}6 \times 10^3 \; \frac{900}{2\,400} = 10{,}7 \times 10^3 \text{ g} \cdot \text{mm} \tag{A.5}$$

$$U_{per\,B} = U_{per} \frac{L_A}{L} = 28{,}6 \times 10^3 \; \frac{1\,500}{2\,400} = 17{,}9 \times 10^3 \text{ g} \cdot \text{mm} \tag{A.6}$$

A.5 Check on limitations in accordance with 7.2.2 for inboard rotors

The larger value of $U_{per\,A}$ and $U_{per\,B}$ shall not be greater than 0,7 U_{per} , i.e. $U_{per\,B} \leq 20{,}0 \times 10^3$ g·mm.

The smaller value of $U_{per\,A}$ and $U_{per\,B}$ shall not be less than 0,3 U_{per} , i.e. $U_{per\,A} \geq 8{,}6 \times 10^3$ g·mm.

For this example, the tolerance planes satisfy the criteria to avoid extreme tolerance conditions.

A.6 Result

For this example, to meet the selected quality grade G, the residual unbalance for plane A shall be equal to or less than $U_{per\,A} = 10{,}7 \times 10^3$ g·mm, and the residual unbalance for plane B shall be equal to or less than $U_{per\,B} = 17{,}9 \times 10^3$ g·mm.

As described in Clause 10, errors need to be accounted for when assessing whether the permissible residual unbalance tolerances have been met.

Annex B
(informative)

Specification of unbalance tolerances based on bearing force limits

B.1 General

A main objective of balancing can be to limit the bearing forces (see 6.5.1). If these bearing force limits are specified, they need transformation into unbalances. This transformation is carried out by using Formulae (B.1) and (B.2) for the centrifugal force, but only in the case of a sufficiently stiff bearing support.

$$U_{\text{per A}} = F_{\text{per A}}/\Omega^2 \tag{B.1}$$

$$U_{\text{per B}} = F_{\text{per B}}/\Omega^2 \tag{B.2}$$

where

$U_{\text{per A}}$	is the permissible residual unbalance in bearing plane A;
$U_{\text{per B}}$	is the permissible residual unbalance in bearing plane B;
$F_{\text{per A}}$	is the permissible bearing force caused by unbalances in bearing A;
$F_{\text{per B}}$	is the permissible bearing force caused by unbalances in bearing B;
$\Omega = 2\pi\, n/(60\text{ s/min})$	is the angular velocity of the maximum service speed n.

Formulae (B.1) and (B.2) are based on SI units. Usually the units of permissible residual unbalance are used with prefixes (see 4.6), so special care is needed to apply these formulae.

As described in Clause 10, errors need to be accounted for when assessing whether the permissible residual unbalance tolerances have been met.

B.2 Example

B.2.1 Assumption

For the rotor described in Annex A, the maximum permissible bearing forces caused by unbalances are specified as follows:

$F_{\text{per A}} = 1\,200$ N permissible force at bearing A;

$F_{\text{per B}} = 2\,000$ N permissible force at bearing B.

B.2.2 Calculation

The permissible residual unbalances in bearing planes A and B are:

$$U_{\text{per A}} = \frac{F_A}{\Omega^2} = \frac{1200}{(314{,}2)^2} = 12{,}2 \times 10^3\ \text{g} \cdot \text{mm} \tag{B.3}$$

$$U_{\text{per B}} = \frac{F_B}{\Omega^2} = \frac{2000}{\left(314{,}2\right)^2} = 20{,}3 \times 10^3 \text{ g} \cdot \text{mm} \tag{B.4}$$

