

International Organization for Standardization

# Rigid Rotor Balancing Specifications

ISO 1940-1 / ISO 21940-11 — Formulas, Grades &amp; Tolerances

## 1. Overview & Scope

ISO 1940-1 (now superseded by ISO 21940-11:2016) is the internationally recognised standard for specifying and verifying balance tolerances for rigid rotors — rotors that do not flex or deform significantly at service speed. The standard defines Balance Quality Grades (G-Grades), provides formulas to convert those grades into measurable tolerances, and specifies verification procedures.

ISO 21940-11 retains all core G-grade principles and formulas of its predecessor, expanding the rotor-type classification table and placing greater emphasis on the full balancing process from specification through to documented verification.

**NOTE** These standards apply ONLY to rigid rotors. For flexible rotors (those that bend at speed), refer to ISO 21940-12 (formerly ISO 11342).

## 2. Balance Quality Grade Definition

The fundamental definition of a G-Grade is derived from the product of specific unbalance (eccentricity) and angular velocity. This product represents a permissible vibration velocity in mm/s:

### ISO 21940-11 | Balance Quality Grade Definition

$$G = e_{per} \times \Omega$$

**G** = Balance Quality Grade value (mm/s) — e.g. G2.5, G6.3

**e<sub>per</sub>** = Permissible specific unbalance / eccentricity of centre of mass (mm)

**Ω** = Maximum service angular velocity (rad/s) =  $2\pi N / 60$

**NOTE** Grades are separated from each other by a factor of 2.5. A lower G-number always means a tighter, more precise balance tolerance.

## 3. Angular Velocity Conversion

Angular velocity in rad/s is required for the G-Grade formula. The conversion from RPM is:

**Angular Velocity | RPM to rad/s**

$$\Omega = 2\pi N / 60 \approx N / 9.549$$

$\Omega$  = Angular velocity (rad/s)

$N$  = Rotational speed (RPM)

$9.549$  = Constant =  $60 / (2\pi)$

## 4. Permissible Specific Unbalance

Once the G-Grade is selected, the permissible specific unbalance (eccentricity of the centre of mass) is calculated as follows:

**ISO 21940-11 | Permissible Specific Unbalance (SI)**

$$e_{per} = (G \times 9549) / N \quad [g \cdot mm/kg]$$

$e_{per}$  = Permissible specific unbalance ( $g \cdot mm/kg = \mu m$  eccentricity)

$G$  = Balance Quality Grade number (mm/s)

$N$  = Maximum service speed (RPM)

$9549$  = Conversion constant =  $60 \times 1000 / (2\pi)$

Alternatively, using the alternative form:

**Permissible Specific Unbalance | Equivalent Form**

$$e_{per} = (10 \times G) / (N / 1000) \quad [\mu m]$$

$e_{per}$  = Result in micrometres ( $\mu m$ ) — equivalent to  $g \cdot mm/kg$

$G$  = Balance Quality Grade (mm/s)

$N$  = Speed (RPM)

## 5. Total Permissible Residual Unbalance

The total permissible residual unbalance for the entire rotor is obtained by multiplying the specific unbalance by the rotor mass:

**ISO 21940-11 | Total Permissible Residual Unbalance**

$$U_{per} = e_{per} \times m \quad [g \cdot mm]$$

$U_{per}$  = Total permissible residual unbalance (g·mm)  
 $e_{per}$  = Permissible specific unbalance (g·mm/kg)  
 $m$  = Rotor mass (kg)

Combined single-step formula for total permissible unbalance:

### Combined Formula | Total Unbalance (g·mm)

$$U_{per} = (9550 \times m \times G) / N$$

$U_{per}$  = Total permissible residual unbalance (g·mm)  
 $m$  = Rotor mass (kg)  
 $G$  = Balance Quality Grade (mm/s)  
 $N$  = Maximum service speed (RPM)  
 $9550$  = Constant  $\approx 60 \times 1000 / (2\pi)$

## 6. Two-Plane Unbalance Allocation

### 6a. General / Symmetric Rotors

For a symmetric rotor (correction planes equidistant from the centre of gravity), the total unbalance is divided equally between the two planes:

#### Symmetric Rotor | Unbalance per Plane

$$U_{per} \text{ (each plane)} = U_{per} / 2$$

$U_{per} / 2$  = Permissible residual unbalance per correction plane (g·mm)

### 6b. Asymmetric / General Two-Plane Rotors

When correction planes L and R are not equidistant from the centre of gravity, the tolerance is allocated in inverse proportion to the plane distances:

#### Asymmetric Rotor | Plane L Allocation

$$U_{L} = U_{per} \times (H_{R} / B)$$

$U_{L}$  = Permissible unbalance allocated to plane L (g·mm)  
 $H_{R}$  = Distance from centre of gravity to correction plane R (mm)  
 $B$  = Distance between the two correction planes (mm)

**Asymmetric Rotor | Plane R Allocation**

$$U_{\underline{R}} = U_{\text{per}} \times (H_{\underline{L}} / B)$$

$U_{\underline{R}}$  = Permissible unbalance allocated to plane R (g·mm)

$H_{\underline{L}}$  = Distance from centre of gravity to correction plane L (mm)

$B$  = Distance between the two correction planes (mm)

**NOTE** Check:  $U_{\underline{L}} + U_{\underline{R}}$  must equal  $U_{\text{per}}$  (within rounding tolerance). If  $H_{\underline{L}} = H_{\underline{R}}$ , both formulas reduce to  $U_{\text{per}} / 2$ .

**6c. Overhung / Narrow Rotors**

For overhung or narrow rotors (where the correction plane lies outside the bearing span), the standard provides a static and dynamic allocation:

**Overhung Rotor | Static Plane**

$$U_{\text{static}} = (e_{\text{per}} \times m / r) \times (2D / C)$$

$r$  = Balancing radius at correction plane (mm)

$D$  = Distance from bearing to correction plane (mm)

$C$  = Bearing span (mm)

**Overhung Rotor | Dynamic Plane**

$$U_{\text{dynamic}} = (e_{\text{per}} \times m / r) \times (3D / 4C)$$

$r$  = Balancing radius at correction plane (mm)

$D$  = Overhang — distance from nearest bearing to correction plane (mm)

$C$  = Bearing span (mm)

**7. Correction Weight at a Given Radius**

Once the permissible residual unbalance per plane is known, the maximum allowable correction weight at a given radius is:

**Maximum Correction Weight**

$$m\_corr = U_{per} (\text{plane}) / r\_corr$$

**m\_corr** = Maximum correction weight (g)  
**U\_per** = Permissible residual unbalance for that plane (g·mm)  
**r\_corr** = Radius at which correction weight is applied (mm)

## 8. Centrifugal Force Check

The centrifugal force generated by the residual unbalance at the bearing journal must not exceed 10% of the static journal load. This is an independent acceptance limit under ISO 21940-11:

### Centrifugal Force from Residual Unbalance

$$F_c = U_{per} \times \Omega^2 \times 10^{-3}$$

**F\_c** = Centrifugal force (N)  
**U\_per** = Permissible residual unbalance (g·mm)  
**Ω<sup>2</sup>** = Square of angular velocity (rad/s)<sup>2</sup>  
**10<sup>-3</sup>** = Unit conversion from g·mm to kg·m

### Acceptance Criterion | Bearing Load Check

$$F_c < 0.10 \times W_{journal}$$

**F\_c** = Centrifugal force at journal (N)  
**W\_journal** = Static load on journal (N) = (m × g) / 2 for symmetric rotor  
**0.10** = 10% limit per ISO 21940-11

## 9. Balance Quality Grade Table

The following table lists the recommended G-Grades for common machinery types (from ISO 21940-11). Grades are separated by a factor of 2.5:

G-Grade	e <sub>per</sub> × Ω (mm/s)	Typical Machinery Types
G 0.4	0.4	Gyroscopes; precision spindles for grinding machines
G 1	1.0	Precision grinding machine drives; small high-speed armatures
G 2.5	2.5	Gas turbines; steam turbines; turbochargers; centrifugal compressors; machine tool spindles; high-speed pumps; API 610 assembled rotors
G 6.3	6.3	Fans; centrifuges; pump impellers; standard electric motors; general industrial machinery; API 610 impellers

G 16	16	Agricultural machinery; crushing machines; drive shafts for special applications
G 40	40	Car wheels & tyres; rigidly mounted crankshafts; automotive drive shafts
G 100	100	Crankshafts on elastically mounted slow marine diesel engines
G 250	250	Crankshafts on rigidly mounted slow marine diesel engines
G 630	630	Crankshaft drives of large two-cycle engines
G 4000	4000	Crankshaft drives of elastically mounted reciprocating machines

## 10. Worked Example

Example: An electric motor rotor, mass = 50 kg, max speed = 3,000 RPM, required grade G6.3.

Step	Formula	Result
1. Angular velocity	$\Omega = 2\pi \times 3000 / 60$	314.2 rad/s
2. Specific unbalance	$e_{per} = (6.3 \times 9549) / 3000$	20.05 g·mm/kg
3. Total U <sub>per</sub>	$U_{per} = 20.05 \times 50$	1002 g·mm
4. Per plane (symmetric)	$U_{plane} = 1002 / 2$	501 g·mm per plane
5. Correction weight @ 100 mm radius	$m = 501 / 100$	5.01 g max per plane

## 11. Unit Conversions

### Unit Conversions | g·mm ↔ oz·in

$$1 \text{ oz} \cdot \text{in} = 720 \text{ g} \cdot \text{mm}$$

**oz·in** = Ounce-inch (imperial)

**g·mm** = Gram-millimetre (SI)

### Unit Conversions | g·mm/kg ↔ μm

$$1 \text{ g} \cdot \text{mm}/\text{kg} = 1 \text{ } \mu\text{m} \text{ (micrometre eccentricity)}$$

**g·mm/kg** = SI specific unbalance unit

**μm** = Micrometre — represents the CG eccentricity from spin axis

## 12. ISO Standards Series Summary

Standard	Title / Scope
ISO 21940-11 (replaces ISO 1940-1)	Rigid rotor balancing — Tolerances, G-grades, verification procedures
ISO 21940-12 (replaces ISO 11342)	Flexible rotor balancing — Rotors that deform at operating speed
ISO 21940-13	Criteria for in-situ balancing of medium and large rotors
ISO 21940-14	Procedures for balancing machines — checking of accuracy
ISO 21940-21	Balancing machine description and evaluation
ISO 21940-31	Susceptibility and sensitivity of machines to unbalance
ISO 1940-2	Errors in balancing (largely still referenced alongside ISO 21940-11)

**NOTE** ISO 1940-1:2003 was formally withdrawn and replaced by ISO 21940-11:2016. The core G-grade system, grade values, and fundamental formulas are unchanged. ISO 21940-11 expands the machinery type table, adds procedural clarity, and aligns with modern balancing machine capabilities.