Verein Deutscher Ingenieure | VDI 2060 (1966) → DIN ISO 21940-11 (2016)

VDI Balancing Standard

History, Quality Classes, Formulas & Successor Standards

WITHDRAWN / SUPERSEDED VDI 2060 (1966) — Beurteilungsmaßstäbe für den Auswuchtzustand rotierender starrer Körper (Standards of evaluation for the state of balance of rotating rigid bodies) — is formally WITHDRAWN. It was superseded by DIN ISO 1940-1 (1993) and is now fully replaced by DIN ISO 21940-11 (2017/2023). This document covers the original VDI 2060 framework, its Quality Class system, and its full lineage through to the current standard.

1. Historical Background & Standard Lineage

VDI 2060 was published in October 1966 by the Verein Deutscher Ingenieure (VDI — Association of German Engineers). It was the first structured, internationally influential framework for evaluating the balance quality of rotating rigid bodies, introducing the concept of numeric Quality Classes (Güteklassen) linked to permissible residual eccentricity and centrifugal force as a percentage of rotor weight.

The standard proved so fundamental that it was directly adopted and expanded by the International Organization for Standardization as ISO 1940/1, which was in turn adopted nationally as:

National Adoption	Standard Number	Status
Germany (VDI / DIN)	VDI 2060 → DIN ISO 1940-1 → DIN ISO 21940-11	Current: DIN ISO 21940-11:2023
International (ISO)	ISO 1940/1 → ISO 1940-1:2003 → ISO 21940-11:2016	Current: ISO 21940-11:2016
United States (ANSI)	ANSI S2.19-1975 → aligned with ISO 21940-11	Current: ANSI S2.19
United Kingdom (BSI)	BS 6861: Part 1	Superseded by adoption of ISO 21940-11
USA (industrial)	API 610 / API RP 684	References ISO G-grade framework

NOTE The Quality Class (Güteklasse) system introduced by VDI 2060 — Classes 0 through VI — was the direct precursor to the ISO G-Grade system. The G-Grade number (G0.4, G1, G2.5, G6.3…) is simply the maximum permissible vibration velocity of the rotor's centre of mass in mm/s, a concept that originated in VDI 2060.

2. VDI 2060 Original Quality Class System

The original VDI 2060 defined seven Quality Classes (0, I, II, III, IV, V, VI), each associated with a speed range, a maximum permissible centrifugal force as a percentage of rotor weight, and a permissible residual eccentricity. These classes were derived from empirical observation of machinery performance across German industry.

VDI 2060 Quality Class	Speed Range (RPM)	Max Centrifugal Force (% of weight)	Residual Eccentricity (µm)	Equiv. ISO G-Grade
0 (finest)	> 10,000	< 0.2%	≤ 0.2	G 0.4
I	7,500 – 10,000	2.5%	0.2 – 0.4	G 1
II	5,000 – 7,000	3%	0.45 – 1.0	G 2.5
III	3,000 – 5,000	4%	1.44 – 4.0	G 6.3
IV	1,500 – 3,000	5%	5.0 – 20.0	G 16
V	750 – 1,500	6.5%	25 – 100	G 40
VI (coarsest)	≤ 1,000	—	50 – 250	G 63 – G 250

NOTE The centrifugal force percentages in VDI 2060 Quality Classes were an alternative acceptance criterion alongside eccentricity. A rotor was acceptable if the centrifugal force generated by the residual unbalance did not exceed the stated percentage of the rotor's static weight. ISO 1940 retained the eccentricity/G-grade basis and dropped the centrifugal force percentage as a primary criterion.

3. Core Balance Quality Formula (from VDI 2060 / ISO 1940-1)

The fundamental relationship introduced by VDI 2060 and carried forward unchanged into ISO 1940-1 and ISO 21940-11 defines the quality grade G as the product of the permissible centre-of-mass eccentricity and the angular velocity:

VDI 2060 | Balance Quality Grade Definition (Gütegrad G)

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

G = Balance quality grade (Gütegrad) in mm/s — e.g. G0.4, G1, G2.5, G6.3
e_{per} = Permissible specific unbalance / eccentricity of centre of mass (mm)
Ω = Maximum service angular velocity (rad/s) = 2πN / 60

This is the foundational relationship of the entire VDI / ISO balance quality system. The G number is simultaneously: (1) the permissible vibration velocity of the rotor's centre of gravity in mm/s; and (2) the product of eccentricity × angular velocity. All quality grades are separated by a factor of 2.5.

4. Angular Velocity Conversion

Angular Velocity | RPM to rad/s

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

Ω = Angular velocity (rad/s)
N = Rotational speed (RPM)
9.549 = Constant = 60 / (2π)

5. Permissible Specific Unbalance (Eccentricity)

Rearranging the grade definition to solve for the permissible eccentricity:

VDI 2060 / ISO 21940-11 | Permissible Specific Unbalance

$$e_{per} = G / \Omega = (G \times 9549) / N$$

eper = Permissible specific unbalance (g·mm/kg) = eccentricity in µm
G = Balance quality grade (mm/s) — from VDI 2060 Quality Class or ISO G-grade
N = Maximum service speed (RPM)
9549 = Conversion constant = 60 × 1000 / (2π)

6. Total Permissible Residual Unbalance

The total permissible residual unbalance for the complete rotor is derived by multiplying the specific unbalance by the rotor mass:

Total Permissible Residual Unbalance (g·mm)

$$U_{per} = e_{per} \times m = (9549 \times G \times m) / N$$

Uper = Total permissible residual unbalance (g·mm)
eper = Permissible specific unbalance (g·mm/kg)
m = Rotor mass (kg)
G = Balance quality grade (mm/s)
N = Maximum service speed (RPM)

7. Centrifugal Force Criterion (Original VDI 2060 Method)

VDI 2060 introduced centrifugal force as a percentage of rotor weight as an alternative acceptance criterion, capturing the intuitive impact of unbalance on bearing loads. The centrifugal force generated by residual unbalance is:

VDI 2060 | Centrifugal Force from Residual Unbalance

$$F\_c = U_{per} \times \Omega^2 \times 10^{-3} \quad [N]$$

F_c = Centrifugal force at correction plane (N)
U_{per} = Permissible residual unbalance (g·mm)
Ω^2 = Square of angular velocity (rad/s)²
10^{-3} = Unit conversion factor (g·mm → kg·m)

VDI 2060 | Centrifugal Force as % of Rotor Weight

$$F\_c\,[\%] = (F\_c / W) \times 100$$

$F\_c\,[\%]$ = Centrifugal force as percentage of rotor static weight
F_c = Centrifugal force (N)
W = Rotor weight (N) = m × g = m × 9.81

VDI 2060 / ISO | Bearing Load Acceptance Criterion

$$F\_c < 0.10 \times W\_journal$$

F_c = Centrifugal force at bearing journal (N)
$W\_journal$ = Static journal load (N) = (m × g) / 2 for symmetric rotor
0.10 = 10% limit (carried forward from VDI 2060 into ISO 21940-11)

8. Two-Plane Unbalance Allocation

8a. Symmetric Rotors (inner correction planes)

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

Symmetric Rotor | Unbalance per Plane

$$U\_L = U\_R = U_{per} / 2$$

U_L, U_R = Permissible unbalance per correction plane (g·mm)
U_{per} = Total permissible residual unbalance for the rotor (g·mm)

8b. Asymmetric Rotors (non-equidistant correction planes)

When the correction planes are not equidistant from the centre of gravity, the allocation is made in inverse proportion to the distance from the CG to each plane:

Asymmetric Rotor | Left-Plane Allocation

$$U_L = U_{per} \times (b_R / b)$$

U_L = Permissible unbalance for left correction plane (g·mm)
b_R = Distance from centre of gravity to right correction plane (mm)
b = Distance between left and right correction planes (mm)

Asymmetric Rotor | Right-Plane Allocation

$$U_R = U_{per} \times (b_L / b)$$

U_R = Permissible unbalance for right correction plane (g·mm)
b_L = Distance from centre of gravity to left correction plane (mm)
b = Distance between left and right correction planes (mm)

NOTE Verification: U_L + U_R must equal U_per. For equidistant planes (b_L = b_R = b/2), both formulas reduce to U_per / 2.

8c. Overhung Rotors (outer correction planes)

For narrow or overhung rotors, where one or both correction planes lie outside the bearing span, the VDI 2060 / ISO framework specifies a different allocation based on the ratio of overhang to bearing span:

Overhung Rotor | Static Unbalance Component per Plane

$$U_s = U_{per} / 2 \times (2d / c)$$

U_s = Static component of permissible unbalance per plane (g·mm)
d = Distance from nearest bearing to correction plane (mm)
c = Bearing span (mm)

Overhung Rotor | Couple Unbalance Component per Plane

$$U\_k = U_{per} / 2 \times (3d / 4c)$$

U_k = Couple (dynamic) component of permissible unbalance per plane (g·mm)
d = Overhang distance (mm)
c = Bearing span (mm)

9. Correction Mass at a Given Radius

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

Maximum Correction Mass

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

m_corr = Maximum correction mass (g)
Uper = Permissible residual unbalance for that plane (g·mm)
r_corr = Radius at which correction mass is applied (mm)

10. VDI 2060 Quality Class ↔ ISO G-Grade Conversion

The original VDI 2060 Quality Classes map directly to ISO G-grades. Both systems use the same underlying formula; the difference is purely in nomenclature. The VDI numeric class system was replaced by the G-grade letter-number system for international clarity:

VDI 2060 Quality Class	ISO G-Grade (Equivalent)	G Value (mm/s)	e_{per} at 3,000 RPM (µm)	Typical Applications
Class 0	G 0.4	0.4	1.27	Gyroscopes; ultra-precision spindles
Class I	G 1	1.0	3.18	Precision grinding spindles; small armatures
Class II	G 2.5	2.5	7.96	Gas turbines; steam turbines; turbocompressors; precision motors
Class III	G 6.3	6.3	20.1	Fans; centrifuges; pumps; general electric motors

Class IV	G 16	16	50.9	Agricultural/crushing machinery; special drive shafts
Class V	G 40	40	127	Car wheels; automotive drive shafts; rigidly mounted crankshafts
Class VI	G 100 – G 250	100–250	318–796	Slow marine diesel crankshafts; large reciprocating engines

NOTE Grades are separated by a factor of 2.5 in each step. Each step up in grade number (looser tolerance) implies roughly 2.5× more permissible eccentricity. This factor was established by VDI 2060 and retained in all subsequent ISO standards.

11. Unbalance Reduction Ratio (URR)

A key concept formalised by the VDI / ISO system is the Unbalance Reduction Ratio (URR). This quantifies the effectiveness of the balancing machine itself, independent of the tolerance specification:

Unbalance Reduction Ratio (URR)

$$URR = (1 - U_{residual} / U_{initial}) \times 100\%$$

URR = Unbalance Reduction Ratio (%)
$U_{residual}$ = Residual unbalance after one balancing run (g·mm)
$U_{initial}$ = Initial unbalance before balancing (g·mm)

NOTE A balancing machine must achieve a URR of at least 90% in a single correction run for qualification under DIN ISO 21940-21. High-quality machines typically achieve URR > 95%.

Minimum Achievable Residual Unbalance (U_mar)

$$U_{mar} = U_{initial} \times (1 - URR/100)$$

U_{mar} = Minimum achievable residual unbalance (g·mm)
$U_{initial}$ = Initial unbalance (g·mm)
URR = Unbalance Reduction Ratio of the balancing machine (%)

12. Balancing Errors and Tolerancing (from VDI 2060 / ISO 1940-2)

VDI 2060 was the first standard to highlight that achieving a specified residual unbalance requires the balancing machine to achieve a tighter intermediate target, to account for systematic errors. This concept is now codified in ISO 1940-2 / ISO 21940-11 Annex B:

Target Residual Unbalance (allowing for balancing errors)

$$U\_target \leq U_{per} - U\_error$$

`U_target` = Balancing machine target during balancing run (g·mm)
`Uper` = Permissible residual unbalance from specification (g·mm)
`U_error` = Total systematic error from balancing process (g·mm)

Principal sources of balancing error identified by VDI 2060 and retained in ISO 21940-11:

Error Source	Symbol	Description
Fixture unbalance	U_fix	Residual unbalance of the mandrel, arbor or fixture used to hold the rotor
Indication error	U_ind	Resolution limit of the balancing machine instrumentation
Mass distribution shift	U_fit	Unbalance introduced by keyway/key, splines, or press fits at assembly
Roundness error	U_rnd	CG offset due to non-circular journal bearing surfaces
Journal run-out	U_ro	Apparent unbalance due to geometric run-out of the balancing journals

NOTE ISO 1940-2 (and now ISO 21940-11 Annex B) provides the mathematical method for RSS (root-sum-square) combination of these errors to calculate U_error. VDI 2060 was the first to require this correction systematically rather than as an engineering approximation.

13. Worked Example — VDI 2060 Quality Class III

A centrifugal pump rotor, mass = 80 kg, service speed = 3,600 RPM. Required quality: VDI 2060 Class III (equivalent ISO G6.3).

Step	Formula / Source	Result
1. Identify G-grade	VDI Class III ≡ ISO G6.3	G = 6.3 mm/s
2. Angular velocity	Ω = 2π × 3600 / 60	376.9 rad/s
3. Permissible eccentricity	eper = 6.3 / 376.9	0.0167 mm = 16.7 µm
4. Total Uper	Uper = 16.7 × 80 × 1000 ÷ 1000	1,338 g·mm

5. Per plane (symmetric)	1338 / 2	669 g·mm per plane
6. Correction mass @ 120 mm	m = 669 / 120	5.57 g max per plane
7. Centrifugal force check	$F_c = 0.669 \times 10^{-3} \times 376.9^2$	95.1 N per plane
8. Journal load (80 kg sym.)	W_j = (80 × 9.81) / 2	392.4 N
9. Fc as % of journal load	95.1 / 392.4 × 100	24.2% — exceeds VDI 10% limit; recheck grade

WITHDRAWN / SUPERSEDED Step 9 above illustrates why the centrifugal force criterion is important for heavy rotors at higher speeds. At G6.3 and 3,600 RPM for 80 kg, the 10% bearing load limit is exceeded, which would require upgrading to G2.5 or reducing operating speed. This dual-criterion check (eccentricity AND centrifugal force) originated in VDI 2060 and remains in ISO 21940-11.

14. Unit Conversions

Unbalance | g·mm ↔ oz·in

1 oz·in = 720 g·mm

oz·in = Ounce-inch (imperial / API unit)
g·mm = Gram-millimetre (SI / VDI / ISO unit)

Eccentricity | g·mm/kg to µm

1 g·mm/kg = 1 µm (micrometre eccentricity)

g·mm/kg = Specific unbalance in SI units
µm = Micrometre = 0.001 mm = centre-of-gravity offset from spin axis

G-Grade	e_{per} at 1500 RPM	e_{per} at 3000 RPM	e_{per} at 6000 RPM
G 0.4	2.55 µm	1.27 µm	0.64 µm
G 1.0	6.37 µm	3.18 µm	1.59 µm
G 2.5	15.9 µm	7.96 µm	3.98 µm
G 6.3	40.2 µm	20.1 µm	10.0 µm
G 16	102 µm	50.9 µm	25.5 µm

G 40	255 µm	127 µm	63.7 µm

15. Standard Lineage & Current References

Standard	Year	Status	Coverage
VDI 2060	1966	WITHDRAWN	Original German Quality Class system (Classes 0–VI); 8 pages
ISO 1940/1	1973	SUPERSEDED	First international adoption of VDI 2060 concepts; G-grade system introduced
DIN ISO 1940-1	1993	WITHDRAWN	German national adoption of ISO 1940; replaced VDI 2060 officially
ISO 1940-1:2003	2003	WITHDRAWN	Major revision; clearer procedures; included unbalance error treatment
DIN ISO 21940-11	2017	CURRENT	Full replacement of ISO 1940-1; expanded machinery table; modern procedures
DIN ISO 21940-11	2023	CURRENT	Latest revision; minor clarifications; aligned with ISO 21940 series
ISO 21940-12	2016	CURRENT	Flexible rotors (replaced ISO 11342)
ISO 21940-21	2012	CURRENT	Balancing machine description and evaluation (replaced ISO 2953)
ISO 21940-31	2013	CURRENT	Machine sensitivity to unbalance
ISO 21940-32	2012	CURRENT	Shaft and fitment key conventions for balancing
ISO 1940-2	1997	CURRENT*	Balancing errors; still widely cited alongside ISO 21940-11 Annex B
VDI 2060 (new)	2014	CURRENT	New VDI 2060:2014 — Non-linear vibratory systems (DIFFERENT standard, same number)

WITHDRAWN / SUPERSEDED IMPORTANT: The VDI 2060 number was reused in 2014 for a completely different standard — “Characteristics and recognition of non-linear vibratory systems.” The 1966 balancing guideline and the 2014 vibration standard share the same designation number but are entirely unrelated in scope. Always specify the date (1966 or 2014) when referencing VDI 2060.