

# Balance Quality Requirements of Rigid Rotors

*The Practical Application of ISO 1940/1*

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### **ABSTRACT**

International Standard ISO 1940/1 is a widely-accepted reference for selecting rigid rotor balance quality. This paper is presented as a tutorial and user's reference of the standard and its practical applications.

A simplified method is shown for determining permissible residual unbalance for various rotor classifications. Emphasis is given to allocating permissible residual unbalance to appropriate correction planes for rotor configurations, such as unsymmetrical, narrow and overhung rotors. Finally, a comparison of various balance quality grades is made with MIL-STD-167-1 and API balance limits.

### **INTRODUCTION**

The International Standards Organization, ISO, published Standard 1940/1 "Balance Quality Requirements of Rigid Rotors," which has been adopted by the American National Standards Institute, ANSI, as S2.19-1975, "Balance Quality Requirements of Rotating Rigid Bodies." It has also been adopted by BRITISH Standards as BS 6861: Part 1 and by GERMAN Standards as VDI 2060.

ISO 1940/1 requires an understanding of balancing and its terminology if the standard is to be understood and used properly. The reader is directed to the paper's "Balance Terminology" section for a summary of terms used in this paper.

### **USING THE STANDARD**

The use of the standard involves the following steps:

1. Select a balance quality grade "G number" from Table 1 based on rotor type.
2. Use the Figure 1 (A or B) graph to determine the permissible residual specific unbalance value,  $e_{per}$  for the rotor's maximum operating speed and the selected "G number." Then multiply  $e_{per}$  by rotor weight to obtain the permissible residual unbalance,  $U_{per}$ .
3. Allocate  $U_{per}$  to the balancing correction planes based on rotor configuration.

Performing step 1 simply requires the user to find the rotor type that most nearly describes the one to be balanced.

Step 2 is more involved as it requires using the graph in Figure 1 to find the permissible specific unbalance, followed by multiplying by rotor weight and then a constant to convert  $U_{per}$  to proper units (gram-millimeters or ounce-inches). This step can be simplified by using some simple equations to calculate  $U_{per}$  directly.

Step 3, allocating  $U_{per}$ , is often not performed because it is not easily understood.

Therefore, the following pages provide a simplified method for step 2 and describe the procedures for step 3.

**Table 1 Balance quality grades for various groups of representative rigid rotors  
(From ISO 1940/1)**

<b>Balance Quality Grade</b>	<b>Product of the Relationship (<math>e_{per} \times \omega</math>)<sup>(1) (2)</sup> mm/s</b>	<b>Rotor Types - General Examples</b>
G 4 000	4 000	Crankshaft/drives <sup>(3)</sup> of rigidly mounted slow marine diesel engines with uneven number of cylinders <sup>(4)</sup>
G 1 600	1 600	Crankshaft/drives of rigidly mounted large two-cycle engines
G 630	630	Crankshaft/drives of rigidly mounted large four-cycle engines Crankshaft/drives of elastically mounted marine diesel engines
G 250	250	Crankshaft/drives of rigidly mounted fast four-cylinder diesel engines <sup>(4)</sup>
G 100	100	Crankshaft/drives of fast diesel engines with six or more cylinders <sup>(4)</sup> Complete engines (gasoline or diesel) for cars, trucks and locomotives <sup>(5)</sup>
G 40	40	Car wheels, wheel rims, wheel sets, drive shafts Crankshaft/drives of elastically mounted fast four-cycle engines with six or more cylinders <sup>(4)</sup> Crankshaft/drives of engines of cars, trucks and locomotives
G 16	16	Drive shafts (propeller shafts, cardan shafts) with special requirements Parts of crushing machines Parts of agricultural machinery Individual components of engines (gasoline or diesel) for cars, trucks and locomotives Crankshaft/drives of engines with six or more cylinders under special requirements
G 6.3	6.3	Parts of process plant machines Marine main turbine gears (merchant service) Centrifuge drums Paper machinery rolls; print rolls Fans Assembled aircraft gas turbine rotors Flywheels Pump impellers Machine-tool and general machinery parts Medium and large electric armatures (of electric motors having at least 80 mm shaft height) without special requirements Small electric armatures, often mass produced, in vibration insensitive applications and/or with vibration-isolating mountings Individual components of engines under special requirements
G 2.5	2.5	Gas and steam turbines, including marine main turbines (merchant service) Rigid turbo-generator rotors Computer memory drums and discs Turbo-compressors Machine-tool drives Medium and large electric armatures with special requirements Small electric armatures not qualifying for one or both of the conditions specified for small electric armatures of balance quality grade G 6.3 Turbine-driven pumps
G 1	1	Tape recorder and phonograph (gramophone) drives Grinding-machine drives Small electric armatures with special requirements
G 0.4	0.4	Spindles, discs and armatures of precision grinders Gyroscopes

1)  $\omega = 2\pi n/60 \approx n/10$ , if  $n$  is measured in revolutions per minute and  $\omega$  in radians per second.

2) For allocating the permissible residual unbalance to correction planes, refer to "Allocation of  $U_{per}$  to correction planes."

3) A crankshaft/drive is an assembly which includes a crankshaft, flywheel, clutch, pulley, vibration damper, rotating portion of connecting rod, etc.

4) For the purposes of this part of ISO 1940/1, slow diesel engines are those with a piston velocity of less than 9 m/s; fast diesel engines are those with a piston velocity of greater than 9 m/s.

5) In complete engines, the rotor mass comprises the sum of all masses belonging to the crankshaft/drive described in note 3 above.

Figure 1-A Maximum permissible residual unbalance,  $e_{per}$   
 (Imperial values adapted from ISO 1940/1)

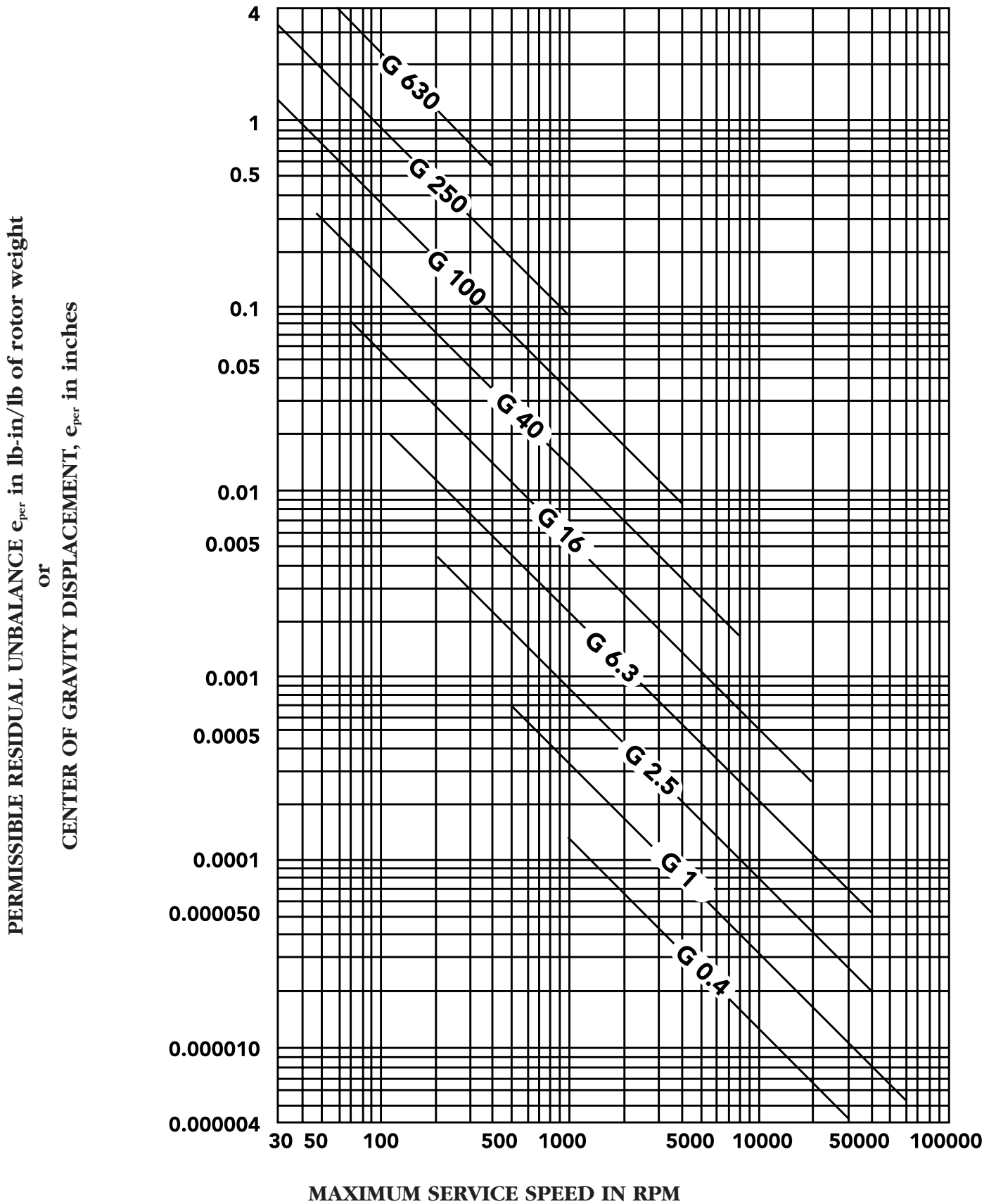
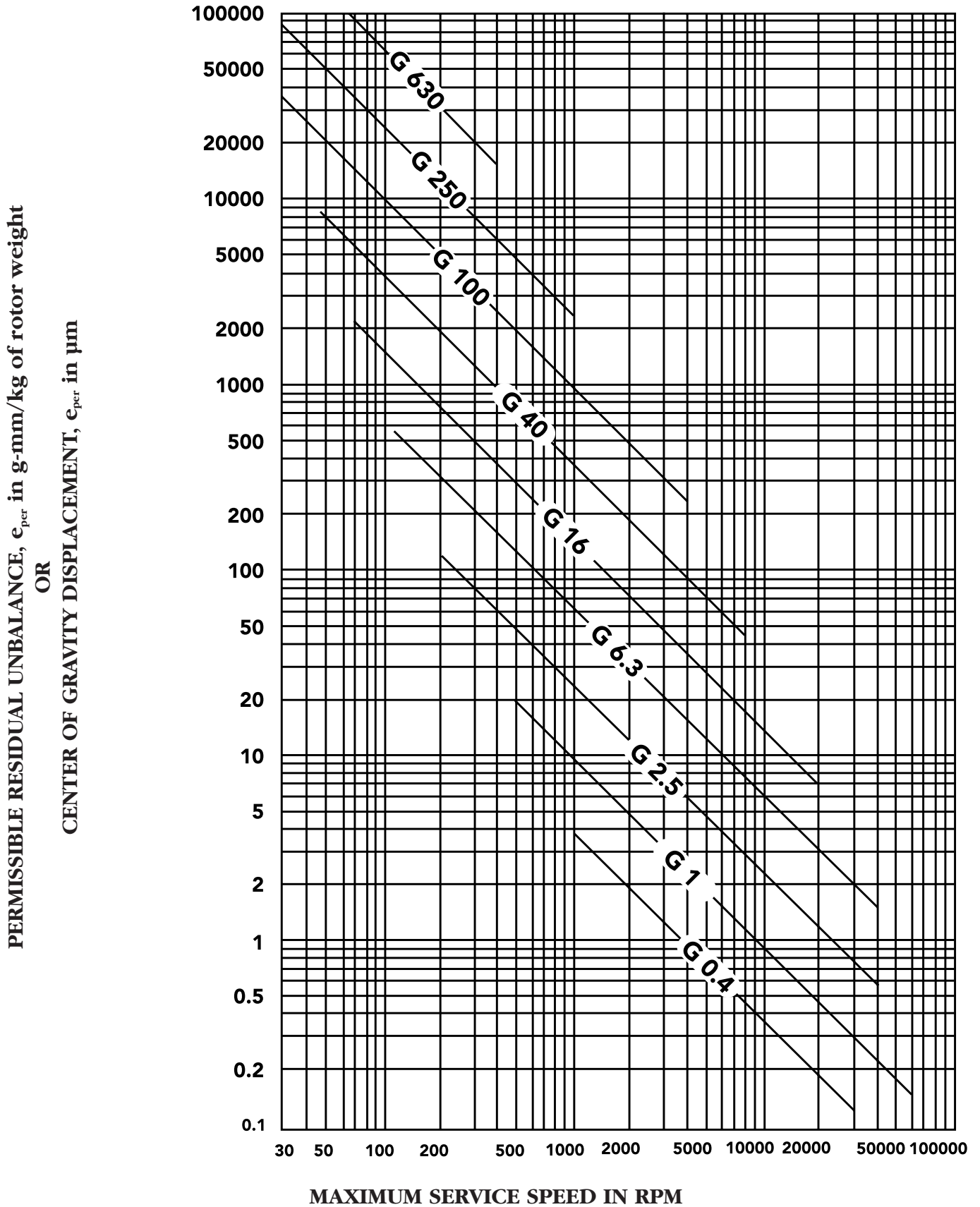


Figure 1-B Maximum permissible residual unbalance,  $e_{per}$   
 (From ISO 1940/1)



## BALANCE QUALITY GRADES

Table 1 shows the balance quality grades for a variety of rotor types. The "G" number is the product of specific unbalance and the angular velocity of the rotor at maximum operating speed and is a constant for rotors of the same type.

$$G = e \times \omega = \text{constant}$$

This is based on the fact that geometrically similar rotors running at the same speed will have similar stresses in the rotor and its bearings.

Balance quality grades are separated by a factor of 2.5. However, G numbers of intermediate value may be used to satisfy special requirements. For example, a standard pump impeller has a suggested balance quality grade of G 6.3. Special conditions may require a better balance quality of G 4.0 to satisfy installation in an area with low structure-borne noise limits.

## DETERMINING PERMISSIBLE RESIDUAL UNBALANCE - $U_{per}$

$$U_{per} = e_{per} \times m$$

(m = rotor mass)

Permissible residual unbalance is a function of G number, rotor weight and maximum service speed of rotation. Instead of using the graph to look up the "specific unbalance" value for a given G number and service RPM and then multiplying by rotor weight (taking care to use proper units),  $U_{per}$  can be calculated by using one of the following formulae:

$$U_{per} (\text{oz-in}) = 6.015 \times G \times W/N \quad (W \text{ in lb})$$

$$U_{per} (\text{g-in}) = 170.5 \times G \times W/N \quad (W \text{ in lb})$$

$$U_{per} (\text{g-mm}) = 9549 \times G \times W/N \quad (W \text{ in kg})$$

G = Balance quality grade from Table 1

W = Rotor weight

N = Maximum service RPM

A slide rule that calculates  $U_{per}$  is also available from some balancing machine manufacturers.

## ALLOCATION OF $U_{per}$ TO CORRECTION PLANES

$U_{per}$  is the total permissible residual unbalance and must be allocated to the balancing correction planes used based on rotor dimensions and configuration.

For rotors balanced in a **single correction plane**, all of the  $U_{per}$  applies to that correction plane.

For rotors balanced in **two correction planes**,  $U_{per}$  must be allocated to each correction plane based on rotor configuration and dimensions.

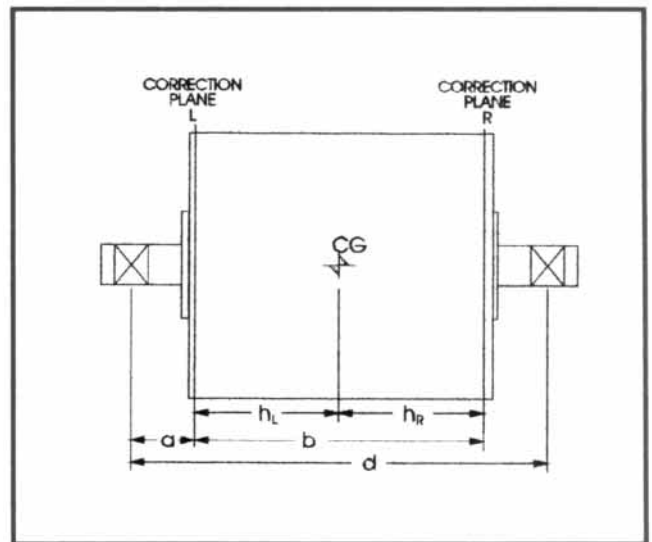


Figure 2 Symmetrical rotors

## SYMMETRICAL ROTORS

Rules for symmetrical rotors. (See Figure 2.)

1. Correction planes are between bearings.
2. Distance "b" is greater than 1/3 "d."
3. Correction planes are equidistant from the center of gravity.

$$U_{per} \text{ left} = U_{per} \text{ right} = U_{per}/2$$

When correction planes are NOT equidistant from the center of gravity, then -

$$U_{per} \text{ left} = U_{per} (h_R/b)$$

$$U_{per} \text{ right} = U_{per} (h_L/b)$$

The  $U_{per} \text{ left}$  or  $U_{per} \text{ right}$  should not be less than 30% or more than 70%  $U_{per}$ . If they are, then use rules for narrow rotors.

**ROTORS WITH OUTBOARD CORRECTION PLANES**

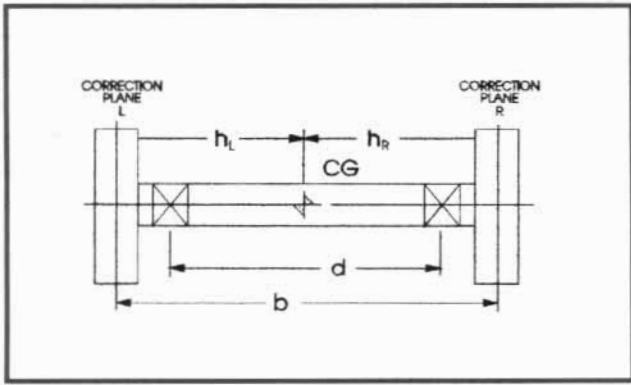


Figure 3 Rotor with outboard planes

Rules for rotors with correction planes outside the bearings. This is often referred to as a "dumb-bell" rotor configuration. (See Figure 3)

Both correction planes are outboard of the bearings.

$$b > d$$

Adjust  $U_{per}$  by ratio of  $d/b$ . (Reduces  $U_{per}$ )

$$U_{per} = U_{per} (d/b) \quad U_{per} = \text{Adjusted value}$$

When correction planes are not equidistant from the center of gravity, calculate  $U_{per}$  left and right as follows:

$$U_{per \text{ left}} = U_{per} (h_R/b) \quad U_{per \text{ right}} = U_{per} (h_L/b)$$

**OVERHUNG AND NARROW ROTORS**

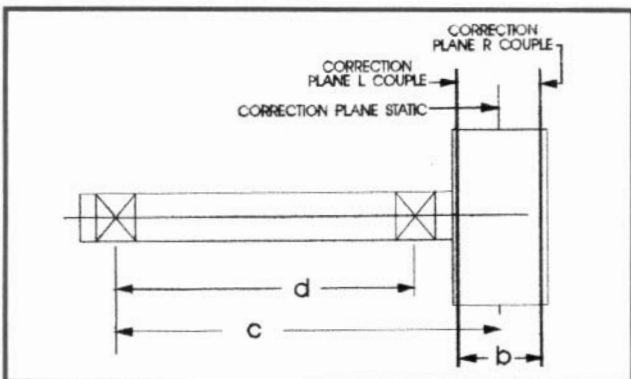


Figure 4 Overhung rotors

Rules for overhung and narrow rotors. (See Figures 4 and 5).

1. Distance between correction planes is less than 1/3 the distance between bearings.  $b < 0.33 d$ .
2. Assumes equal permissible dynamic bearing loads.

3. Couple corrections are made 180° apart in their respective planes.
4. The plane for static corrections may be a third plane or either of the planes used for couple corrections.
5. Allocate  $U_{per}$  as static and couple residual unbalance as follows:

$$U_{per \text{ static}} = U_{per}/2 \times d/2c$$

$$U_{per \text{ couple}} = U_{per}/2 \times 3d/4b$$

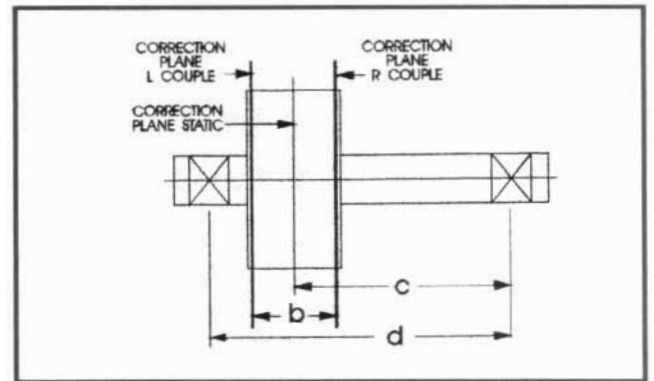


Figure 5 Narrow rotors

Permissible unbalance allocations for overhung and narrow rotors require that two plane unbalance corrections be divided into static and couple unbalance equivalents. This can be done graphically by plotting the two plane balance solution vectors  $U_L$  and  $U_R$  as shown in Figure 6. Connect vectors  $U_L$  and  $U_R$  as shown. The vector from the origin to the mid-point of vector  $C_L-C_R$  is one-half the rotor's static unbalance. Vectors  $C_L$  and  $C_R$  are the couple unbalance.

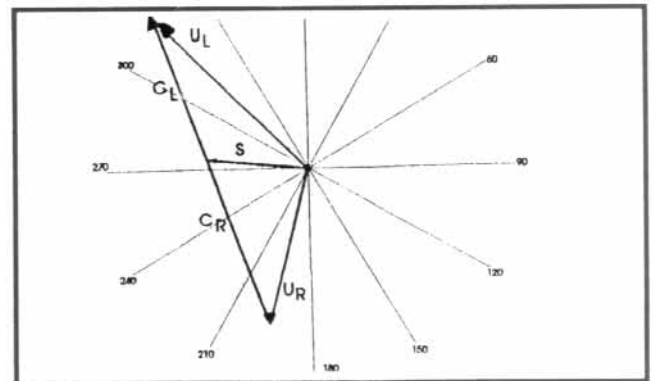
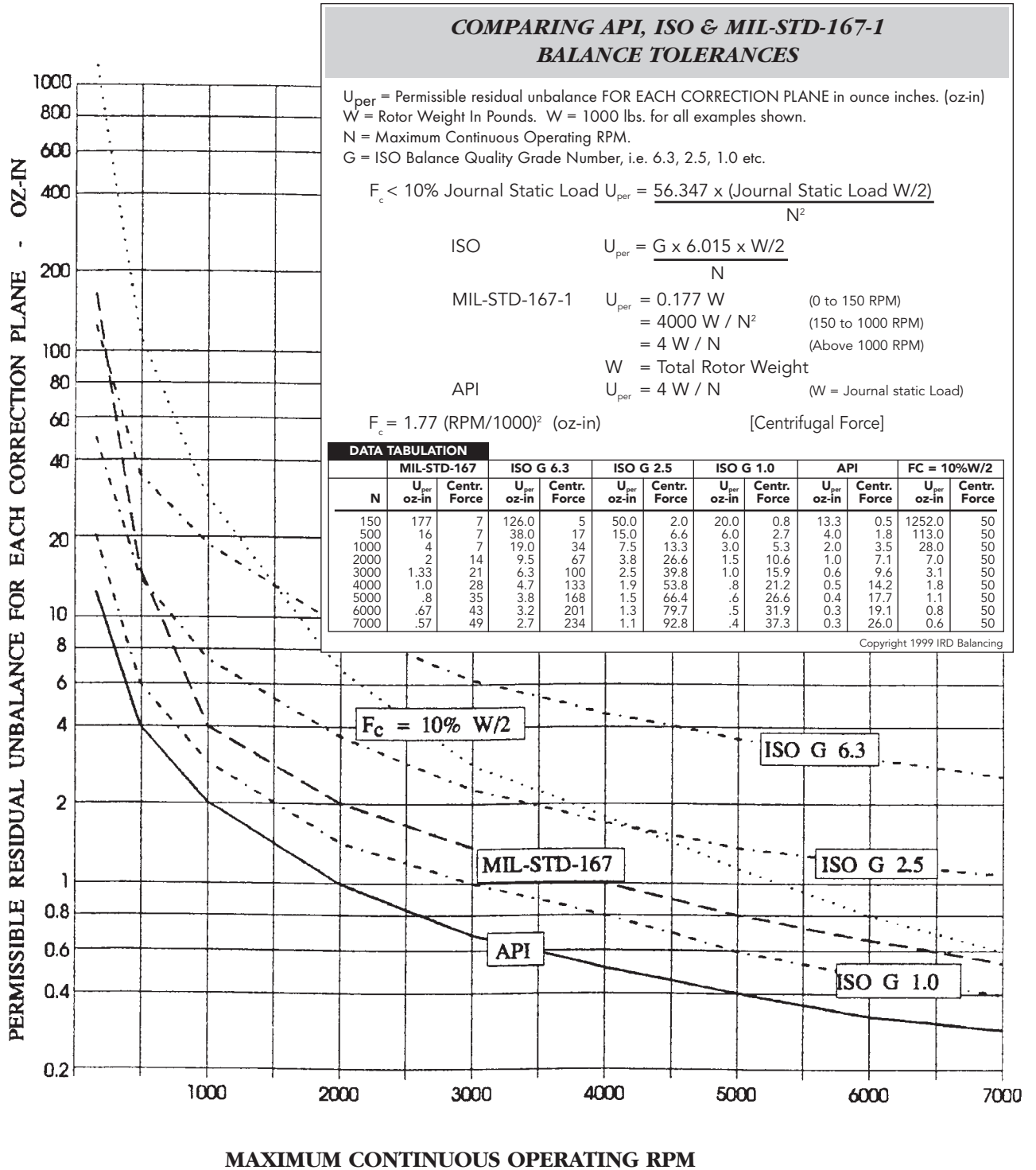


Figure 6 Static-couple graphical derivation

**Figure 7 Comparison of API, ISO & MIL-STD-167-1 balance tolerances**



Useful Conversions		
1 in = 25.4 mm	1 mil = 25.4 $\mu$ m	1 oz in = 720 g mm
1 mm = .0394 in	1 $\mu$ m = .0394 mil	1 g mm = .00139 oz in
1 lb = 454 g	1 oz = 28.35 g	
1 kg = 2.2 lb	1 g = .0353 oz	



**STANDARDS COMPARISON**

A frequent question is, "How do the ISO 1940/1 quality grades compare with other balancing standards, such as API and MIL-STD-167-1?" A comparison graph and data tabulation appears in Figure 7. Three ISO grades (6.3, 2.5 and 1.0), MIL-STD-167-1 and API balance quality standards are compared in tabular and graphical form. In addition,  $U_{per}$  was calculated for a constant centrifugal force of 50 pounds (10% of static journal load). A symmetrical 1000 pound rotor with the C.G. midway between bearings and correction planes was used. Static load at each journal is 500 pounds and centrifugal force was calculated for each  $U_{per}$ .

To more clearly show the relationship, a summary of balance quality standards and their corresponding centrifugal forces are shown in Table 2 as a percentage of journal static loading for 900, 1200, 1800 and 3600 RPM.

*Table 2 Centrifugal force as a percent of journal static load*

Balance Quality Std.	900 RPM		1200 RPM		1800 RPM		3600 RPM	
	$U_{per}$ oz-in	F/L %	$U_{per}$ oz-in	F/L %	$U_{per}$ oz-in	F/L %	$U_{per}$ oz-in	F/L %
ISO G6.3	21	6.0%	15.8	8.1%	10.5	12.0%	5.3	24.1%
ISO G2.5	8.3	2.4%	6.3	3.2%	4.2	4.8%	2.1	9.6%
MIL-STD	4.4	1.3%	3.3	1.7%	2.2	2.5%	1.1	5.1%
ISO G1.0	3.3	0.9%	2.5	1.3%	1.7	1.90%	0.8	3.7%
API	2.2	0.6%	1.7	0.8%	1.1	1.3%	0.6	2.6%

$U_{per}$  = Permissible residual unbalance for each correction plane  
**F** = Centrifugal force due to residual unbalance  
**L** = Journal static load  $L = W/2$  **W** = 1000 lbs.

From the graph and Table 2, it is easy to see that the API standard demands a low residual unbalance level and with a smaller unbalance force load on the rotor's bearings. However, the effort to achieve this result may not always be cost effective.

Published balance tolerances provide everyone with a common reference for communicating balance quality expectations, as well as what the provider promises. Proper interpretation and application of each is needed to realize satisfaction for everyone.

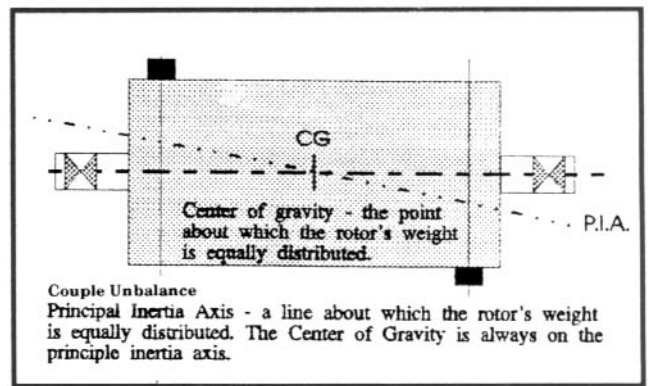
**BALANCE TERMINOLOGY**

**BALANCE QUALITY GRADE - GXXX** - for rigid rotors, G, is the product of specific unbalance, e, and rotor maximum service angular velocity. Service angular velocity is service RPM expressed in radians per second.

$$G = e \times \omega = \text{constant}$$

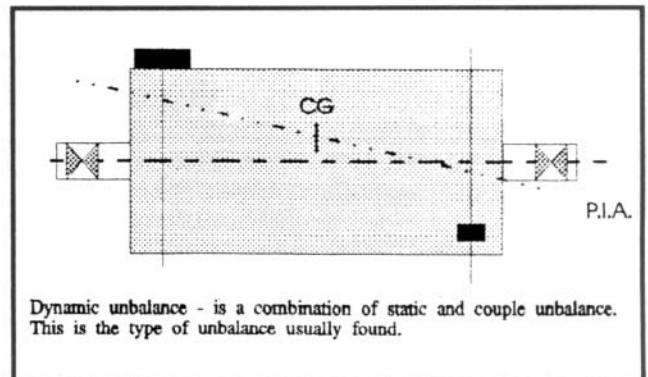
**CENTER OF GRAVITY** - the point in a body through which the resultant of the weights of its component particles passes for all orientations of the body with respect to a gravitational field C.G.

**CORRECTION (BALANCING) PLANE** - plane perpendicular to the shaft axis of a rotor in which correction for unbalance is made.



**COUPLE UNBALANCE** - that condition of unbalance for which the central principal axis intersects the shaft axis at the center of gravity.

**CRITICAL SPEED** - speed at which a system resonance is excited. The resonance may be of the journal supports (rigid mode) or flexure of the rotor (flexural mode).



**DYNAMIC UNBALANCE** - that condition of unbalance for which the central principal axis is not parallel to and does not intersect the shaft axis.

Note: Dynamic unbalance is equivalent to two unbalance vectors in two specified planes which completely represent the total unbalance of the rotor.

Note: Dynamic unbalance may also be resolved into static and couple unbalance vectors whose vector sum is also equal to the total unbalance of the rotor.

**FLEXIBLE ROTOR** - a rotor that does not satisfy the rigid rotor definition because of elastic deflection.

**PERMISSIBLE RESIDUAL UNBALANCE  $U_{per}$**  - the maximum residual unbalance permitted for a rotor or in a correction plane.

$$U_{per} = e_{per} \times m$$

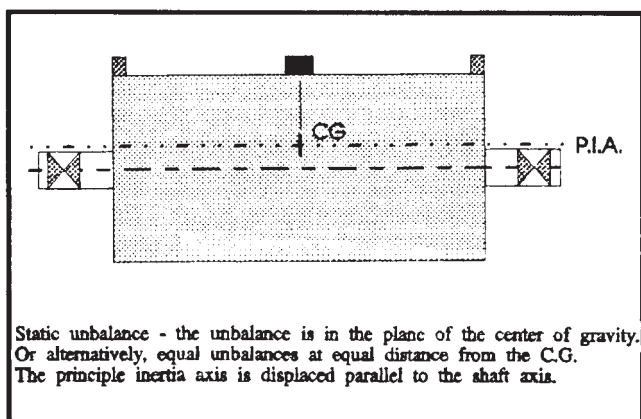
where  $m$  = rotor mass

**PRINCIPAL INERTIA AXIS** - the coordinate directions corresponding to the principal moments of inertia. In balancing, the term *principal inertia axis* is used to designate the *central principal axis* most nearly coincident with the shaft axis of the rotor.

**RESIDUAL (FINAL) UNBALANCE** - the unbalance of any kind that remains after balancing.

**RIGID ROTOR** - a rotor is considered rigid if its unbalance can be corrected in any two correction planes. After the correction, the residual unbalance does not change significantly at any speed up to the maximum service speed.

**ROTOR** - a body capable of rotation which generally has journals supported by bearings.



**STATIC UNBALANCE** - that condition of unbalance for which the central principal axis is displaced only parallel to the shaft axis.

**SPECIFIC UNBALANCE** - static unbalance  $U$  divided by rotor mass  $m$  (i.e., mass eccentricity).

Note: In the case of a rotor with two correction planes, specific unbalance may refer to the unbalance in one plane divided by rotor mass allocated to that plane.

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[www.irdbalancing.com](http://www.irdbalancing.com)  
[sales@irdbalancing.com](mailto:sales@irdbalancing.com)

USA Headquarters	USA: Louisville, KY 1.888.473.2251 <i>phone</i> 1.502.238.1001 <i>fax</i>	UK: Chester 44.1244.538170 <i>phone</i> 44.1244.528900 <i>fax</i>	MEXICO: Mexico City 52.55.5689.8325 <i>phone</i> 52.55.5689.8160 <i>fax</i>	CANADA: Quebec 1.450.724.4066 <i>phone</i> 1.450.724.4077 <i>fax</i>
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