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Determination of Balancing Quality Limits

Is a vibration reading of 4 mm/sec a proper limit for accepting balancing quality of a new forced draft fan? Is this limit also applicable on a new cooling water pump? How to find an acceptance limit for variable speed machines? The proper limit is dependent on many factors including rotor mass, speed and the application in which the machine is used. In fact, the standard limit of balancing quality acceptance is different from the limits given for accepting vibration levels due to unbalance! Understanding balancing limits should enable the manufacturer, vendor, owner and service shop to come up with a doable agreement on target balancing specifications- it is helpful for contractual and technical purposes.

This simplified article will answer prime questions about balancing quality faced in the process of accepting balancing quality of newly purchased or serviced machines. It is based on an interpretative reading of ISO 1940/1. Illustrative figures are given to emphasize the major concepts of that standard.

Unbalance occurs in a rotating machine when the mass centerline and the geometric center do not coincide on each other. Unbalanced rotors generate vibration which may damage their components. In order to extend the life of the machine, vibration due to unbalance must be reduced to acceptable level. Despite the ability to reduce unbalance to low levels, these levels or limits must be defined.

It would be uneconomical to exaggerate balancing quality requirements. However, if the balancing quality is underestimated, it would reduce machine reliability and availability. Moreover, sometimes demanding overqualified balancing reduces machine availability by consuming necessary time in unnecessary balancing.

Introduction: Unbalance and Vibration

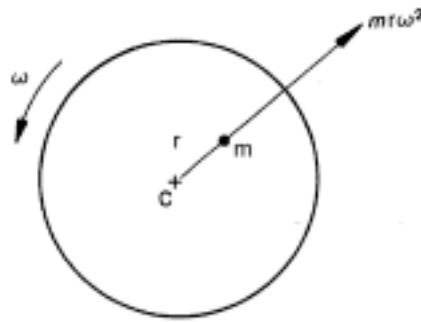Unbalance amount is expressed as:

$$U = m \times r \quad \textit{where,}$$

$m = $ *unbalance mass (in kg)*

$r = $ *distance from unbalance mass to shaft/rotor centerline (in m)*

The unbalance force generating the vibration is expressed as:

$$F = m * r * \omega^2 \, where \begin{cases} r = raduis \quad (m) \\ \omega = speed \quad (rad/\sec) \\ m = mass \quad (kg) \\ m * r = amount \quad (kg.m) \\ F = force \quad (N) \end{cases}$$

Or F(kg)=0.01*m(g)*r(cm)*(rpm/1000)^2

Unbalance Vibration = Unbalance Force/Dynamic Stiffness

There is no handy recognizable general relation between rotor unbalance and the machine vibrations. The unbalance response depends essentially on speed, the geometric proportions and mass distribution of rotor, as well as on the dynamic stiffness of the shaft, bearings and the foundation. Machine stiffness is unknown to owners in most cases. Moreover, combining all of these factors will truly result in complicated equations between the unbalance and resulting vibration. In other words, for a particular rotor, unbalance vibration will have different values depending on its operating speed, type of bearings(e.g. fluid film or rolling element), foundation etc. while the unbalance amount itself is constant and only related to the rotor. So, the balancing quality limit should not be oversimplified and given through vibration readings only. This is especially true for new machines for which no pervious vibration experience exists.

The vibration standards commonly used in industry put their criteria based on the unbalance response (vibration amplitude) irrespective of rotor and foundation stiffness. Also, the magnitude of the force generated due to unbalance and rotor mass are not addressed. In balancing, the mass, stiffness and vibration of an unbalanced rotor are related through a parameter called influence vector.
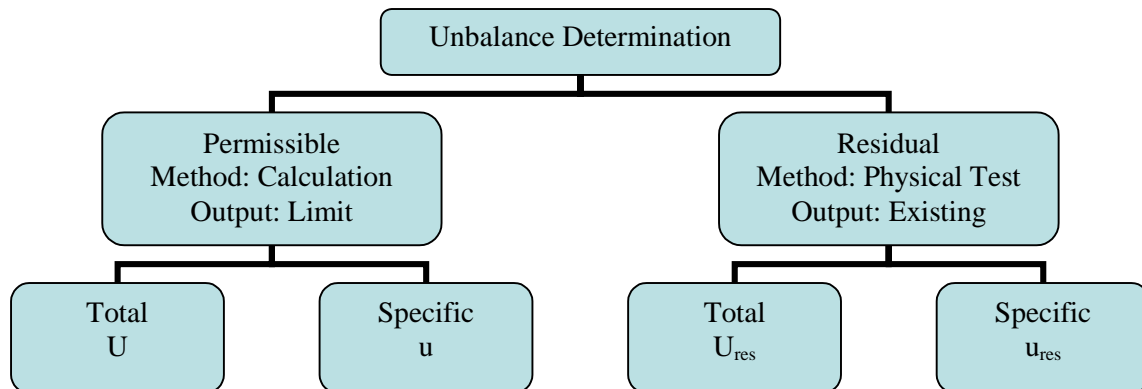
Unbalance: Existing and Limit

The term "unbalance" is referred to two quantities. First is the balancing acceptance *limit* of a rotor and is usually called *permissible or allowable unbalance*. Second is

the *existing or residual unbalance* in a rotor. In acceptance tests, the following logic is implicitly applied:
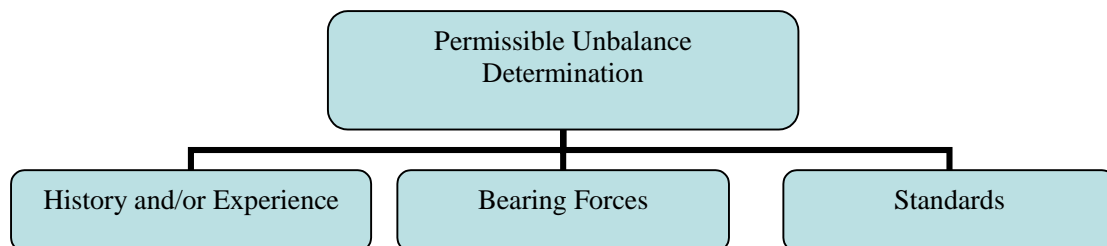

$U_{Limit} > U_{Existing}$ → Balancing Quality within Tolerance (Accepted)

$U_{Limit} < U_{Existing}$ → Balancing Quality out of Tolerance (Rejected)

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                        Unbalance Determination
          ┌──────────────────────┴──────────────────────┐
     Permissible                                    Residual
  Method: Calculation                        Method: Physical Test
     Output: Limit                               Output: Existing
    ┌──────┴──────┐                            ┌──────┴──────┐
  Total        Specific                      Total        Specific
    U             u                          U_res         u_res
```

This article is dedicated to highlight the determination of permissible unbalance. Determination of residual unbalance is left for another article.

Balance Quality Determination Methods


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                Permissible Unbalance
                    Determination
      ┌──────────────────┼──────────────────┐
History and/or Experience   Bearing Forces      Standards
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The permissible unbalance can be determined based on :

    1.   history and/or experiments done on several similar machines (vibration limits can be extracted from the history)

    2.   pre-specified permissible bearing forces in the stage of bearing selection

    3.   standards like 1940/1 (typically followed in industry)

Balance Quality Based on Standardized Grades

The standard is valid only for rigid ([1]) rotors and does not define permissible residual unbalances for flexible rotors. This standard does not cover neither the sources of errors involved in balancing nor the balancing procedure. (This information is

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[1] A rotor is considered rigid if it does not run above its first critical speed through its operation up to its maximum service speed.

available in other standards.) . Balancing standard provides generalized grades for which rotor application, mass, and speed can tailored for specific cases.

In general, the larger the rotor mass, the greater the permissible residual unbalance. To relate the value of the *total permissible unbalance*, U, to the rotor mass, M, the term *specific permissible unbalance* value, u, is defined. It is the maximum limit of unbalance amount per unit mass of the rotor. It is analogous to the specific enthalpy or specific entropy used in thermodynamics. Mathematically,

$$u = (e_{per} =) \ U/M$$

where u = permissible specific unbalance (sometimes referred to as mass eccentricity) (um*kg/kg), U = rotor total permissible unbalance (um*kg), M= rotor mass (kg).

Quality grade (the lines in the figure) relates *max service speed*[2] to the permissible specific unbalance. For a specific grade, as the speed of the rotor increases (rightwards in the figure), u gets tighter (downwards). This means that the unbalance amount allowed deceases as machine speed increases. Balance quality grades (lines) are separated from each other by a factor of 2.5. However, sometimes grades between these lines are used.

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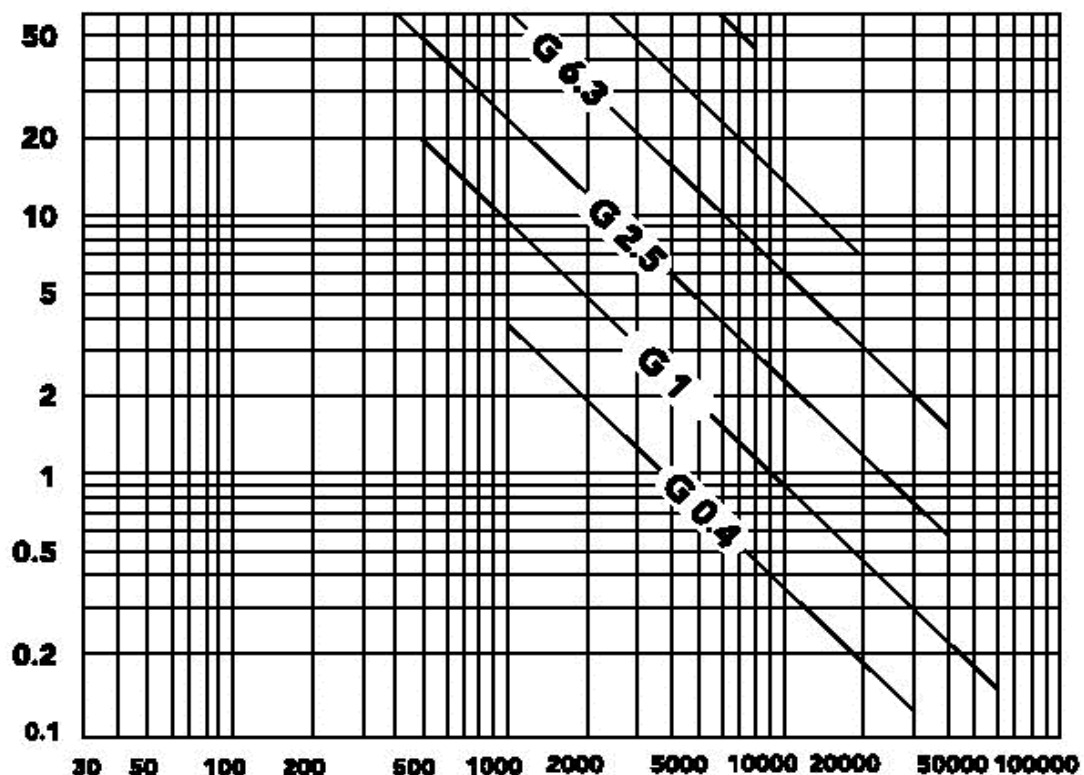
[2] It is the highest speed the machine should broach by design under all operating modes. To illustrate, synchronous and induction motors and their driven machines, max service speed is the synchronous rpm. Notice that max service speed is not the same as and in most cases higher than balancing speed. Max service speed may be increased over 110% to accommodate the margin of load, pressure, temperature etc.

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Hor. Axis= Max Service Speed (rpm). Ver. Axis= Specific Permissible Unbalance, u (g*mm/kg).

Quantity	Symbol	Units
Balance Grade Code	G	mm/sec
Rotor mass	M	kg
Unbalance mass	m	kg
(Total) Permissible Unbalance	U_{per}	kg*mm
Specific Permissible Unbalance	u	um
(Total) Residual Unbalance	U_{res}	kg*mm
Specific Residual Unbalance	u_{res}	mm

General Procedure of Finding U

The steps described below may be applied to all rotors regardless of their mass distribution and the position of the correction planes.

1.   Gather machine's design and operation information (minimum: speed, mass and criticality).

2.   Using Table 2, compare this information and decide the proper balance grade.

3.   Specify the Grade line and the max service speed in Figure 2.

4.   Impose the max service speed of the rotor and then determine the corresponding permissible specific unbalance value, u.

5.   Multiply u by rotor mass to obtain the total permissible unbalance, U.

6.   Allocate U to the balancing correction planes based on rotor configuration.[3]

Grade	Application
G 16	Drive shafts (propeller shafts) with special requirements. Parts of crushing machinery. Parts of agricultural machinery. Slurry or dredge pump impeller. Individual components of engines (gas or diesel) for cars, trucks and locomotives. Crankshaft drives of engines with six or more cylinders under special requirements.
G 6.3	Parts or process plant machines. Fans. Fly wheels. Pump impellers. Machine tool and general machinery parts. Normal electrical armatures. Individual components of engines under special requirements Marine main turbine gears (merchant service).
G 2.5	Gas & steam turbines, including marine main turbines. Rigid turbo-generator rotors. Turbo-compressors. Machine tool drives. Medium and large electrical armatures with special requirements. Small electrical armatures. Turbine driven pumps.
G 1	Grinding machine drives. Small electrical armatures with special requirements.
G 0.4	Spindles, disks and armatures of precision grinders.
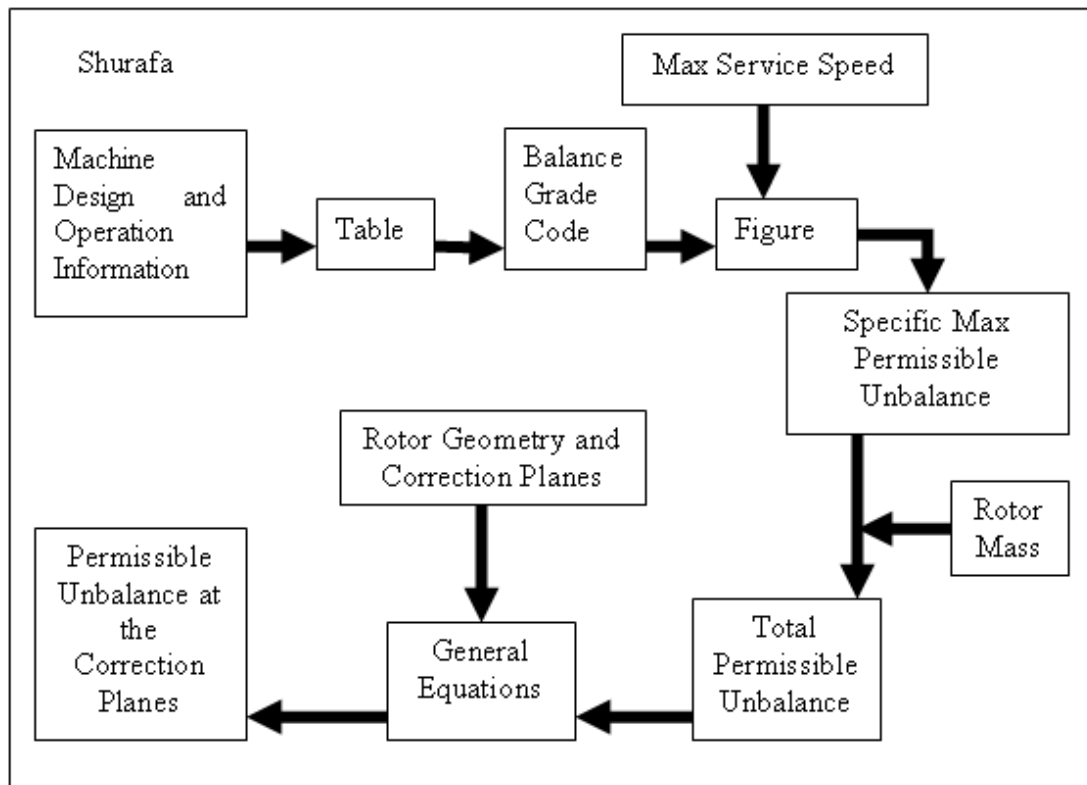
Notes on Step 8: Notice that measurement, bearing and correction (balancing) planes might be different and this is not unusual practical case. Total permissible unbalance, U, should be allocated to specific planes e.g. balancing correction. This step involves a series of calculation based on the mass distribution of the rotor and the location of the correction plane. Usually, these calculations can be reduced to get an approximate result. The Total Permissible Unbalance per plane would be approximated by ½ U in case two correction planes would be used.

Shortcut

Following is a short cut for the steps 3, 4 and 5. 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 can be calculated by using the following formula:

$$U \ (g*mm) = 9549 \times G \times M(kg)/rpm$$

Example:

Find the allocated permissible unbalance of a critical induction motor rotor of the following information:

Operation speed: 1800 rpm, Mass =120 kg, running under sever conditions, two balancing planes close to the bearings and measurement planes are available.

Using the table, G2.5 is selected. Compensating sever load conditions for this motor, max service speed is increased to 2000 rpm. Using the formula U= 9549* 2.5 *120/2000= 1432 g*mm

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(Or alternatively, the grade and speed are imposed on graph to find u = 12 g*mm/kg then this value in multiplied by the mass to get U= 12* 120= 1440 g*mm)

Allocating U to the two plane with the approximate method, U1=U2= U/2= 716 g*mm.

Caution: This article does not replace the original standard by any means.

For more details, the complete title of the Standard is:

ISO 1940-1: Mechanical Vibration - Balance Quality Requirements of Rigid Rotors - Determination of Permissible Residual Unbalance. (14 pages).