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Mechanical vibration — Rotor balancing —

Part 14:
Procedures for assessing balance errors

Vibrations mécaniques — Équilibrage des rotors —

Partie 14: Modes opératoires d'évaluation des erreurs d'équilibrage

Reference number
ISO 21940-14:2012(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 21940-14 was prepared by Technical Committee 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 of ISO 21940-14 cancels and replaces ISO 1940-2:1997, of which it constitutes a technical revision. The main change is extension of the applicability to rotors with flexible behaviour.

ISO 21940 consists of the following parts, under the general title *Mechanical vibration — Rotor balancing*:

— *Part 1: Introduction*[1)]

— *Part 2: Vocabulary*[2)]

— *Part 11: Procedures and tolerances for rotors with rigid behaviour*[3)]

— *Part 12: Procedures and tolerances for rotors with flexible behaviour*[4)]

— *Part 13: Criteria and safeguards for the* in-situ *balancing of medium and large rotors*[5)]

— *Part 14: Procedures for assessing balance errors*[6)]

— *Part 21: Description and evaluation of balancing machines*[7)]

— *Part 23: Enclosures and other protective measures for the measuring station of balancing machines*[8)]

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1) Revision of ISO 19499:2007, *Mechanical vibration — Balancing — Guidance on the use and application of balancing standards*

2) Revision of ISO 1925:2001, *Mechanical vibration — Balancing — Vocabulary*

3) Revision of ISO 1940-1:2003 + Cor.1:2005, *Mechanical vibration — Balance quality requirements for rotors in a constant (rigid) state — Part 1: Specification and verification of balance tolerances*

4) Revision of ISO 11342:1998 + Cor.1:2000, *Mechanical vibration — Methods and criteria for the mechanical balancing of flexible rotors*

5) Revision of ISO 20806:2009, *Mechanical vibration — Criteria and safeguards for the* in-situ *balancing of medium and large rotors*

6) Revision of ISO 1940-2:1997, *Mechanical vibration — Balance quality requirements of rigid rotors — Part 2: Balance errors*

7) Revision of ISO 2953:1999, *Mechanical vibration — Balancing machines — Description and evaluation*

8) Revision of ISO 7475:2002, *Mechanical vibration — Balancing machines — Enclosures and other protective measures for the measuring station*

— *Part 31: Susceptibility and sensitivity of machines to unbalance*[9)]

— *Part 32: Shaft and fitment key convention*[10)]

9) Revision of ISO 10814:1996, *Mechanical vibration — Susceptibility and sensitivity of machines to unbalance*

10) Revision of ISO 8821:1989, *Mechanical vibration — Balancing — Shaft and fitment key convention*

Introduction

The balance quality of a rotor is assessed in accordance with the requirements of ISO 1940-1 or ISO 11342 by measurements taken on the rotor. These measurements might contain errors which can originate from a number of sources. Where those errors are significant, they should be taken into account when defining the required balance quality of the rotor.

ISO 1940-1 and ISO 11342 do not consider in detail balance errors or, more importantly, the assessment of balance errors. Therefore this part of ISO 21940 gives examples of typical errors that can occur and provides recommended procedures for their evaluation.

Mechanical vibration — Rotor balancing —

Part 14: Procedures for assessing balance errors

1 Scope

This part of ISO 21940 specifies the requirements for the following:

a) identifying errors in the unbalance measuring process of a rotor;

b) assessing the identified errors;

c) taking the errors into account.

This part of ISO 21940 specifies balance acceptance criteria, in terms of residual unbalance, for both directly after balancing and for a subsequent check of the balance quality by the user.

For the main typical errors, this part of ISO 21940 lists methods for their reduction in an informative annex.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1925, *Mechanical vibration — Balancing — Vocabulary*[11)]

ISO 1940-1, *Mechanical vibration — Balance quality requirements for rotors in a constant (rigid) state — Part 1: Specification and verification of balance tolerances*[12)]

ISO 11342, *Mechanical vibration — Methods and criteria for the mechanical balancing of flexible rotors*[13)]

ISO 21940-21, *Mechanical vibration — Rotor balancing — Part 21: Description and evaluation of balancing machines*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 1925 apply.

4 Balance error sources

4.1 General

Balancing machine balance errors can be classified into:

a) systematic errors, in which the magnitude and angle can be evaluated either by calculation or measurement;

b) randomly variable errors, in which the magnitude and angle vary in an unpredictable manner over a number of measurements carried out under the same conditions;

11) To become ISO 21940-2 when revised.

12) To become ISO 21940-11 when revised.

13) To become ISO 21940-12 when revised.

c) scalar errors, in which the maximum magnitude can be evaluated or estimated, but its angle is indeterminate.

Depending on the manufacturing processes used, the same error can be placed in one or more categories.

Examples of error sources which may occur are listed in 4.2, 4.3, and 4.4.

Some of these errors are discussed in greater detail in Annex A.

4.2 Systematic errors

Examples of balancing machine systematic error sources are:

a) inherent unbalance in the drive shaft;

b) inherent unbalance in the mandrel;

c) radial and axial runout of the drive element on the rotor shaft axis;

d) radial and axial runout in the fit between the component to be balanced or in the balancing machine mandrel (see 5.3);

e) lack of concentricity between the journals and support surfaces used for balancing;

f) radial and axial runout of rolling element bearings which are not the service bearings and which are used to support the rotor;

g) radial and axial runout of rotating races (and their tracks) of rolling element service bearings fitted after balancing;

h) unbalance due to keys and keyways;

i) residual magnetism in the rotor or mandrel;

j) reassembly errors;

k) balancing equipment and instrumentation errors;

l) differences between service shaft and balancing mandrel diameters;

m) universal joint defects;

n) temporary bend in the rotor during balancing;

o) permanent bend in the rotor after balancing.

4.3 Randomly variable errors

Examples of balancing machine randomly variable error sources are:

a) loose parts;

b) entrapped liquids or solids;

c) distortion caused by thermal effects;

d) windage effects;

e) use of a loose coupling as a drive element;

f) transient bend in the horizontal rotor caused by gravitational effects when the rotor is stationary.

4.4 Scalar errors

Examples of balancing machine scalar error sources are:

a) changes in clearance at interfaces that are to be disassembled after the balancing process;

b) excessive clearance in universal joints;

c) excessive clearance on the mandrel or shaft;

d) design and manufacturing tolerances;

e) runout of the balancing machine support rollers if their diameters and the rotor journal diameter are the same, nearly the same or have an integer ratio.

5 Error assessment

5.1 General

In some cases, rotors are in balance by design, are uniform in material and are machined to such narrow tolerances that they do not need to be balanced after manufacture. Where rotor initial unbalance exceeds the permitted values given in ISO 1940-1 or ISO 11342, the rotor should be balanced.

5.2 Errors caused by balancing equipment and instrumentation

Balance errors caused by balancing equipment and instrumentation can increase with the magnitude of the unbalance present. By considering unbalance causes during the design stage, some error sources can be completely eliminated (e.g. by combining several parts into one) or reduced (e.g. by specifying decreased tolerances). It is necessary to weigh the cost due to tighter specified tolerances against the benefit of decreased unbalance. Where the causes of unbalance cannot be eliminated or reduced to negligible levels, they should be mathematically evaluated.

5.3 Balance errors caused by component radial and axial runout

When a perfectly balanced rotor component is mounted eccentrically to the rotor shaft axis, the resulting static unbalance, $\boldsymbol{U}_\mathrm{S}$, of the component, in g·mm, is given by Formula (1):

$$\boldsymbol{U}_\mathrm{S} = m \cdot \boldsymbol{e} \tag{1}$$

where

m is the mass of the component, in g;

$\boldsymbol{e}$ is the eccentricity of the rotor component relative to the rotor shaft axis, in mm.

NOTE The mass can be stated in kg, the eccentricity in μm, but the static unbalance remains in units of g·mm.

The static unbalance of the component creates an identical static unbalance of the assembled rotor. An additional moment unbalance results if the component is mounted eccentrically in a plane other than that of the centre of mass. The further the plane distance is from the centre of mass, the larger the moment unbalance.

If a perfectly balanced component is mounted concentrically, but with its principal axis of inertia inclined to the rotor shaft axis, a moment unbalance results; see Figure 1.

For a small inclination angle, $\Delta\gamma$, between the two axes, the resulting moment unbalance. $\boldsymbol{P}_\mathrm{r}$, in g·mm^2, is approximately equal to the difference between the moments of inertia about the component x- and z-axes, multiplied by the angle, $\Delta\gamma$, in radians; see Formula (2):

$$\boldsymbol{P}_\mathrm{r} \approx (I_x - I_z)\,\Delta\gamma \qquad (2)$$

where

I_x is the moment of inertia about the transverse x-axis through the component centre of mass, in g·mm^2;

I_z is the moment of inertia about the principal z-axis of the component, in g·mm^2;

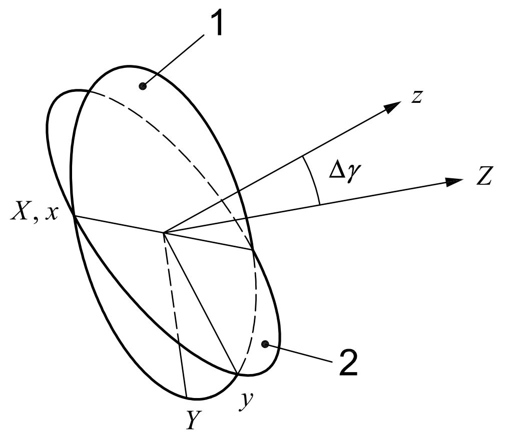
$\Delta\gamma$ is the small angle between the component principal axis of inertia and the rotor shaft axis, in radians.

Formula (2) is valid only if the component is symmetric about its rotational axis and is therefore particularly applicable to the balancing of disks on arbors.

The effects of radial runout and axial runout of a component mounted on the rotor can be calculated separately.

For rotors with rigid behaviour, the separate unbalance components can be allocated to the bearing or correction planes and then combined vectorially.

For rotors with flexible behaviour, a rigid balance quality might be maintained, but accumulated axial disk runout errors (often described as skew) can lead to significant vibration due to the moment unbalance generated by the skewed disk(s).



Key

1	rotor plane, perpendicular to the rotor shaft axis	x	component transverse axis
2	component plane	y	component transverse axis
X	rotor shaft transverse axis	z	component principal axis
Y	rotor shaft transverse axis	$\Delta\gamma$	angle between the component principal axis of inertia and the rotor shaft axis
Z	rotor shaft axis		

Figure 1 — Coordinates of the rotor shaft and component axes, showing a component inclined to the rotor shaft axis

5.4 Assessment of balancing operation errors

The purpose of balancing is to produce rotors that are within specified limits of residual unbalance or vibration. To ensure that the set limits have been met, errors need to be controlled and taken into account.

When a balancing machine is used, various error sources exist, for example:

a) the type of rotor to be balanced;

b) the tooling used to support or drive the rotor;

c) the balancing machine support structure (e.g. machine bearings and cradles);

d) the balancing machine sensing system;

e) the electronic and read-out system.

However, it is important that in those cases where the error is taken into account by calculation, both the measured unbalance before correction and the corrected value are reported.

The balancing machine used should be such that all its systematic errors are eliminated or corrected. When balancing rotors that have a rigid behaviour at their balancing speed, the requirements of ISO 21940-21 apply.

5.5 Experimental assessment of randomly variable errors

5.5.1 General

If significant randomly variable errors are suspected to exist it is necessary, where practical, to carry out several measuring runs to assess their magnitude.

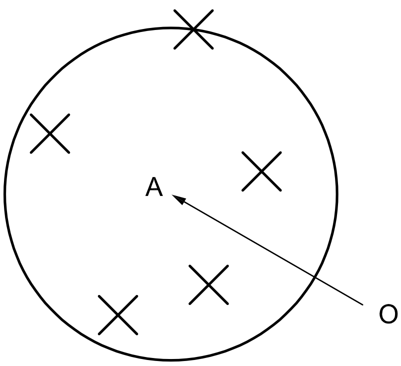
When carrying out measuring runs, it is important to ensure that the random errors are themselves produced randomly in each run (e.g. by ensuring that the angular position of the rotor is different at the start of each run).

The random error magnitude can be evaluated by applying standard statistical techniques to the measurement results obtained. However, in most cases, carrying out the procedure described in 5.5.2 is adequate.

5.5.2 Procedure

Plot the measured vectors of residual unbalance or vibration and find the mean vector $\overrightarrow{OA}$ from all the runs (see Figure 2). Draw the smallest circle about centre A to enclose all the points. The vector $\overrightarrow{OA}$ represents an estimation of the measured residual unbalance or vibration, and the radius of the circle an estimation of the maximum possible error of each single reading. The uncertainty of these results is usually diminished by increasing the number of runs carried out.

NOTE In some cases, particularly if one point is significantly different from the others, the error estimated can be unacceptably large. In this case, a more detailed analysis is necessary to determine the errors.



Plots of several measurements are indicated by .

Figure 2 — Plot of measured vectors of residual unbalance or vibration (randomly variable errors)

5.6 Experimental assessment of systematic errors

In many cases, most of the systematic errors can be found using index balancing.

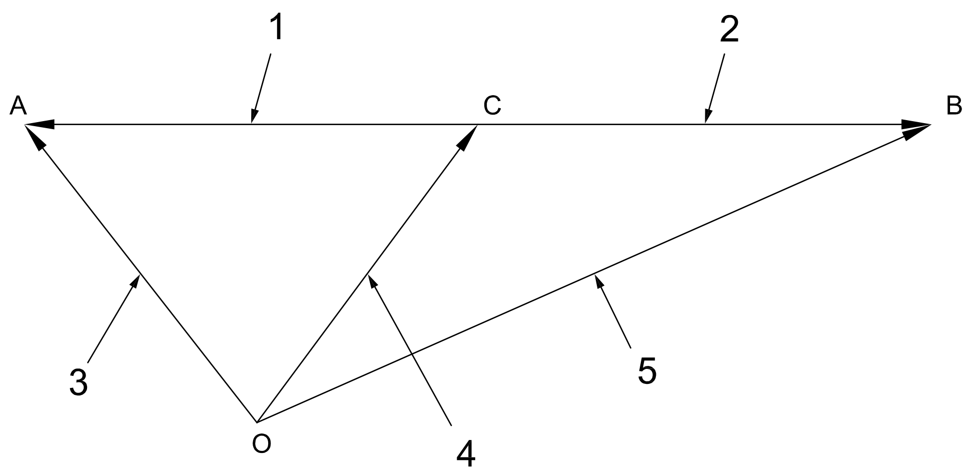
Index balancing can be performed by:

a) mounting the rotor alternately at 0° and 180° relative to the item which is the source of the particular error being investigated; and

b) measuring the residual unbalance or vibration several times in both positions.

If $\overrightarrow{OA}$ and $\overrightarrow{OB}$, as shown in Figure 3, represent the mean vectors of measured residual unbalance or vibration with the rotor mounted at 0° and 180°, respectively, a diagram can be constructed for each measurement plane where C is the mid-point of the distance AB. The vector $\overrightarrow{OC}$ represents the particular systematic error and the vectors $\overrightarrow{CA}$ and $\overrightarrow{CB}$ represent the rotor residual unbalance or vibration with the rotor at 0° and 180°, respectively.

NOTE In this case, it has been assumed that the rotor has been turned relative to the phase reference. If, however, the phase reference remains fixed relative to the rotor, the vector $\overrightarrow{OC}$ represents the rotor residual unbalance or vibration; and the vectors $\overrightarrow{CA}$ and $\overrightarrow{CB}$ represent the particular systematic error with the phase reference at 0° and 180°, respectively.



Key

1 rotor residual unbalance or vibration for rotor mounted at 0°: $\overrightarrow{CA}$

2 rotor residual unbalance or vibration for rotor mounted at 180°: $\overrightarrow{CB}$

3 mean vector of measured residual unbalance or vibration for rotor mounted at 0°: $\overrightarrow{OA}$

4 systematic error: $\overrightarrow{OC}$

5 mean vector of measured residual unbalance or vibration for rotor mounted at 180°: $\overrightarrow{OB}$

Figure 3 — Plot of mean vectors of residual unbalance or vibration and systematic error

6 Combined error evaluation

Systematic errors whose magnitude and phase angle are known can be eliminated (e.g. by applying temporary correction masses to the tooling or the rotor during the balancing process or by mathematically correcting the results). If the systematic errors are not corrected or not correctable, they should be combined with randomly variable errors and scalar errors by using Formula (3) or Formula (4) for each measuring plane.

Formula (3) gives the worst case evaluation of the magnitude ΔU of the combined uncorrected errors, in g·mm:

$$\Delta U = \sum_i \left| \overrightarrow{\Delta U}_i \right| \tag{3}$$

where $\left| \overrightarrow{\Delta U}_i \right|$ is the magnitude of the uncorrected error, in g·mm, from any source i.

Formula (3) guarantees that, even in case of the most unfavourable error combination, the rotor is acceptable, provided the requirements of Clause 7 are met. It is based upon the assumption that all of the uncorrected errors fall in the same angular direction and that their absolute numeric values should be summed.

After applying Formula (3), if it is found that the combined uncorrected error would cause the rotor to be out of tolerance, then an attempt to reduce the more significant errors is recommended.

In some cases, a more realistic approach may be used which takes into account that not all errors from various sources are likely to fall in the same angular direction. Here, the magnitude of the combined error ΔU, in g·mm, may be evaluated by using Formula (4):

$$\Delta U = \sqrt{\sum_i \left| \overrightarrow{\Delta U}_i \right|^2} \qquad (4)$$

Under appropriate conditions, the errors can be evaluated by measurements on a significant rotor sample. It is then assumed that errors of the same magnitude are present on all similar rotors which have been manufactured and assembled in the same way.

For mass-produced rotors, a statistically based process for finding the combined error may need to be agreed between the user and supplier.

7 Acceptance criteria

If the assessment parameters are residual unbalances in tolerance planes (in case of rotors with flexible behaviour residual equivalent modal unbalances), the rotor balance shall be considered acceptable by the party which carries out the balancing if the condition for $U_{\mathrm{r\,m}}$ in Formula (5) is satisfied for each and every tolerance plane (each and every equivalent modal unbalance). $U_{\mathrm{r\,m}}$ is the magnitude of the residual unbalance in a tolerance plane, in g·mm, measured by a single reading, or the magnitude of the residual equivalent modal unbalance for a rotor with flexible behaviour based on a single data set.

$$U_{\mathrm{r\,m}} \leq U_{\mathrm{per}} - \Delta U \qquad (5)$$

where

U_{per} is the magnitude of the permissible residual unbalance, in g·mm, obtained from ISO 1940-1 or ISO 11342;

ΔU is the magnitude of the combined error, in g·mm, as defined in Clause 6.

If ΔU is found to be less than 5 % of U_{per}, it may be disregarded.

If a subsequent balance check is performed by the user, the rotor balance shall be accepted if the condition in Formula (6) is satisfied. The balancing machine used for this check shall be qualified to balance the rotor, i.e. even in the check the balance errors shall be well below the balance tolerance.

$$U_{\mathrm{r\,m}} \leq U_{\mathrm{per}} + \Delta U \qquad (6)$$

If the condition given by Formula (6) is not met, the balancing procedures may need to be reviewed or repeated.

If the assessment parameter is vibration, the same process can be applied by replacing U_{per}, $U_{\mathrm{r\,m}}$ and ΔU by the relevant vibration quantities.

If a change of unbalance during transportation of the rotor is expected, this should also be taken into consideration.

Annex A
(informative)

Error examples, their identification and evaluation

A.1 Errors originating from auxiliary equipment

A.1.1 General

Examples of errors associated with residual unbalance and originating from auxiliary equipment are discussed in this clause and are summarized in Table A.1 (also see Figures A.1, A.2 and A.3).

A.1.2 Errors originating from inherent unbalance and eccentricity

These errors (e.g. in the drive element or mandrel) can be evaluated by index balancing. This procedure can be complicated by the non-repeatability of mechanical fit (see A.1.4) and workpiece errors (see A.2).

A.1.3 Errors originating from bearings

If rolling element bearings are fitted for a balancing operation, they introduce an error proportional to the eccentricity or angular misalignment of their rotating races (and their tracks) and rotor mass. This error can be determined by indexing the bearing races 180° on their mounting surfaces.

NOTE Eccentricity is assumed to result from radial and/or axial runout.

A.1.4 Errors originating from mechanical fits

Mechanical fit can be a potential source of error (e.g. a change of unbalance can result from reassembly of parts), and there are many possible sources (e.g. if there is radial clearance or if the interference is too great or if the connecting bolts interfere with the spigot location).

The scatter caused by fit non-repeatability should be determined by repeated reassembly, with clearances taken up at different angles. For each reassembly, unbalance or vibration readings are taken and a mean value can be obtained.

A.1.5 Errors associated with balancing equipment mass

In order to reduce the error resulting from spigot clearance or runout, the mass of the rotating tooling used for balancing (not necessarily the mandrel) should be reduced to a minimum.

Reducing the mandrel mass increases the sensitivity of a soft-bearing machine, but normally produces little benefit on a hard-bearing machine.

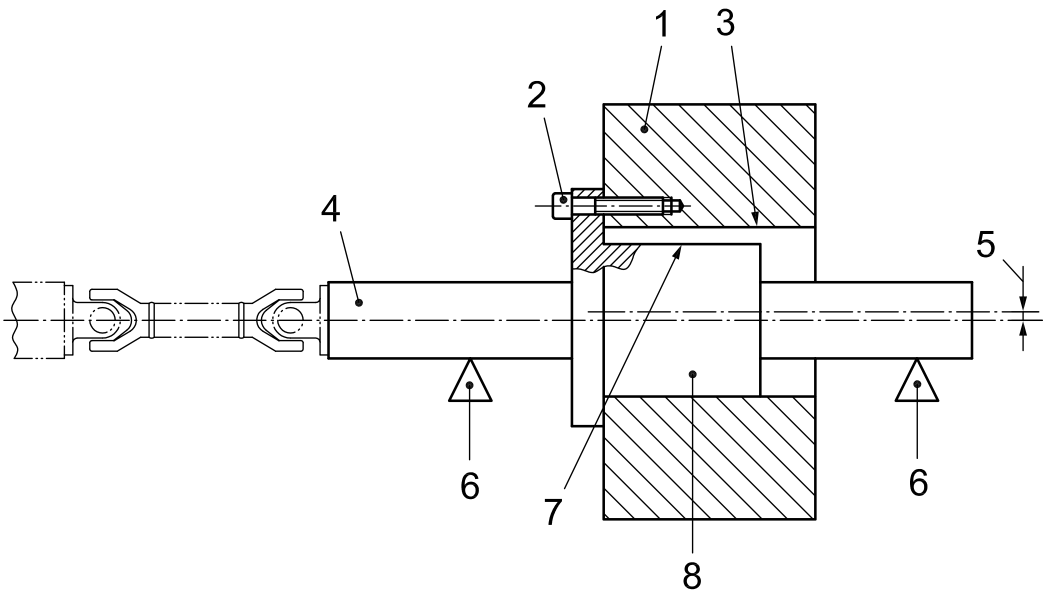
A.2 Errors originating from the workpiece

A.2.1 General

Examples of errors associated with residual unbalance and originating from the workpiece are discussed in A.2 and summarized in Table A.1 (also see Figure A.2).

A.2.2 Errors originating from loose parts

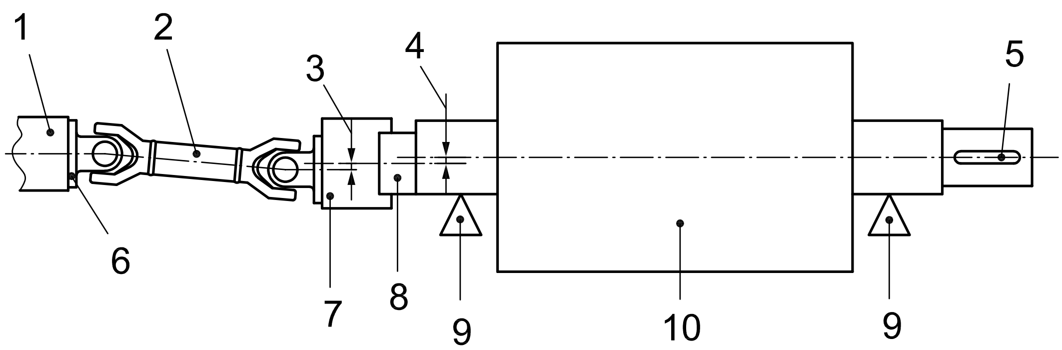
Errors caused by loose parts can be established by starting and stopping the rotor, ensuring that the angular position of the rotor is different at the start of each run, and taking a reading for each run. The error and mean value can be found using the method described in 5.5. In certain cases, changing the direction of the machine rotor rotation can be helpful, but should be undertaken with caution. It should be noted that on certain machines, the effect of loose parts may only become apparent under actual service conditions.



Key

1 workpiece
2 mounting bolts
3 workpiece reference diameter
4 mandrel
5 spigot eccentricity
6 bearing
7 mandrel reference diameter
8 spigot

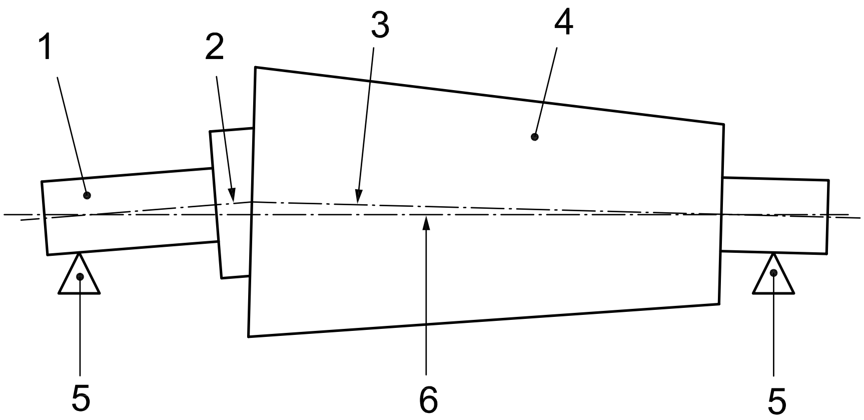
Figure A.1 — Workpiece located on mandrel



Key

1 drive
2 drive shaft
3 adapter eccentricity
4 shaft extension eccentricity
5 key or keyway
6 face plate
7 drive adapter
8 shaft extension
9 bearing
10 workpiece

Figure A.2 — Workpiece located on its own journals



Key

1 mandrel
2 geometric axis of the mandrel
3 geometric axis of the workpiece
4 workpiece
5 bearing
6 shaft axis

Figure A.3 — One journal on mandrel and one on workpiece

A.2.3 Errors originating from the presence of entrapped liquids or small loose particles

Where the presence of entrapped liquids or loose particles is suspected but cannot be avoided, the rotor should be left standing with 0° positioned pointing vertically upwards for a period of time, restarted and then a reading taken. This procedure is repeated having the 90°, 180° and 270° positions of the rotor successively pointing vertically upwards at the start of each run. The method described in 5.5 can then be applied to find the error and mean unbalance.

Results should be examined in order to avoid confusion with thermal effects (e.g. due to the rotor standing still for some time); see A.2.4.

A.2.4 Errors originating from thermal effects

Distortion and the resulting unbalance caused by non-uniform temperatures across and/or along the rotor are particularly noticeable in those that are long or tubular.

These errors can be reduced by not allowing the rotor to remain stationary in the balancing machine (even for relatively short periods) or by running the rotor until the unbalance or vibration vector has stabilized. This can be done at a very low speed (e.g. 5 r/min to 10 r/min).

When welding or heat-generating operations are used for unbalance correction, significant rotor distortion can result. Dissipation of the localized heat and/or certain stabilizing running periods are usually required to equalize the temperature in the rotor and restore it to its normal shape.

A.2.5 Errors originating from bearings

A.2.5.1 General

In operation, rotating bearing races should retain the angular relationship to the rotor they had during the balancing operation; otherwise errors similar to those described in A.1.2 can occur.

Spurious couple unbalance readings in both soft- and hard-bearing balancing machines can, for example, result from axial runout of the rotating thrust face, a ball bearing being tilted relative to the shaft axis or a bent rotor.

Table A.1 — Error examples and methods for their assessment and reduction

Error origin	Error source description	Unbalance error reduction method	Unbalance error assessment			See subclause
			Experiment for systematic errors	Experiment for random errors	Other methods	
Balancing machine	Measuring equipment systematic and random errors	Check machine calibration and operation; correct if necessary. Recalibrate or repair machine	—	—	Refer to ISO 21940-21[a]	5.2 5.4 to 5.6
Auxiliary equipment	Unbalance in drive element	Balance auxiliary equipment	Applicable, rotor being shifted 180° relative to drive element or mandrel. Error amount and phase obtained are global	Possible, but index balancing more economical	Measure error amount and phase by separate balancing of item[b]	A.1.1 A.1.3
	Unbalance in mandrel (or stub shaft)	Balance mandrel (or stub shaft) or other auxiliary equipment more finely. Reduce mass of auxiliary equipment				
	Radial and axial runout in drive element	Balance or repair drive element	—	—	—	—
	Radial and axial runout in mandrel (or stub shaft)	Repair or compensate with bias mass or compensator	—	—	—	—
	Eccentricity of slave rolling element bearing	Balance with service bearing in place. If removal is required for rotor assembly into housing, match mark bearing inner races to shaft	Applicable, refitting one bearing at the time after turning 180°	—	—	A.1.2

Table A.1 *(continued)*

Error origin	Error source description	Unbalance error reduction method	Unbalance error assessment			See subclause
			Experiment for systematic errors	Experiment for random errors	Other methods	
Rotor	Loose parts, e.g. compressor rotor blades	Make several start-and-stop runs and take average vectors; correct average	—	Applicable, starting the rotor from a different stopping position for each run	—	A.2.2
	Presence of entrapped liquids or solids	Remove the liquids or solids; if not possible, make several start-and-stop runs and correct the average unbalance	—	Applicable, but approximately 30 min stop between each run[c]	—	A..2.3
	Thermal and gravitational effects	Run rotor until stabilized before balancing. Do not allow the rotor to remain stationary in the balancing machine for long periods	—	Applicable, but these effects are to be reduced as much as possible[c]	—	A.2.4
	Windage effects	Enclose rotor or cover intake openings, or run rotor backwards	—	—	Compare measurements at different running speeds	—
	Magnetic effects (i.e. magnetized rotor)	Demagnetize rotor, select higher balancing speed to minimize magnetic effects	—	—	Measure error amount and phase in low-speed run	A.2.8
	Tilted service ball bearings	Straighten out races on shaft, remachine shaft shoulders. Reduce these effects by reducing the resistance of the saddle to spherical movements, if possible	—	—	Compare measurement at different running speeds	A.2.5

Table A.1 *(continued)*

Error origin	Error source description	Unbalance error reduction method	Unbalance error assessment: Experiment for systematic errors	Unbalance error assessment: Experiment for random errors	Unbalance error assessment: Other methods	See subclause
Rotor	Poor journal surface finish; inadequate lubrication	Remachine journals, lubricate	—	—	—	—
	Misalignment (rotors with more than two bearings)	Balance in two bearings only (one per support), or mount rotor in a rigid frame with multiple bearings	—	—	—	—
	Keys and keyways	Insert proper half key per ISO 21940-32	—	—	—	—
	Axial and radial runout of the drive attachment interface	Remachine surface or use belt drive	—	—	—	A.2.7
Assembly	Clearance in mechanical joints of universal shaft	Tighten universal joints, replace drive shaft or switch to belt drive	Possible, if zero clearance can be assessed for each run	Applicable, disassembling and reassembling suspect joints between runs (rotor stopped in different angular positions)	—	A.1.3 A.2.6
	Incorrect shrink fits in assembly	Dismantle and reassemble shrink fit	Measure axial runout	—	—	—
		Reconsider dimensioning	—	Check repeatability	—	—

[a] Where the workpiece mass or measuring plane positions differ significantly from those of the proving rotor used in the tests described in ISO 21940-21, further tests should be carried out to determine the minimum achievable residual unbalance at the specified measuring planes on the workpiece or rotor itself.

[b] In general, it is possible to apply corrections for errors of known amount and phase. However, if these errors are in excess of U_{per}, it may be advisable to take other steps to reduce their magnitude before proceeding with the balancing process.

[c] Results should be examined to avoid confusion between zhe entrapped material effect and thermal effects.

Formulae (A.1) and (A.2) hold true only if measurements are taken at a speed far enough away from the resonance speed of the rotor and/or the balancing machine to prevent induced vibration.

Similar effects can be observed at very low balancing speeds when there is a lack of alignment between the balancing machine bearings and the rotor journals (e.g. when open rollers are used or when the supports of a balancing machine with flat roller surfaces lack vertical axis freedom). These errors can be minimized by appropriate design of the balancing machine support structure. In some cases, the error caused by axial runout of the thrust face can be avoided by adjustment of the thrust bearing.

A.2.5.2 Unbalance in a hard-bearing machine

For a hard-bearing balancing machine running at speeds n_1 and n_2, the axial runout effects, in unbalance units, for the left-hand plane, $\overrightarrow{\Delta U}_{1\mathrm{L}}$, in g·mm, may be found by using Formula (A.1):

$$\overrightarrow{\Delta U}_{1\mathrm{L}} = \frac{1}{1-\left(n_1/n_2\right)^2}\left(\boldsymbol{U}_{1\mathrm{L}} - \boldsymbol{U}_{2\mathrm{L}}\right) \tag{A.1}$$

where

n_1 is the balance machine first rotational speed expressed in r/min;

n_2 is the balance machine second rotational speed expressed in r/min;

$\boldsymbol{U}_{1\mathrm{L}}$ is the sum of the unbalance effect, in g·mm, of the runout and residual unbalance in the left plane at speed n_1;

$\boldsymbol{U}_{2\mathrm{L}}$ is the sum of the unbalance effect, in g·mm, of the runout and residual unbalance in the left plane at speed n_2.

The machine should be calibrated in the same unbalance units for each speed and plane.

For a hard-bearing balancing machine running at speeds n_1 and n_2, the axial runout effects, in unbalance units, for the right-hand plane, $\overrightarrow{\Delta U}_{1\mathrm{R}}$, in g·mm, may be found by using Formula (A.2):

$$\overrightarrow{\Delta U}_{1\mathrm{R}} = \frac{1}{1-\left(n_1/n_2\right)^2}\left(\boldsymbol{U}_{1\mathrm{R}} - \boldsymbol{U}_{2\mathrm{R}}\right) \tag{A.2}$$

where

n_1 is the balance machine first rotational speed expressed in r/min;

n_2 is the balance machine second rotational speed expressed in r/min;

$\boldsymbol{U}_{1\mathrm{R}}$ is the sum of the unbalance effect, in g·mm, of the runout and residual unbalance in the right plane at speed n_1;

$\boldsymbol{U}_{2\mathrm{R}}$ is the sum of the unbalance effect, in g·mm, of the runout and residual unbalance in the right plane at speed n_2.

The machine should be calibrated in the same unbalance units for each speed and plane.

In these calculations, it is assumed that the forces on the bearings of a hard-bearing balancing machine are caused by axial runout of a rotating thrust face and are independent of speed.

A.2.5.3 Unbalance in a soft-bearing machine

For a soft-bearing machine, the unbalance simulating effect depends on the vibratory masses in the soft-bearing machine suspension system and is, therefore, inversely proportional to the square of the speed. Thus Formulae (A.1) and (A.2) can be used.

In these calculations for a soft-bearing machine, it is assumed that the bearing vibration caused by unbalance is independent of speed.

A.2.6 Errors originating from variations in mechanical fit

Unbalance can change in operation owing to the design or improper assembly of components. It can also change if the rotor is partially disassembled after balancing and reassembled in a different position (also see A.1.3.)

A.2.7 Errors originating from runout of the end-drive mounting surface

Where the balancing machine end-drive shaft is attached to an eccentric spigot at the end of the rotor, an error is introduced which cannot be detected by index balancing. The error can only be calculated knowing the effective drive mass and the spigot eccentricity vector relative to the rotor shaft axis. If necessary, temporary compensation can be applied at the appropriate angle during balancing.

A.2.8 Errors originating from magnetic effects

Magnetic effects primarily manifest themselves by causing an erroneous unbalance read-out if their frequency is at or near the balancing machine rotational frequency.

For instance, an erroneous unbalance read-out can be caused by the rotor magnetic field wiping across the balancing machine pick-ups at a once-per-revolution frequency. The influence of a magnetized rotor is best eliminated either by shielding the pick-ups or by selecting, on a hard-bearing balancing machine, a sufficiently higher balancing speed, where the influence is no longer significant. The presence of magnetic effects is best discovered by taking unbalance or vibration vectors at different speeds at which the rotor has rigid behaviour.

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