International Standard 4291

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Methods for the assessment of departure from roundness — Measurement of variations in radius

Méthodes d'évaluation des écarts de circularité — Mesurage des variations de rayon

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Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council. They are approved in accordance with ISO procedures requiring at least 75 % approval by the member bodies voting.

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Methods for the assessment of departure from roundness — Measurement of variations in radius

1 Scope and field of application

This International Standard specifies a method for determining departures from roundness by measuring variations in radius by means of contact (stylus) instruments.

It establishes

a) types of instruments and general requirements;

b) recommendations for the use of instruments;

c) procedures for calibration of instruments and verification of their characteristics.

This International Standard applies to the assessment of the departures from ideal roundness of a workpiece through the medium of a profile transformation, obtained under reference conditions, expressed with respect to any one of the following centres :

a) centre of the least squares circle;

b) centre of the minimum zone circle;

c) centre of the minimum circumscribed circle;

d) centre of the maximum inscribed circle.

Each of these centres may have its own particular application. The position of the least squares centre can be calculated from a simple explicit equation given in annex F.

Departures from roundness of the measured profile, procedure, calibration and determination of systematic errors of rotation are dealt with in annexes A to D, respectively. Annex E gives rules for plotting and reading polar graphs.

NOTES

1 Profile transformation is defined in ISO 6318.

2 Reference conditions include the stylus, frequency limitations of an electric wave filter (if used), permissible eccentricity of the graphical or digital representation of the profile (generally 7 % to 15 % of its mean radius, see annex E), the position of the measured section or sections relative to some feature of the workpiece.

2 Reference

ISO 6318, *Measurement of roundness — Terms, definitions and parameters of roundness.*

3 Definitions

For the purposes of this International Standard, the definitions given in ISO 6318 apply.

4 Instruments

4.1 Instrument types and general requirements

Instruments of the stylus type employed for the determination of departures from ideal roundness may be of one of two types :

a) a stylus and transducer rotating round a stationary workpiece;

b) a rotating workpiece engaged by a stationary stylus and transducer.

According to the nature of the output information, instruments for the measurement of roundness fall into two groups :

a) profile recording;

b) with direct display of the values of the parameters.

Both groups may be combined in one instrument.

Stylus instruments should comply with the requirements of 4.1.1 to 4.1.3.

4.1.1 Stylus types and dimensions

The surface characteristics of the part under examination are of primary importance in the choice of stylus. Variations to meet different requirements, depending upon the nature and magnitude of the irregularities which are to be taken into account, are permitted as shown in figures 1 to 4 (see also clause B.3).

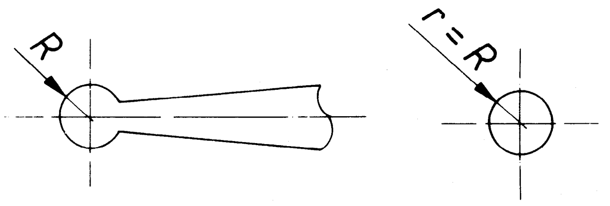


Figure 1 — Spherical stylus

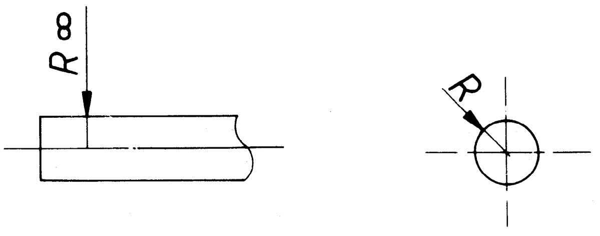


Figure 2 — Cylindrical stylus

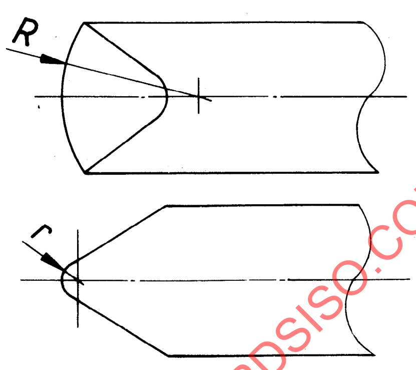


Figure 3 — Toroidal (hatchet) stylus

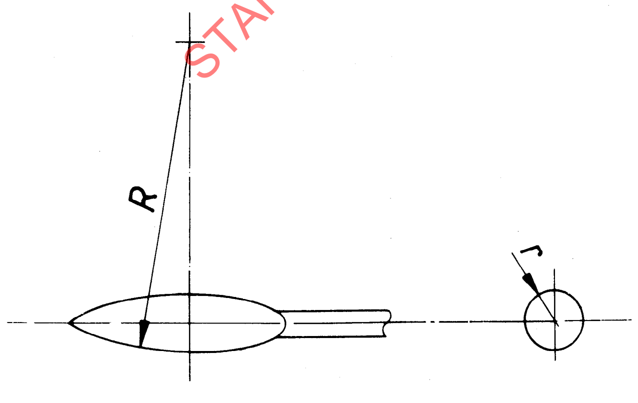


Figure 4 — Ovoidal stylus

The dimensions *r* and *R* of the various styli shall be selected from the following values :

— 0,25; 0,8; 2,5; 8 and 25 mm.

4.1.2 Stylus static force

The force shall be adjustable up to 0,25 N and in use shall be adjusted down to the lowest value that will ensure continuous contact between the stylus and the surface being measured.

4.1.3 Instrument response for sinusoidal undulations

The range of periodic sinusoidal undulations per revolution (upr) (i.e. per 360°) of the workpiece to which the instrument responds shall be terminated by values taken from the table.

Table — Limiting values of upr

Filters transmitting from 1 upr up to	Filters rejecting below
15	15
50	50
150	150
500	
1 500	

The response at the rated termination of the band shall be 75 % of the maximum transmission within the band except for 1 upr which represents direct mechanical coupling between input and output. [See note 2c).]

The transmission characteristics of the filter shall be equivalent to those produced by two independent C-R[1)] networks of equal time constant (see figure 5). These curves show only the amplitude attenuation characteristics and do not take phase shift into account. A phase corrected filter of known characteristics giving the same rate of attenuation may be used provided that these characteristics are indicated in the test report.

NOTES

1 When a filter attenuating high frequencies is required, the two C-R form will generally be acceptable, distortion of the transmitted profile due to phase shift of the high relative to the low frequencies being generally unimportant.

When a filter attenuating low frequencies is required, distortion due to phase shift may be more significant and have to be taken into account, or avoided by using a phase corrected filter.

2a) It is necessary to distinguish clearly between the undulations per revolution (i.e. per 360°) of the workpiece and the response of electronic circuits in the instrument in hertz.[2)]

The frequency, in hertz, generated by the instrument will be given by the number of sinusoidal undulations per 360° of the workpiece multiplied by the number of revolutions per second of the spindle.

2b) Eccentricity will count as 1 upr. A sinusoidal component of 1 upr will be found when the periphery of the workpiece is assessed from a centre other than the centre of the least squares circle.

1) "C" stands for "capacitive", "R" for "resistive".

2) 1 Hz = 1 cycle per second

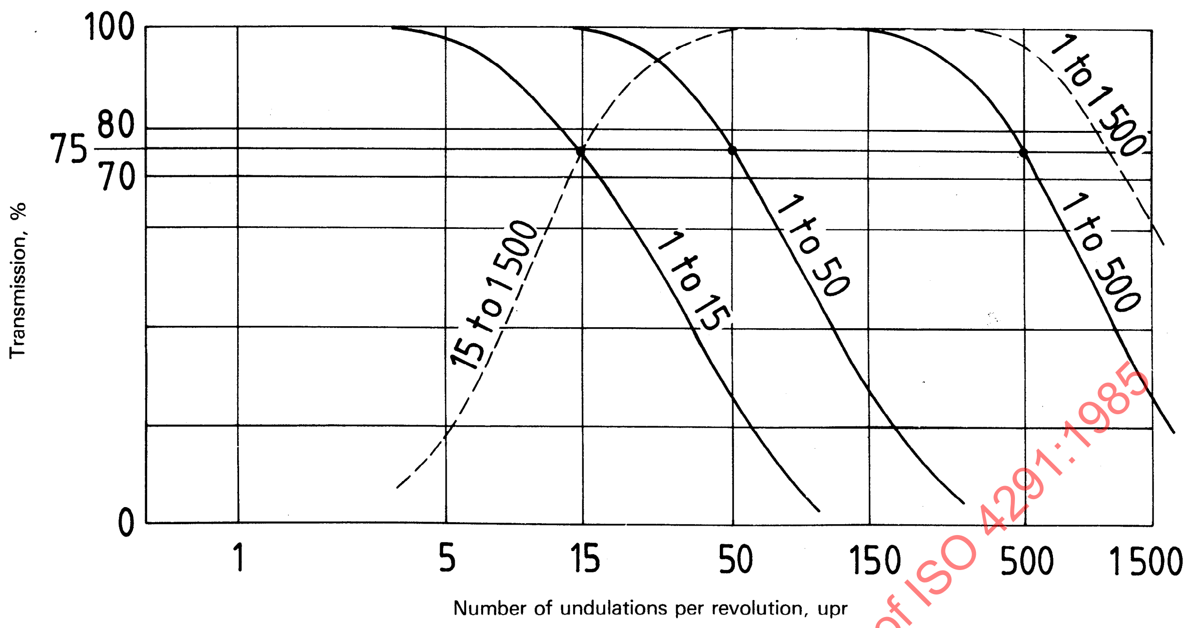


Figure 5 — Typical transmissions showing rate of attenuation given by two independent C-R networks of equal time constant

2c) When electronic circuits of instruments are required to respond down to 1 upr, they are often made responsive down to zero frequency (0 Hz), this being a natural way of avoiding phase distortion and permitting calibration by static means.

4.2 Instrument errors

4.2.1 Overall instrument error

This is the difference between the value of the parameter indicated, displayed or recorded by the instrument and the true value of this parameter. The value of this error is determined when measuring a test piece. The overall instrument error shall be expressed as a percentage of the upper limiting value of the measuring range used. This error comprises systematic and random components from the spindle error, electric noise, vibration, magnification, etc.

4.2.2 Errors of rotation of the instrument

The errors of rotation are determined under reference conditions at assigned positions of measurement :

a) radial instrument error — the value of the roundness parameter which would be indicated by the instrument when measuring a perfectly round and perfectly centred section of a test piece, in a direction perpendicular to the reference axis of rotation;

b) axial instrument error — the value derived from the zonal parameter displayed by the instrument when measuring on a perfectly flat test piece set perfectly perpendicular to the reference axis of rotation.

NOTE — The components of errors of rotation are vector quantities and should not therefore be algebraically added to the measured value of a roundness parameter in an attempt to allow for errors of rotation.

4.2.3 Statements of errors of rotation

The rotating member can exhibit, within the confines of its bearings, combinations of

a) radial displacements parallel to itself;

b) axial displacements parallel to itself;

c) tilt.

The magnitude of the radial instrument error, measured at the stylus, depends on the position of the measurement plane along the axis of rotation. The magnitude of the axial instrument error depends on the radius at which the flat test piece is measured. The axial and radial positions selected for test shall therefore be stated.

The radial instrument error shall be expressed at two stated and well separated positions along the axis or at one position together with the rate of change of the radial instrument error along the axis.

The axial instrument error shall be expressed on the axis and at one stated radius.

Annex A

Departure from roundness of the measured profile of the workpiece

In this International Standard, the departure from ideal roundness is assessed as the difference between the largest and the smallest radii of the measured profile of the workpiece, measured from one or other of the following centres :

a) least squares centre (LSC) — the centre of the least squares mean circle (see figure 6);

b) minimum zone centre (MZC) — the centre of the minimum zone circle (see figure 7);

c) minimum circumscribed circle centre (MCC) — the centre of the minimum circumscribed circle for external surfaces (see figure 8);

d) maximum inscribed circle centre (MIC) — the centre of the maximum inscribed circle for internal surfaces (see figure 9).

The largest and smallest radii, in each case, are commonly used to define a concentric zone. The width of the zone may be designated by ΔZ, with a subscript denoting its centre. For the purposes of this International Standard, the following subscripts are used :

least squares	subscript q, thus ΔZ_q
minimum width	subscript z, thus ΔZ_z
minimum circumscribed	subscript c, thus ΔZ_c
maximum inscribed	subscript i, thus ΔZ_i

NOTE — The use of circles drawn on the chart to represent circles fitting the profile of the workpiece assumes that the workpiece is sufficiently well centred on the axis of the instrument (see B.1.1, figure 10 and annex F).

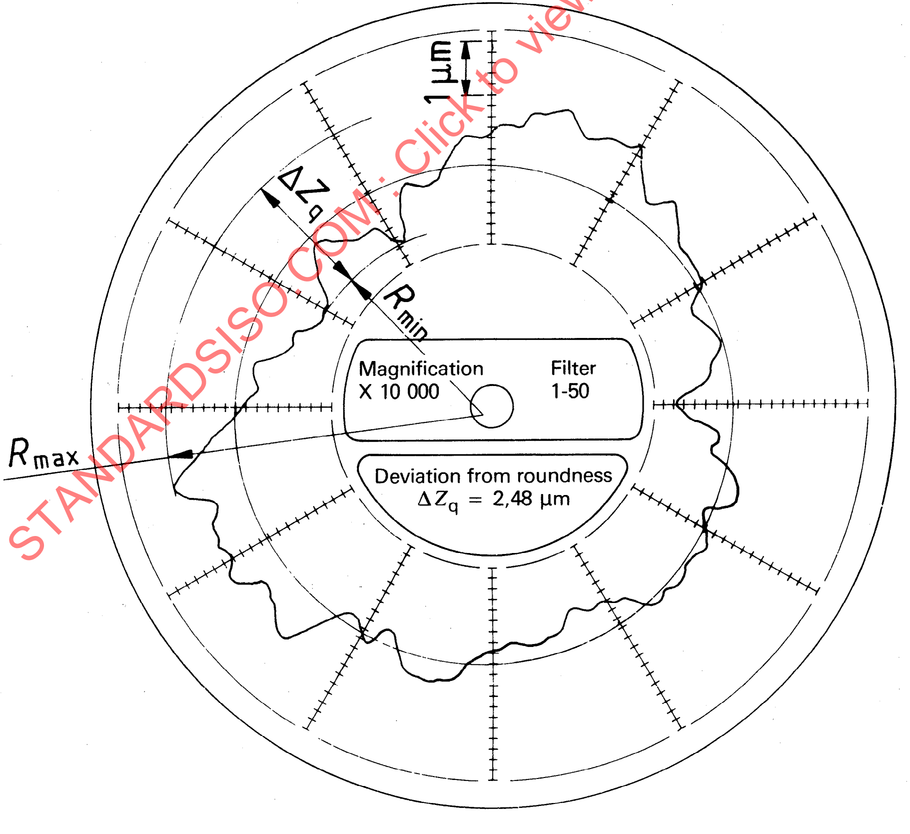


Figure 6 — Assessment of roundness from least squares centre, ΔZ_q

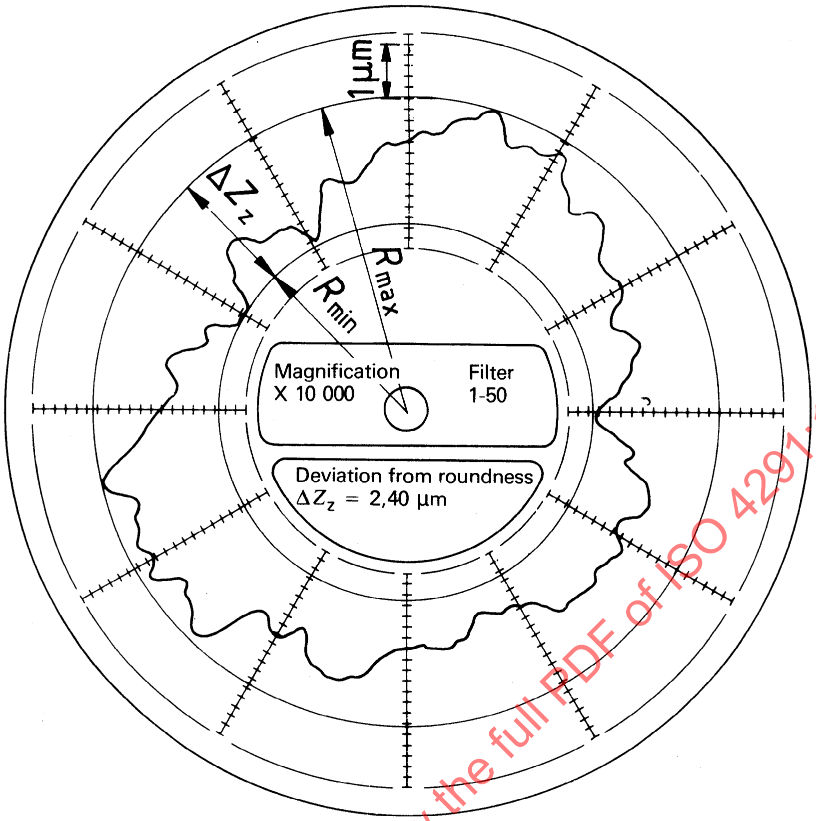


Figure 7 — Assessment of roundness from minimum zone centre, ΔZ_z

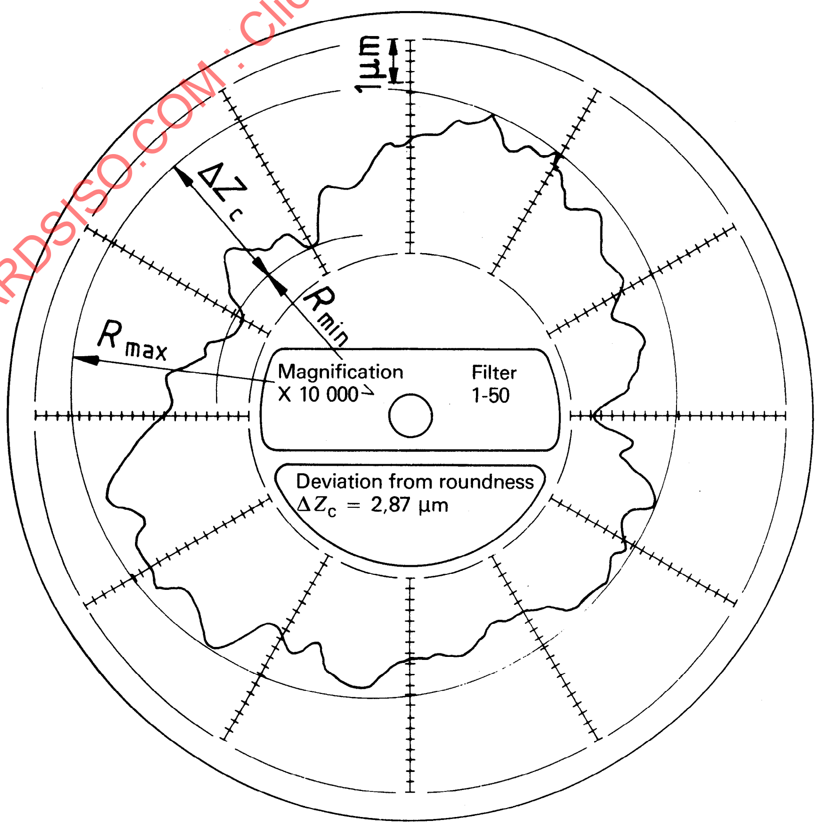


Figure 8 — Assessment of roundness from centre of minimum circumscribed circle, ΔZ_c

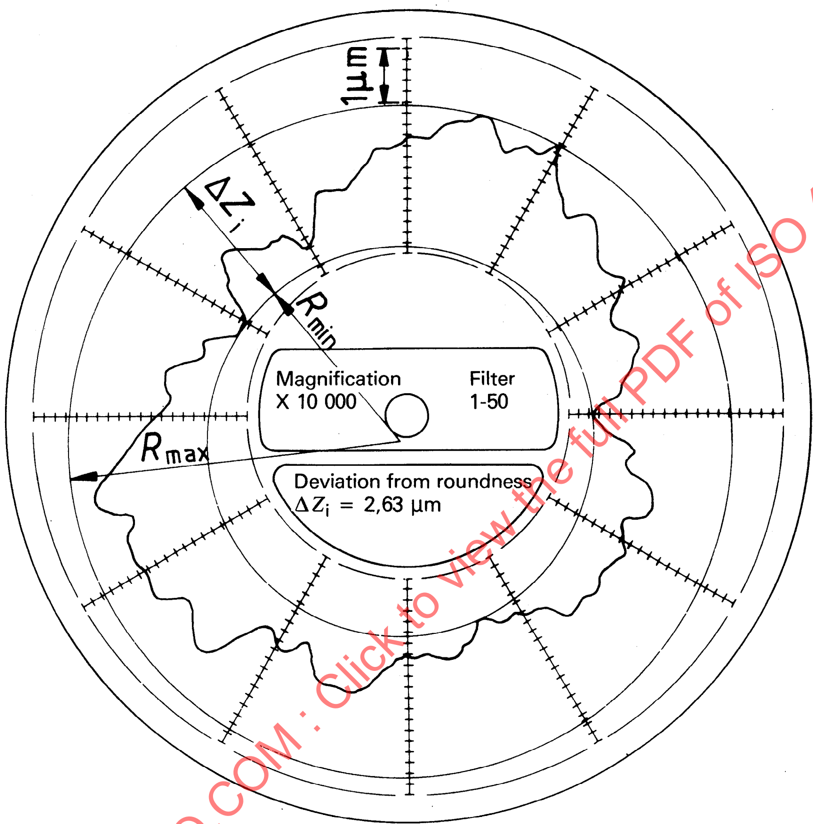


Figure 9 — Assessment of roundness from centre of maximum inscribed circle, ΔZ_i

Annex B

Procedure

(This annex gives general guidance on setting up and measurement.)

B.1 Guidance on setting up prior to measurement

The workpiece shall be set up so that the section to be measured is sufficiently well centred on the axis of rotation to avoid excessive distortion due to eccentricity, and with its axis sufficiently parallel to the axis of rotation to avoid excessive inclination errors.

Several kinds of distortion result from polar plotting because, on the chart, only the variations in radius of the workpiece, together with the eccentricity, and not the radius itself, are highly magnified.

B.1.1 In the direction of eccentricity, the radius of the eccentric plot is independent of the eccentricity, but in the perpendicular direction the radius is slightly increased in proportion to the square of the eccentricity (see figure 10). Strictly, the eccentric plot of a perfect circle has the form of a limaçon; however, this is hardly perceptible as such when the eccentricity is very small. Graphical compensation is sometimes possible; compensation by electrical methods is widely practised, and elimination of the distortion by digital correction is in course of development.

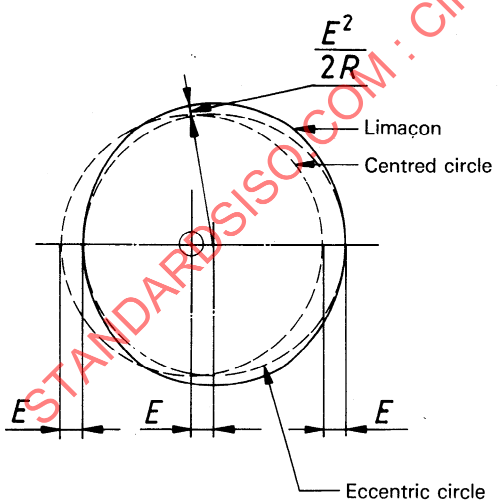


Figure 10 — Slight increase of the radius of the eccentric plot in the perpendicular direction

B.1.2 The circumferential separation of the peaks round a periodic profile is greater than that of the valleys, even though the difference on the workpiece is negligibly small and, to avoid giving a misleading impression, the ratio of peak-to-valley radius measured from the centre of the chart shall not be too great.

B.1.3 Inclination of the axis of the workpiece to the axis of rotation will cause a perfectly round cylinder to appear elliptical. If D is the diameter of the workpiece, θ the angle of inclination (see figure 11) and M the magnification, the diametral difference on the chart will be MD (1-sec θ).

Conversely, appropriate inclination can cause an elliptical cylinder to appear to be round.

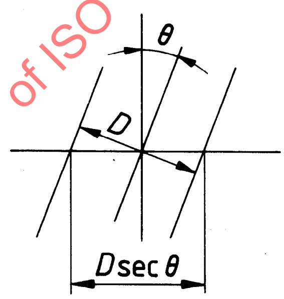


Figure 11 — Inclination of the axis of the workpiece to the axis of rotation

B.1.4 Some guiding rules for plotting and reading polar graphs are given in annex E.

B.2 Direction of measurement

B.2.1 When the workpiece is a cylinder, its roundness will be assessed in a cross-section perpendicular to the axis of rotation of the instrument, the direction of measurement will be perpendicular to this axis, and the traced profile which is plotted and measured will be that of the cross-section. This forms the normal basis of roundness measurement and assessments.

B.2.2 When the workpiece is conical or toroidal, the question of which is the more significant functional direction shall be determined by details of the application and the direction in which the surface is likely to be operative. Furthermore, the question can arise as to whether the direction of measurement should be perpendicular to the axis or normal to the surface (see figure 12). If the direction of measurement is normal to the surface, the profile will be that formed by the intersection of the workpiece with a perfect, nominally coaxial cone of complementary semi-angle, along the generators of which the variations in the profile will be measured. On the profile graph, however, these variations will be displayed as though they were normal radial variations, and their zone width will have to be multiplied by the secant of the semi-angle of the workpiece cone if the radial value expressed in the normal cross-section is required. A ball-bearing ring raceway (see figure 13), which is a portion of a toroid, can be treated as a conical surface formed by the tangents to the zone contacted by the stylus.

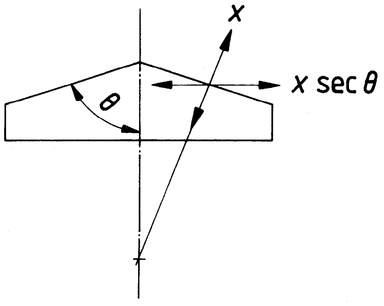


Figure 12 — Choice of direction of measurement for a conical or toroidal workpiece

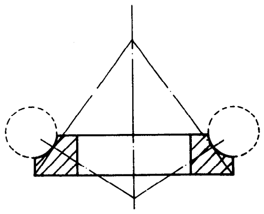


Figure 13 — Ball-bearing raceway

B.3 Interdependence of roundness, roughness and stylus radius — Considerations regarding roughness texture

B.3.1 The question will arise as to whether closely spaced irregularities of the cross-section, which can generally be traced to circumferential components of the roughness texture, should be included in or excluded from the zonal assessment of roundness (the roundness parameters as so far defined).

The decision shall reflect the intended use of the information obtained and the intended use of a workpiece. For example, sliding contact with another surface of similar form can be distinguished from rolling contact with balls and rollers. The inclusion or exclusion of the effects of roughness texture by instrumental means can greatly affect the value of the roundness parameter.

Consider the profiles in figure 14. They have the same value of zonal parameter, but their very different characteristics are traceable to different causes and they are unlikely to be equal functionally.

If the two profiles are those of ball-bearing raceways, figure 14a) would give rise to high-frequency vibration and noise, and figure 14b) might be preferred; but if they are the profiles of shafts, mandrels, piston, etc., it is likely that figure 14a) will be preferred.

If the point of interest is the geometry of the workpiece or of the machine that made it, this geometry being generally characterized by a relatively small number of peripheral undulations, it is likely that the most meaningful assessment will be made by excluding the roughness, which could sometimes be large enough to mask the departure from roundness. The roughness may then have to be considered separately.

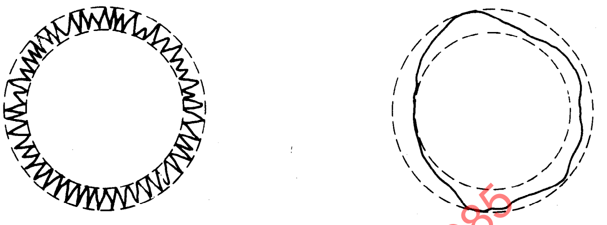


Figure 14 — Closely and widely spaced irregularities

B.3.2 The extent to which the circumferential components of the roughness texture are taken into account depends on the characteristics of the texture (lay, height, spacing) and on the dimensions of the stylus in combination with the frequency response of the instrument.

B.3.3 Experimental evidence has indicated that a stylus of about 10 mm radius engaging a workpiece with straight generators will suppress most of the axial component of the grinding and turning marks normally encountered, but is less effective in suppressing residual circumferential components or roughness having an axial lay (extrusion, broaching), because of difficulty in securing a small enough difference of circumferential curvature.

Figure 15 shows diagrammatically how styli of short and long radii react to the tool marks on a turned cylinder. The short radius stylus will move from the crest on the one side to a valley on the other side and back to the crest again, and in doing so will follow a truly circular path only if the shape of a tool mark happens to be truly sinusoidal, which it rarely is. On the other hand, if a hatchet-like stylus of long radius is used, the record will be representative of the roundness of the envelope of the part. It will be substantially circular despite the presence of the tool marks.

The principle is illustrated in figure 16 which shows the envelope A, traced with a hatched stylus, and the cross-section B, traced with a sharply pointed stylus, of a part turned in an ordinary tool room lathe, the tool producing a tool mark as shown separately. The styli were adjusted so that they would contact a smooth cylinder in the same transverse plane. Thus the trace of the sharp stylus should lie everywhere inside that of the hatchet, except at the highest crest where the two traces could touch. The envelope traced by the hatchet is as round as can be assessed at the low magnification, but the lack of roundness in the cross-section traced by the sharp stylus is obvious.

A spherical radius of less than 0,8 mm, for example 0,25 mm, would fully enter turned texture produced by a tool having the widely used radius of 0,8 mm, and would largely enter many scratch marks produced by grinding, but could still suppress the finest texture as produced by lapping, honing and the finest grinding.

There are advantages in using a small radius for the circumferential direction combined with a large axial radius : hence the often used toroidal (hatchet) form, which facilitates measurement in holes.

B.3.4 High-frequency circumferential components, whether found by a sharp or by a blunt stylus, are best suppressed by means of an electric wave filter having a suitable cut-off.

B.3.5 The choice of stylus radius for the measurement of grooves (for example ball-bearing raceways) involves not only the question of roughness, but also that of positioning the stylus in the groove.

It will be seen from figure 17 that if the centre of the stylus is offset from the direction of measurement X-X, errors in the measurement will result if the offset y varies as the stylus rotates, and that the probability of error will increase as the difference in radii of stylus and workpiece is reduced.

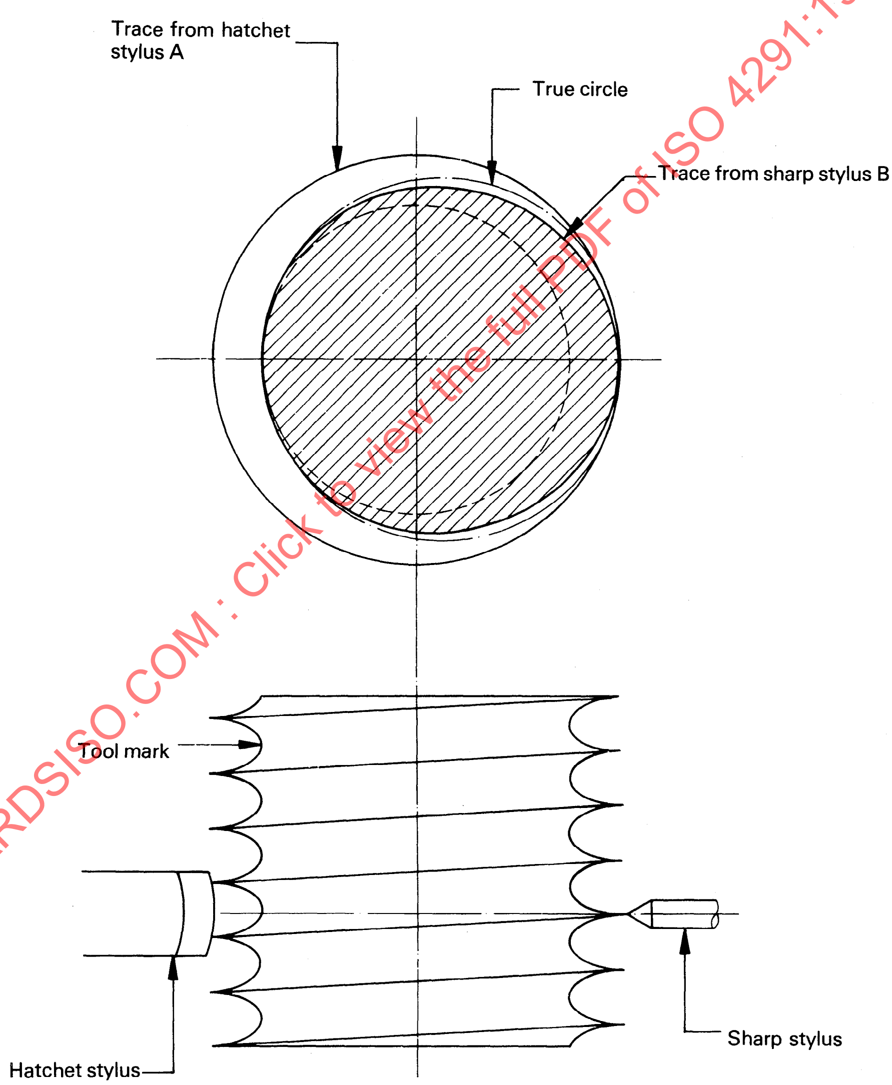


Figure 15 — Effect of stylus radius when in contact with surface

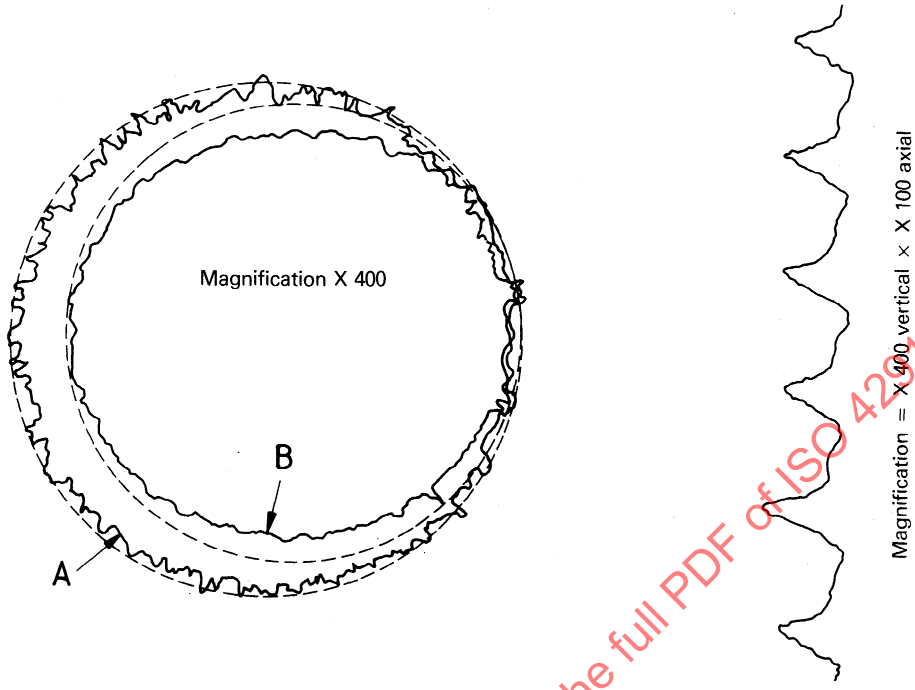


Figure 16 — Traces by hatchet and sharp styli

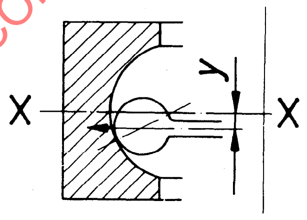


Figure 17 — Errors in measurement resulting from variation of the offset

Annex C

Calibration

C.1 Calibration of radial magnification

Static calibration can be carried out by displacing the stylus in any convenient and precise way, for example by means of a screw-driven reducing lever or by gauge blocks.

Dynamic calibration can be carried out by means of a cylinder having one or more small flats round the periphery (see figure 18). Since the angular subtense of a flat is generally small and may come near the high-frequency response of the instrument, such specimens need to be proportioned and calibrated for the particular characteristics of the instrument with which they can be used.

C.2 Calibration of axial magnification

Static calibration can generally be carried out using the same devices as for the calibration of radial magnification.

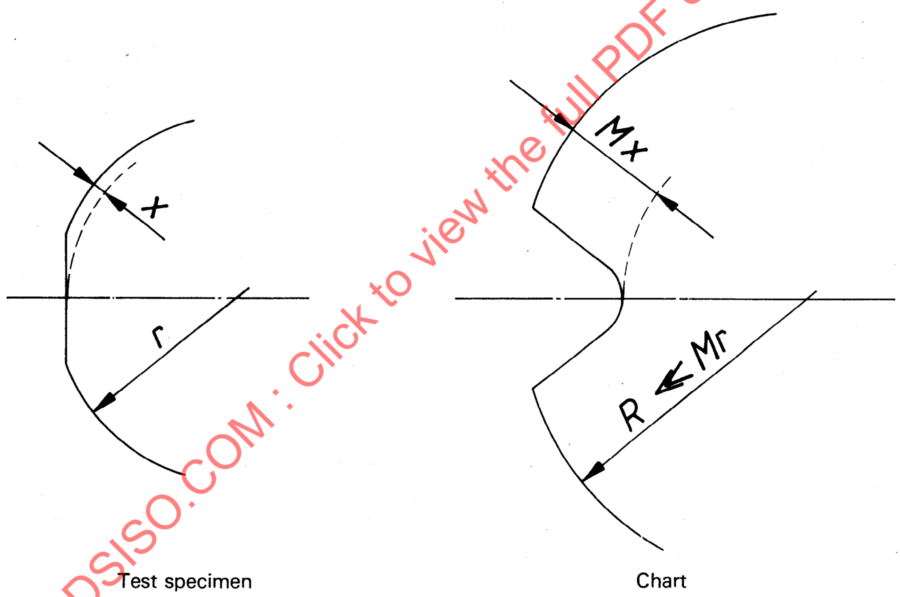


Figure 18 — Dynamic calibration

Annex D

Determination of systematic errors of rotation

D.1 Provided that the errors of a given spindle are sufficiently repeatable, their polar values can be determined and applied as corrections to the profile. In some instruments this is done automatically so that the recorded profiles and output data are presented as though the spindle error were zero.

It is important to understand that the errors of the spindle and specimen combine vectorially so that those of the spindle cannot be determined or allowed for by simple subtraction from the combined profile of spindle and test piece or spindle and specimen.

D.2 Methods of determining spindle errors

Two methods are used for separating the errors of the spindle from those of a test piece which is supposed to be truly round. They are known as the multi-step and reversal methods.

Both these techniques assume that the rotational errors of the spindle repeat every revolution and that random errors are reduced to a minimum by carrying out the tests in a suitable environment and by averaging over one or more revolution.

D.2.1 In the multi-step technique, which is applicable to radial and axial errors and combinations of these, the test piece is mounted on an indexing table. The accuracy of rotation of the indexing table is unimportant since it remains stationary while actual measurements are being made. Roundness data are recorded over, for example, four revolutions of the spindle to permit assessment of the random error to give some degree of averaging, and the information is stored. The test piece is then indexed through 30° and roundness data are again recorded and stored before indexing the test piece to its next position. The process is continued until the test piece has been indexed in 12 steps through 360° when additional data may be obtained which can be used to identify any system drift.

At each measuring position, the data will be a combination of the rotational errors of the spindle and the out-of-roundness of the test piece. When the test piece is indexed through 30°, the errors will combine in different phases as illustrated in figure 19. A complete matrix of equations will therefore be obtained after indexing the test piece through 360° relative to the instrument spindle. This matrix can be solved in a computer and the individual errors of either the spindle or the test piece can be printed out or shown on the graph recorder of the instrument after reversion from digital to analogue form.

D.2.2 The reversal method, which is applicable only to radial errors, is one which has been commonly applied in many fields of metrology. The procedure is to record the profile of the test piece at the highest possible instrument magnification and then to record on the same chart the profile obtained after rotating the test piece through 180° with the instrument pick-up relocated 180° from its normal position relative to the spindle. The locus of the bisector of the two profiles represents the out-of-roundness of the test piece. The rotational error of the spindle can be found in a similar manner but it is necessary to change the sign convention of the instrument for the second profile recording before plotting the bisector of the two profiles. The principle is similar to solving two equations of the form $x + y$ and $x - y$.

The separated radial errors of the spindle and test piece are shown in figure 20.

D.2.3 Tilt (or coning error) can be taken into account by measuring the errors at two axial and/or two radial positions stated with reference to a feature or features of the spindle. The tilt error may then be expressed by giving these values and positions or by giving the value at one of these positions and the rate of change therefrom, expressed, for example, in micrometres per metre, assuming adequate linearity.

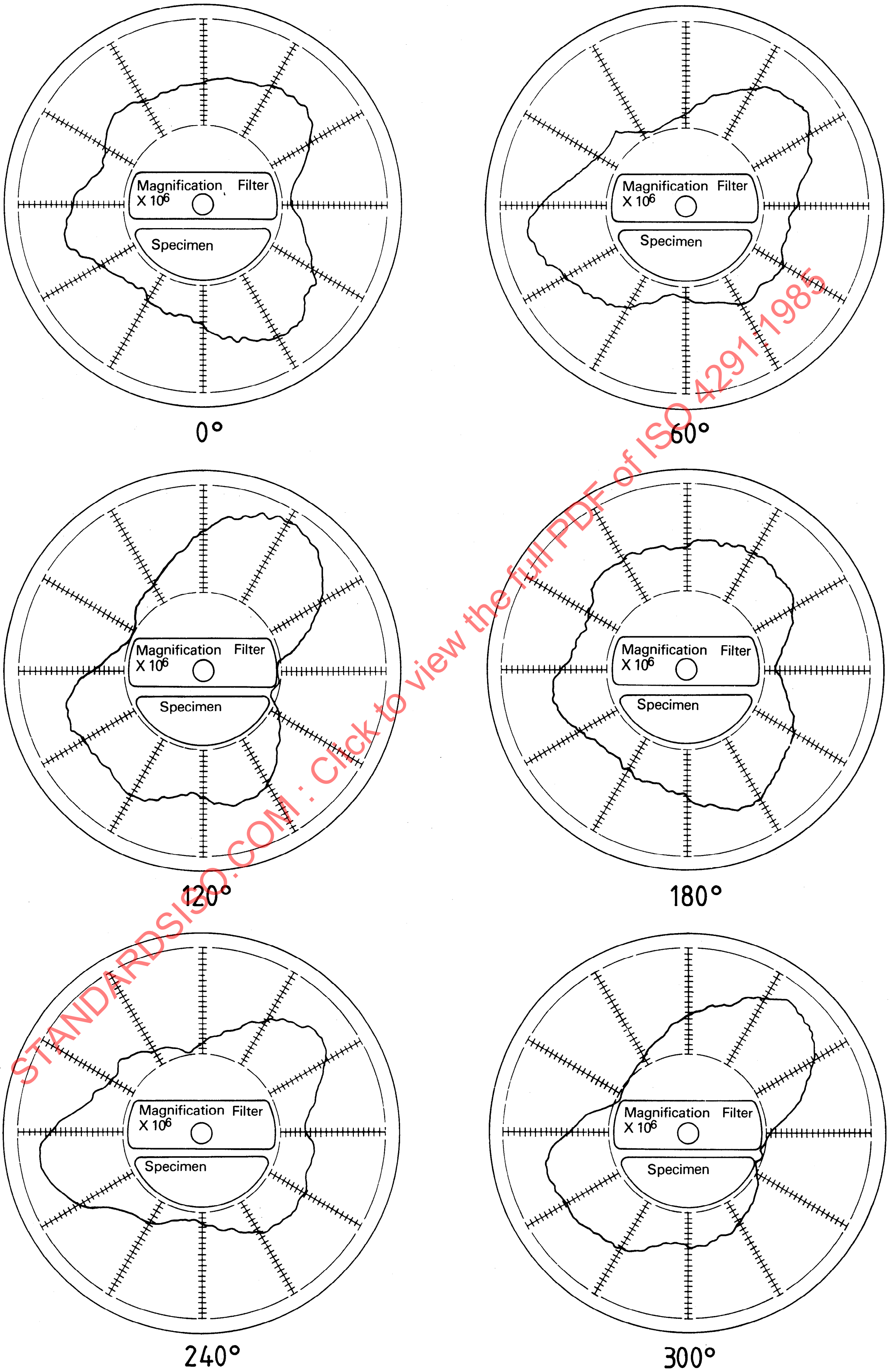
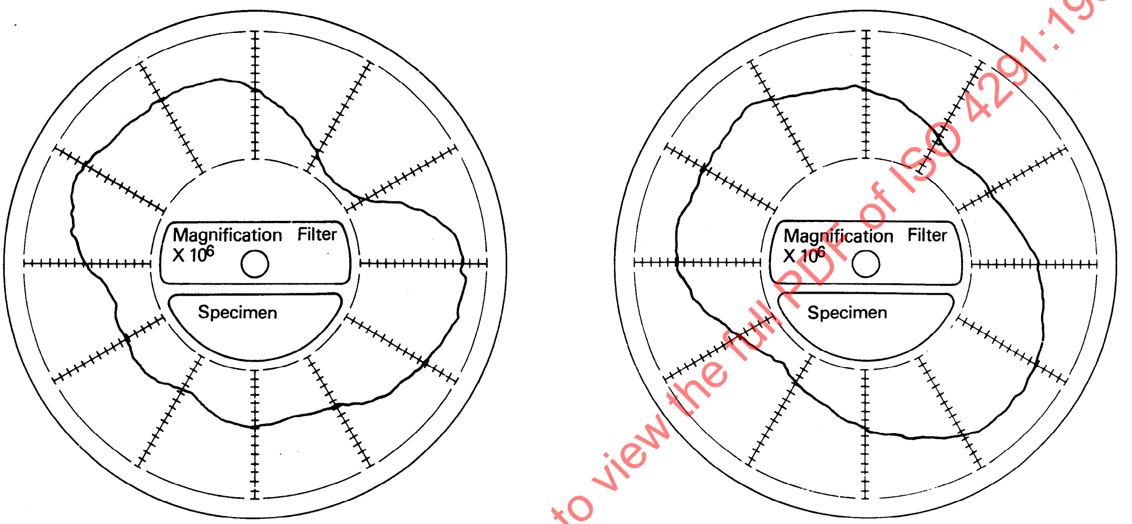


Figure 19 — Illustrations of spindle errors and test piece out-of-roundness



Spindle error

Test piece out-of-roundness

Figure 20 — Example of spindle error and test piece error