Assessment of departures from roundness —

Part 2: Specification for characteristics of stylus instruments for measuring variations in radius (including guidance on use and calibration)

UDC 531.717.2:621.7.08

Cooperating organizations

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Contents

Foreword

This Part of this British Standard has been prepared under the direction of the Mechanical Engineering Standards Committee. It takes account of discussions within ISO/TC 57, Metrology and properties of surfaces, the results of which will be published as ISO 4291. At the time of publication the technical content of this Part of this standard was in agreement with the ISO draft.

This standard together with Parts 1 and 3 supersedes BS 3730:1964 which is now withdrawn.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 18, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

1 Scope

This Part of this British Standard specifies the characteristics of contact (stylus) instruments based on the method of determining departures from roundness by measuring variations in radius.

It relates 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;

NOTE 1 Each of the foregoing centres may have its field of application. The position of the least squares centre can be calculated from a simple explicit formula given in Appendix E.

Departures of roundness from the measured profile, use of instrument, calibration and determination of systematic errors of rotation are dealt with in Appendix A to Appendix D, respectively. Appendix F gives rules for plotting and reading polar graphs.

NOTE 2 Reference conditions include the stylus, frequency limitations of an electric wave filter (if used), permissible eccentricity of the graphic or digital representation of the profile (generally 1/7 to 1/15 of its mean radius, see Appendix F) and the position of the measured section or sections relative to some feature of the workpiece.

NOTE 3 The titles of the publications referred to in this standard are listed on the inside back cover.

2 Definitions

For the purposes of this Part of BS 3730 the definitions given in BS 3730-1 apply, together with the following.

overall instrument error
the difference between the value of the parameter indicated, displayed or recorded by the instrument and the true value of the parameter. The value of this error is determined by measuring a test piece

3 Instruments

3.1 Instrument types and general requirements

3.1.1 *General.* Instruments of the stylus type employed for the determination of departures from ideal roundness shall be one of the following types:

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

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

NOTE By the character of the output information, instruments for the measurement of roundness fall into two groups:

a) profile recording;

b) direct display of the values of the parameters.

Both groups can be combined in one instrument.

Stylus instruments shall comply with **3.1.2** to **3.1.4**.

3.1.2 *Stylus types and dimensions.* The surface characteristics of the part under examination are of primary importance in the choice of stylus and variations to comply with different requirements, depending upon the nature and magnitude of the irregularities that are to be taken into account, shall be as shown in Figure 1 to Figure 4 (see Appendix A).

NOTE No order of preference is implied by the order of Figure 1 to Figure 4.

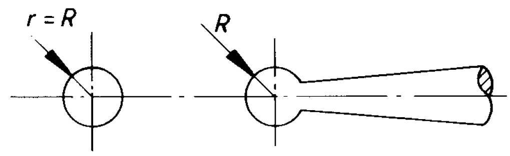


Figure 1 — Spherical stylus

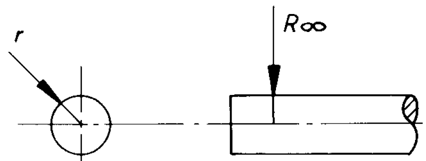


Figure 2 — Cylindrical stylus

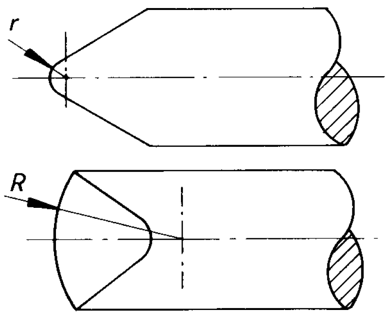


Figure 3 — Toroidal (hatchet) stylus

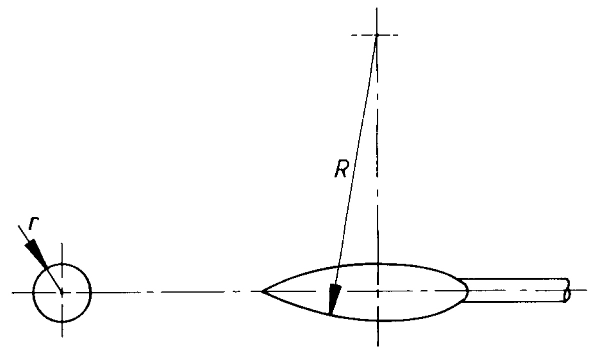


Figure 4 — Ovoidal stylus

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

0.25 mm, 0.8 mm, 2.5 mm and 8 mm.

3.1.3 *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.

3.1.4 *Instrument response for sinusoidal undulations.* The range of periodic sinusoidal undulations per revolution (i.e. per 360°) of the workpiece to which the instrument responds shall be terminated by values taken from Table 1.

Table 1 — Limiting values of undulations per revolution

Filters transmitting from 1 undulation per revolution up to	Filters rejecting below
undulations per revolution	undulations per revolution
15	50
50	100
150	500
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 undulation per revolution which represents direct mechanical coupling between input and output (see note 5).

The transmission characteristics of the filter shall be equivalent to those produced by two independent CR networks of equal time constant (see Figure 5).

NOTE 1 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 (or a higher rate) of attenuation may be used.

NOTE 2 When a filter attenuating high frequencies is required, the 2-CR form will generally be acceptable, distortion of the transmitted profile due to phase shift of the high frequencies 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.

NOTE 3 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.

The frequency in cycles per second (hertz) generated by the instrument will be given by:

sinusoidal undulations per 360° of the workpiece x revolutions per second of the spindle.

NOTE 4 Eccentricity will count as 1 undulation per revolution. A sinusoidal component of 1 undulation per revolution will be found when the periphery of the workpiece is assessed from a centre other than the centre of the least squares circle.

NOTE 5 When electronic circuits of instruments are required to respond to down to 1 undulation per revolution, 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.

3.2 Instrument error

3.2.1 *Overall instrument error.* The overall instrument error, comprising systematic and random components from the spindle error, electric noise, vibration, magnification, etc., shall be expressed as a percentage of the upper limiting value of the measuring range used.

3.2.2 ***Errors of rotation of the instrument***

3.2.2.1 *General.* The following errors of rotation shall be determined under reference conditions at assigned positions of measurement:

a) *Radial instrument error:* the value of roundness parameter that 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.

3.2.2.2 *Statements of errors of rotation.* The displacements that the rotating member can exhibit, within the confines of its bearings, shall be divided into combinations of:

a) radial displacements parallel to itself;

b) axial displacements parallel to itself;

c) tilt.

As the magnitude of the radial instrument error measured at the stylus depends on the position of the measurement plane along the axis of rotation and 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 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.

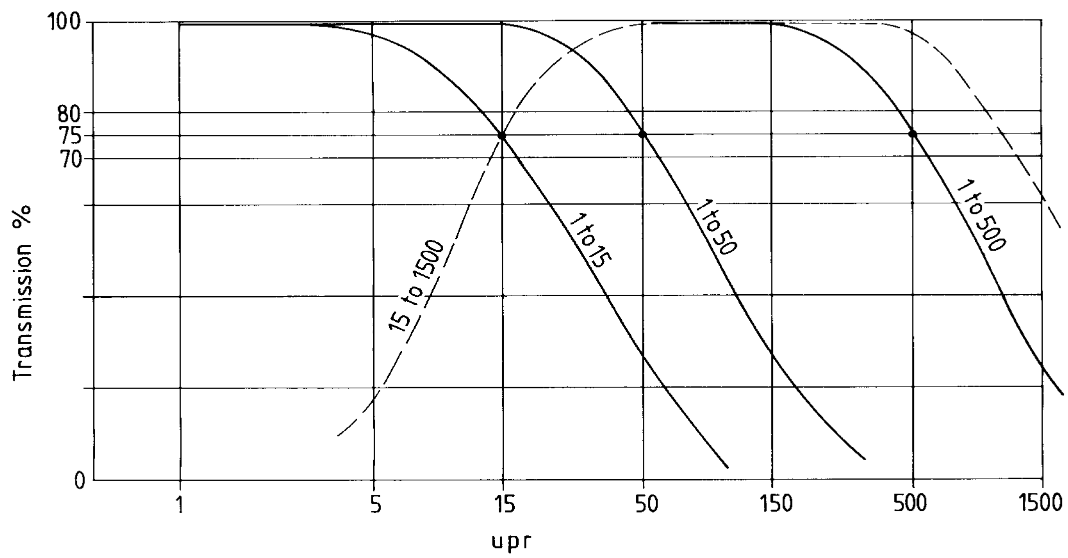


Figure 5 — Typical transmissions showing rate of attenuation given by two independent CR networks of equal time constant

Appendix A Departure from roundness of the measured profile of the workpiece

In this Part of this 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 radius, in each case, is commonly used to define a concentric zone. The kind of zone may be designated by the letter *z*, together with a suffix denoting its centre. For the purposes of this standard the following suffices are used:

e) least squares: suffix q, thus Z_q;

f) minimum width: suffix z, thus Z_z;

g) minimum circumscribed: suffix c, thus Z_c;

h) maximum inscribed: suffix i, thus Z_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 Appendix F).

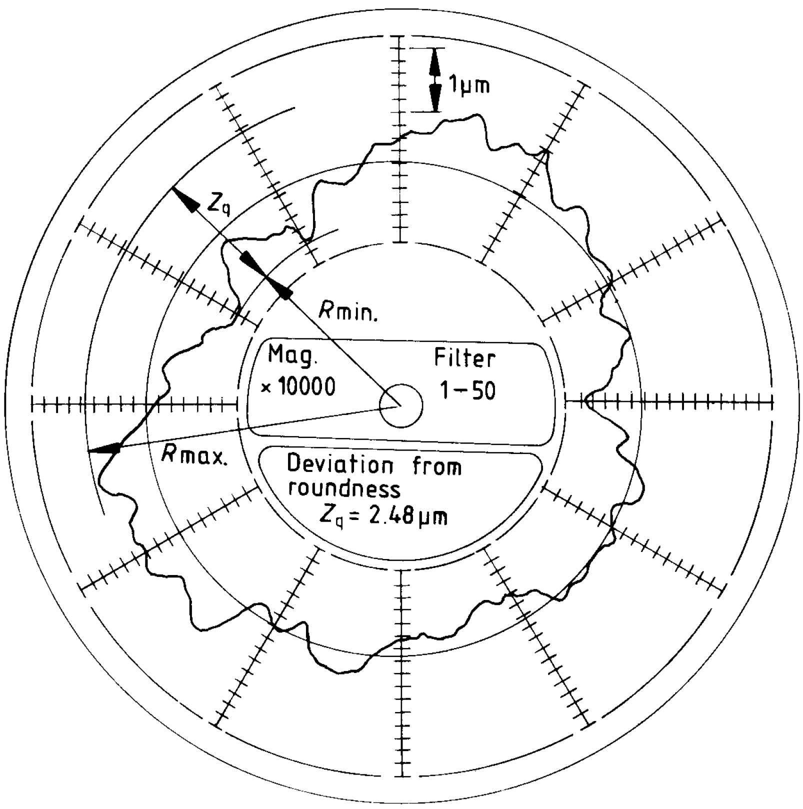


Figure 6 — Assessment of roundness from least squares centre (Z_q)

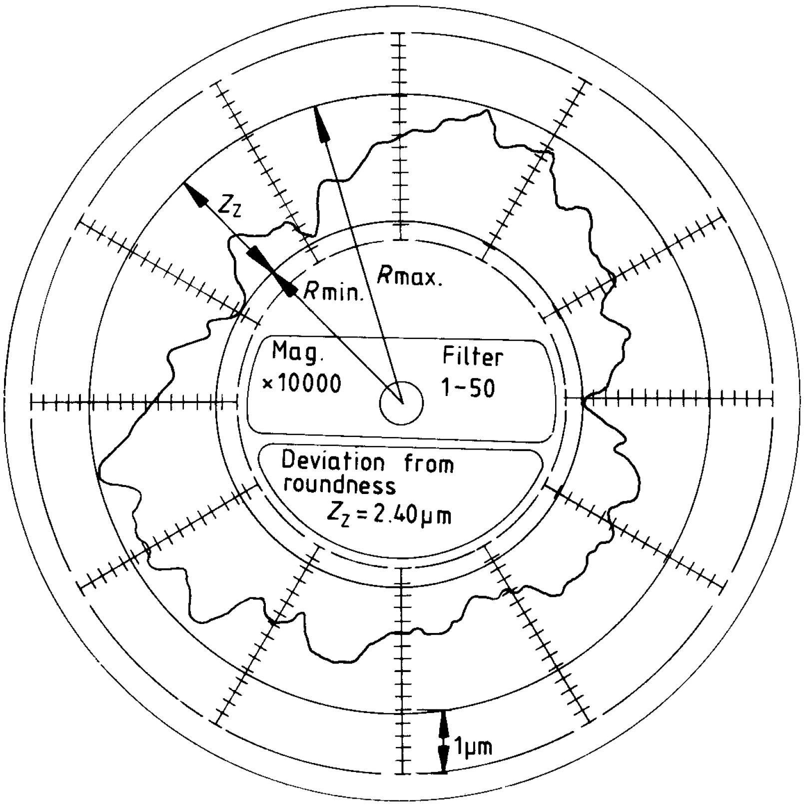


Figure 7 — Assessment of roundness from minimum zone centre (Z_z)

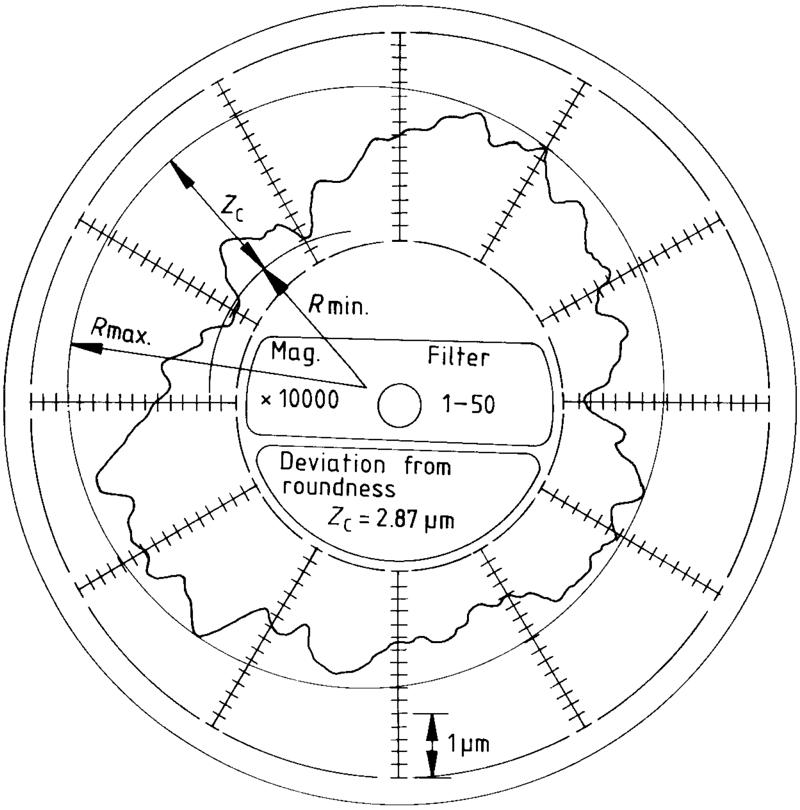


Figure 8 — Assessment of roundness from centre of minimum circumscribed circle (Z_c)

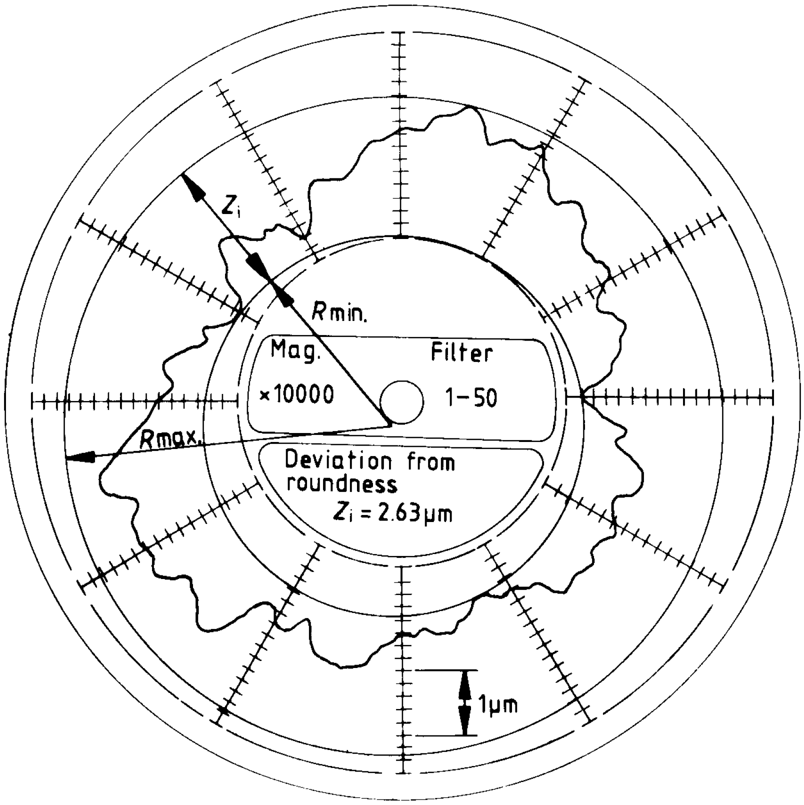


Figure 9 — Assessment of roundness from centre of maximum inscribed circle (Z_i)

Appendix B Use of the instrument

B.1 General

B.1.1 This appendix gives general guidance on setting up and measurement. The workpiece is 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.1.2 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, which however 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 being realized.

B.1.3 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 should not be too great.

B.1.4 Inclination of the axis of the workpiece to the axis of rotation will cause a perfectly round cylinder to appear elliptical. The diametral difference on the chart will be given by:

$MD\,(1 - \sec\theta)$

where

- D is the diameter of the workpiece (see Figure 11);
- θ is the angle of inclination (see Figure 11);
- M is the magnification.

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

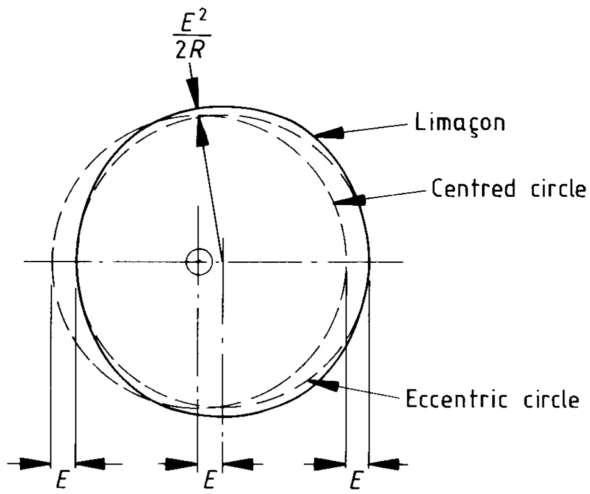


Figure 10 — Effect of eccentricity

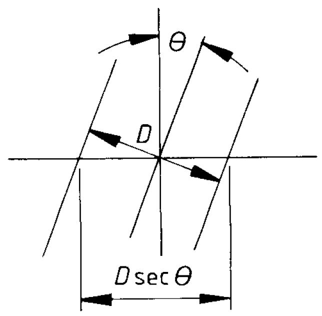


Figure 11 — Effect of inclination of workpiece axis

B.1.5 Some guiding rules for plotting and reading polar graphs are given in Appendix F.

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 that is plotted and measured will be that of the cross section. This forms the normal basis of roundness measurement and assessment.

B.2.2 When the workpiece is conical or toroidal, the question of which is the more significant functional direction has to be determined by details of the application and the direction in which the surface is likely to be operative. Also, the question can arise 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.

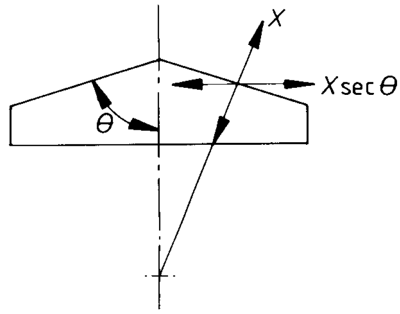


Figure 12 — Conical surface

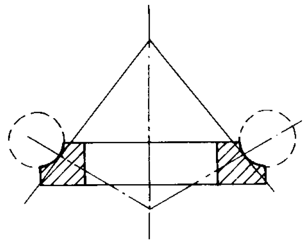


Figure 13 — Toroidal surface

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

B.3.1 The question will arise of 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 has to 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(a) and Figure 14(b). 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 14(a) would give rise to high frequency vibration and noise and Figure 14(b) might be preferred; but if they are the profiles of shafts, mandrels, piston, etc., it is likely that Figure 14(a) will be preferred.

If the point of interest is the geometry of the workpiece or of the machine that made it, the geometry generally being 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.

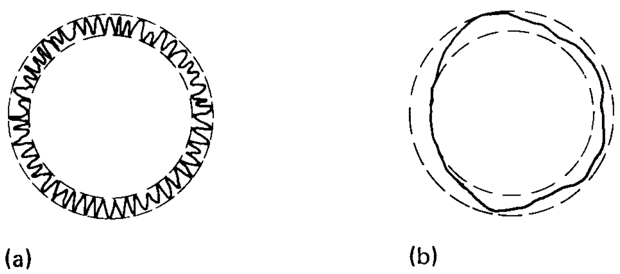


Figure 14 — Effect of roughness texture

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 with an axial lay (extrusion, broaching) because of difficulty in securing a small enough difference of circumferential curvature.

Figure 15 shows diagrammatically how stylii 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 hatchet stylus and the cross section B traced with a sharply pointed stylus of a part turned in an ordinary toolroom lathe, the tool producing a tool mark as shown separately. The stylii 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 a 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 (e.g. ball bearing raceways) involves not only the question of roughness but also that of positioning the stylus in the groove.

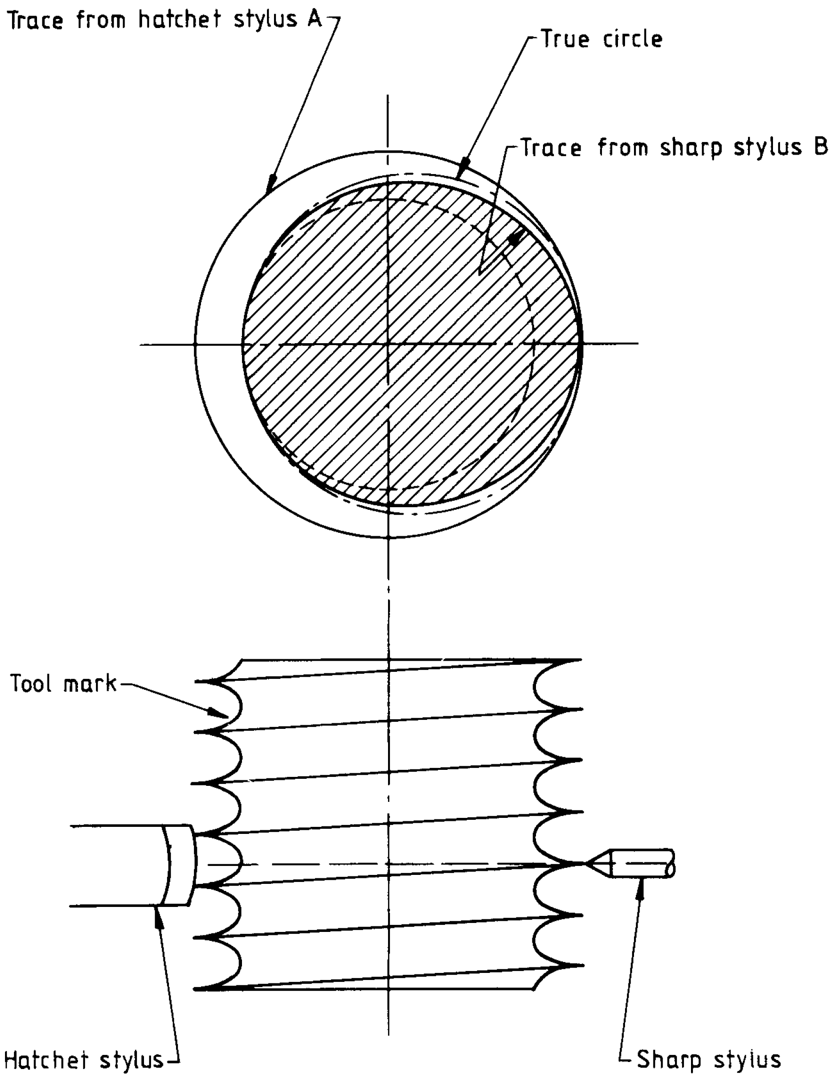


Figure 15 — Effect of stylus radius when in contact with surface

It will be seen from Figure 17 that if the centre of the stylus is offset from the direction of measurement XX, 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.

Appendix C Calibration

C.1 Calibration of radial magnification. Static calibration can be effected 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 effected by means of a cylinder having one or more small flats round the periphery (see Figure 18). Because 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 effected with the same devices as are used for the calibration of radial magnification.

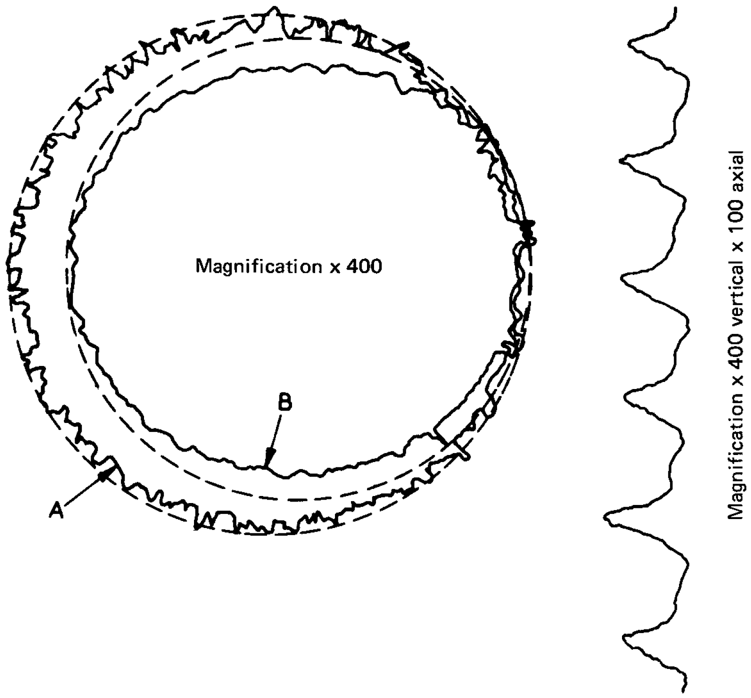


Figure 16 — Traces by hatchet and sharp stylii

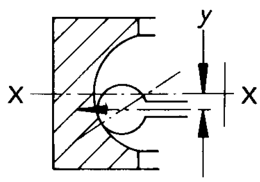
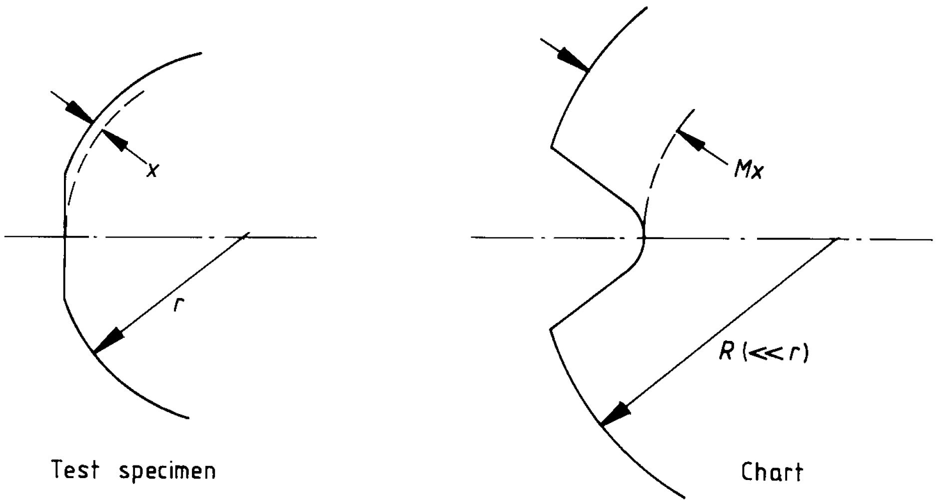


Figure 17 — Positioning of a stylus in a groove



(a) Test specimen (b) Chart

Figure 18 — Error due to stylus displacement

Appendix D Determination of systemmatic errors of rotation

D.1 General. 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 was 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

D.2.1 Two methods are used for separating the errors of the spindle from those of a test piece that 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.2.2 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 whilst actual measurements are being made. Roundness data is recorded over, for example, 4 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 is 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.2.3 The reversal method, which is applicable only to radial errors, is one that 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 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.2.4 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, for example in micrometres per metre, assuming adequate linearity.

Appendix E Determination of least squares centre and circle

From the centre of the chart (see Figure 21), draw a sufficient even number of equally spaced radial ordinates. In Figure 21 they are shown numbered 1 to 12. Two of these at right angles are selected to provide a system of rectangular coordinates XX, YY.

The distances of the points of intersection of the polar graph with these radial ordinates, P_1 to P_{12}, are measured from the axes XX and YY, taking positive and negative signs into account.

The distances x_4 and y_4 of the least squares centre from the centre of the paper are calculated from the following approximate formula:

$$a = \frac{2\ \Sigma x}{n}$$

$$b = \frac{2\ \Sigma y}{n}$$

where

Σx is the sum of the x values;

Σy is the sum of the y values;

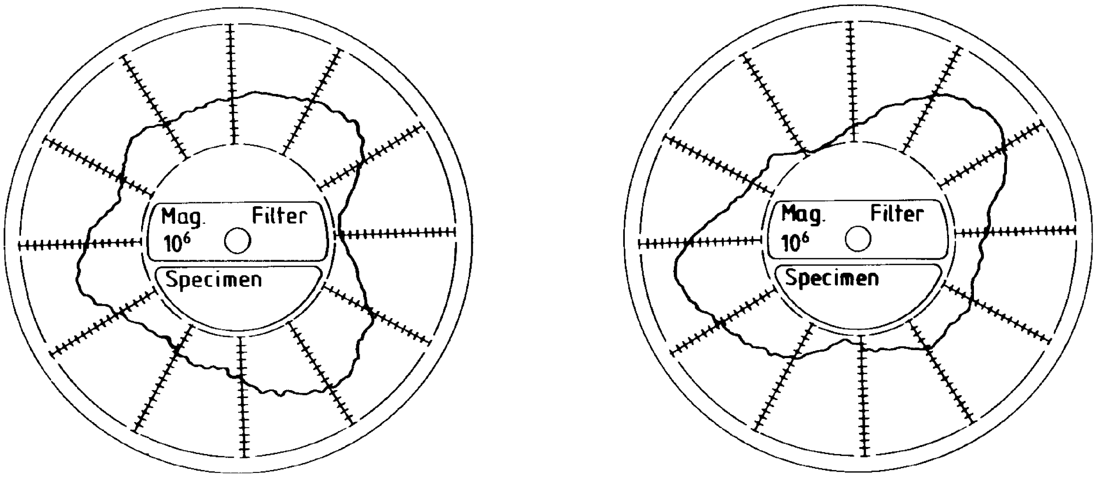
n is the number of ordinates.

The radius R of the least squares circle, if wanted, is calculated as the average radial distance of the points P from the least squares centre, that is:

$$R = \frac{\Sigma r}{n}$$

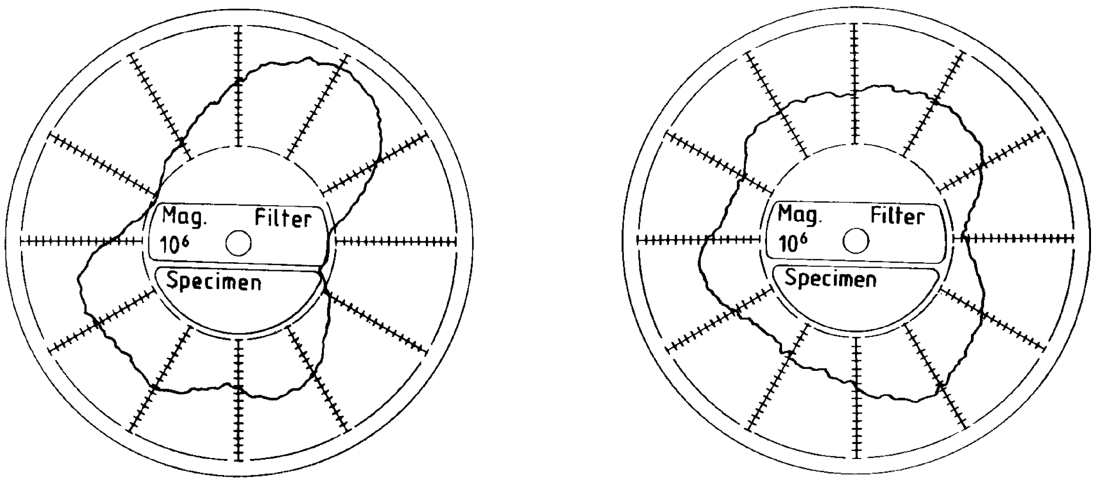
where

Σr is the sum of radial values.



(a) Test piece rotation 0° relative to the instrument spindle

(b) Test piece rotation 60° relative to the instrument spindle



(c) Test piece rotation 120° relative to

(d) Test piece rotation 180° relative to

[redacted]

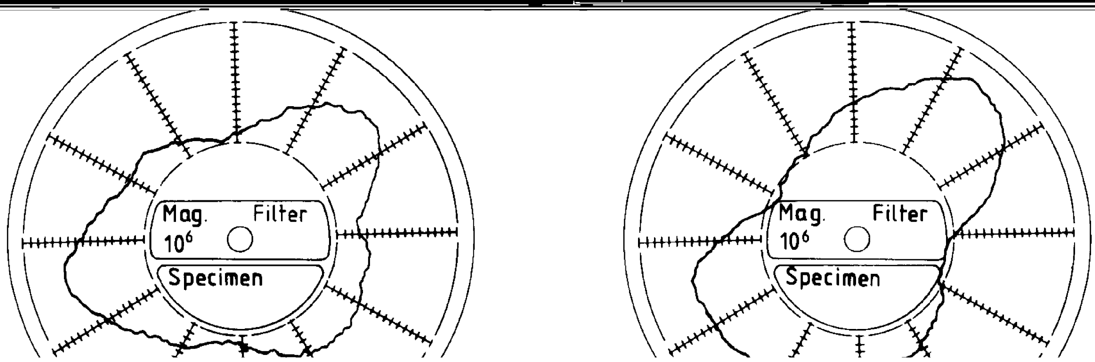
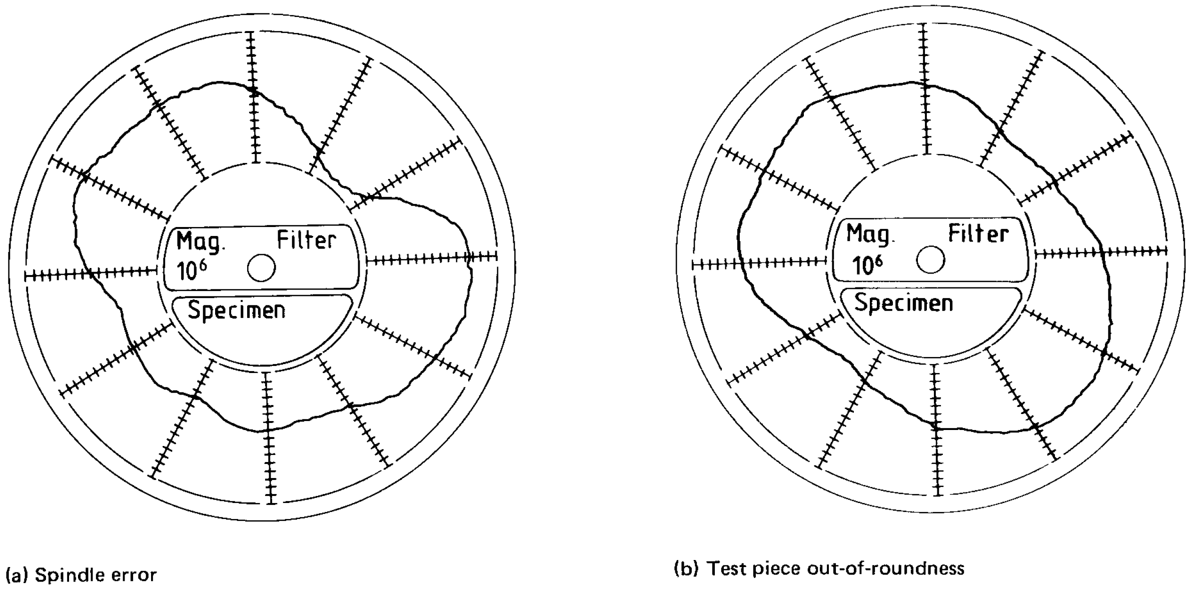


Figure 19 — Illustrations of spindle errors and test piece out-of-roundness



(a) Spindle error

(b) Test piece out-of-roundness

Figure 20 — Example of spindle error and test piece error

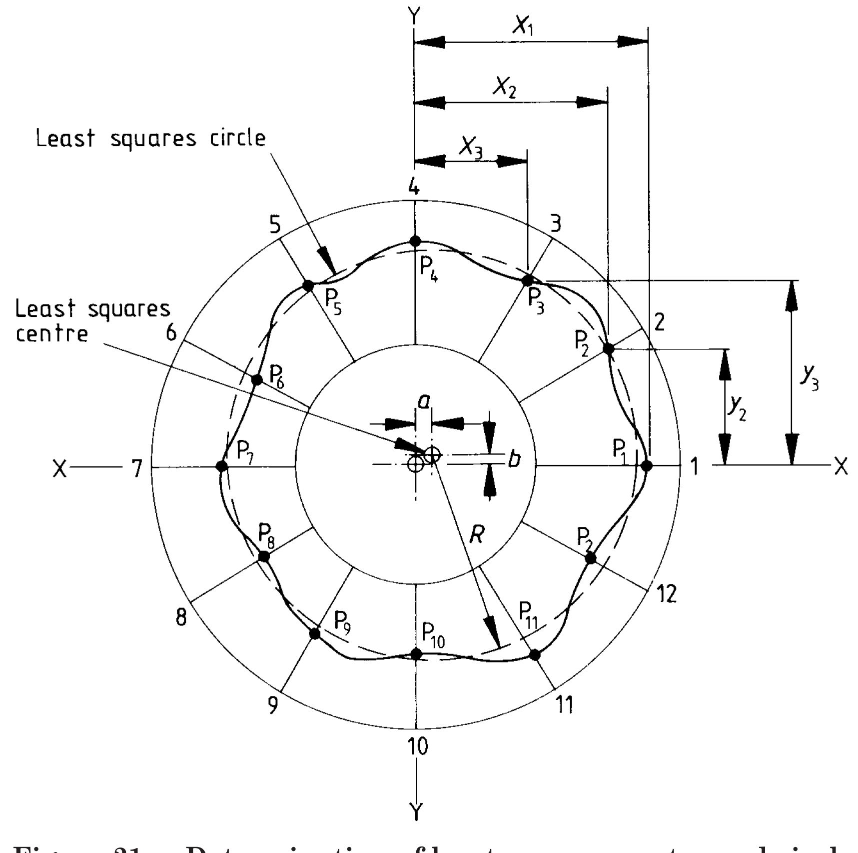


Figure 21 — Determination of least squares centre and circle

Appendix F Rules for plotting and reading polar graphs

F.1 General. The rules given in **F.2** and **F.3** can generally be applied.

F.2 Plotting

F.2.1 To avoid excessive distortion due to polar plotting, the trace should generally be kept within a zone of which the radial width is not more than about a half of its mean radius (see Figure 22).

F.2.2 The eccentricity *E* should be kept within about 15 % of the mean radius of the graph for general testing, and to within 7 % for high precision testing.

F.3 Reading

F.3.1 Angular relationships are read from the centre of rotation of the chart.

For example, points 180° apart on the workpiece are represented by points 180° apart through the centre of rotation of the chart (see Figure 23).

F.3.2 Diametral variations are assessed through the centre of rotation of the chart (see Figure 24).

F.3.3 Radial variations are assessed from the centre of the profile graph but are subject to a small error that limits the permissible eccentricity.

F.3.4 It should be noted that, as a result of highly magnifying the radial variations without correspondingly magnifying the actual radius of the workpiece, portions of the surface that are convex may appear as being concave around the periphery of the displayed profile (see Figure 18 and Figure 25).

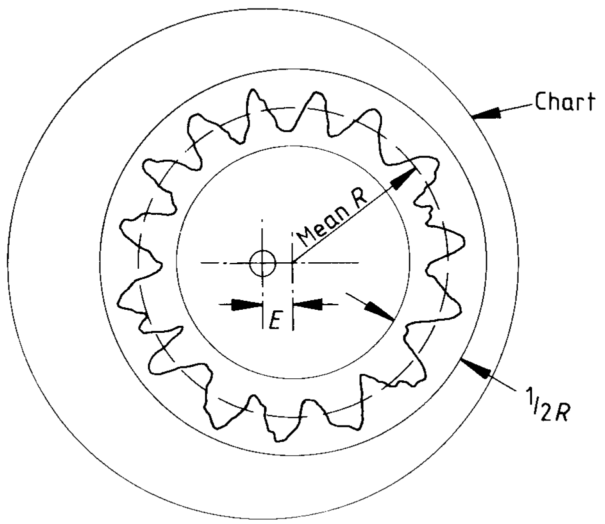


Figure 22 — Distortion due to polar plotting

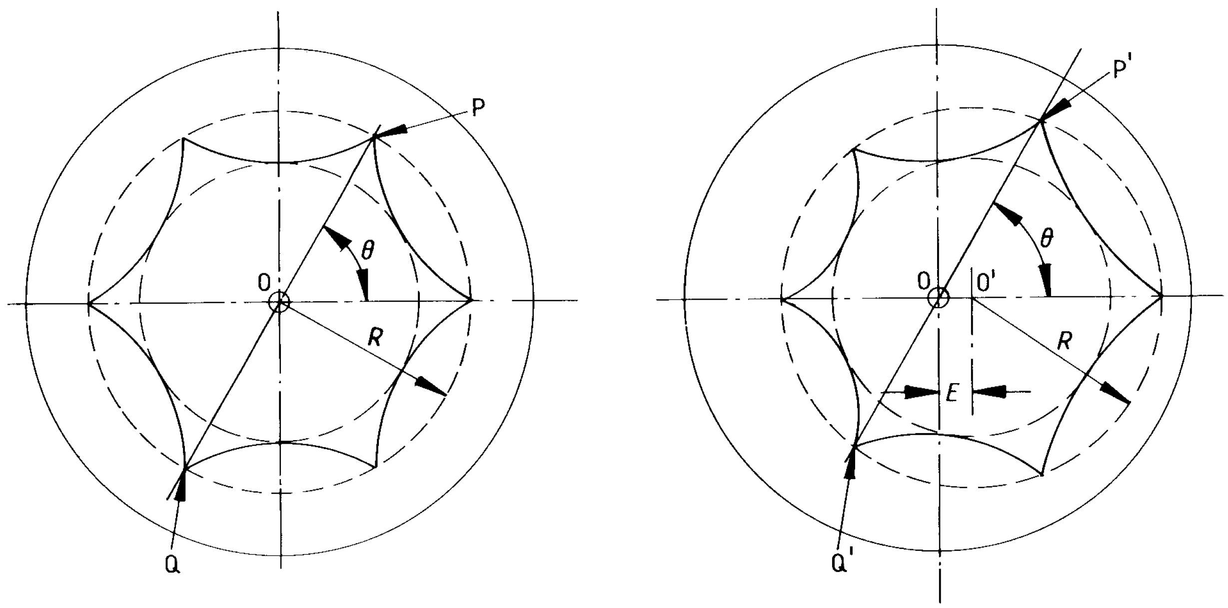
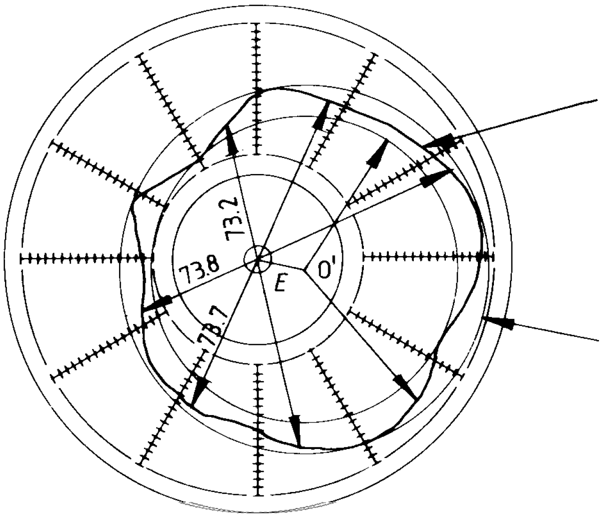


Figure 23 — Diametral variations



Profile of 5-lobed specimen of substantially equal angular spacing and constant diameter. Diameters drawn through centre of rotation are independent of eccentricity.

Circles struck from the eccentric centre 0′ approximately represent reference circles fitted round the workpiece.

Figure 24 — Radial variations

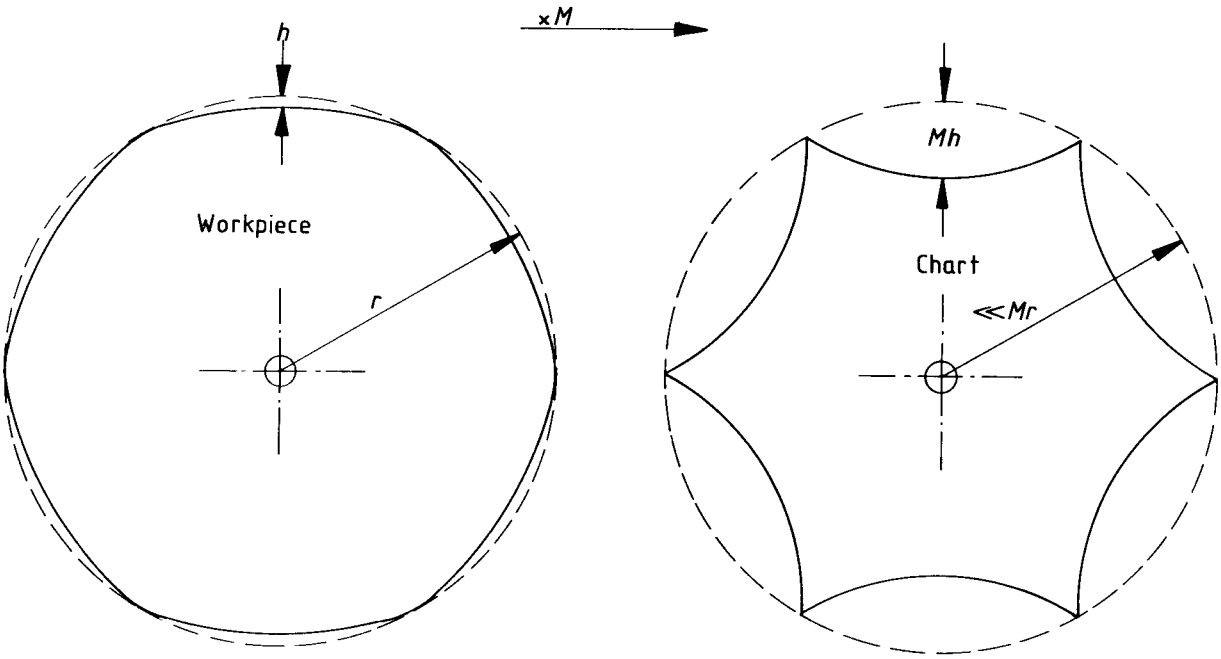


Figure 25 — Error due to stylus displacement

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Publication referred to

BS 3730, *Assessment of departures from roundness*.
BS 3730-1, *Glossary of terms relating to roundness measurement*.

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