TECHNICAL REPORT

ISO/TR 10064-5

First edition
2005-04-15

Cylindrical gears — Code of inspection practice —

Part 5: Recommendations relative to evaluation of gear measuring instruments

Engrenages cylindriques — Code pratique de réception —

Partie 5: Recommandations relatives à l'évaluation des instruments de mesure des engrenages

Reference number
ISO/TR 10064-5:2005(E)

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Page

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.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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/TR 10064-5 was prepared by Technical Committee ISO/TC 60, *Gears*.

ISO/TR 10064 consists of the following parts, under the general title *Cylindrical gears — Code of inspection practice*:

— *Part 1: Inspection of corresponding flanks of gear teeth*

— *Part 2: Inspection related to radial composite deviations, runout, tooth thickness and backlash*

— *Part 3: Recommendations relative to gear blanks, shaft centre distance and parallelism of axes*

— *Part 4: Recommendations relative to surface texture and tooth contact pattern checking*

— *Part 5: Recommendations relative to evaluation of gear measuring instruments*

Cylindrical gears — Code of inspection practice —

Part 5:
Recommendations relative to evaluation of gear measuring instruments

1 Scope

This part of ISO/TR 10064 provides additional information and examples to support the implementation of ISO 18653. It proposes evaluation and calibration procedures for involute, helix, pitch, runout, and tooth thickness measurement processes.

Methods are given for evaluation of the condition and alignments of instrument elements such as centres, guideways, probe systems, etc. Recommendations are included for establishment of a proper environment and for statistical data evaluation procedures.

It also covers the application of gear artifacts to the estimation of U_{95} measurement process uncertainty. Guidance on the application of measurement processes to the inspection of product gears is provided, including fitness for use and the recommended limits for U_{95} uncertainty based upon the accuracy tolerances of product gears to be inspected.

Many of its recommendations may also be applicable to the measurement of worms, worm wheels, bevel gears and gear cutting tools.

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 1122-1:1998, *Vocabulary of gear terms — Part 1: Definitions related to geometry*

ISO 1328-1:1995, *Cylindrical gears — ISO system of accuracy — Part 1: Definitions and allowable values of deviations relevant to corresponding flanks of gear teeth*

ISO 1328-2:1997, *Cylindrical gears — ISO system of accuracy — Part 2: Definitions and allowable values of deviations relevant to radial composite deviation and runout information*

ISO/TR 10064-1:1992, *Cylindrical gears — Code of inspection practice — Part 1: Inspection of corresponding flanks of gear teeth*

ISO/TR 10064-2:1996, *Cylindrical gears — Code of inspection practice — Part 2: Inspection related to radial composite deviations, runout, tooth thickness and backlash*

ISO/TR 10064-3:1996, *Cylindrical gears — Code of inspection practice — Part 3: Recommendations relative to gear blanks, shaft centre distance and parallelism of axes*

ISO 10360-1:2000, *Geometrical Product Specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 1: Vocabulary*

ISO/TS 14253-1:1998, *Geometrical Product Specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 1: Decision rules for proving conformance or non-conformance with specifications*

ISO/TS 14253-2:1999, *Geometrical Product Specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 2: Guide to the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification*

ISO 18653:2003, *Gears — Evaluation of instruments for the measurement of individual gears*

Guide to the expression of uncertainty in measurement (GUM), BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, 1st edition 1993, corrected and reprinted in 1995

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 1122-1, ISO 1328-1, ISO 1328-2 and ISO 18653 apply.

4 Instrument environment

4.1 Environment

The stability of the environment will affect accuracy of the calibration process and measurement of production parts. The measurement temperature should be maintained as a constant. It is recommended that the temperature be 20 °C. Standards or instrument manufacturer's recommendations often require an environment controlled to the extent necessary to assure continued measurements of required accuracy considering temperature, humidity, vibration, cleanliness and other controllable factors affecting precision measurement.

4.1.1 Important parameters

The following parameters are of primary importance [1]:

— the cooling (heating) medium, usually air;

— flow rate, distribution and velocity of the cooling (heating) medium;

— frequency and amplitude of temperature variations of the cooling (heating) medium;

— temperature gradients within the cooling (heating) medium;

— vibrations;

— electrical power supply quality.

1) A more thorough discussion of the effects may be found in such standards as ASME B89.6.2, *Temperature and Humidity Environment for Dimensional Measurement* R(2002).

4.1.2 Practical guidelines

The following are practical guidelines for gear measurement. However, compliance with these guidelines does not guarantee measurements to a specific accuracy.

— **Artifact temperature**. Tooling, artifacts and other test pieces should be left for an adequate period to stabilize to ambient temperature. Artifact temperature ideally should be the temperature at which it was calibrated.

— **Mean temperature variation**. The instrument manufacturer's temperature variation guidelines for the desired accuracy should be consulted. If this information is not available, it is recommended that the mean temperature should not change more than 1 °C per hour, with a maximum change of 3.5 degrees per day.

— **Temperature cycles**. The temperature may cycle ± 2 °C, centred on the mean temperature, every 5 min or faster. The thermal inertia of most mechanical systems will allow for rapid cyclic temperature undulations within these guidelines for the stated accuracy. If a temperature cycle of the instrument approaches 1 °C in 15 min, serious effects on the measuring system accuracy may occur. Many people use an air conditioner in an attempt to achieve thermal control. The temperature sensors in these units may be very slow to respond to temperature changes. If the response is slower than 5 min, serious effects on measurement accuracy may be noted.

— **Temperature gradient**. The temperature should be within 0,5 °C over the entire area of the instrument surface. The best way to do this is with a high air flow. Air flow must be uniform throughout the room to prevent dead spots and gradients. To accomplish this, diffuse the air coming in to the room and, if possible, design multiple air returns to further diffuse the air uniformly in the room. The goal is to have all air moving uniformly in the room and at the same temperature. Moving air must remove heat from electronic controls, computers, motors, hydraulics, people, lights, etc., to prevent gradients.

— **Vibrations** caused by instrument movements should not be allowed to interfere with measurements. Also, vibrations from the surrounding environment should be observed or measured. If they are affecting instrument accuracy, vibration isolation of the instrument or a suitable foundation may be necessary.

— **Electrical power supply**. Power fluctuation may cause some electronic instruments and computers of numerical control positioning systems to malfunction.

4.1.3 Workshop environment

It is recommended that measuring instruments be situated in a temperature controlled room. However, many measuring instruments are placed in a workshop environment where it is difficult to maintain a process measurement uncertainty of 5 microns. Accumulation of dirt or other contaminants on the ways of the instrument can cause inaccuracies as well as premature wear.

If an instrument must be used in this kind of environment, care must be taken to avoid certain conditions, such as

— local radiant heat sources such as space heaters or sunlight through nearby windows that may distort the instrument,

— roof vents that allow cold air to drop on the instrument, and

— cooling systems or open windows that cause a draft to hit one side of the instrument.

The formulae in 4.2.1 and 4.2.2 may also be used for estimating the effect of a stable, but consistent, difference in instrument temperature from the standard temperature (20 °C). If the formulae are used, CTE should be the instrument material or encoder scale value and the sign of the resulting compensation should be changed. The user should be aware that the results might vary depending upon the location of temperature measurement.

4.2 Effect of temperature on gears and artifacts

Temperature can have a significant effect on the geometry of gears and artifacts. Temperature effects upon involute profile slope, $f_{H\alpha}$, helix slope, $f_{H\beta}$, and tooth thickness measurements of external gears and artifacts can be predicted using the following formulae. Such calculations assume uniform temperature of the given test piece; localized temperature variations cannot be conveniently modelled. Temperature of the measuring instrument is not considered in these calculations.

The temperature of the measuring instrument is not considered in these calculations, but a difference between standard temperature (20 °C) and the instrument temperature will also cause errors in measurement result.

It may be desirable to correct profile and helix slope measurement values for temperature effect. Such corrections are required by U_{95} estimation methods described in Clause 7 of this document.

Uniform temperature variations of a gear or artifact are not considered to have an effect upon pitch or runout (tooth position) parameters.

4.2.1 Profile temperature effect calculation

For involute profile measurement, the effect of temperature can be modelled by considering the associated change in the base circle diameter. The effect upon profile slope $f_{H\alpha}$ can be calculated as follows:

a) Given (typical) data:

z is number of teeth;

m_n is normal module;

β is helix angle;

α_n is normal pressure angle;

$L_{\alpha s}$ is roll length to the start of profile analysis;

$L_{\alpha e}$ is roll length to the end of profile analysis;

CTE is coefficient of thermal expansion (approximately $11{,}5 \times 10^{-6}$ C^{-1} for steel).

NOTE When profile analysis start and end points are specified in roll angle degrees (ξ_y), conversion to roll length can be done with the following formula:

$$L_y = \left(\frac{\xi_y}{360}\right)\left(d_b \pi\right) \quad (1)$$

b) Calculate the slope change due to the temperature difference:

$$\Delta f_{H\alpha} = \left(L_{\alpha e} - L_{\alpha s}\right)\left(t_a - t_s\right)\text{CTE} \quad (2)$$

where

t_a is the actual (measured) temperature;

t_s is the standard temperature (20 °C).

See Annex A for an example and further information.

4.2.2 Helix temperature effect calculation

For helix measurement, the effect of temperature can be modelled by considering the associated change in the lead. The effect upon helix slope, $f_{H\beta}$, can be estimated as follows.

a) Given (typical) data in 4.2.1 a), plus:

L_{β} is helix evaluation range;

b) Calculate the base helix angle, β_b:

$$\beta_b = \arcsin(\sin\beta\cos\alpha_n) \tag{3}$$

c) Calculate the slope change due to the temperature difference:

$$\Delta f_{H\beta} = -L_{\beta}\tan\beta_b(t_a - t_s)\mathrm{CTE} \tag{4}$$

See Annex A for an example and further information.

4.2.3 Tooth thickness temperature effect calculation

In addition to involute profile and helix, tooth thickness may be significantly affected by temperature. These effects can be modelled by considering the associated change in the tooth section intersecting the pitch diameter, where tooth thickness is usually measured. The effect of temperature upon normal tooth thickness of an external gear can be estimated as follows.:

a) Given (typical) data in 4.2.1 a), plus:

s_n is normal tooth thickness at the reference pitch diameter, d:

b) Calculate the reference pitch diameter, d:

$$d = z\frac{m_n}{\cos\beta} \tag{5}$$

c) Calculate the change in normal circular tooth thickness at the reference pitch diameter of an external gear due to the temperature difference:

$$\Delta s_n = d\tan\alpha_n(t_a - t_s)\mathrm{CTE} \tag{6}$$

See Annex A for an example and further information.

5 Measurement system condition

Many factors affect the accuracy of gear measuring instruments. These include squareness and parallelism of the instrument guideways to each other and to the rotary table, straightness of the guideways, linear positioning errors, and angular motion errors (pitch, roll and yaw) of the moving components of the instrument. Errors caused by electronic components, scales, controls, and software may also adversely effect the accuracy of a measuring instrument. There are various methods of measuring these errors. While a complete discussion of machine kinematics and electronic controls is beyond the scope of this document, it is recommended that users of these instruments be aware of the many possible sources of inaccuracy.

Some manufacturers of measuring instruments provide detailed procedures for periodically verifying their product’s conformance to original factory specifications. The generalized tests and recommended tolerances found in this section are for use in the absence of, or in addition to, the instrument manufacturer’s recommended procedures. These tests are not to be considered a replacement for the manufacturer's procedures.

Gear accuracy grade and parameters to be tested should be identified prior to starting verification procedures. The actual work envelope should also be known. Results of all procedures should be recorded to document this verification work and to provide data for statistical analysis.

5.1 Evaluation procedure for generative instruments

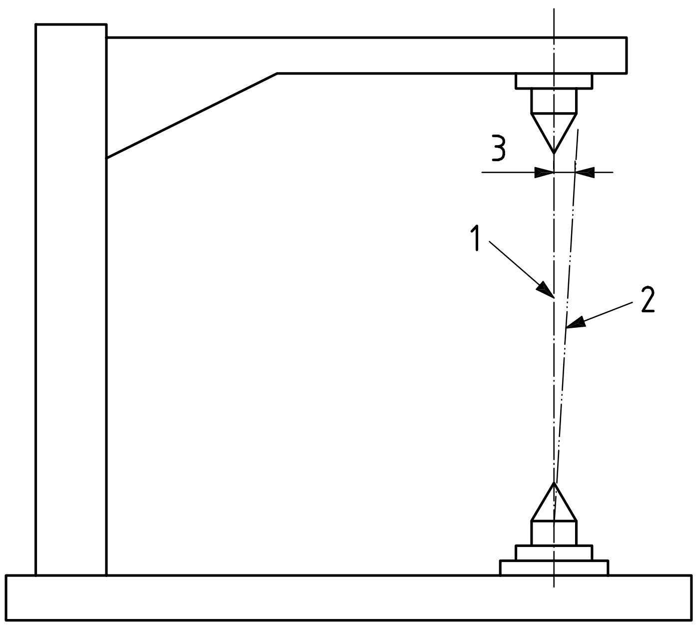
Proper operation of important components of gear measuring instruments can be verified by the procedures outlined in the following. This verification procedure should begin with a visual inspection of the instrument to assure that no obvious detrimental conditions exist that would impair proper operation. Centres, drivers and measuring probe styli that are subject to wear and damage should be checked. Confirm also that environmental conditions meet the requirements of 4.1.

The probe systems and indicators that measure instrument errors should be calibrated and have an appropriate discrimination (1 µm or less is recommended). The user should note that data capture rates and filters will affect the measurement results. See 5.4 for further information.

5.1.1 Verification of mounting centres

Inspection of gear geometry by generative methods requires mounting the gear such that its datum axis of rotation is coincident with the instrument's main spindle axis. See ISO/TR 10064-3. Any eccentricity or non-parallelism of this mounting will cause an error in measurement results. See Figure 1.

Between-centres mounting of test gears is a common practice. Most gear testing instruments are fitted with centres, one on the main spindle and one on a tailstock assembly. Misalignment and runout of these centres are common. Verification of instruments used for testing should therefore begin with the observation of these mounting centres.



Key

1 between-centres axis

2 workspindle axis

3 error

Figure 1 — Alignment error of the spindle axis and the between-centres axis

5.1.1.1 Centre runout

Using an indicator with an appropriate discrimination, measure the runout (TIR) of the main spindle centre in a direction normal to the surface. This measurement of runout should be within the manufacturer's specifications or the guidelines listed in Table 1. It is advisable to measure runout of each centre at the small and large end to detect bent or skewed centres.

Table 1 — Recommended guidelines for deviations when checking instrument alignment [a]

Accuracy grade to be tested ISO 1328-1 ISO 1328-2	Runout of centres (TIR) µm	Z-axis parallelism with spindle axis in any measured 200 mm region		Alignment of top centre with spindle axis (TIR) per 200 mm [d]
		A [b] µm	B [c] µm	
2	1	1	2	2
3	1	2	2	2
4	1	2	3	3
5	2	3	4	4
6	2	4	6	6
7	3	5	6	6
8	4	5	6	6
9	5	7	6	6
10	7	10	8	8
11	10	10	12	12
12	10	10	12	12

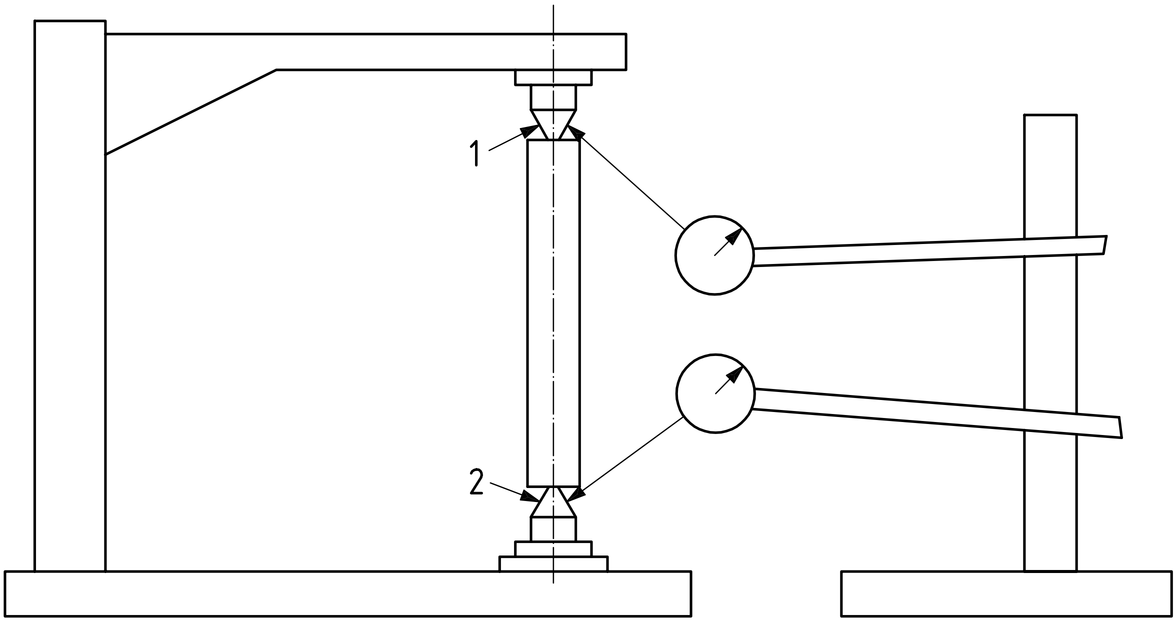
[a] The guidelines are for multi-purpose instruments. Single-purpose instruments may only require one or more of the parameters.

[b] In the measuring (base tangent) plane. See Figure 5.

[c] Perpendicular to the measuring plane. See Figure 6.

[d] Alignment tolerance is the greater of 2 µm or the table tolerance per 200 mm of the length, R, in Figures 3 and 4.

Load the spindle assemblies by mounting an arbor between centres. The length, accuracy, or configuration of this arbor is not significant. See Figure 2.



Key

1 tailstock live centre

2 work spindle centre

Figure 2 — Centre runout test

5.1.1.2 Tailstock centre positioning

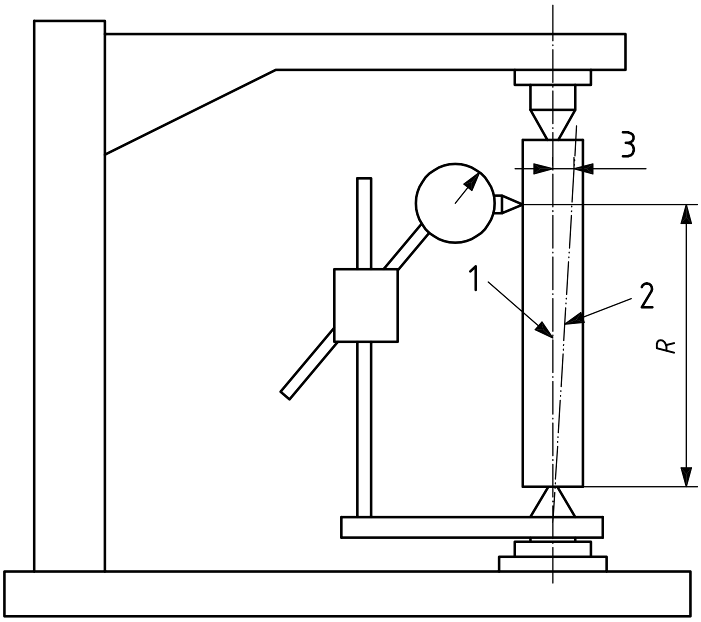
A testing practice often called sweeping can be used to effectively evaluate the position of the tailstock centre relative to the main spindle axis. Sweeping the tailstock centre at only one location on the tailstock slide verifies its positioning for testing gears at that location only. Sweeping the tailstock centre at two significantly separated tailstock slide locations verifies both lateral positioning and angular alignment of the tailstock slide with the main spindle axis. If straightness of travel of the tailstock slide has been confirmed to be within manufacturer's specifications by other methods, a two-location test will verify tailstock centre positioning at all locations. Otherwise, sweeping of the tailstock centre at a minimum of three significantly separated locations within its range of operation is required. For high-quality gears, it is recommended sweeping of the tailstock be done for each unique configuration before inspection.

Two sweeping test set-ups will be described.

a) The first is recommended only for instruments with a vertical main spindle axis. Figure 3 provides an example of this set-up. The spindle assemblies are loaded by mounting an arbor between centres. The accuracy and configuration of this arbor is not significant as the indicator and arbor rotate together. A minimum of two such sweeping tests, each using different length arbors, is normally required. Instruments that use base discs should be tested with a base disc contacting the base tangent slide to ensure spindle clearance effects are included. The lengths of the two arbors should be selected to be toward opposite ends of the range of tailstock operation.

   An indicator with an appropriate discrimination is mounted so as to be carried by the rotating main spindle and simultaneously to measure in a radial direction the alignment (TIR) of the arbor near the tailstock centre. These measurements of the tailstock centre alignment with the spindle axis should be within the value listed in Table 1.

   The value is stated as a ratio of permissible centre alignment (TIR) to the axial distance of that measurement from the main spindle centre. The recommended value therefore changes with measurement location and should be adjusted accordingly. The tolerance value is the greater of 2 µm or the table tolerance per 200 mm of the length, R, in Figure 3.



Key

1 between-centres axis

2 work spindle axis

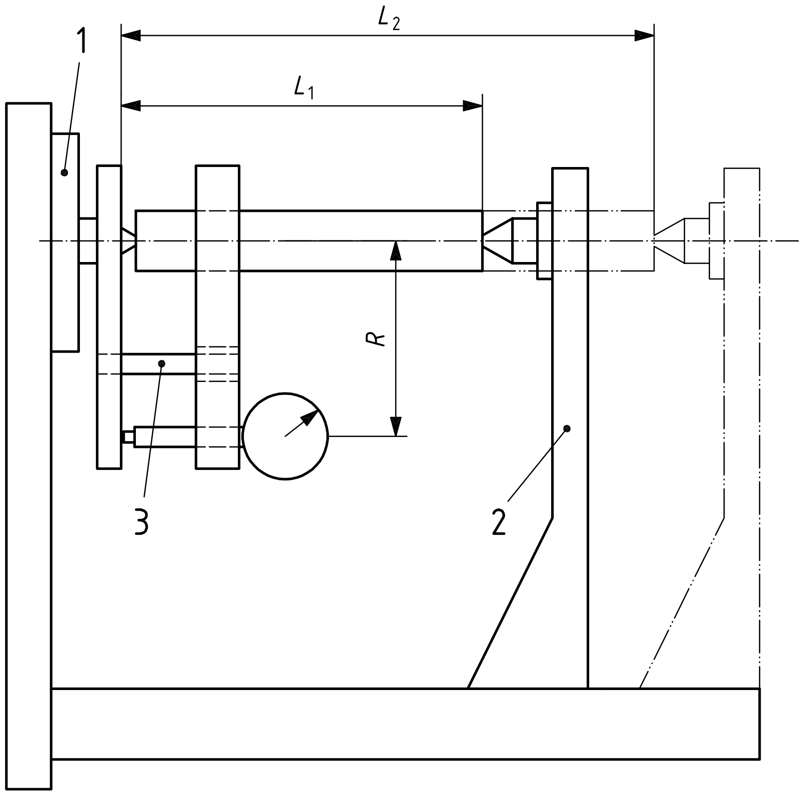
3 error

Figure 3 — Tailstock alignment measurement method (vertical axis instruments only)

b) The second sweeping test set-up is recommended for instruments with a horizontal main spindle axis, but may also be used for vertical instruments. Figure 4 provides an example of this set-up. This figure shows the sweeping set-up made at two locations, L_1 and L_2. As before, the spindle assemblies are loaded by mounting different length arbors between centres at the two locations.

In this case, an indicator with appropriate discrimination is mounted so as to be carried by the rotating test arbor and to measure in an axial direction the alignment (TIR) of a fixture carried by the rotating main spindle. These alignment measurements of the tailstock centre with the spindle axis should be within the value listed in Table 1.

The value is stated as a ratio of permissible centre alignment (TIR) to the axial distance of that measurement from the main spindle centre. The recommended value therefore changes with measurement location and should be adjusted accordingly. The tolerance value is the greater of 2 µm or the table tolerance per 200 mm of the length, R, in Figure 4.



Key

1 work spindle

2 tailstock

3 driver pin (clearance in hole)

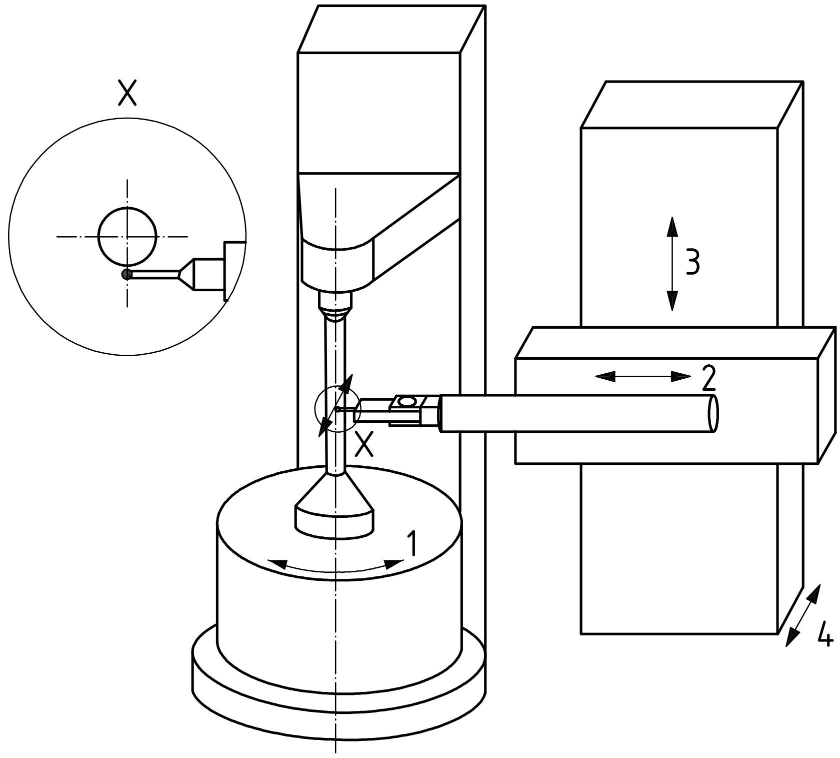
Figure 4 — Tailstock centre alignment fixture for horizontal or vertical work spindles

5.1.2 Axial measuring slide verification

Parallelism of the path of the axial measuring slide with the main spindle axis should be confirmed. A parallel mandrel is required for this evaluation. Alternatively, an accurately manufactured mandrel can be used in conjunction with a self-proving, reversal-method. This verification should apply to the length of the work envelope, or at minimum 80 % of the full travel, see Figures 5 and 6.

5.1.2.1 Centre-mounted mandrel

The mandrel may be mounted between centres. In this case, its orientation concentric with the main spindle axis should be confirmed by two observations. First, its concentricity near the main spindle centre and near the tailstock centre can be confirmed by measuring its radial runout near those centres. Second, its concentricity near the tailstock centre can be confirmed by sweeping the mandrel. If the sweeping set-up recommended for vertical axis instruments is used, the test indicator should be positioned near the tailstock centre. It is recommended that this mounting of the test mandrel be optimized before observation of axial measuring slide parallelism. This may include minimizing runout of the main spindle centre, runout of the tailstock spindle centre, and alignment error of the tailstock slide assembly at this test location.



Key

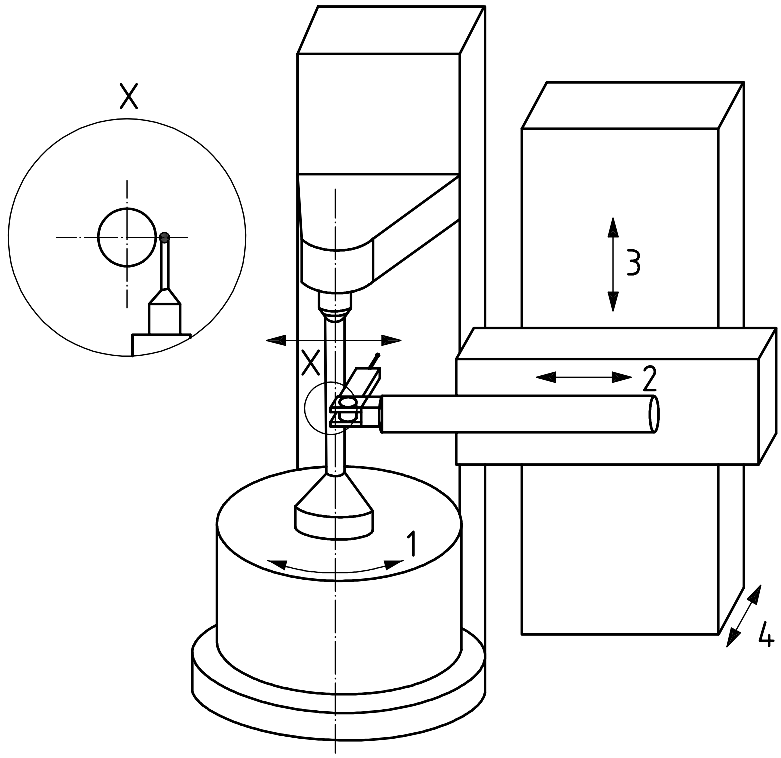
1 rotary direction

2 radial direction

3 axial direction (Z)

4 tangential direction

Figure 5 — Z-axis to between-centres axis alignment verification axial plane parallel to the measuring (base tangent) plane



Key

1 rotary direction

2 radial direction

3 axial direction (Z)

4 tangential direction

Figure 6 — Z-axis to between-centres axis alignment verification, perpendicular to measuring plane

5.1.2.2 Direct mounted mandrel

Alternatively, the test mandrel can be attached directly to the main spindle, thereby eliminating adverse influences of mounting centres. In this case, its orientation concentric with the main spindle axis must be confirmed by observation of radial runout near each end of the mandrel. Centring and tilting adjustments will be required to optimize this mounting before observation of axial measuring slide parallelism.

5.1.2.3 Axial slide parallelism testing

Once a calibrated mandrel has been properly oriented on the instrument, it should be tested by traversing its length with the measuring probe carried by the axial measuring slide. This will reveal errors of straightness and alignment of the axial slide. The observation should be made in a radial direction within two different axial planes:

a) the plane parallel with the measuring plane (the base tangent plane);

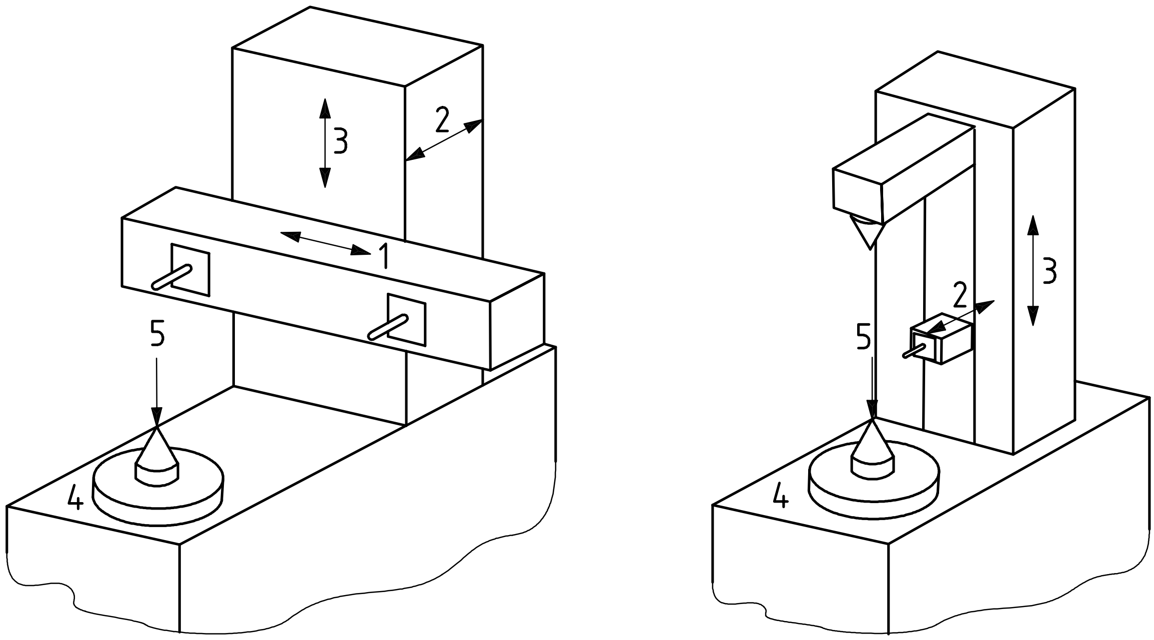
b) the plane perpendicular to the measuring plane.

See Figures 5 and 6.

These measurements of axial measuring slide parallelism with the main spindle axis should be within the guidelines listed in Table 1. Two such guideline values are provided: one for observations parallel with the measuring plane, and one for those that are perpendicular to the measuring plane. These value(s) apply to any measured 200 mm region of the axial measuring slide.

5.1.2.4 Change in alignment with heavy load

Ideally, tests should be carried out with the instrument head placed at the limits of the measuring capacity [i.e. with the tangential slide length at ± the maximum length of roll (4-axis instruments only) and radial slide at the limiting base radius], see Figure 7.



a) Four-axis measuring instrument **b) Three-axis measuring instrument**

Key

1 tangential

2 radial

3 axial

4 rotary

5 load

Figure 7 — Position of the base tangent slide during the deflection tests (± maximum length of roll for the verified measuring volume)

The measuring instrument table or table centre should be loaded with a test gear or artifact that provides a tooth geometry that satisfies the measuring volume as mentioned above. Weights are then to be added in increments to represent the maximum weight capacity expected in service or the instrument's work spindle weight capacity as stated by the original equipment manufacturer. The smaller of the two values should be used.

Coordinate measuring machines (CMM) may be loaded uniformly over the work table area, as appropriate for typical measuring applications.

The change in relative alignment and machine bed deformation should be such that the alignment and straightness accuracy requirements specified, or in accordance with Table 1, are still satisfied with the load applied.

The test procedure should be carried out as follows.

a) Load and secure a flat test gear on the measuring table.

b) Check the helix of the test gear on a marked and designated tooth. Note the present deviations in alignment from the recording chart.

c) With the test gear remaining on the measuring table, place a weight of approximately 1/4 of the required weight capacity on top of the test gear.

d) Repeat the same test as indicated in b) above. The same tooth and radial tooth position as in b) should be used. Compare the test result to that obtained in the original test b).

e) Increase the incremental load, if possible, with a total of four increments, checking the test results at each incremental increase.

f) Verify that the change in relative alignment and bed deformation is within the specified limits as stated, or in accordance with Table 1.

5.2 Evaluation procedures for CMM type measuring instruments

On CMMs with or without rotary table, the measurement of gears is possible when dedicated software is available. The gear axis definition is achieved by the measurement of the bearings (journals) or other reference surfaces and used for the further measurement.

5.2.1 Performance test according to ISO 10360

In ISO 10360, a special test for the performance of coordinate measuring machines is established. The verification is executed on gauge blocks and on a high-precision calibration sphere with a diameter of normally 25 or 30 mm.

There are 3 tests specified:

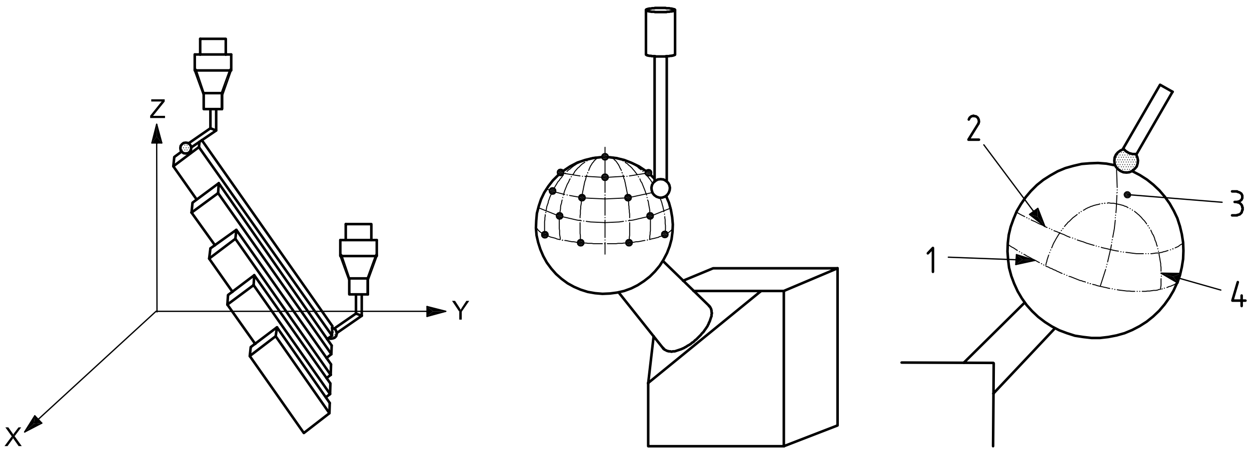
E volumetric length measuring deviation

R volumetric probing deviation

THP volumetric scanning deviation

For test E, a set of 5 calibrated gauge blocks must be measured 3 times at 7 positions with 2 probings per gauge. The orientation of the gauges can be in any direction in space (volumetric). All of the 105 measurements must be in tolerance (100 %).

For test R a high precision (half) sphere must be measured with 25 equally distributed single probing points. All probing (100 %) must be used for the evaluations. The total measured form deviation is the volumetric probing uncertainty R.



E R THP

Key

E volumetric length measurement deviation

R volumetric probing deviation

THP volumetric scanning deviation

Figure 8 — CMM volumetric tests

For test THP, several scanning lines on the sphere must be executed.

Tests R and THP are influenced more by the performance of the probing system, while test E covers both the probing system and the overall accuracy of the system.

5.2.2 Ball plate test

Alternatively, a ball plate is commonly used to check CMM accuracy. A ball plate consists of a steel plate or other material on which a rectangular grid pattern of high precision spheres are placed, see Figure 9. With a special software program the positions of the spheres are automatically measured and compared with the calibrated positions. The ball plate is mounted in different orientations in the measuring volume i.e. parallel to the coordinate planes and in the diagonal.

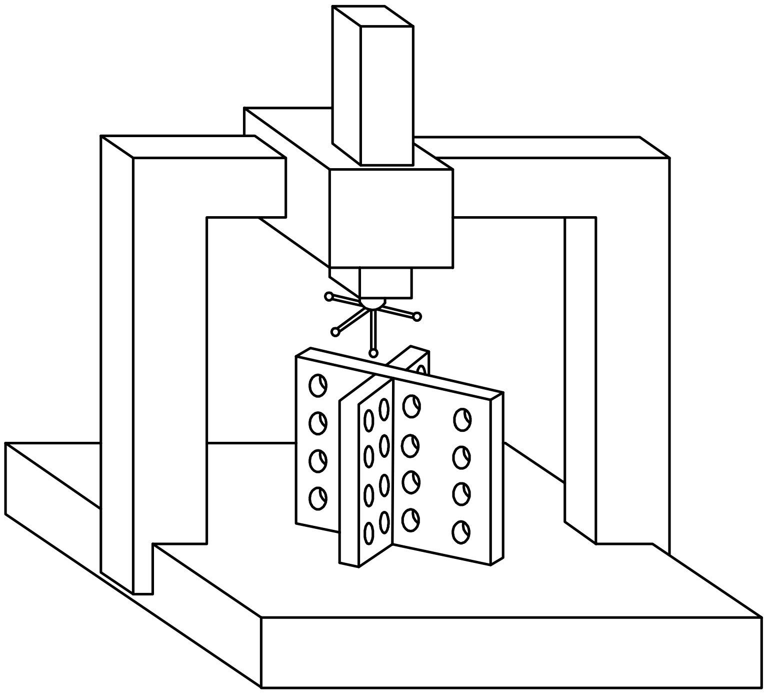


Figure 9 — Ball plate tests

5.2.3 Rotary tables

For CMM instruments with rotary tables, the procedures of ISO 10360 should also be followed, see Figure 10.

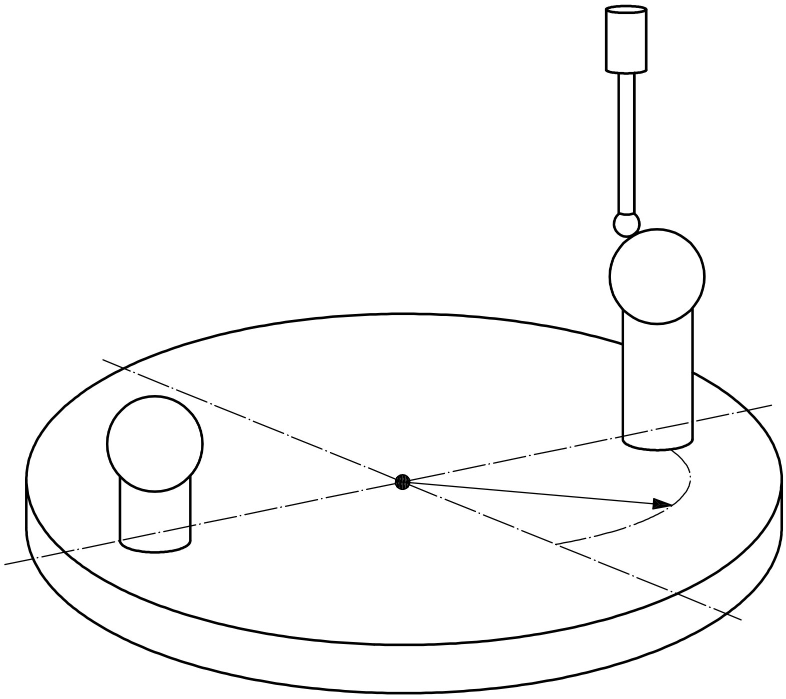


Figure 10 — Rotary table tests

5.3 Probe system

The data acquisition and processing system consists of the probe stylus, probe mechanism and the data recording system.

5.3.1 Stylus

Select and check the condition of the stylus and record its size and geometry. Verify the position of the stylus on the instrument by re-qualifying, or use the manufacturer's setting fixture.

5.3.1.1 Spherical stylus tips used on generative instruments

Spherical stylus tips are often used, particularly on computer-controlled generative or CMM instruments. Spherical stylus tips are less subject to wear, less likely to mark the surface of the tooth flank, and are better suited to computer-controlled position qualification methods than sharp stylus tips.

Generative instruments measure tooth geometry errors as deviations from a generated nominal geometry. Involute profile testing involves generating a nominal involute according to the constant-rise-cam characteristic of that curve. During such tests, the centre of the spherical probe tip and its point of contact with the tooth surface are constrained within the plane of action. Generative helix testing is carried out according to generation of the nominal helix. Generative pitch testing involves rotational positioning of the gear according to ideal equally-spaced tooth locations. On unmodified involute helicoid tooth flanks, the point of contact between the spherical stylus tip and the tooth flank will remain constant during the course of tests carried out according to these generative methods. Contact vector variation and stylus tip sphericity are not significant issues in this case.

However, tooth flanks may present substantial deviations from involute geometry. This may be due to intentional modifications such as tip relief, or unintentional production variations. Substantial deviations from involute geometry cause variation in the contact vector that may affect observations of the position and contour of these regions of deviation, even when employing generative testing methods. In such cases, it may be necessary to apply software corrections to the test data.

Use of spherical stylus tips will cause apparent rounding at the ends of tooth flank surfaces even in the presence of relatively sharp edges. This commonly occurs at the outside diameter on involute profile tests and at the face ends on helix tests. Such apparent rounding may be eliminated by application of software corrections. Alternatively, it may simply be ignored, since the apparent rounding occurs only beyond the edge of the tooth flank. Evaluation of edge rounding or chamfer features is usually best carried out with instruments other than those intended for gear flank metrology.

Spherical stylus tips produce a higher level of mechanical filtering of test data than sharp stylus tips. In most cases, this is not a significant issue.

5.3.1.2 Spherical stylus tips used on CMM instruments

A CMM typically does not use generative methods. Rather, tooth flank geometry is considered as a series of points, each with a set of three dimensional coordinates. During such tests the points of contact between the spherical stylus tip and the tooth flanks will vary substantially. To achieve valid measurements, this contact vector variation must be accommodated by the associated computer program. Stylus tip sphericity should also be considered.

A polar CMM typically measures gear helix and involute profile according to generative methods. This involves tracing the tooth surface along a series of radial points while gear rotational position varies as necessary to maintain contact with the measurement probe.

5.3.1.3 Sharp stylus tips

Sharp (short-radius) stylus tips are often used on generative instruments, but not generally on a CMM. Sharp stylus tips are better suited to mechanical position qualification methods than spherical stylus tips. Commonly used sharp stylus tips include the chisel type and the disk (single or double conical) type.

The chisel type is relatively simple to qualify for position by contact with an accurate mandrel of known diameter. This practice is only valid if the chisel type stylus tip is kept sharp, thereby assuring that contact will occur only at the extremity of the tip. Usually, chisel-type styli are only used on involute profile testers.

Disk-type stylus tips are more challenging to produce and maintain with the required accuracy. They may be qualified for position with a mandrel, but often a special fixture is used instead. Disk-type styli are particularly well suited to instruments that test both involute profile and helix.

Compared with spherical stylus tips, sharp stylus tips are far less affected by substantial deviations of tooth flanks from involute geometry, produce less mechanical filtering of test data, and cause very little apparent edge rounding on involute profile tests. Disk-type sharp stylus tips will cause apparent edge rounding on helix tests equivalent to that caused by spherical stylus tips.

5.3.2 Data recording system

The following provides an explanation and general guidelines for critical probe measurement errors. The evaluation methods relate mainly to mechanical gear instruments using an electronic or mechanical probe system. For computer-controlled measuring systems, such as CMMs or CNC generative types, follow the manufacturer's recommendations for probe system evaluation and adjustment.

See Table 2 for probe accuracy and measuring system guidelines.

Most probe systems are bi-directional so that they can measure left and right flanks of teeth. It is important that the probe be tested in both directions. Also note that the dynamic characteristics are not verified with this test procedure.

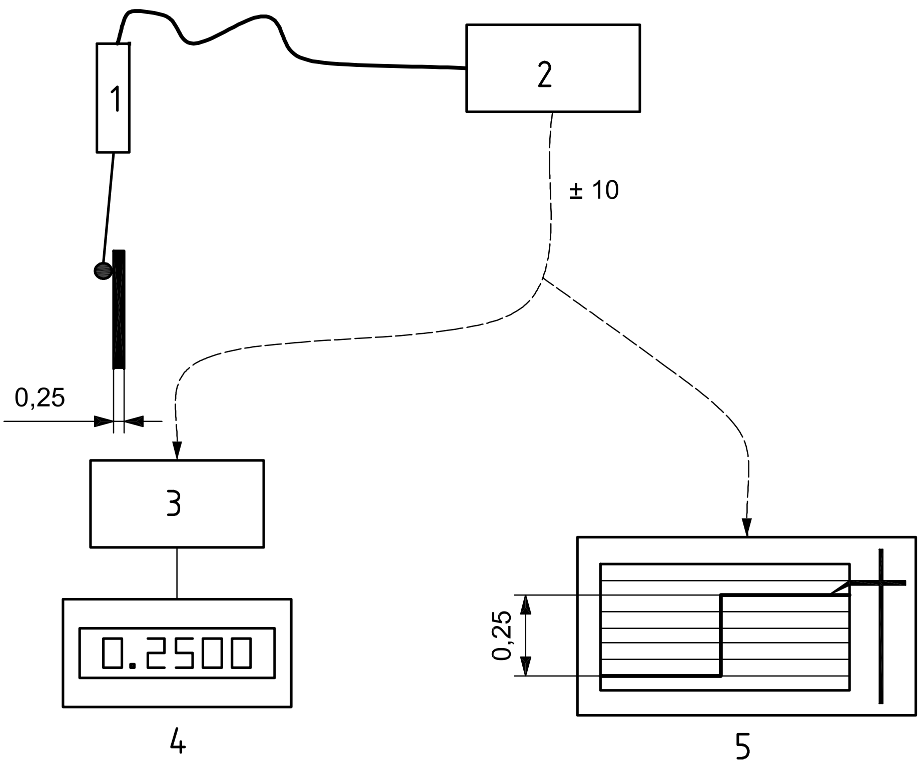
Table 2 — Probe system guidelines

Accuracy grade to be tested **ISO 1328-1** **ISO 1328-2**	**Probe gain error** (% of measurement range)	**Resolution** µm	**Lost motion** µm
2	1	0,1	0,2
3	1	0,1	0,2
4	1	0,1	0,2
5	2	0,2	0,4
6	2	0,2	0,4
7	3	0,2	0,4
8	3	0,5	0,5
9	3	0,5	0,5
10	3	1,0	1,0
11	3	2,0	2,0
12	3	2,0	2,0

5.3.2.1 Gain

Evaluation of gauging system gain involves comparing the actual probe deflection to the amount of deflection indicated by the final output device (see Figure 11). Gain should be measured by deflecting the probe an amount relative to the full system scale on each magnification available on the instrument. This should be done making sure all measurements are taken moving in the same direction. This can be accomplished using gauge blocks, a micrometre, calibrated drop or flat, axis scale, or other calibrated device. Bring the probe to a known position on one end of the scale in a predetermined direction. Using one of the above methods, bring the probe to a position at the other end of the scale approaching in the same direction as before. The gain should be adjusted as necessary to obtain an acceptable comparison between actual deflection and indicated deflection.

Dimensions in millimetres

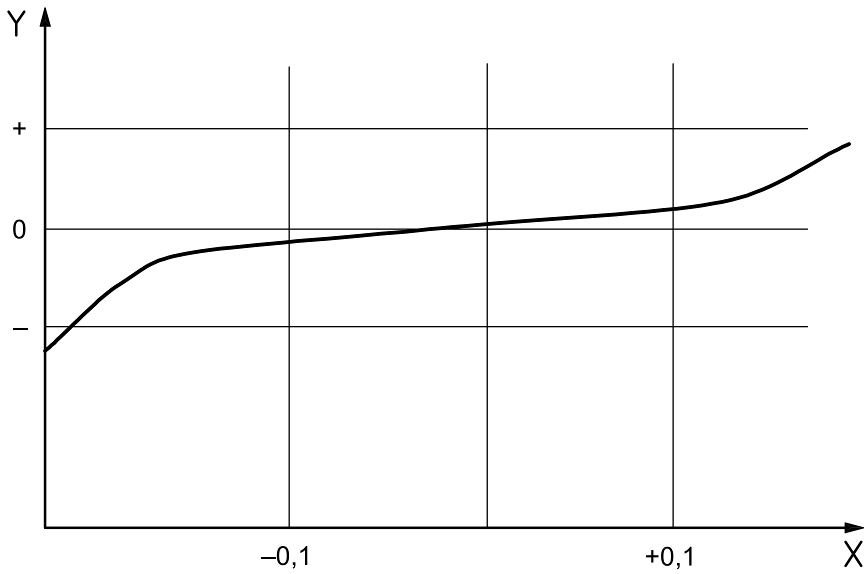


Key

1 LVDT measuring probe
2 probe amplifier (analog)
3 analog to digital converter
4 final readout device — digital
5 final readout device — strip chart

Figure 11 — Gauging system gain

In addition to this test, incremental measurements to test for linearity and bi-directional measurements to test for lost motion should be made. See Figures 12 and 13.



Key

X probe deflection, mm
Y gain error

Figure 12 — LVDT system linearity

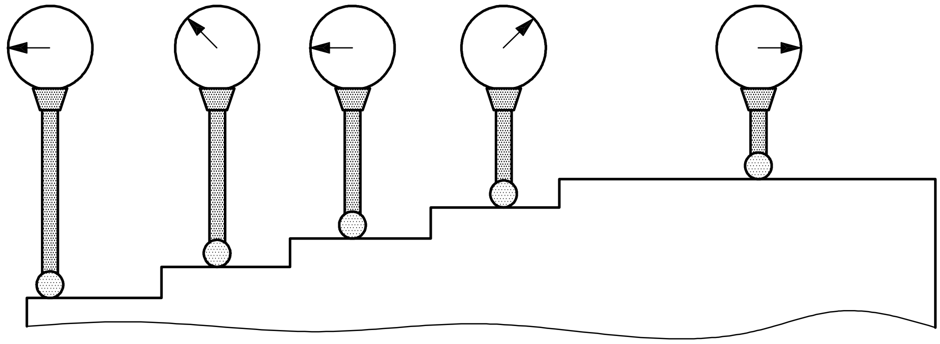


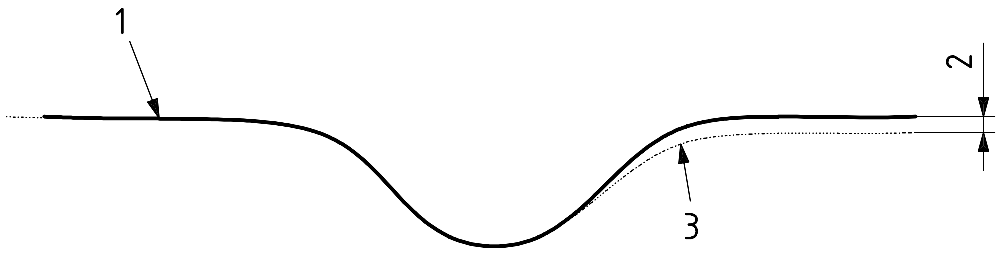
Figure 13 — Linearity with step gauge

5.3.2.2 Lost motion

Lost motion can be described as the difference displayed when the probe is at the exact same position after approaching in opposite directions. See Figure 14.

This lost motion can be determined by carefully measuring a calibrated drop in an involute profile or lead surface. Since it cannot be assumed that the surface is at exactly the same position on both sides of the drop, the depth of the drop should be measured two ways. First, bring the probe to a known position against the surface next to the drop moving in the plus direction, then measure the drop depth. Second, repeat the measurement after bringing the probe to the known position moving in the minus direction. The difference in the depth measured is lost motion.

On a tooth spacing instrument, the above artifacts cannot be used. One method would be to use a mandrel with a ground flat. Bring the probe to a known position on the concentric portion next to the flat moving in the plus direction, and rotate the mandrel to measure the flat depth. Next, repeat the measurement by bringing the probe to the known position moving in the minus direction. Again, the difference in the depth measured is lost motion.



Key

1 tooth surface with depression

2 lost motion

3 readout displayed deviation

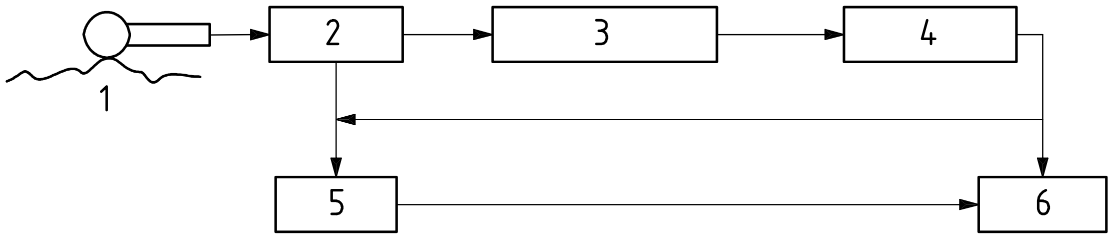
Figure 14 — Gauging system lost motion

Another method of measuring lost motion is to approach the same position on an axis scale in opposite directions with the probe against a fixed object. The difference displayed by the probe output is the lost motion. Caution should be used to ensure there is no lost motion in the axis scale/reader head, or else this method will give false results.

5.4 Filtering

Measurements include variations of many different wavelengths or frequencies. A filter that reduces short wavelength (high-frequency) data is called a low-pass filter. This is the only type of filtering commonly employed by gear metrology instruments. It tends to smooth the data and eliminate the effects of surface texture.

It is important to know the type of filtering used. There are three general categories of filtering: mechanical, electrical and mathematical. See Figure 15.



Key

1 probe tip shape — mechanical filtering

2 analog probe amplifier — electronic or mechanical filtering

3 analog to digital converter — input signal may be conditioned with active low-pass electronic filter

4 software digital filter — after conversion of deviation to numeric values, software may apply digital filtering

5 analog display — input signal may be conditioned by the electromechanical filtering of the display

6 digital display — additional digital filtering may apply to both samples

Figure 15 — Types of filtering

5.4.1 Mechanical filtering

Mechanical filtering limits the test data gathered to longer-wavelength (lower-frequency) values and is thus a low-pass type filter. This occurs when the surface of the probe tip bridges the high-frequency (short-wavelength) surface irregularities, thereby suppressing variations in that portion of the spectrum.

In most cases, the wavelengths excluded from the test data by the mechanical filtering effects of the spherical stylus tip are not significant. In applications that require inclusion of this very high frequency data, smaller stylus radii designs can be specified.

When using a small-tip, long-reach probe, care must be taken that the spring-mass inertia of the instrument probe system does not dampen the trace of the actual tooth form.

5.4.2 Electrical filtering

Electrical filtering limits the test data gathered to longer-wavelength (lower-frequency) values and is thus a low-pass type filter. During electrical filtering, the test data signal passes from the probe head through an electrical filtering (RC) circuit and finally on to the data output devices for observation.

Electrical filtering circuits are designed to accomplish the elimination of high-frequency test data at a specified wavelength called the cut-off. All data at frequencies significantly higher than the cut-off are eliminated.

An unfortunate effect of RC electrical filtering is a phase shifting of data that can influence analysis of test results.

5.4.3 Mathematical filtering

Mathematical filtering requires that test data first be converted from analog to digital to permit processing by a digital computer. Two general types of mathematical filter are commonly available. One type emulates the characteristics of electrical filters (with or without the phase shifting characteristic of RC circuits). The other type employs Gaussian mathematics. Based upon sine wave amplitude transmission characteristics and compliance with ISO standards, use of the digital Gaussian filter is recommended.

It is advantageous to be able to view the test data with different mathematical filtering applied.

5.5 Uncertainty estimation

The final procedure is to estimate the uncertainty of the measurement process. Use of artifacts such as those described in Clause 6 and measurement uncertainty estimation procedures such as those described in Clauses 7, 8 and 9 are recommended. Guidance on the determination of measurement process fitness-for-use, and recommendations for reducing measuring uncertainty, are provided in Clause 11.

6 Artifacts

A reference artifact is any suitable object having an unbroken chain of traceable calibrations with proper treatment of measurement uncertainties at each step in the chain. Reference artifacts normally comprise high-quality reference surfaces to establish a reference axis and high-quality test surfaces representative of involute helicoid gear tooth flank geometry. The reference artifacts should be similar in size and geometry to the production gears inspected on the measuring instrument. Artifacts should be stored in the same environmental conditions as the gear measuring instrument and protected from damage or corrosion.

A key characteristic of reference artifacts is their geometric stability. Adequate stability is an inherent requirement of the comparator method of measurement uncertainty estimation. Since it is very difficult to detect stability problems in reference artifacts during usage, it is important that their design, material, manufacture, and handling minimise instability.

Features of an artifact such as flank and tooth identification should be in accordance with ISO/TR 10064-1.

6.1 Mounting reference features

Artifacts are normally mounted between centres on the test instrument. This is convenient and acceptable, as are a variety of other possible configurations. However, since the physical orientation of the artifact to the instrument can affect test results, artifacts should be provided with appropriate reference surfaces to permit confirmation of proper mounting. Typically, this requirement is addressed by identifying datum diameter locations toward either end of the artifact. The amplitude and angular orientation of the runout characteristics of these reference surfaces must be included in the artifact certification data and confirmed as part of the involute profile test instrument calibration procedure.

Artifacts may also be constructed without provision for mounting between centres on the test instrument. Such artifacts must be provided with either two datum diameter locations near either end of the artifact or one datum diameter location and a datum band located on one face. Careful positioning of the artifact so as to minimize runout of the reference surfaces is required for this type artifact. Artifacts of this type must have a circular chart documenting the amount and orientation of runout of these reference features included with the certification statement.

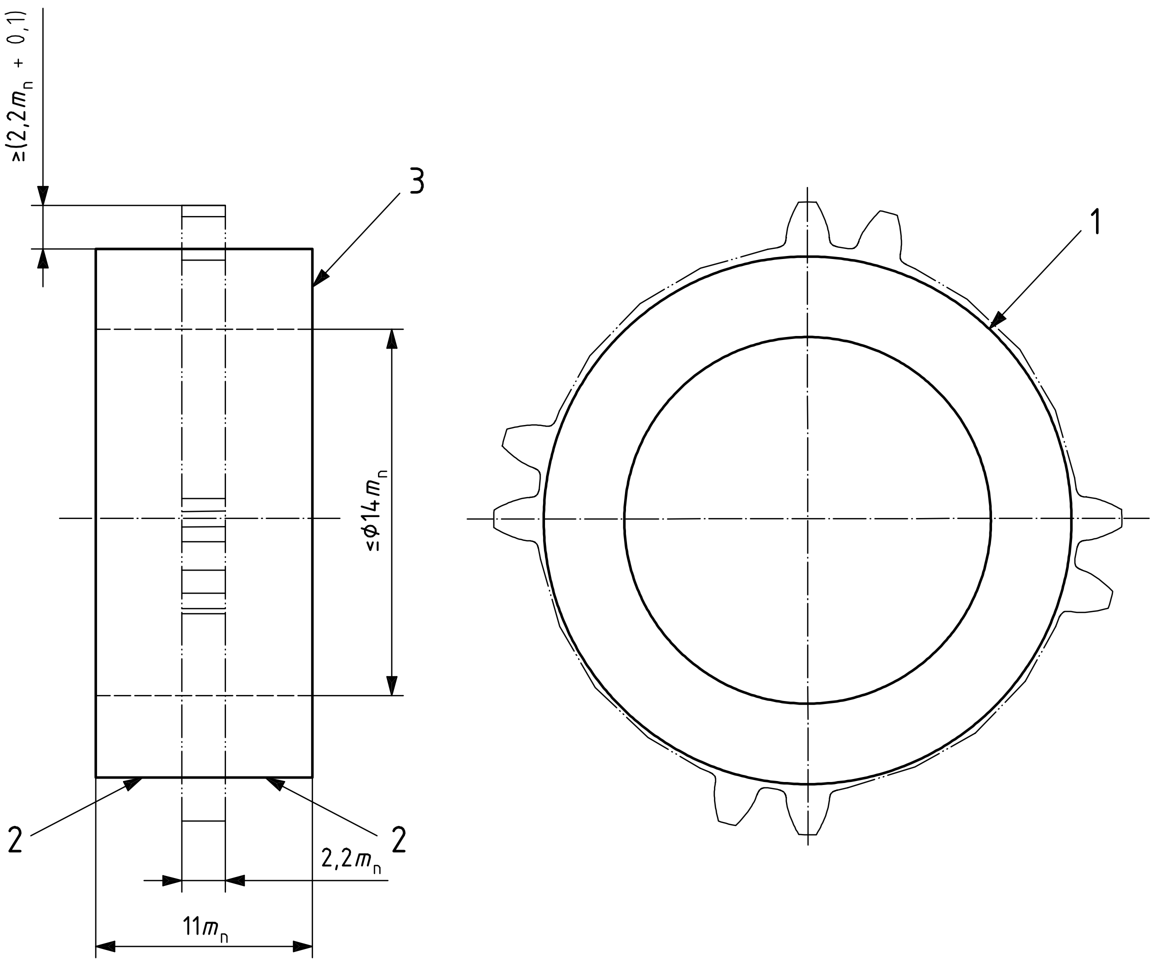
6.2 Suggested master artifacts

As indicated in ISO 18653, there are many methods and artifacts which can be used for calibration. Suggested artifact designs which use an actual involute tooth form are given in 6.2.2 to 6.2.5.

6.2.1 Integral base circle involute master

The artifact shown in Figure 16 is one way to use an actual involute tooth form. This design allows checking the involute from basic principles, by rolling and aligning on the base circle.

Dimensions in millimetres



Recommended proportions: pitch diameter at 24 m_n and standard pressure angle at 20°.

Key

1 base circle

2 radial datum

3 axial datum

Figure 16 — Proportions for involute master

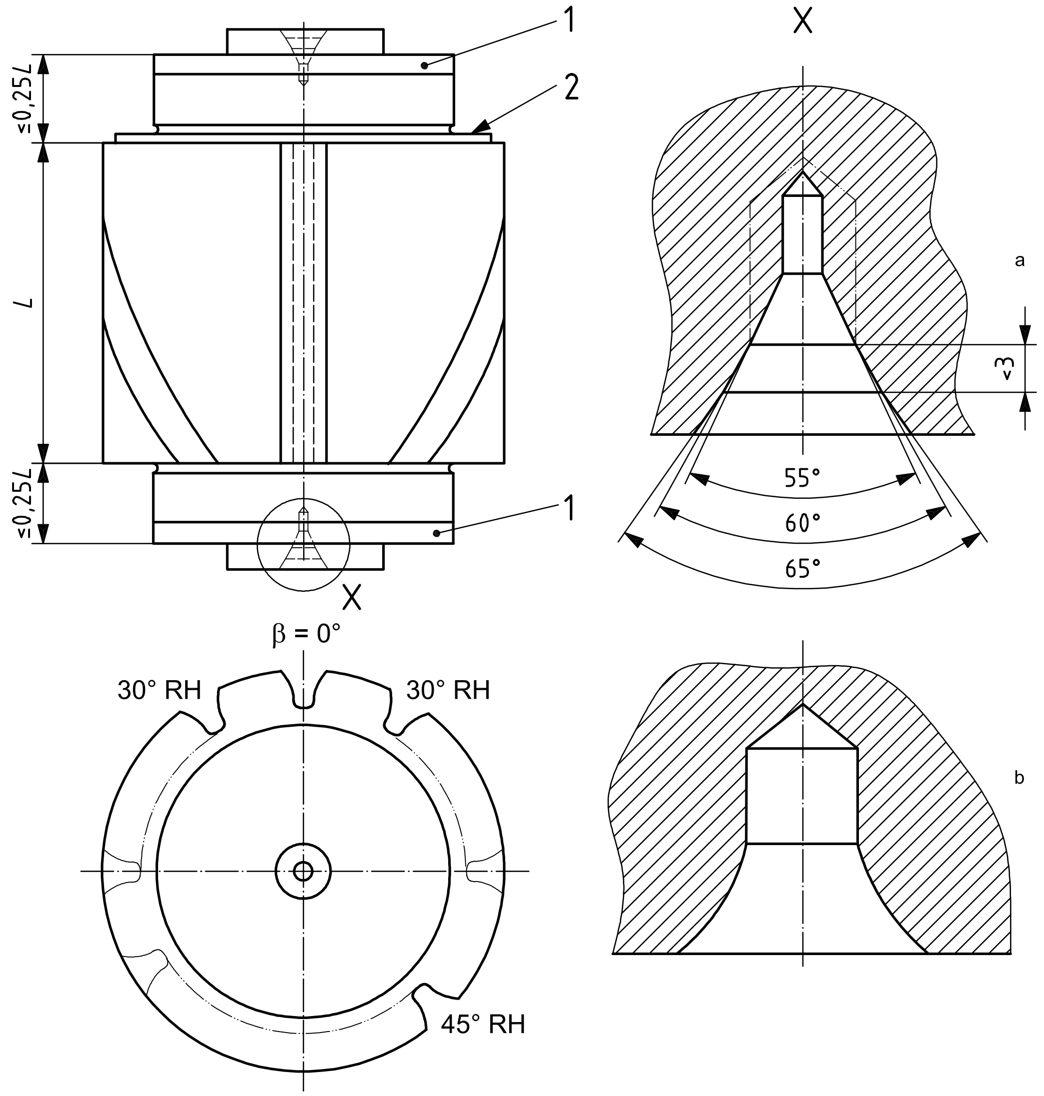
6.2.2 Helix artifact

There are many methods and artifacts which can be used for helix calibration. The artifact shown in Figure 17 is one way to use an actual helical tooth form.

This artifact can be used between centres or placed on the lower ground surface. Axial and radial reference bands have been provided for determining if the artifact is properly placed in the instrument being calibrated. Use either both radial datum surfaces or one radial and the axial surface. The artifact should have one right-hand helix, one left-hand helix and one slot with no helix. The helix angle for the RH and LH slots should be the same. They should be greater than or equal to the helix angle of the gears to be measured on the instrument.

The recommended face width is 100 mm or greater than the face width of the product gear, and the OD should be less than or equal to the length, L. The shaft extensions on either end should be no longer than 0,25 times the face width for best stability.

Dimensions in millimetres



Recommended proportions: length L = 100 mm or greater than the face width of the product gears.

The axial datum surface high spot and amount of runout, relative to centres, shall be marked on artifact.

Key

1 radial datum surface

2 axial datum surface

a Narrow band 60° centres, with minimum form error.

b Radius type centres.

Figure 17 — Proposed design for helix artifact

6.2.3 Pitch variation, total cumulative pitch variation and runout artifact

The suggested design for a calibration artifact is one way to use a gear type artifact with two different radial reference surfaces, see Figure 18.

6.2.3.1 Pitch and runout artifact description

The artifact can be mounted between centres on an arbor or placed on the lower ground surface. Axial and radial reference surfaces have been provided for determining if the artifact is properly placed in the instrument being calibrated. There are two different radial reference surfaces. The artifact is certified to each of them, independently. One radial reference surface locates the artifact with a minimum amount of pitch variation, cumulative pitch and runout. The other radial reference surface locates the artifact with a typical amount of runout. This provides a known amount of radial runout to enable checking of the instrument's software ability to calculate runout from index readings. There is also an axial reference band that must be aligned or referenced. If the artifact is mounted between centres, these reference surfaces must be properly aligned or trued to minimum runout.

The artifact should have between 18 and 30 teeth, and a prime number may be desirable. At least three successive slots (or teeth) must have numbers etched on them. This provides a reference for the starting point and sequence of measurements around the artifact, see Figure 18.

Blank proportions can vary from the proposed recommendations. The surface texture and geometry of the teeth and reference surfaces must be held to accuracy sufficient for the required calibration and uncertainty.

6.2.3.2 Certification

The artifact should be certified for maximum pitch variation, cumulative pitch variation and pitch line runout relative to both radial reference surfaces. See ISO 18653:2003, Annex A for further information. The data for right and left flanks should be identified according to the convention given in Figure B.1.

The location of pitch and runout measurements must be defined and reported on the calibration report.

6.2.4 Tooth thickness artifacts

Tooth thickness is measured in very different ways, i.e. as dimensions over pins, over balls, as span measurement or as a measurement of the angle between two flanks. On CMMs or CNC-gear measuring instruments, the dimension over balls can be measured or the measurement of the angle can be done. To verify the measuring results of these measuring instruments, a traceable calibrated artifact is necessary.

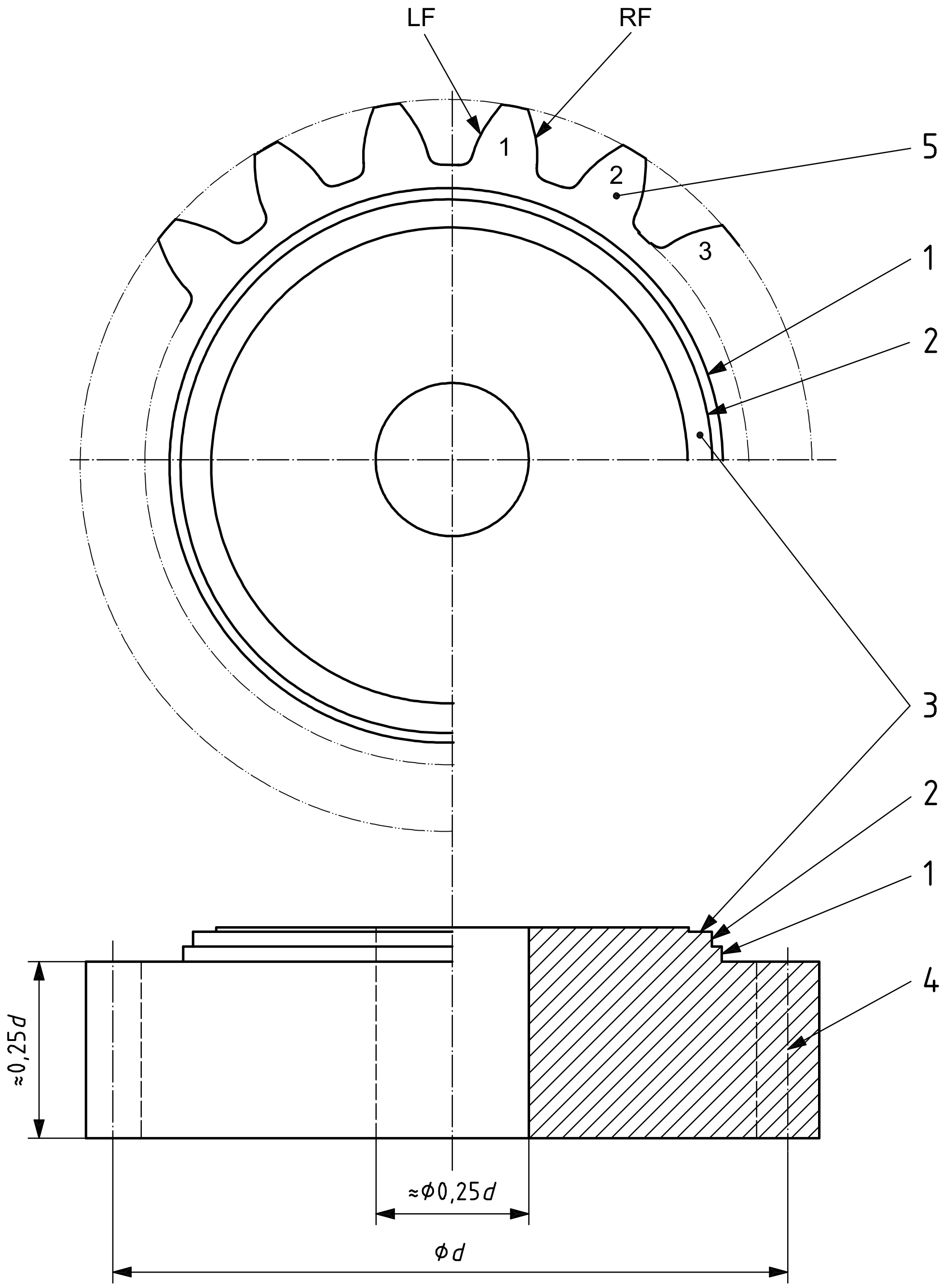
A tooth thickness artifact is a calibration artifact that provides some teeth or gaps of involute form with a right and a left flank. The tooth thickness or space width is certified as an arc at the pitch circle between the right and left flank. There should always be teeth or gaps on the opposite side so that the effects of eccentricity are minimized by calculating the mean of two opposite teeth. The use of gaps instead of teeth on the artifacts has advantages because the stiffness of the geometry is increased and the flanks are secured against damage.

When measuring the tooth thickness with different methods, it is important to touch the same points that are used for calibration. To get minimum uncertainty, the calibration of the artifact may be done with the same measuring method that is used to verify the instrument. These effects are especially important on a helical artifact. To get similar measuring results for different measuring methods, the artifact must be manufactured with minimum deviation of geometry, form, and surface texture. Refer to ISO/TR 10064-2 for recommended measuring methods and tooth thickness analysis.

6.2.5 Workpiece-like artifacts

Workpiece-like artifacts can provide every parameter measured by an instrument, namely helix, involute, pitch, runout and tooth thickness, using only one object (body). Its size and geometry should be similar or close to gears used in the production line. The artifacts can be of external or internal type. Modifications on the gear flanks are possible. It is recommended that artifacts be manufactured with stable material and measurement surfaces of minimal form and roughness errors. In addition, artifacts require reference bands of high quality in order for axial and radial runout to be determined. Usually, workpiece-like artifacts are used to easily estimate a task-specific measurement uncertainty by using the direct comparator method. As well, they are qualified for carrying out interim checks.

Master gears, commonly produced for double-flank composite testing, can be used as reference artifacts when provided with appropriate traceable calibrations. Such gears typically have high-accuracy test surfaces as well as excellent stability and durability. Usually, master gears also have high-accuracy reference surfaces.



It is recommended that there be two radial reference surfaces: one true to bore plus tooth pitch diameter, d, and a second radial reference band approximately 0,07 mm runout relative to the bore (each band 3 to 5 mm wide).

Key

1 primary radial reference (true)

2 secondary radial reference (0,07 mm Fr)

3 axial reference band

4 defined measurement location

5 reference surface

Figure 18 — Proposed design for pitch, cumulative pitch and runout artifact

6.3 Modified base circle involute artifact testing

It may be desirable to test an involute master against a larger or smaller module to produce a sloped test trace. Refer to ISO 1328-1 and ISO/TR 10064-1 for recommended methods of profile slope analysis. A calculation to provide an amount of slope, $\Delta f_{\text{H}\alpha}$, introduced into the involute test trace by using a module change is:

$$m_{\text{n2}} = m_{\text{n1}}\left[1-\left(\frac{\Delta f_{\text{H}\alpha}}{L_{\alpha}}\right)\right] \tag{7}$$

where

m_{n1} is the normal module associated with the calibration data;

m_{n2} is the normal module to generate the modified slope deviation;

L_{α} is profile evaluation range.

All other gear parameters must remain constant.

It should be noted that this method changes the lead as well as the base diameter. Helix test results also will be affected by this change in the normal module. Another method is provided in Annex B that achieves the change in base diameter by modification of the normal pressure angle instead of the normal module, thereby maintaining the same lead.

Changes in modules that produce slope deviations significantly in excess of those measured on product gears measured by the given instrument are not recommended. It is necessary to verify that the limits of evaluation are at the correct diameter after the module and base diameter are changed. This process should only be applied to gears or gear artifacts with small form errors, and where the limits of profile evaluation lines are clear of the base diameter and tip diameter.

6.4 Non-involute — Pin (cylindrical), plane (flank) and ball (spherical) artifacts

A non-involute artifact is a calibration artifact which provides a feature of known form other than involute. In practice, the known non-involute form is tested by an involute profile testing instrument which has been configured to generate a true involute form reference associated with a specified base circle. The deviation of the given non-involute form from the specified involute form can be calculated thereby defining the correct test result values which should be produced by the instrument. Certification of non-involute artifacts involves both the metrological analysis of the given artifact feature geometry and calculation of the feature's deviation from a specified involute.

6.4.1 Types of non-involute artifacts

Non-involute artifacts may take a variety of forms. The most common are plane artifacts (also known as flank artifacts, see Figure 19) and pin artifacts (see Figures 20 and 21). Another design is the ball artifact (see Figures 22). Plane artifacts consist of a flat-surface feature which represents a plane parallel to, and offset from, the artifact axis of rotation. Pin artifacts consist of a pin feature that represents a cylinder with its axis parallel to, and offset from, the artifact axis of rotation. Ball artifacts consist of two ball features, one of which defines the artifact axis of rotation and the other which represents the measured surface. Plane, pin and ball artifacts serve similar functions in calibration of involute profile testing instruments.

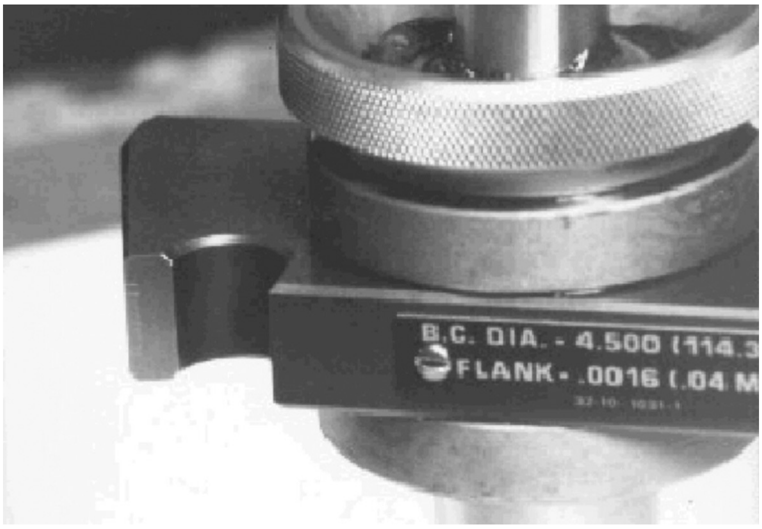


Figure 19 — Plane artifact (flank artifact)

Figure 20 — Pin artifact

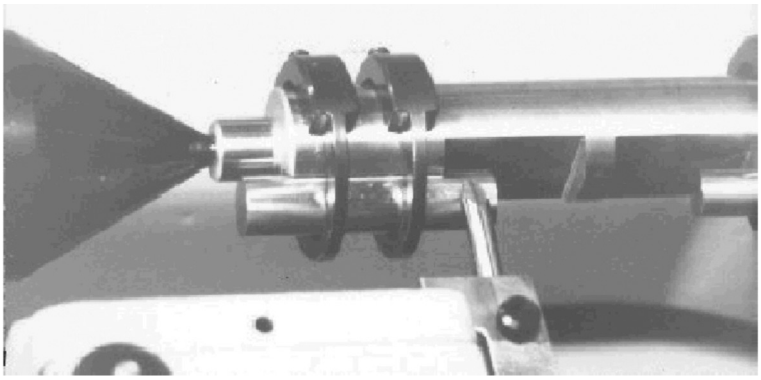


Figure 21 — Measurement of pin artifact

Figure 22 — Ball (sphere) artifact

6.4.2 Non-involute artifact function

Direct calibration of involute profile testing instruments may be accomplished by use of a certified involute artifact. Instrument calibration can be further enhanced by the use of a non-involute (plane/pin/ball) artifact. Non-involute artifact test results provide a collective observation of instrument conformance including all the instrument's individual sources of variation. However, unlike the involute artifact, the non-involute artifact combines the individual sources of variation in a proportion which does not directly relate to the instrument's ability to generate a specified reference form. Certain sources of variation, in particular measurement probe position variation, have an exaggerated effect. It is this characteristic which permits further refinement of involute profile test instrument calibration through observation of non-involute artifact tests.

Non-involute artifact testing is directly affected by slope or ratio type variations of the instrument in the same manner as involute artifact testing. This category of error is recognized by a progressive trend of the test trace away from the nominal reference as the test proceeds. However, the involute artifact is a preferable reference for this observation since it is simpler and more direct to reference the basically straight involute trace than the highly curved non-involute artifact trace.

The non-involute artifact can also serve as a reference for observation of form or localized variations. However, owing to the highly curved form of the non-involute artifact trace, involute artifacts manufactured with minimum deviation from specified nominal are preferred.

The characteristic trace of a pin or ball artifact is a smooth curve which includes two trend reversals of significant amplitude. This form is recommended as an excellent reference for observation of instrument variations of hysteresis or gain. The plane artifact trace which provides only a single trend reversal before the maximum diameter is encountered is not an appropriate reference for instrument gain.

The non-involute artifact is far more sensitive to variations of instrument probe-tip location than an involute artifact. It is particularly sensitive to positioning variation of the probe tip from the correct location within the plane of action tangent to the base cylinder of the specified involute. The non-involute artifact is the recommended reference for observation of this category of instrument variation.

6.4.3 Plane artifact calibration

Plane artifact calibration involves dimensional testing and certification of the following geometry parameters.

- **Plane flatness.** Any deviation in plane flatness in the testing location area will affect the instrument calibration on a direct one-to-one basis. Such deviations are not normally included in calculations of plane artifact deviation from the specified involute. It is therefore important that the plane surface be manufactured with minimum flatness deviation and certified in the testing location area.

- **Plane offset.** The plane artifact must be constructed with the plane test surface parallel to the reference axis of the plane artifact. The offset dimension of the plane test surface to the rotational axis of the artifact must be known in order to calculate the deviation of the plane artifact from the specified involute. The certification should therefore list this information. Variation of the offset dimension from the certified dimension will have only a very fractional effect upon the functional accuracy of the plane artifact as it is employed in the calibration of involute profile testing instruments.

6.4.4 Pin or ball artifact calibration

Pin or ball artifact calibration involves dimensional testing and certification of the following geometry parameters.

- **Pin or ball roundness.** Any deviation in pin or ball roundness in the testing location area will affect the instrument calibration on a direct, one-to-one basis. Such deviations are not normally included in calculations of pin or ball artifact deviation from the specified involute. It is therefore important that the pin or ball be manufactured with minimum roundness deviation and certified in the testing location area.

- **Pin or ball diameter.** The pin or ball diameter in the testing location area must be known in order to calculate the deviation of the pin or ball artifact from the specified involute. The certification should therefore list this information. Deviation of the pin or ball diameter from the certified dimension will have only a very fractional effect upon functional accuracy of the pin or ball artifact as it is employed in the calibration of involute profile test instruments.

- **Pin axis.** The pin artifact must be constructed with the axis of the pin parallel to the reference axis of the pin artifact.

- **Pin or ball offset.** The offset dimension of the axis of the pin or ball to the rotational axis of the artifact must be known in order to calculate the deviation of the pin or ball artifact from the specified involute. The certification should therefore list this information. Deviation of the offset dimension from the certified dimension will have an effect (roughly 50 %) upon the functional accuracy of the pin or ball artifact as it is employed in the calibration of involute profile testing instruments.

6.4.5 Probe-tip effects when calculating reference curve

If the non-involute artifact is to be employed for calibration of generating-type, involute-profile test instruments which employ spherical-gauge probe tips, the diameter of the tip must be known to permit calculation of associated contact vector deviations. The calculations of non-involute artifact deviation from the specified involute must be compensated according to the vector deviations. Certification of spherical-probe-tip diameter is typically carried out separately from non-involute artifact certification measurements. However, the data must all be available for complete and accurate calculations of non-involute artifact deviation from the specified involute. Deviation of the probe-tip diameter from the certified dimension will have only a very fractional effect upon the accuracy of the non-involute artifact test.

Probe-tip sphericity in the testing location area will affect instrument calibration on a direct one-to-one basis. Since sphericity deviations are not normally included in the calculations, it is important that the tip be manufactured with minimum deviation and certified accordingly.

6.4.6 Measurement location

It may be desirable to limit testing of the non-involute artifact to a specified axial location to minimize the effects of manufacturing deviations.

6.4.7 Non-involute master interpretation

Non-involute masters (plane, pin and ball masters) provide highly curved test traces which respond in an exaggerated manner to certain categories of test instrument variation. Included are measurement probe position variation, gain variation and hysteresis variation. It is best to restrict observation of test traces of non-involute masters to these characteristics.

The test instrument must achieve satisfactory performance in testing of involute masters before further refinement is attempted by use of non-involute masters. Furthermore, if certain types of adjustments are made to the instrument to improve non-involute master tests, retesting of the involute master will be required because of the interactive nature of such adjustments. Non-involute masters can be a valuable tool in the hands of a skilled gear metrologist, but they must be employed with caution. See Annex C for non-involute master interpretation.

6.5 Helix artifact testing

6.5.1 Modified-lead helix artifact testing

It may be desirable to test a helix artifact against a longer or shorter lead to produce a sloped trace. Refer to ISO/TR 10064-1 for recommended methods of slope analysis. The example calculation of Equation (8) provides a method of estimating the amount of slope introduced into the helix test trace by lead modification.

Calculation required to determine a modified lead that would produce the desired amount of helix test trace slope modification, $\Delta f_{H\beta}$:

$$\sin\beta_2 = \sin\beta_1\left(1 - \frac{\Delta f_{H\beta}}{L_\beta \tan\beta_b}\right) \tag{8}$$

where

L_β is the helix evaluation range;

β_b is the base helix angle, $\beta_b = \arcsin(\sin\beta \cos\alpha_n)$;

β_1 is the helix angle associated with the calibration data;

β_2 is the helix angle to generate the modified slope deviation.

NOTE 1 When $\Delta f_{H\beta}$ is positive, the trend of the helix slope deviation correlates with a positive (larger) helix angle deviation and a negative (smaller) lead deviation, and vice versa. The associated plus or minus material trend of the test trace is dependent upon the hand of the helix, the flank being measured, and the direction of the test trace.

NOTE 2 The $\Delta f_{H\beta}$ deviation is in a transverse plane, on a line tangent to the base diameter. Calculations assume that the instrument is configured to report deviations in that direction.

All other gear parameters must remain constant.

It should be noted that this method changes the base diameter as well as the lead. Involute profile test results will therefore also be affected by this change of helix angle. A method is provided in Annex B that achieves the change in lead by modification of multiple parameters, thereby maintaining the same base diameter.

Changes that produce slope deviations significantly in excess of those measured on product gears measured by the given instrument are not recommended. This process should only be applied to gears or gear artifacts with small form errors. It is necessary to verify that the diameter of measurement is correct after the helix angle is changed.

6.5.2 Non-involute helix masters

There are helix masters that have straight line profiles in the transverse plane. The helical surface looks like a small chamfer at the corner of a slot. Typically, only the lead of this surface is specified. This requires the use of special software for calibration, or the use of gear parameters that represent an involute gear surface which is tangent to the straight line profile at the measurement diameter.

6.6 Modified eccentricity pitch artifact testing

As discussed in ISO 18653, it may be desirable to measure a pitch artifact with additional eccentricity induced. The effect of the added eccentricity on pitch and total cumulative pitch (total index variation) can be determined by using calculations described in the example provided in Annex B.

On instruments where the artifact must be physically positioned true to the axis of rotation, eccentricity must be induced through physical displacement of the artifact. On equipment where the instrument is mathematically aligned to the artifact datums (CMMs), the eccentricity may be induced by mathematical displacement of the part coordinate system.

7 Uncertainty estimation guidelines

The estimation of U_{95} uncertainty is to determine how various sources of error combine to affect measurement processes. When a calibration document or inspection report states a U_{95} measurement uncertainty, it certifies that the measured values will be valid, within the stated limits, at a 95 % confidence level.

The determination of measurement uncertainty is closely tied to instrument calibration; it could be said that an instrument has been calibrated once its measurement uncertainty has been determined. However, it is important to understand that many factors beyond performance of the given instrument can influence the uncertainty of a measurement process. Often, the contribution of the instrument is small compared to other sources. Therefore, it is better referring to the uncertainty of a measurement process rather than to the uncertainty of an instrument.

Application of any measurement uncertainty calculation will always be limited. These limitations vary considerably depending on the method used. Any document stating the results of an instrument calibration or measurement process uncertainty estimation shall provide the associated limitations of applicability, including the measurement parameters, size of the measuring envelope, configurations of instrument hardware and software, and environmental conditions.

The uncertainty estimation methods described in this clause comply with GUM.

7.1 Uncertainty estimation methods

Methods for estimating measurement uncertainty vary greatly as to complexity, validity, and scope of applicability. Typically, increased validity is achieved only with increased complexity or decreased scope of applicability. Selection of an uncertainty estimation method involves striking a balance between these factors.

This document provides a range of example measurement uncertainty estimation methods. Some methods are suitable for use in product gear measurement operations. Others require complex analysis of measurement processes and are only appropriate for high-level measurement operations such as those involved in calibration of reference gear artifacts.

7.1.1 General methods

In some cases, a given instrument is used for a very broad scope of measurement applications including tasks other than gear measurement. This often occurs for a CMM. A common approach to this requirement is application of a single, highly non-specific, method of measurement uncertainty estimation, which can accommodate the very broad scope of applicability. Such methods typically involve substantial complexity and limited validity. Examples of general methods are the global, modified global, decomposition and surrogate approaches.

7.1.2 Comparator methods

When the scope of applicability of the measurement uncertainty estimation is limited to gear measurement, the comparator method may be used. It can usually increase validity while significantly reducing complexity. The comparator method evaluates the measurement process by use of a calibrated artifact with gear tooth geometry.

It is important to consider the configuration, geometric accuracy, surface finish and stability of any gear or gear artifact used in estimation of measurement uncertainty by the comparator method. See 5.1.

It should be noted that the uncertainty of the reference artifact calibration is always a subset of, and thus always smaller than, the resulting uncertainty value for the given measurement process.

7.1.2.1 Direct comparator method

Direct application of this method requires that the calibrated reference artifact and subsequent work pieces have equivalent specified geometry and quality level. Often this is the case for intermediate-level gear artifact calibration laboratories. Use is made of a reference artifact, calibrated by a primary calibration laboratory, to calibrate the process that will subsequently be used to calibrate equivalent working reference artifacts. This method may also be applied to certain product gear measurement operations.

Use of the direct comparator method is desirable, owing to its relatively low complexity and high validity.

7.1.2.2 Expanded comparator methods

The comparator method may be expanded to include the measurement of workpieces that are significantly different from the artifact used to calibrate the measurement instrument. This is considered valid, so long as the differences between the work piece and the reference artifact are within limits specified in the uncertainty statement.

The disparity between reference artifact and measured workpieces can take two general forms. One is called geometry similarity influence, u_{g}, and includes consideration for differences such as diameter, module, face width, and helix angle. The other is called workpiece characteristic influence, u_{w}, and includes differences associated with such items as surface finish and accuracy grade. These differences necessitate the application of more complex variations in the uncertainty estimation and usually result in larger uncertainty values. When the scope of application is broad, use of multiple sizes and configurations of reference artifacts is usually required. Also, it may be necessary to include measurements of sample workpieces in addition to reference artifact tests.

7.2 Calculation of U_{95} measurement uncertainty

Equations used for calculation of U_{95} measurement uncertainty vary considerably. The general form of the uncertainty equation for comparator methods is shown in Equation (9):

$$U_{95} = \left[k \left(u_{\mathrm{m}}^2 + u_{\mathrm{n}}^2 + u_{\mathrm{g}}^2 + u_{\mathrm{w}}^2 \right)^{0,5} \right] + |E| \quad (9)$$

Where — depending on the particular method being used, the following components, which represent sources of measurement uncertainty, may be included in the given uncertainty calculation —

U_{95} is the measurement uncertainty, the expanded uncertainty of the given measurement process with a 95 % confidence level;

k coverage factor — usually set to k = 2, thereby producing an expanded uncertainty value with a confidence level of 95 %;

u_{m} is the standard uncertainty, the variability of a series of measurements (reproducibility) made on the same workpiece by the given instrument;

u_n is the reference artifact calibration uncertainty; the U_{95} value should be clearly stated on the reference artifact calibration document and the division by 2 of this value produces u_n;

u_g is the geometry similarity influence, the uncertainty associated with dissimilarity between the reference artifact and measured workpiece geometry;

u_w is the workpiece characteristic influence, the uncertainty associated with dissimilarity between the reference artifact and measured workpiece, such as surface finish and accuracy grade;

E is the bias (accuracy), which is the offset of the average value of a series of measurements made by the given instrument from the calibrated value of the measured reference artifact.

In some cases the bias will, in practice, be adjusted out of the measurement process, either by adjusting the instrument or compensating the results. For involute gear measurements, bias should only be compensated in slope and tooth thickness measurements. In other cases, bias should be included in the estimation of uncertainty.

All the parameters, except for bias and coverage factor, are normally entered into the calculations as standard deviations. The standard deviation is a statistical parameter that is commonly used to evaluate consistency. The combination of standard deviations is properly done by a sum-of-the-squares method. The result is a composite standard deviation value applicable to the given measurement process as a whole.

With the application of a coverage factor of $k = 2$, the final U_{95} value for the process will be reported as a 2 s (two standard deviations) value. Statistically, this confers a 95 % confidence level that the measurements made by that process will be within the ± 2 s limit.

If a different confidence interval is used, the coverage factor k value may be changed (such as $k = 3$ gives a $U_{99,7}$ or 99,7 % confidence interval, often used for proving machine tools).

7.3 Measurement parameters

Measurements of gear tooth surface shape or position must be analyzed according to standardized methods to produce consistent numerical values. These values can be compared to tolerances to determine fitness for use of the workpiece. Additionally, they may be used in estimation of measurement uncertainty. A great variety of such measurement parameters are available. Selection of such parameters for measurement uncertainty estimation will affect the resulting U_{95} values.

7.3.1 Line-fit parameters

A standardized method of analyzing profile and helix test traces is by line fitting. This method provides a specified shape line that is considered the design (ideal) shape of actual work piece test traces. In practice, this specified reference line is fit to each individual test trace, typically by the method of least squares. Various analysis methods can then be used to measure the relationship between the best-fit specified reference line and the actual traces. Common measurement parameters using the line-fit method include total, slope and form deviations, such as those described in ISO 1328-1.

The form deviation quantifies the conformity of the shape of test traces with that of the specified reference line. This parameter cannot be compensated for bias E. For high accuracy applications, it may be desirable to devise form measurement evaluation methods using surrogate artifacts, such as pin, ball or plane masters, having simpler geometry than gears, that can be produced with much lower form error.

The slope deviation quantifies the conformity of the orientation (tilt) of test traces with that of the specified reference line. It is sometimes possible to compensate this parameter for bias E.

The total deviation is essentially a composite observation, quantifying the combined effects of form and slope deviations. If E of the slope deviation is compensated, it may thereby affect the total deviation parameter. However, since form deviation is also a component of total deviation, it is not possible to fully compensate the total deviation parameter for bias.

The inherent composite nature of the total deviation parameter makes it a desirable choice for estimation of measurement uncertainty. When the U_{95} uncertainty of a process is estimated for the total deviation parameter, it may be assumed that the measurement uncertainties for form and slope deviations will be equivalent or smaller.

7.3.2 Band-fit parameters

Another standardized method of analyzing profile and helix test traces is by band fitting. This method provides a specified size and shape band within which each individual test trace must fit if it is to be considered acceptable. Since the result of this measurement parameter is only a pass or fail observation, it is not appropriate for statistical analysis including estimation of measurement uncertainty.

7.3.3 Pitch parameters

Two standardized methods of analyzing gear tooth position or pitch are single pitch and total cumulative pitch, as described in ISO 1328-1. The single pitch deviation parameter quantifies the conformity of positions of an adjacent pair of teeth to their proper positions, as determined by dividing a pitch circle by the number of teeth in the gear. The cumulative pitch deviation parameter quantifies the conformity of any two nonadjacent teeth to their proper positions. This observation is also based upon division of a pitch circle by the number of teeth.

When performing repeated measurements of the pitch deviations of a gear, very small variations in measurements may result in values for different pairs of teeth being reported. In estimation of measurement uncertainty of pitch parameters, it is important to restrict observations to specified teeth.

When the U_{95} uncertainty of a process is estimated for the cumulative pitch deviation parameter, it may be assumed that the measurement uncertainties for single pitch deviations will be equivalent or smaller.

8 Measurement procedures

8.1 Traceability

All equipment used for measurement uncertainty estimations shall be traceably calibrated to a national standard. See ISO 18653, Clause 4.

8.2 Operating conditions

Two sets of operating conditions must be considered: those associated with determination of bias, E, and those associated with estimation of standard uncertainty, u_m. In some cases, these may be combined.

8.2.1 Conditions for bias determination

The operating conditions during measurements of reference artifacts that will be entered into calculations of E should, as nearly as possible, conform to the conditions specified in the artifact calibration documents. This applies to measurement process factors such as mounting conditions, test location, and measurement parameters. Also, measurement values should be compensated for temperature effects (see 4.2).

8.2.2 Conditions for standard uncertainty estimation

The operating conditions during measurements of either reference artifacts or other workpieces that will be entered into calculations of standard uncertainty, u_m, should as nearly as possible reflect the conditions that will be specified in the resulting U_{95} measurement uncertainty statement. Measurement process factors that could significantly influence measurement values should be permitted to vary within specified limits. This applies to environmental conditions, instrument condition, mounting conditions including test arbors and fixtures, and test operators. For best validity, tests should be made over a significant period of time. Measurement values should not be compensated for temperature effects unless all measurements made subject to the given uncertainty statement will also be compensated.

8.2.3 Conditions for combined determinations

When the operating conditions required for measurements leading to calculation of bias and standard uncertainty are equivalent, a single set of measurements can be carried out to fulfil both requirements. This equivalence obligation may apply to a variety of factors, including mounting conditions, measurement parameters, and environmental conditions. Also the size, configuration and accuracy grade of the reference artifact must meet the equivalency requirements.

8.3 Measurements

Carry out a preliminary visual inspection of the instrument and required apparatus to confirm the absence of unusual wear or damage. Initialize the instrument and carry out required procedures such as probe qualification.

The minimum number of measurements for U_{95} measurement uncertainty estimation shall be ten. Improved validity could be achieved by additional measurements, to a point of diminishing returns at about thirty. The artifact or workpiece should be fully dismounted and remounted, including arbors or fixtures if included in the procedure, between each test. Measurements should be made at a number of different positions on the instrument, covering the range of positioning of workpiece measurements that will subsequently be used. When possible, measurement of the reference artifact should include an inverted orientation. It is also advisable to make the measurements over a period of time, e.g. several days, to include the effects of the stability of the measurement process. The data should be plotted to see if it is a normal distribution, for validity.

8.4 Calibration procedure

Typical calibration procedures used in initial and ongoing evaluation of an instrument should be accomplished in accordance with instrument manufacturer’s recommendations, if available.

8.4.1 Initial set-up and adjustments

The considerations of the procedure are the following:

- to calibrate, the environment and measurement system conditions should be established in accordance with Clauses 4 and 5;
- an initial statistical evaluation of the measuring instrument is made, using the calibration artifact, while additional evaluation with other artifacts, as outlined in Clause 10, is desirable.

8.4.2 Initial calibration procedure

A minimum of ten individual checks is required, without any instrument calibration adjustments. For each of these, the following steps apply.

a) Set up the instrument to measure the artifact.

b) Place the calibration artifact in the instrument.

c) Measure and record desired parameters.

d) Break down the set-up.

e) Repeat steps a) to d) at least nine times.

f) Plot the data points on an X and MR chart as outlined in Clause 10.

g) Examine the control chart, to see if it meets the requirements outlined in 10.3. Evaluation of the control chart may indicate the need for additional data points and re-evaluation.

h) If required, make system adjustments. Do not continue if the system is out of control. If control adjustments are required, determine assignable causes, correct, and repeat the above steps;

i) Adjust bias, if required, and verify.

At this point, the instrument may be considered calibrated and fit for evaluation in accordance with specifications.

8.4.3 Ongoing calibration procedure

To maintain statistical confidence in the instrument's fitness for use, ongoing calibration is necessary. The interval between measurements of the artifact may be extended when supported by data, for example, once per shift, daily, weekly. When statistics show that bias adjustment is necessary, measurement of the artifact should be performed more frequently, see Clause 10 and ISO 18653.

The X and MR chart is extended and new control limits calculated with each measurement, using up to 100 previously recorded data points.

The procedures outlined in Clause 10 should be repeated on a regular basis.

At any time while measuring product, questionable data may indicate that a calibration check is necessary.

8.4.4 Tooling and gauges

Any tooling or gauges used in the set-up or calibration of a measuring instrument should also be calibrated on a regular basis.

9 Comparator measurement uncertainty estimation guidelines

This clause provides a range of guideline measurement-uncertainty-estimation cases. It does not cover all possible cases.

9.1 Direct comparator example A

One example of a direct U_{95} uncertainty estimation method is provided. It may be used when measuring workpieces that are equivalent to, but not the same as, the reference artifact used to calibrate the measuring process. This procedure can provide good validity with minimal complexity within its limited scope of applicability. It provides some range of application while requiring use of only one reference artifact.

To meet the geometry equivalency requirement, the pitch diameter, module, face width, and helix angle of the given workpiece should be within ± 25 % of those specified parameters for the reference artifact. Above a 10 % difference a consideration should be given to the addition of another uncertainty component. Inclusion of other geometry equivalency requirements, such as mass and test location, may also be desirable.

To meet the characteristic equivalency requirement, the specified accuracy of the workpiece should be grade 5, or better, in accordance with ISO 1328-1, and have a measurement surface roughness, Ra, of 0,4 µm or better.

NOTE The equivalency obligation factors listed here have been arbitrarily selected for this example. The exact factors used may vary according to the application being considered.

The calibration procedure can be carried out as follows.

a) Perform a series of measurements on the calibrated reference artifact following the procedure outlined under Clause 8. The minimum number of measurements is ten.

b) Determine the mean value, X, of the results produced in step 1. The bias, E, is then found by subtracting the calibrated value of the reference artifact from the mean value of the results.

c) Determine the standard uncertainty, u_m, of the results produced in step 1 using Equation (10):

$$u_\mathrm{m} = \left(\sum_{i=1}^{n} \frac{\left(X_\mathrm{i} - \overline{X} \right)^2}{n-1} \right)^{0,5} \tag{10}$$

where

u_m is the standard uncertainty;

X_i is the individual measured value of the parameter calibrated;

$\overline{X}$ is the mean of measured values;

n is the number of measurements.

d) Determine the reference artifact calibration uncertainty, u_n, associated with the calibration of the reference artifact using Equation (11):

$$u_\mathrm{n} = \frac{U_{95(\mathrm{cal})}}{2} \tag{11}$$

where

u_n is the reference artifact calibration uncertainty;

$U_{95(\mathrm{cal})}$ is the U_{95} measurement uncertainty stated in the reference artifact calibration document.

e) Determine the U_{95} measurement uncertainty for this method using Equation (12) or (13), depending on whether bias, E, will be eliminated:

Equation (12) is applicable only when bias determined in step 2 is eliminated from this measurement process, either by adjusting the operation of the instrument or compensating the results.

$$U_{95} = 2\left(u_\mathrm{m}^2 + u_\mathrm{n}^2 \right)^{0,5} \tag{12}$$

Equation (13) is applicable when bias determined in step 2 is not eliminated from this measurement process.

$$U_{95} = 2\left(u_\mathrm{m}^2 + u_\mathrm{n}^2 \right)^{0,5} + \left| E \right| \tag{13}$$

Numerical example: The results from measuring profile slope deviation, $f_{H\alpha}$, on a calibrated left flank of a spur gear (Normal module, m_n = 3,0 mm, number of teeth, z = 33; pressure angle, α_n = 20°; Helix angle, β = 0°), ten times, are given as:

Item	Test										Mean $\bar{X}$	Standard uncertainty u_m
	1	2	3	4	5	6	7	8	9	10		
$f_{H\alpha}$	2,3	2,4	2,4	2,8	2,8	2,6	1,5	2,8	1,7	1,9	2,32	0,47

The calibration value of $f_{H\alpha}$, X_{cal}, is 3,3 µm with a U_{95} of ± 1,5 µm (standard uncertainty 0,75 µm).

The data is used in this example and is summarized as follows.

Measured data: $\bar{X}$ = 2,32 µm, standard uncertainty 0,47 µm.

Calibration data: X_{cal} = 3,3 µm, U_{95} = ± 1,5 µm (standard uncertainty 0,75 µm).

If the bias in the measurement process is compensated or adjusted, Equation (12) may be used yielding the following results.

$$U_{95} = 2\left(0{,}47^2 + 0{,}75^2\right)^{0{,}5} = \pm 1{,}77 \text{ µm}$$

If the bias determined by the calibration artifact is not eliminated, the measurement uncertainty may be estimated using Equation (13).

The bias, E, is found by subtracting the calibrated value of the reference artifact from the mean value of the results.

$$U_{95} = 2\left(0{,}47^2 + 0{,}75^2\right)^{0.5} + \left|0{,}98\right| = \pm 2{,}75 \text{ µm}$$

9.2 Comparator approach, expanded for workpiece characteristic influence

Two example expanded U_{95} uncertainty-estimation methods are provided that may be used when the measuring process in question will be applied to workpieces that meet equivalency requirements for geometry, u_g, with the reference artifact used to calibrate that process, but which do not meet equivalency requirements for characteristics, u_w. Example geometry and characteristic equivalency requirements are offered in 9.1.

9.2.1 Comparator example B

This method accounts for the influence of workpiece characteristic (accuracy grade and surface finish) by modification of the standard uncertainty u_m estimation method so that the characteristic effects will be included in those observations. The workpiece characteristic influence, u_w, will therefore not be estimated as a separate variable in the calculation of U_{95} measurement uncertainty. This procedure can provide good validity with moderate complexity within its moderate scope of applicability. It provides good range-of-characteristic applicability with limited range of geometry applicability. Only one reference artifact is required.

The calibration procedure can be carried out as follows.

a) Perform a series of measurements on the calibrated reference artifact following the procedure outlined in Clause 8. The minimum number of measurements is ten.

b) Determine the mean value, $\bar{X}$, of the results produced in step a). The bias, E, is then found by subtracting the calibrated value of the reference artifact from the mean value of the results.

c) Select a workpiece with a specified accuracy grade and surface finish that is equivalent to the worst accuracy grade and surface finish that will be included in the scope of application specified for this uncertainty estimation. Perform a series of measurements on the selected workpiece following the procedure outlined in Clause 8. The minimum number of measurements is ten.

   An acceptable alternative is to gather this data by application of gauge repeatability and reproducibility (GR and R) procedures to workpieces with a specified accuracy grade and surface finish equivalent to the worst accuracy grade and surface finish that will be included in the given uncertainty scope of application. If this method is used, it is important to derive the proper values from the GR&R data set following the procedures recommended in step d).

d) Determine the standard uncertainty, u_m, of the results produced in step c) using Equation (10). If the alternative GR and R data collection method is used, determine the standard uncertainty by the following method:

   GR and R procedures typically report three error values: repeatability (equipment variation), reproducibility (appraiser variation), and measurement error. The measurement error value, which is produced by combination of the repeatability and reproducibility error values by sum-of-the-squares method, should serve as the basis for determination of the standard uncertainty, u_m.

   The R&R value reported by a GR&R study represents 5,15 standard deviations. Therefore, an R and R value must be divided by 2,575 to obtain a value representing the standard uncertainty, u_m.

e) Determine the reference artifact calibration uncertainty, u_n, associated with the calibration of the reference artifact using Equation (11).

f) Determine the U_{95} measurement uncertainty for this method using Equation (12) or (13), depending on whether bias E will be eliminated.

Numerical example: This method allows workpiece characteristics including mounting errors, geometry and surface finish effects to be included in the analysis.

Using the data from 9.1 as an example for profile measurement of a calibrated reference artifact, the following values remain unchanged.

Measured data: $\bar{X}$ = 2,32 µm, standard uncertainty 0,47 µm.

Calibration data: X_{cal} = 3,3 µm, U_{95} = ± 1,5 µm (standard uncertainty 0,75 µm).

The results from measuring profile slope deviation, $f_{H\alpha}$, on a left flank of a selected representative gear, ten times, are given as:

Item	Test										Standard uncertainty u_m
	1	2	3	4	5	6	7	8	9	10	
$f_{H\alpha}$	11,0	10,4	9,4	10,2	10,1	7,8	7,1	10,7	8,0	9,3	1,34

If the bias in the measurement process is compensated or adjusted, Equation (12) may be used yielding the following results.

$$U_{95} = 2\left(1{,}34^2 + 0{,}75^2\right)^{0{,}5} = \pm 3{,}07 \ \mu m$$

If the bias determined by the calibration artifact is not eliminated, the measurement uncertainty may be estimated using Equation (13).

$$U_{95} = 2\left(1{,}34^2 + 0{,}75^2\right)^{0{,}5} + \left|0{,}98\right| = \pm 4{,}05 \ \mu m$$

9.2.2 Comparator example C

This example provides a means for estimating the influence of workpiece characteristic, u_w, where u_g meets the geometry equivalency requirements stated in 9.1. This procedure can provide acceptable validity with low complexity within its moderate scope of applicability. It provides good range of characteristic applicability with limited range of geometry applicability. Only one reference artifact is required.

The calibration procedure can be carried out as follows.

a) Perform a series of measurements on the calibrated reference artifact following the procedure outlined in Clause 8. The minimum number of measurements is ten.

b) Determine the mean value, $\bar{X}$, of the results produced in step a). The bias, E, is then found by subtracting the calibrated value of the reference artifact from the mean value of the results.

c) Estimate the influence of workpiece accuracy grade on measurement uncertainty using Equation (14):

$$u_{wg} = F_x \left(k_{wg} \right) \tag{14}$$

where

u_{wg} is the workpiece accuracy grade influence;

F_x is a tolerance for the given measurement parameter for an example gear — gear dimensions and accuracy grade should be near the limits specified in the measurement uncertainty statement;

k_{wg} is a constant factor representing the fraction of the tolerance contributing to the workpiece accuracy grade influence.

NOTE The workpiece accuracy grade influence constant factor, k_{wg}, provided here has been arbitrarily selected for this example. The exact factor used may vary according to the application being considered.

d) Estimate the influence of workpiece surface finish on measurement uncertainty using Equation (15):

$$u_{ws} = Ra \left(k_{ws} \right) \tag{15}$$

where

u_{ws} is the workpiece surface finish influence;

Ra is a tolerance for the surface finish for an example gear — this value should be near the limits specified in the measurement uncertainty statement;

k_{ws} is a constant factor representing the fraction of the tolerance contributing to the workpiece surface finish influence.

NOTE The workpiece surface finish influence constant factor, k_{ws}, provided here has been arbitrarily selected for this example. The exact factor used may vary according to the application being considered.

e) Estimate the workpiece characteristic influence, u_w, for this method using Equation (16):

$$u_w = \left(u_{wg}^2 + u_{ws}^2 \right)^{0,5} \tag{16}$$

f) Determine the standard uncertainty, u_m, of the results produced in step a) using Equation (10).

g) Determine the reference artifact calibration uncertainty, u_n, associated with the calibration of the reference artifact using Equation (11).

h) Determine the U_{95} measurement uncertainty for this method using Equation (17) or (18), depending on whether bias, E, will be eliminated:

— Equation (17) is applicable only when bias determined in step b) is eliminated from this measurement process, either by adjusting the operation of the instrument or compensating the results.

$$U_{95} = 2\left(u_m^2 + u_{wg}^2 + u_w^2\right)^{0,5} \tag{17}$$

— Equation (18) is applicable when bias determined in step b) is not eliminated from this measurement process.

$$U_{95} = 2\left(u_m^2 + u_n^2 + u_w^2\right)^{0,5} + |E| \tag{18}$$

Numerical example: Using the data from 9.1 as an example for profile measurement of a calibrated reference artifact, the following values remain unchanged.

Measured data: $\bar{X}$ = 2,32 µm, standard uncertainty 0,47 µm.

Calibration data: X_{cal} = 3,3 µm, U_{95} = ± 1,5 µm (standard uncertainty 0,75 µm).

The ($f_{H\alpha}$) tolerance for the workpiece is 12,0 µm.

It is estimated that the effect of the gear accuracy on the measurement process will not exceed 10 % of the tolerance value.

From Equation (14), the workpiece accuracy grade influence, U_{wg} is

$$u_{wg} = 12,0(0,10) = 1,2 \ \mu m$$

The effect on surface finish, Ra of 1,6 µm is estimated to not exceed 10 % of tolerance. So from Equation (15), U_{ws}

$$u_{ws} = 1,2(0,1) = 0,16 \ \mu m$$

Thus from Equation (16) the workpiece characteristic is estimated to be

$$u_w = \left(1,2^2 + 0,16^2\right)^{0,5} = 1,21 \ \mu m$$

The overall process uncertainty U_{95} is estimated from Equation (17) if bias is eliminated:

$$U_{95} = 2\left(0,47^2 + 0,75^2 + 1,21^2\right)^{0,5} = \pm 3,0 \ \mu m$$

If bias is not eliminated, the process uncertainty U_{95} is estimated from Equation (18) that yields

$$U_{95} = 2\left(0,47^2 + 0,75^2 + 1,21^2\right)^{0,5} + |0,98| = \pm 3,98$$

9.3 Comparator approach, expanded for workpiece characteristic and geometry similarity influences

It may be desirable to construct measurement uncertainty estimation procedures for use when the measuring process in question will be applied to workpieces that do not meet equivalency requirements for characteristics, u_w, or geometry, u_g, with the reference artifact used to calibrate that process. Example geometry and characteristic equivalency requirements are offered in 9.1.

A great variety of such procedures can be developed. Typically, this will involve extraction and combination of the concepts outlined according to the requirements of the given application. These methods are beyond the scope of this document.

10 Statistical process control

If an artifact is measured several times, with a given measuring device of sufficient resolution, all measurements will not turn out to be the same. There is inherent variability in the measuring system just as there is inherent variability from piece to piece in the product. The variability of the measurement system is often called measurement error, but variability is always present and is not to be considered the same as an error. In the normal process of measuring artifacts, the resultant measurements have only measurement system variability. The artifact measured is assumed to be stable.

To apply statistical process control to a calibration study, the individuals and moving range (X and MR) control chart method is recommended. In some cases, it is necessary for process control to be based on individual readings, rather than subgroups. The X and MR chart method has been chosen for the following reasons.

- Real-time determination of statistical uniformity for each observation determines what is happening with the individuals in time order.
- Plotted points can be compared directly with specifications.
- Magnitude of predictable variation due to the chance of common causes is defined.
- Natural variation and day-to-day fluctuations of the process are distinguished from assignable cause variations that are the unique and identifiable causes for bias change. Although a statistical chart detects the existence of an assignable cause of variation that lies outside the system, it does not identify the cause.

Control charts for individuals can be constructed as described in this clause.

10.1 Definitions

LCL: Lower control limit.

Statistical control: This is the condition describing a process from which all special causes of variation have been eliminated and only common causes remain; i.e. measured variation can be attributed to a constant system of chance causes; evidenced on a control chart by the absence of points beyond the control limits and by the absence of non-random patterns or trends within the control limits.

UCL: Upper control limit.

10.2 Constructing the X and MR chart

Figure 23 shows the construction of an X and MR chart.

a) Use individual readings collected from master gauges (preferably 30 or more, but initial estimates may be made with 10 readings).

b) Calculate moving range (MR) values. A moving range value is obtained by determining the difference between two sequential observations, the result always being a positive number. Note that the first observation will not have a corresponding MR value.

c) Calculate the mean (average) of the X values to establish the centre line (X) for the individual portion of the chart.

d) Calculate the mean of the MR values to establish the centre line (R) for the moving range portion of the chart.

e) Calculate control limits for both portions of the chart, as follows.

— For the individual portion:

$$UCL\left(X\right)=\overline{X}+\left(2{,}66\ \overline{R}\right) \tag{19}$$

$$LCL\left(X\right)=\overline{X}-\left(2{,}66\ \overline{R}\right) \tag{20}$$

— For the moving range portion:

$$UCL\left(MR\right)=3{,}27\overline{R} \tag{21}$$

$$LCL\left(MR\right)=0 \tag{22}$$

f) Plot the centreline and control limits. Establish a scale for both portions of the chart to suit the data. Once determined, draw the centre lines and the control limits in the appropriate section and label them.

g) Plot the data. Plot the X and MR values in the appropriate section. Once plotted, connect points with a line to aid in visual analysis of the data. Mark all indications of lack of control.

10.3 Criteria for evidence of lack of control

The following criteria are applicable to the individuals (X) in the “X values of the MR chart” in Figure 23. A normal distribution is assumed. When one or more of the criteria are seen, it means that the process is not “in control”.

a) One point outside of the 3 sigma limit.

b) Two out of three successive points above the +2 sigma limit or two out of three successive points below the −2 sigma limit.

c) Four out of five successive points above the +1 sigma limit or four out of five successive points below the −1 sigma limit.

d) Fifteen successive points within +1 sigma or −1 sigma.

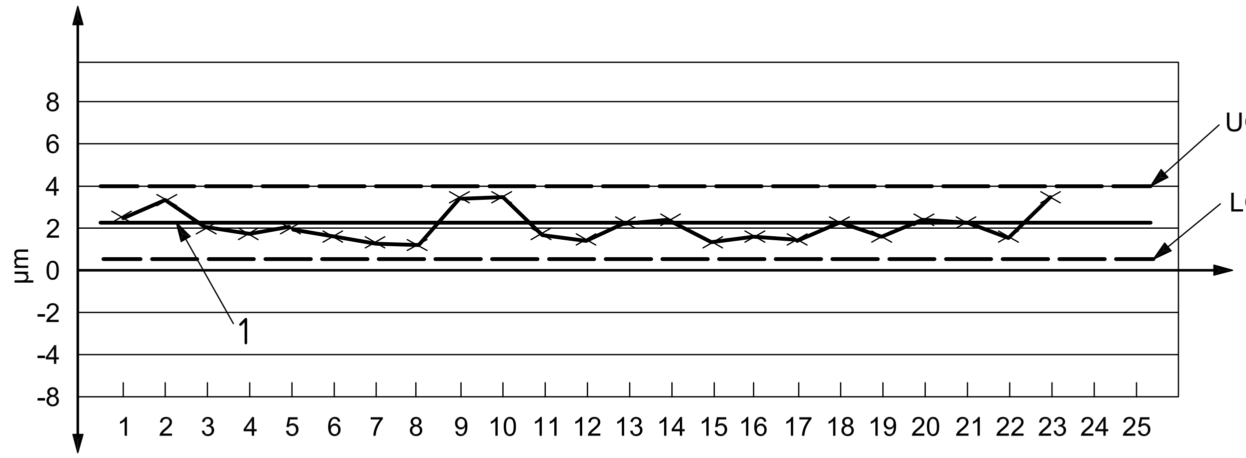
e) Eight successive points, none within +1 sigma or −1 sigma.

f) Eight successive points on one side of the centre line.

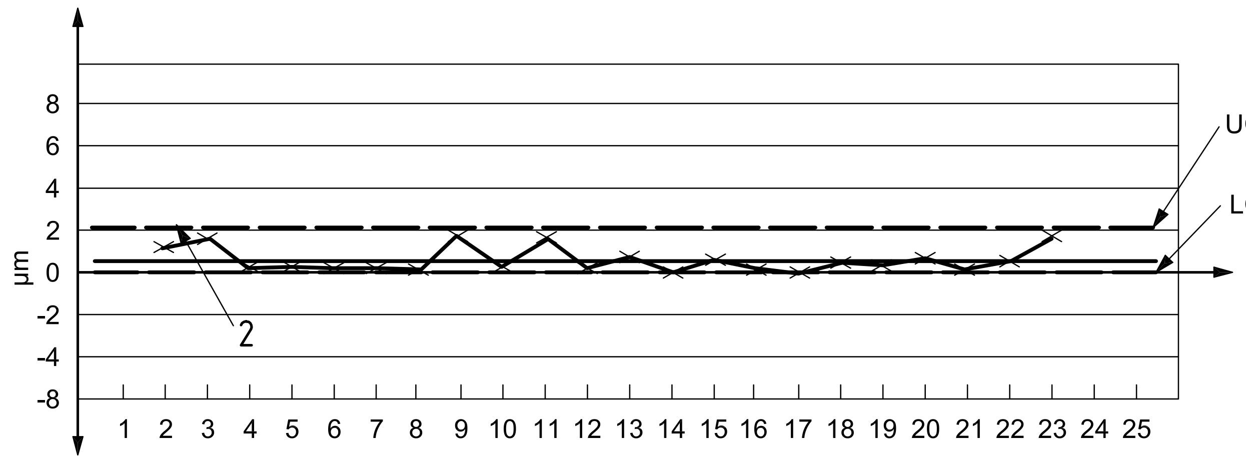
g) Seven successive points constantly ascending or descending.

h) Number of centre line crossings is not within the limits of $K/2$ plus the square root of K, or $K/2$ minus the square root of K, where K is equal to the total number of points.

If one or more of the above criteria exists, corrective action may be necessary.



a) X values of MR chart



b) Range values of MR chart

Key

1 Average (X)

2 Average (R)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	AVG
Reading	2,4	3,7	2,0	1,8	2,1	1,8	1,6	1,7	3,5	3,5	1,8	1,6	2,5	2,5	1,6	1,8	1,7	2,2	1,8	2,5	2,3	1,7	3,7			2,25
Range		1,3	1,7	0,2	0,2	0,3	0,2	0,1	1,8	0	1,7	0,2	0,9	0	0,9	0,2	0,1	0,5	0,1	0,7	0,2	0,6	2,0			0,65

c) Calibration data

X UCL = average reading + 2,66(average range)

X UCL = 2,25 + 2,66(0,65)

X UCL = 3,98

X LCL = average reading −2,66(average range)

X LCL = 2,25 −2,66(0,65)

X LCL = 0,52

R UCL = 3,27(average range)

R UCL = 3,27(0,65)

R UCL = 2,13

R LCL = 0

Figure 23 — Constructing the X and MR chart

10.4 When control chart data fails one or more criteria according to 10.3

The control chart is used to sound an alarm when an established normal or stabilized process is threatened by negative, unwanted assignable influences. In production usage, these influences can result from the following general areas: man, machine, material, method, measurement and management. In calibration, these influences are more likely from the following: environment (see Clause 4), measurement system (see Clause 5) and operator. When the calibration data fail one of the tests in 10.3, then these latter influences should be looked at to identify the cause of the unwanted influence.

A major factor in determining the seriousness of the unwanted influences, and thus the resources used to find and correct these influences, is the variability that is in the production gears which are to be measured by this measurement system. If the standard deviation in the product is high relative to the standard deviation in the measurement system, then only limited resources should probably be expended to find and correct the influences. On the other hand, if the margin is thin, then finding and correcting the influences is mandated.

11 Instrument fitness for use

Once an instrument has been calibrated by estimating its U_{95} measuring uncertainty for a given set of conditions and scope of application, a decision should be made as to whether this uncertainty is appropriate for measuring tasks that will be done under this calibration. Generally, this involves comparing the uncertainty to the associated manufacturing tolerance.

11.1 Limiting measurement uncertainty

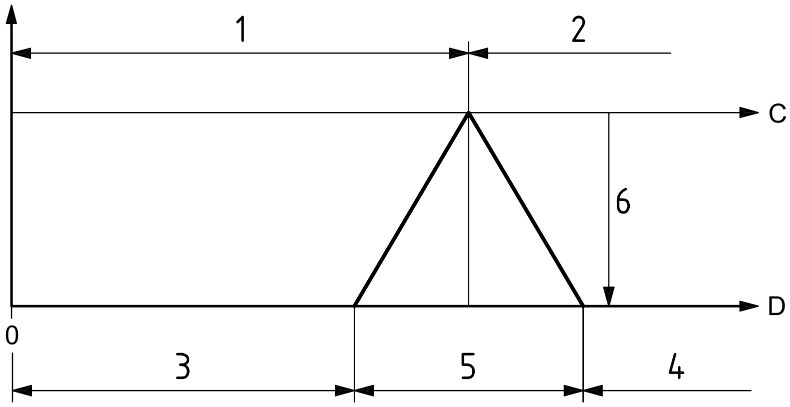
An instrument that might produce measurements that are in error by up to 100 % of the given tolerance is obviously unsatisfactory. An instrument that may be in error by 50 % of the tolerance has the possibility of mistakenly passing or failing an unacceptably large number of pieces. If the potential error drops below 10% the tolerance, the measuring process would normally be considered acceptable.

The decision then is exactly where to set the allowable percentage of error, given the tradeoffs between the improved manufacturing reliability that comes with good measurements and the increased cost of more reliable measurements. Three methods are outlined here to provide guidance to this decision process. If a manufacturing operation is to operate efficiently, the validity of associated measuring operations must be confirmed by one of these methods.

It is recommended that unless there is specific agreement between customer and supplier, the method according to 11.1.1 be adopted, because it is in accordance with an established ISO method.

11.1.1 GPS Tolerance reduction method

A flexible approach is offered by ISO/TS 14253-1:1995. This method is based on the recognition that measurement errors reduce the portion of the tolerance zone where test pieces are known to be acceptable. See Figure 24.



Key

C design/specification phase

D verification phase

1 specification zone (in specification)

2 out of specification

3 conformance zone

4 non-conformance zone

5 uncertainty range

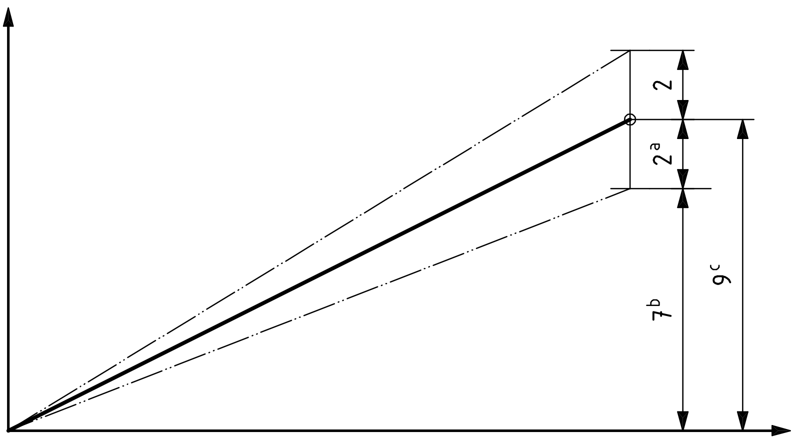
6 increasing measurement uncertainty, U

NOTE The design requirement is shown on line C and the actual measurement needs shown on D account for the measurement uncertainty. Investing in measurement capability increases the range of tolerance available for the manufacturer.

Figure 24 — Graphical representation of GPS method

To illustrate this method, consider a gear specified with an involute profile slope tolerance of 9 µm and an associated U_{95} measurement uncertainty of 2 µm. If a test result indicates a profile deviation between 7 µm and 9 µm, there is a significant probability that a piece which is actually out of tolerance will be incorrectly accepted. (Conversely, a test result indicating a deviation between 9 µm and 11 µm has a significant probability of incorrectly rejecting a piece that was actually in tolerance.) With the tolerance reduction method, the tolerance would be reduced to 7 µm, thereby substantially reducing the probability of accepting an out-of-tolerance piece owing to measurement error. See Figure 25.

Dimensions in micrometres



a Uncertainty range.

b Conformance zone.

c Specification zone.

Figure 25 — Example of GPS approach to determining fitness for purpose

The tolerance reduction method transfers the instrument fitness-for-use issue from the realm of the arbitrary to that of the economic. In the example presented in the paragraph above, the uncertainty to tolerance ratio would be 28 %, [2/(9-2)]. With an arbitrary tolerance ratio requirement of 25 %, the instrument would be considered unacceptable without further consideration. However, for the case of a manufacturing process that could reliably produce pieces within the 5 µm tolerance, the instrument might be deemed satisfactory without further action. If the manufacturing process were instead known to produce pieces within 6 µm on a consistent basis, it might be deemed appropriate to pursue improvements in the measurement operation to reduce uncertainty.

11.1.2 Tolerance ratio method

Traditionally, the question of instrument fitness-for-use has been addressed by requiring that measurement uncertainty be less than a specified percentage of the associated manufacturing tolerance. For gear manufacturing, this ratio has commonly been set at 25 % to 30 %.

The simplicity of this tolerance ratio method is attractive. On the other hand, fixing an arbitrary percentage may result in a larger or smaller measurement uncertainty (and associated cost) than optimum for the given application.

11.1.3 Instrument uncertainty guidelines

A further method is to define the performance of the instrument with calibrated gear artifacts. To improve uncertainty, the effects of items discussed in Clause 5 should be minimized. The requirements depend on the accuracy grade of the gear to be inspected, but the requirements relate to the uncertainty calibration method and the calibrated gear artifact used. Table 3 gives some gear measurement process uncertainty guidelines.

A limitation of this method is that it produces a single uncertainty requirement that applies to a wide range of gear tolerances that depend on the gear geometry.

Table 3 — Gear measurement process uncertainty guidelines

<table>
<tr><th rowspan="2">Accuracy grade to be tested

ISO 1328-1
ISO 1328-2</th><th colspan="5">Maximum recommended uncertainty, U_{95}
µm</th></tr>
<tr><th>Single pitch [a]</th><th>Runout</th><th>Total helix per 100 mm face-width [b c]</th><th>Total profile</th><th>Total cumulative pitch</th></tr>
<tr><td>2</td><td rowspan="2">1,0</td><td rowspan="2">1,5</td><td rowspan="2">2,5</td><td rowspan="2">2</td><td rowspan="2">2</td></tr>
<tr><td>3</td></tr>
<tr><td>4</td><td rowspan="3">1,5</td><td rowspan="3">2,5</td><td rowspan="3">3,5</td><td rowspan="3">3</td><td rowspan="3">3</td></tr>
<tr><td>5</td></tr>
<tr><td>6</td></tr>
<tr><td>7</td><td rowspan="3">3,0</td><td rowspan="3">5,0</td><td rowspan="3">6,0</td><td rowspan="3">6</td><td rowspan="3">6</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td></tr>
<tr><td>10</td><td rowspan="3">4,0</td><td rowspan="3">7,0</td><td rowspan="3">8,0</td><td rowspan="3">8</td><td rowspan="3">8</td></tr>
<tr><td>11</td></tr>
<tr><td>12</td></tr>
</table>

[a] The measurement uncertainty applies to the estimation with artifacts up to module 5 and 400 mm reference diameter and tooth numbers $\geqslant 30$.

[b] The measurement uncertainty based on helical artifacts with a helix angle $\beta \leqslant 30°$.

[c] For face-widths less than or equal to 100 mm, table values apply. For face-widths greater than 100 mm, values should be increased proportionately.

11.2 Measurement uncertainty sources

A summary of uncertainty sources from ISO/TS 14253-2, for calibration of measuring equipment in product verification, is shown in Figure 26.

Common problems can include

- inappropriate specifications,
- runout errors throughout the manufacture and measurement of a gear,
- mounting errors on measuring instruments and machine tools, and
- inappropriate measurement methods.

Guidance on improving the process should be available from the instrument manufacturer.

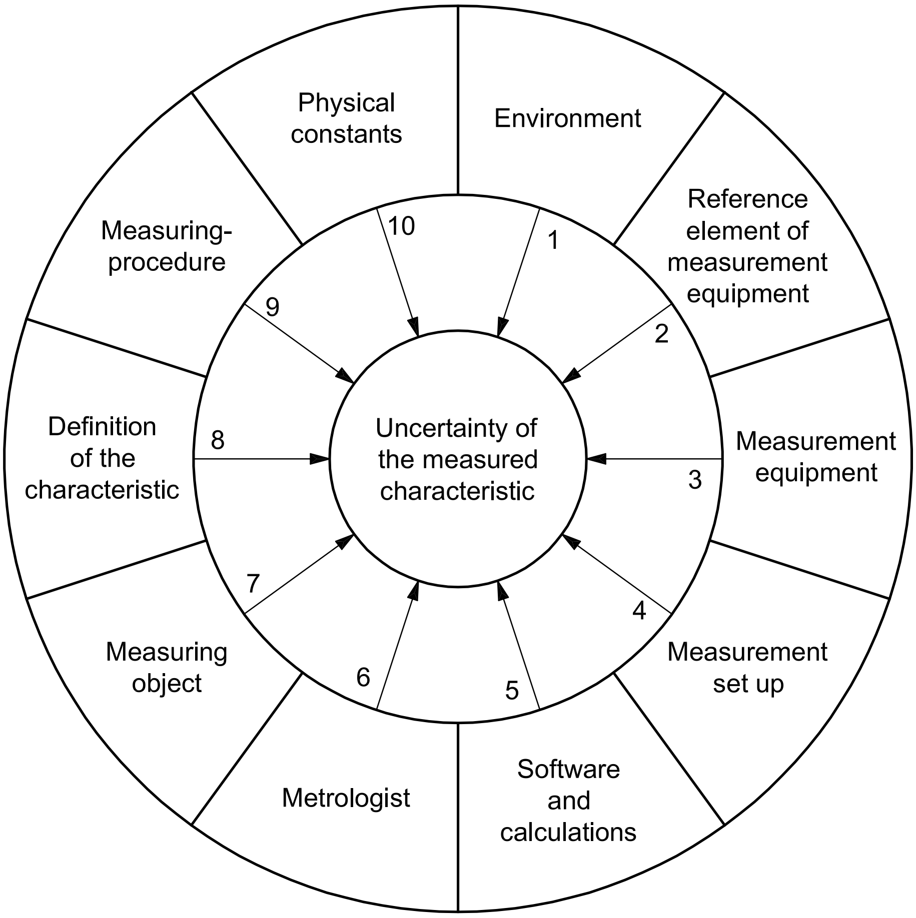


Figure 26 — Uncertainty contributors in measurement

11.3 Reducing measurement uncertainty

Three general methods can be followed to improve the uncertainty of a measuring process that has been determined to be unsatisfactorily large.

11.3.1 Following a different calibration procedure

The uncertainty estimation methods provided by this document produce increasing U_{95} values as the similarity decreases between the given procedure and a strict comparator method. Following a procedure that is closer to the comparator method will therefore usually improve measurement uncertainty.

One way to improve conformance with the comparator method is to improve the similarity of the reference artifact with the given test piece. Use of a different or additional reference artifact, so as to improve similarity, will reduce calibration uncertainty.

Another way to reduce measurement uncertainty is to eliminate bias measured during the calibration procedure from the measurement process, either by adjusting the operation of the instrument or compensating the results.

When the specified accuracy of the workpiece is grade 5 or better in accordance with ISO 1328-1 or equivalent, then U_{95} uncertainty could be optimized by use of a reference artifact of the same size and configuration as the given workpiece. Elimination of bias measured during the calibration procedure would also be required. This could result in measurement uncertainty values only slightly larger the uncertainty associated with the certification of the reference artifact.

11.3.2 Reducing uncertainty of the reference master certification

The uncertainty value of an instrument cannot be less than the uncertainty value of the certification of the reference artifact. Depending on the method, the certification uncertainty may be the dominant factor.

Reducing certification uncertainty usually involves reducing the number of steps in the calibration hierarchy. It may also be possible to negotiate special testing procedures to reduce certification uncertainty.

11.3.3 Improving the measuring process

A list of measurement process factors that could potentially reduce measurement uncertainty would be very lengthy indeed. General categories would include

— environmental influences,

— instrument condition and alignment,

— operator training, and

— arbors and fixtures.

Uncertainty can be reduced by making repeated measurements on the workpiece and using the mean of the measurements and the standard deviation of the mean, where

$$\sigma_{\mathrm{m}} = \frac{u_{\mathrm{m}}}{\sqrt{n}}$$

Some of these topics are discussed in greater detail elsewhere in this document. In addition, guidance on improving process should be available from the instrument manufacturer.

12 Measurement process (instrument) correlation

When a given test piece is measured by different measurement processes, the resulting values will be different. Comparison of test results obtained from different measurement processes is commonly referred to as measurement process correlation.

12.1 Basis for comparison

Before measurement process correlation can be observed, it is important to assure that the measurement processes being compared are following equivalent testing procedures. Common sources of differences include

- mounting conditions,
- tooth flank naming,
- tooth numbering,
- measurement location,
- measurement direction,
- trace data filtering,
- analysis method,
- operator practices, and
- environmental conditions.

12.2 Correlation of measurement

It may be desirable to quantify the ratio of correlation. The following method statistically combines individual measurement uncertainties.

Correlation can be considered within the limits of statistical probability with a 95 % confidence interval where E_N is less than or equal to 1, using the following formula to calculate E_N:

$$E_N = \frac{\left| x_a - x_b \right|}{\left[\left(U_{95a} \right)^2 + \left(U_{95b} \right)^2 \right]^{0,5}} \tag{23}$$

where

E_N is the correlation ratio, with 95 % confidence level;

x_a is the individual test result from the first measurement process;

x_b is the individual test result from the second measurement process;

U_{95a} is the U_{95} measurement uncertainty of the first measurement process;

U_{95b} is the U_{95} measurement uncertainty of the second measurement process.

If E_N is calculated to be greater than 1, the individual test results do not correlate within a 95 % confidence interval. Further work may be required to determine the cause of the difference.

Annex A
(informative)

Effect of temperature on gears and artifacts

A.1 Purpose

The purpose of this annex is to quantify the temperature effects upon involute profile slope, $f_{H\alpha}$, helix slope, $f_{H\beta}$, and tooth thickness measurements of external gears and artifacts. Such calculations assume uniform temperature of the given test piece; localized temperature variations cannot be conveniently modelled.

The temperature of the measuring instrument is not considered in these calculations.

A.2 Profile temperature effect calculation

For involute profile measurement, the effect of temperature can be modelled by considering the associated change in the base circle diameter. The effect upon profile slope $f_{H\alpha}$ can be calculated as follows:

a) Given (typical) data:

z	=	14	Number of teeth
m_n	=	8 mm	Normal module
β	=	23°	Helix angle
α_n	=	20°	Normal pressure angle
L_s	=	7 mm	Roll length to the start of profile analysis
L_e	=	37 mm	Roll length to the end of profile analysis

NOTE When profile analysis start and end points are specified in roll angle degrees (ξ_y), conversion to roll length can be done with the following formula:

$$L_y = \left(\frac{\xi_y}{360}\right)\left(d_b \pi\right) \quad \text{(A.1)}$$

CTE	= 11,5 10^{-6} C^{-1}	Coefficient of thermal expansion of the steel
Δ_t	= + 2,5 °C	Temperature difference ($t_a - t_s$) = (22,5° −20°) = +2,5°

where

t_a is the actual (measured) temperature;

t_s is the standard temperature (20 °C).

b) Calculate the transverse module, m_t:

$$m_t = \frac{m_n}{\cos\beta} = 8{,}690\ 88 \text{ mm} \quad \text{(A.2)}$$

c) Calculate the pitch diameter, d:

$$d = m_t z = 121{,}672\ 36 \text{ mm} \tag{A.3}$$

d) Calculate the transverse pressure angle, α_t:

$$\alpha_t = \arctan\left(\frac{\tan\alpha_n}{\cos\beta}\right) = 21{,}573\ 98\ ° \tag{A.4}$$

e) Calculate the unmodified base diameter, d_b:

$$d_b = d\cos\alpha_t = 113{,}148\ 43 \text{ mm} \tag{A.5}$$

f) Calculate the profile evaluation range, L_α (analyzed portion of the profile):

$$L_\alpha = L_e - L_s = 30 \text{ mm} \tag{A.6}$$

g) Calculate the new base diameter, d_{b2}, expanded or contracted by temperature effect:

$$d_{b2} = d_b + \left(d_b\ \Delta_t\ \text{CTE}\right) = 113{,}151\ 68 \text{ mm} \tag{A.7}$$

h) Calculate the new functional profile length, $L_{\alpha 2}$, lengthened or shortened by temperature effect:

$$L_{\alpha 2} = L_\alpha\left(\frac{d_{b2}}{d_b}\right) = 30{,}000\ 86 \text{ mm} \tag{A.8}$$

i) Calculate the profile slope deviation $f_{H\alpha}$, resulting from temperature effect:

$$f_{H\alpha} = \left(L_{\alpha 2} - L_\alpha\right) = 0{,}000\ 86 \text{ mm} = 0{,}86\ \mu\text{m} \tag{A.9}$$

The calculated $f_{H\alpha}$ deviation is along a line tangent to the base circle, within a transverse plane. The polarity of this deviation is plus when the given actual temperature is above the standard temperature of 20° Celsius, thereby enlarging the base diameter and reducing the pressure angle. This slope deviation direction and polarity conform to that specified in ISO 1328-1.

A.3 Helix temperature effect calculation

For helix measurement, the effect of temperature can be modelled by considering the associated change in the lead. The effect upon helix slope, $f_{H\beta}$, can be estimated as follows.

a) Given (typical) data:

z	=	14	Number of teeth
m_n	=	8 mm	Normal module
β	=	23°	Helix angle
α_n	=	20°	Normal pressure angle
L_b	=	45,72 mm	Helix evaluation range
CTE	=	$11{,}5 \times 10^{-6}\ \text{C}^{-1}$	Coefficient of thermal expansion of the steel

Δ_t = +2,5 °C Temperature difference ($t_a - t_s$) = (22,5° − 20°) = +2,5°

where

t_a is the actual (measured) temperature;

t_s is the standard temperature (20° C).

b) Calculate the transverse module, m_t:

$$m_t = \frac{m_n}{\cos\beta} = 8{,}690\ 88 \tag{A.10}$$

c) Calculate the pitch diameter, d:

$$d = m_t z = 121{,}672\ 36 \text{ mm} \tag{A.11}$$

d) Calculate the transverse pressure angle, α_t:

$$\alpha_t = \arctan\left(\frac{\tan\alpha_n}{\cos\beta}\right) = 21{,}573\ 98\ ° \tag{A.12}$$

e) Calculate the base diameter, d_b:

$$d_b = d \cos\alpha_t = 113{,}148\ 43 \text{ mm} \tag{A.13}$$

f) Calculate the lead, L:

$$L = \frac{d\pi}{\tan\beta} = 900{,}512\ 79 \tag{A.14}$$

g) Calculate the base helix angle, β_b:

$$\beta_b = \arcsin\left(\sin\beta \cos\alpha_n\right) = 21{,}54101° \tag{A.15}$$

h) Calculate the new lead, L_2, expanded or contracted by temperature effect:

$$L_2 = L + \left(L\ \Delta_t\ \text{CTE}\right) = 900{,}538\ 68 \text{ mm} \tag{A.16}$$

i) Calculate the new base helix angle, β_{b2}, enlarged or reduced by temperature effect:

$$\beta_{b2} = \arctan\left[\frac{\left(d_b\pi\right)}{L_2}\right] = 21{,}540\ 45\ ° \tag{A.17}$$

j) Calculate the portion of the base diameter circumference, C_1, associated with the helix evaluation range:

$$C_1 = L_\beta \tan\beta_b = 18{,}047\ 40 \text{ mm} \tag{A.18}$$

k) Calculate the new portion of the base diameter circumference, C_2, associated with the helix evaluation range, enlarged or reduced by temperature effect:

$$C_2 = L_\beta \tan\beta_{b2} = 18{,}046\ 88 \text{ mm} \tag{A.19}$$

l) Calculate the helix slope deviation, $f_{H\beta}$, resulting from temperature effect:

$$f_{H\beta} = (C_2 - C_1) = -0{,}000\,52 \text{ mm} = -0{,}52 \text{ µm} \quad \text{(A.20)}$$

The calculated $f_{H\beta}$ deviation is along a line tangent to the base circle, within a transverse plane. The polarity of this deviation is minus when the given actual temperature is above the standard temperature of 20 °C, thereby enlarging the lead and reducing the helix angle. This slope deviation direction and polarity conform to that specified in ISO 1328-1.

Temperature is not considered to a significant effect on zero-helix-angle gears.

A.4 Tooth thickness temperature effect calculation

In addition to involute profile and helix, tooth thickness may be significantly affected by temperature. These effects can be modelled by considering the associated change in the tooth section intersecting the pitch diameter, where tooth thickness is usually measured. The effect of temperature upon normal tooth thickness of an external gear can be estimated as follows.

a) Given (typical) data:

z	=	14	Number of teeth
m_n	=	8 mm	Normal module
β	=	23°	Helix angle
α_n	=	20°	Normal pressure angle
s_n	=	12,566 37 mm	Normal tooth thickness at the pitch diameter
CTE	=	$11{,}5 \times 10^{-6}$ C^{-1}	Coefficient of thermal expansion of the steel
Δ_t	=	+2,5 °C	Temperature difference ($t_a - t_s$) = (22,5° −20°) = +2,5°

where

t_a is the actual (measured) temperature;

t_s is the standard temperature (20 °C).

b) Calculate the transverse module, m_t:

$$m_t = \frac{m_n}{\cos\beta} = 8{,}690\,88 \text{ mm} \quad \text{(A.21)}$$

c) Calculate the pitch diameter, d:

$$d = m_t z = 121{,}672\,36 \text{ mm} \quad \text{(A.22)}$$

d) Calculate the transverse pressure angle, α_t:

$$\alpha_t = \arctan\left(\frac{\tan\alpha_n}{\cos\beta}\right) = 21{,}573\,98\,° \quad \text{(A.23)}$$

e) Calculate the base diameter, d_b:

$$d_b = d \cos \alpha_t = 113{,}148\ 43 \text{ mm} \tag{A.24}$$

f) Calculate the diameter, d_2, of the new tooth section presented at the pitch diameter due to temperature effect:

$$d_2 = d - \left(d\ \Delta_t \text{ CTE} \right) = 121{,}668\ 86 \text{ mm} \tag{A.25}$$

g) Calculate the transverse pressure angle, α_{t2}, at diameter d_2:

$$\alpha_{t2} = \arccos\left(\frac{d_b}{d_2} \right) = 21{,}569\ 82\ ° \tag{A.26}$$

h) Calculate the roll angle, ξ, at the reference pitch diameter:

$$\xi = \left(\tan \alpha_t \right) \left(\frac{180}{\pi} \right) = 22{,}654\ 91° \tag{A.27}$$

i) Calculate the roll angle, ξ_2, at diameter d_2:

$$\xi_2 = \tan \alpha_{t2} \left(\frac{180}{2} \right) = 22{,}650\ 10\ ° \tag{A.28}$$

j) Calculate the involute function, inv α_t, at the reference pitch diameter:

$$\text{inv}\ \alpha_t = \xi - \alpha_t = 1{,}080\ 93\ ° \tag{A.29}$$

k) Calculate the involute function, inv α_{t2}, at diameter d_2:

$$\text{inv}\ \alpha_{t2} = \xi - \alpha_{t2} = 1{,}080\ 28\ ° \tag{A.30}$$

l) Calculate the transverse tooth thickness, s_t, at the reference pitch diameter:

$$s_t = \frac{s_n}{\cos \beta} = 13{,}651\ 61 \text{ mm} \tag{A.31}$$

m) Calculate the transverse tooth thickness angle, ϕ_t, at the reference pitch diameter:

$$\phi t = \left(\frac{s_t}{d \pi} \right) 360 = 12{,}857\ 14\ ° \tag{A.32}$$

n) Calculate the transverse tooth thickness angle, ϕ_{tb}, at the base diameter:

$$\phi_{tb} = \phi_t + \left(2 \text{ inv } \alpha_t \right) = 15{,}019\ 00\ ° \tag{A.33}$$

o) Calculate the transverse tooth thickness angle, ϕ_{t2}, at diameter d_2:

$$\phi_{t2} = \phi_{tb} - \left(2 \text{ inv } \alpha_{t2} \right) = 12{,}858\ 45\ ° \tag{A.34}$$

p) Calculate the transverse tooth thickness, s_{t2}, at diameter d_2:

$$s_{t2} = \left(\frac{\phi_{tw}}{360}\right)\left(d_2 \pi\right) = 13{,}652\ 60\ \text{mm} \tag{A.35}$$

q) Calculate the transverse tooth thickness, s_{tp}, at the reference pitch diameter, expanded or contracted by temperature effect:

$$s_{tp} = s_{tw}\left(\frac{d}{d_2}\right) = 13{,}652\ 99\ \text{mm} \tag{A.36}$$

r) Calculate the normal tooth thickness, s_n, at the reference pitch diameter, expanded or contracted by temperature effect:

$$s_n = s_{tp} \cos\beta = 12{,}567\ 64\ \text{mm} \tag{A.37}$$

s) Calculate the normal tooth thickness change, Δ_{sn}, due to temperature effect:

$$\Delta_{sn} = \left(s_n - s_n\right) = 0{,}001\,27\ \text{mm} = 0{,}127\ \mu\text{m} \tag{A.38}$$

The calculated Δ_{sn} change in normal tooth thickness has a positive polarity when the given actual temperature is above the standard temperature of 20 °C.

Annex B
(informative)

Modified involute, helix, pitch artifact testing

B.1 Purpose

This annex provides calculation examples of modified involute, modified helix, and modified pitch artifact testing. Refer to ISO 1328-1 and ISO/TR 10064-1 for recommended methods of analysis. The following example calculations provide methods of estimating the amount of introduced deviation into testing by various modifications.

Changes in test deviations significantly in excess of those measured on product gears by the given instrument are not recommended.

B.2 Modified base circle involute artifact testing

B.2.1 Given data describing the subject involute master:

z	=	14	Number of teeth
m_n	=	8 mm	Normal module
β	=	23°	Helix angle
α_n	=	20°	Pressure angle
L_{a1}	=	7 mm	Length of roll to the start of profile analysis
L_{a2}	=	37 mm	Length of roll to the end of profile analysis

NOTE 1 When profile analysis start and end points are specified in roll angle degrees ($\xi\alpha$), conversion to roll length can be done with the following formula:

$$L_{\alpha x} = \left(\frac{\xi_x}{360}\right)\left(d_b \pi\right) \quad \text{(B.1)}$$

$\Delta f_{H\alpha}$	=	50 mm	Desired amount of profile slope modification between start and end of profile analysis

NOTE 2 When $f_{H\alpha}$ is positive, the trend of the profile slope deviation is toward plus material at the tip of the tooth, which correlates with a negative (smaller) pressure angle deviation and a positive (larger) base diameter deviation, and vice versa.

NOTE 3 The $f_{H\alpha}$ deviation is in a transverse plane, on a line tangent to the base diameter. Calculations assume that the instrument is configured to report deviations in that direction.

B.2.2 Calculations required to determine a modified base circle diameter that would produce the desired amount of profile test trace slope modification.

a) Calculate the transverse module, m_t:

$$m_t = \frac{m_n}{\cos \beta} = 8{,}690\ 88 \tag{B.2}$$

b) Calculate the pitch diameter, d:

$$d = m_t\ z = 121{,}672\ 36 \text{ mm} \tag{B.3}$$

c) Calculate the transverse pressure angle, α_t:

$$\alpha_t = \arctan\left(\frac{\tan \alpha_n}{\cos \beta}\right) = 21{,}573\ 98\ ° \tag{B.4}$$

d) Calculate the unmodified base diameter, d_b:

$$d_b = d \cos \alpha_t = 113{,}148\ 43 \text{ mm} \tag{B.5}$$

e) Calculate the profile evaluation range, L_α (analyzed portion of the profile):

$$L_\alpha = L_{\alpha 2} - L_{\alpha 1} = 30 \text{ mm} \tag{B.6}$$

f) Calculate the base circle diameter modification, Δd_b, required to produce the desired profile slope deviation:

$$\Delta d_b = d_b \left(\frac{\Delta f_{H\alpha}}{L_\alpha}\right) = 0{,}188\ 58 \text{ mm} \tag{B.7}$$

g) Calculate the modified base circle diameter, d_{b2}, that will produce the desired profile slope deviation:

$$d_{b2} = d_b - \Delta d_b = 112{,}959\ 85 \text{ mm} \tag{B.8}$$

h) Calculate the modified transverse pressure angle, α_{t2}, for the modified base diameter d_{b2} (assuming a fixed pitch diameter, d):

$$\alpha_{t2} = \arccos\left(\frac{d_{b2}}{d}\right) = 21{,}814\ 22\ ° \tag{B.9}$$

i) Calculate the modified normal pressure angle, α_{n2}, for the modified base diameter d_{b2}:

$$\alpha_{n2} = \arctan\left(\tan \alpha_{t2} \cos \beta\right) = 20{,}225\ 85\ ° \tag{B.10}$$

The original values for number of teeth (z), normal module (m_n) and helix angle (β) should then be used with the modified normal pressure angle (α_{n2}) to produce the modified base diameter (d_{b2}).

B.3 Modified-lead helix artifact testing

It may be desirable to test a helix artifact against a longer or shorter lead to produce a sloped trace. Refer to ISO/TR 10064-1 for recommended methods of slope analysis. The example calculation provides a method of estimating the amount of slope introduced into the helix test trace by lead modification.

Changes in leads that produce slope deviations significantly in excess of those measured on product gears measured by the given instrument are not recommended.

B.3.1 Given data describing the subject helix master:

z	=	14	Number of teeth
m_n	=	8 mm	Normal module
β	=	23°	Helix angle
α_n	=	20°	Pressure angle
L_b	=	90 mm	Helix evaluation range
$\Delta f_{H\beta}$	=	50 µm	Desired amount of helix slope modification within the helix evaluation range

NOTE 1 When $f_{H\beta}$ is positive, the trend of the helix slope deviation correlates with a positive (larger) helix angle deviation and a negative (smaller) lead deviation, and vice versa. The associated plus or minus material trend of the test trace is dependent upon the hand of the helix, the flank being measured, and the direction of the test trace.

NOTE 2 The $f_{H\beta}$ deviation is in a transverse plane, on a line tangent to the base diameter. Calculations assume that the instrument is configured to report deviations in that direction.

B.3.2 Calculations required to determine a modified lead that would produce the desired amount of helix test trace slope modification.

a) Calculate the transverse module, m_t:

$$m_t = \frac{m_n}{\cos\beta} = 8{,}690\ 88 \qquad \text{(B.11)}$$

b) Calculate the pitch diameter, d:

$$d = m_t\ z = 121{,}672\ 36\ \text{mm} \qquad \text{(B.12)}$$

c) Calculate the transverse pressure angle, α_t:

$$\alpha_t = \arctan\left(\frac{\tan\alpha_n}{\cos\beta}\right) = 21{,}573\ 98\,^\circ \qquad \text{(B.13)}$$

d) Calculate the base diameter, d_b:

$$d_b = d\cos\alpha_t = 113{,}148\ 43\ \text{mm} \qquad \text{(B.14)}$$

e) Calculate the lead, L:

$$L = \frac{(d\pi)}{\tan\beta} = 900{,}512\ 79\ \text{mm} \qquad \text{(B.15)}$$

f) Calculate the base helix angle, β_b:

$$\beta_b = \arctan\left[\frac{(d_b\pi)}{L}\right] = 21{,}541\,01\,\text{mm} \tag{B.16}$$

g) Calculate the portion, C_a, of the base circle circumference associated with the helix evaluation range, L_β:

$$C_a = L_\beta \tan\beta_b = 35{,}526\,39\,\text{mm} \tag{B.17}$$

h) Calculate C_{a2}, the modified C_a value required to produce the helix slope modification, $\Delta f_{H\beta}$:

$$C_{a2} = C_a + \left(\Delta f_{H\beta} \times 10^{-3}\right) = 35{,}576\,39\,\text{mm} \tag{B.18}$$

i) Calculate the modified base helix angle, β_{b2}, required to produce the helix slope modification, $\Delta f_{H\beta}$:

$$\beta_{b2} = \arctan\left(\frac{C_{a2}}{L_\beta}\right) = 21{,}568\,55\,° \tag{B.19}$$

j) Calculate the modified lead, L_2, required to produce the helix slope modification, $\Delta f_{H\beta}$:

$$L_2 = \frac{d_b\pi}{\tan\beta_{b2}} = 899{,}247\,18\,\text{mm} \tag{B.20}$$

k) Calculate the modified helix angle β_2, required to produce the helix slope modification, f_{Hb} (assuming a fixed pitch diameter, d):

$$\beta_2 = \arctan\left(\frac{d\pi}{L_2}\right) = 23{,}029\,00\,° \tag{B.21}$$

l) Calculate the modified normal module m_{n2}, for the modified helix angle β_2 (assuming a fixed pitch diameter, d):

$$m_{n2} = m_t \cos\beta_2 = 7{,}998\,28 \tag{B.22}$$

m) Calculate the modified normal pressure angle, α_{n2}, for the modified base diameter d_{b2}:

$$\alpha_{n2} = \arctan\left(\tan\alpha_t \cos\beta_2\right) = 19{,}996\,04\,° \tag{B.23}$$

The original number of teeth (z), should then be used with the modified helix angle (β_2), normal module (m_{n2}), and normal pressure angle (α_{n2}) to produce the modified lead (L_2).

When base helix angle is required for set-up of a mechanical helix measurement instrument, use β_{b2}. The base diameter, d_b, remains unchanged by these calculations.

B.4 Modified eccentricity pitch artifact testing

As discussed in ISO 18683, it may be desirable to measure a pitch artifact with additional eccentricity induced. The effect of the added eccentricity on pitch and total cumulative pitch (total index variation) can be determined by using calculations described in the following example. In this example, all calculations are done in the transverse plane tangent to the specified diameter.

B.4.1 Methods of introducing eccentricity

On instruments where the artifact must be physically positioned true to the axis of rotation, eccentricity must be induced through physical displacement of the artifact. On equipment where the instrument is mathematically aligned to the artifact datums (CMMs), the eccentricity may be induced by mathematical displacement of the part coordinate system.

Calculating change of pitch and index values caused by added eccentricity.

Pitch values may be calculated as the difference between successive index values, or the index values can be calculated by summing successive pitch values. Use of either method will produce the same results.

Index values:

Left flank CCW rotation

Right flank CW rotation

$$M_{x1} = \frac{f_{\mathrm{e}}}{\cos\alpha_{\mathrm{yMt}}}\sin\left[\varphi_{\mathrm{fe1M}} + \alpha_{\mathrm{yMt}} - \psi_{\mathrm{pMt}} + \tau(k-1)\right] \quad \text{(B.24)}$$

Right flank CCW rotation

Left flank CW rotation

$$M_{x2} = \frac{f_{\mathrm{e}}}{\cos\alpha_{\mathrm{yMt}}}\sin\left[\alpha_{\mathrm{yMt}} - \psi_{\mathrm{pMt}} - \varphi_{\mathrm{fe1M}} + \tau(k-1)\right] \quad \text{(B.25)}$$

Pitch values:

Left flank CWW rotation

Right flank CW rotation

$$M_{\mathrm{p1}} = \frac{f_{\mathrm{e}}}{\cos\alpha_{\mathrm{yMt}}}\frac{2\pi}{z}\cos\left[\varphi_{\mathrm{fe1M}} - \alpha_{\mathrm{yMt}} - \psi_{\mathrm{pMt}} + \tau(k-1)\right] \quad \text{(B.26)}$$

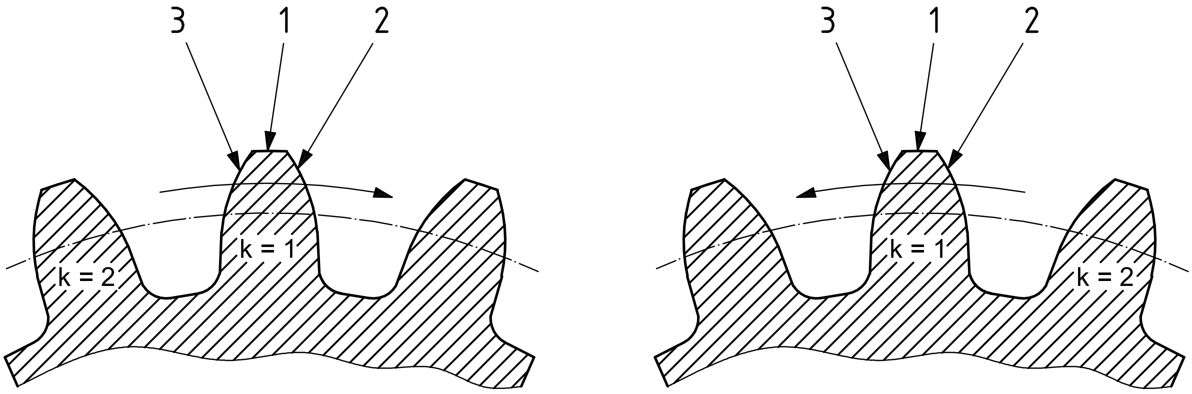
Right flank CCW rotation

Left flank CW rotation

$$M_{\mathrm{p2}} = \frac{f_{\mathrm{e}}}{\cos\alpha_{\mathrm{yMt}}}\frac{2\pi}{z}\cos\left[80 - \varphi_{\mathrm{fe1M}} + \alpha_{\mathrm{yMt}} - \psi_{\mathrm{pMt}} + \tau(k-1)\right] \quad \text{(B.27)}$$

Because calculation of the change in index values is more direct, this method is used in the following example.

The definitions of tooth and flank identifications used are shown in Figure B.1. Table B.1 contains definitions of symbols and data sources. Gear design data and inspection set-up data used in the example are shown in Table B.2. The index values caused by the added eccentricity are shown for each flank in Table B.3. The certified index values, without added eccentricity, are shown in Table B.4.



a) Clockwise (CW) rotation **b) Counter-clockwise (CCW) rotation** [a]

Key

1 Datum tooth
2 Right flank
3 Left flank

[a] “Counter-clockwise” is the US equivalent of "anticlockwise".

Figure B.1 — Tooth and flank identification

Table B.1 — Symbols, their descriptions and data sources

Symbol	Description	Data source	Example
d	Standard pitch diameter	$= \dfrac{z\, m_n}{\cos\beta}$	156
d_b	Base circle diameter	$= d \cos\alpha_t$	146,592
d_p	Probe ball diameter (use 0 if compensated for by instrument)	Test set-up	0
d_M	Measurement diameter	Test set-up	156
F_r	Runout variation (from eccentricity only)	Test set-up = $2f_e$	67,4
f_e	Eccentricity	Test set-up $= \dfrac{F_r}{2}$	33,7
k	Tooth number (1 to N)	Test set-up	1 to 24
m_n	Normal module	Gear data	6,5
M_{p1}	Pitch value of added eccentricity, (transverse plane, tangential to measurement circle), flank 1	Equation 28	—
M_{p2}	Pitch value of added eccentricity, (transverse plane, tangential to measurement circle), flank 2	Equation 29	—
M_{x1}	Index value of added eccentricity, (transverse plane, tangential to measurement circle), flank 1	Equation 26	—
M_{x2}	Index value of added eccentricity, (transverse plane, tangential to measurement circle), flank 2	Equation 27	—
p_z	Lead (negative for LH helix CCW rotation, and for RH helix CW rotation)	$= \pi z \dfrac{m_n}{\sin\beta}$	0 (spur)
s_n	Normal tooth thickness at reference pitch diameter	Gear data	10,137 5

Table B.1 (*continued*)

Symbol	Description	Data source	Example
s_t	Transverse tooth thickness at reference pitch diameter	$= \frac{s_n}{\cos\beta}$	10,137 5
X_M	Axial distance from reference face to measurement plane	Test set-up	23,8
z	Number of teeth	Gear data	24
α_{yMt}	Transverse pressure angle at measurement diameter	$= \arccos\left(\frac{d_b}{d_M}\right)$	20
α_n	Normal pressure angle at reference pitch diameter	Gear data	20
α_t	Transverse pressure angle at reference pitch diameter	$= \arctan\left(\frac{\tan\alpha_n}{\cos\beta}\right)$	20
β	Helix angle at reference pitch diameter, positive for right hand helix	Gear data	0
β_b	Base helix angle	$= \arccos\left(\frac{\sin\alpha_n}{\sin\alpha_t}\right)$	0
ψ_{bt}	Half angle base tooth thickness, in transverse plane	$\left(\frac{s_t}{d} + \mathrm{inv}\,\alpha_t\right)\frac{180}{\pi}$	4,577 26
ψ_{pbt}	Half-angle base tooth thickness with adjustment for probe diameter, transverse plane	$= \psi_{bt} + \left(\frac{d_p}{d_b\cos\beta_b}\right)\frac{180}{\pi}$	4,577 26
ψ_{pMt}	Half-angle tooth thickness at measurement diameter with probe adjustment, transverse plane	$= \psi_{bt} - \left(\mathrm{inv}\,\alpha_{yMt}\right)\frac{180}{\pi}$	3,723 31
τ	Tooth pitch angle	$= \frac{360}{z}$	15
φ_{fe1}	Angle from eccentricity direction to centre of tooth number 1, at reference face in direction of tooth count (opposite direction of rotation)	Test set-up	136,2
φ_{fe1M}	Angle from eccentricity direction to centre of tooth number 1, at measurement plane	$= \varphi_{fe1} + 360\frac{X_M}{p_z}$	136,2

Table B.2 — Example input data

Gear design data (basic)	Number of teeth, z	24
	Normal module, m_n, mm	6,5
	Normal pressure angle, α_n	20
	Helix angle, β	0 (spur)
	Normal tooth thickness, s_n, mm	10,137 5
Inspection set-up data	Eccentricity, f_e, µm	33,7
	Angle from eccentricity direction to centre of tooth number 1, at reference face in direction of tooth count (opposite direction of rotation), φ_{fe1}	136,2
	Direction of rotation for index measurement	CW
	Probe ball diameter, d_p, mm	0
	Measurement diameter, d_M, mm	156
	Axial distance from reference face to measurement plane, X_M, mm	23,8

Table B.3 — Index variations caused by added eccentricity

Values in micrometres

Tooth number	Calculated LF Equation 3 and RF Equation 2		Value of tooth 1 subtracted from values to set value of tooth 1 to 0	
	LF index variation added	RF index variation added	LF index variation added	RF index variation added
1	−31,1	16,6	0,0	0,0
2	−25,4	7,8	5,7	−8,8
3	−18,0	−1,5	13,1	−18,1
4	−9,3	−10,8	21,8	−27,3
5	0,0	−19,3	31,0	−35,8
6	9,2	−26,4	40,3	−43,0
7	17,9	−31,8	49,0	−48,4
8	25,3	−35,0	56,4	−51,6
9	31,0	−35,8	62,1	−52,4
10	34,6	−34,2	65,7	−50,8
11	35,9	−30,3	66,9	−46,8
12	34,7	−24,2	65,7	−40,8
13	31,1	−16,6	62,2	−33,1
14	25,4	−7,8	56,5	−24,3
15	18,0	1,5	49,1	−15,0
16	9,3	10,8	40,4	−5,8
17	0,0	19,3	31,1	2,7
18	−9,2	26,4	21,8	9,9
19	−17,9	31,8	13,2	15,2
20	−25,3	35,0	5,8	18,4
21	−31,0	35,8	0,0	19,3
22	−34,6	34,2	-3,5	17,6
23	−35,9	30,3	-4,8	13,7
24	−34,7	24,2	-3,6	7,7
1	−31,1	16,6	0,0	0,0

Table B.4 — Certified index values (without added eccentricity)

Values in micrometres

Tooth number	LF index values	RF index values
1	0,0	0,0
2	−0,1	−1,1
3	−0,1	0,4
4	0,7	−1,1
5	0,0	−0,3
6	1,1	1,3
7	1,1	−0,1
8	0,4	−1,2
9	0,6	−0,8
10	1,3	−0,7
11	1,7	−1,4
12	1,1	−1,0
13	1,5	−0,4
14	1,2	−0,6
15	1,3	−0,9
16	1,4	−0,7
17	0,6	0,0
18	1,2	−0,1
19	0,8	−0,1
20	0,4	0,0
21	−0,3	−0,1
22	0,1	−1,0
23	0,2	−0,6
24	0,9	−0,2
1	0,0	0,0

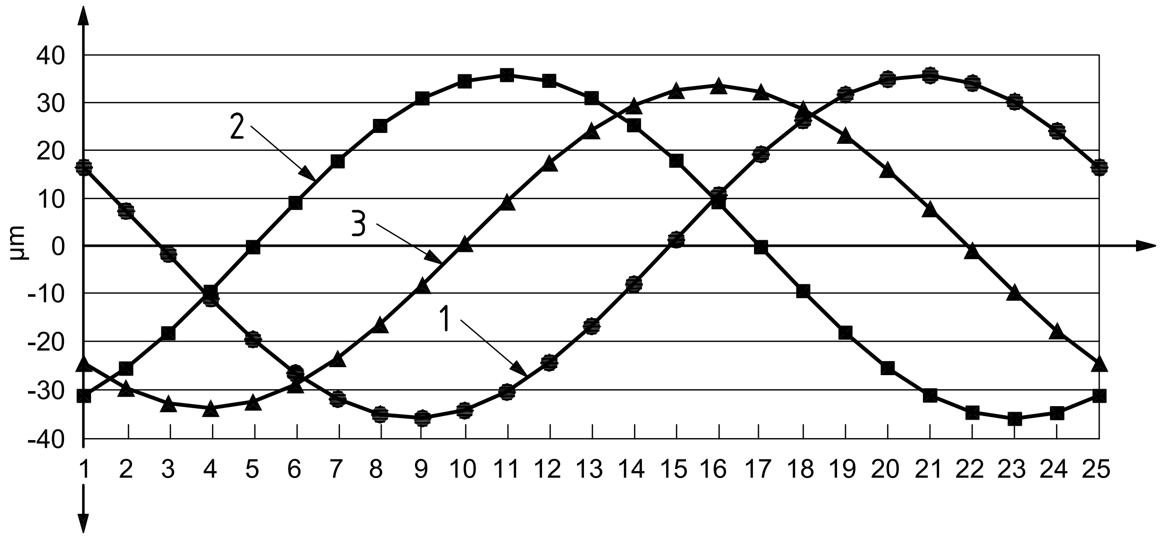
B.4.2 Comparison of predicted values to actual

To obtain the predicted index values for this test, the index values from added eccentricity and the certified index values for each tooth are summed. The predicted values are shown numerically in Table B.5. The predicted values and their relationship to the runout are shown graphically in Figure B.2. The actual measured values for this test can be compared (by subtraction) to these predicted values to assess the ability of the measurement system to accurately measure the resulting index variations.

Table B.5 — Index values predicted, micrometres

Values in micrometres

Tooth number	LF index predicted	RF index predicted
1	0,0	0,0
2	5,6	−9,9
3	13,0	−17,7
4	22,5	−28,4
5	31,0	−36,1
6	41,5	−42,7
7	50,0	−48,4
8	56,8	−52,7
9	62,7	−53,2
10	67,0	−51,5
11	68,6	−48,2
12	66,8	−41,8
13	63,7	−33,5
14	57,7	−25,0
15	50,4	−16,0
16	41,8	−6,5
17	31,8	2,7
18	23,1	9,7
19	14,0	15,1
20	6,2	18,5
21	−0,2	19,1
22	−3,5	16,6
23	−4,6	13,1
24	−2,7	7,5
1	0,0	0,0



Key

1 RF (f_l)

2 LF (f_l)

3 F_r

Figure B.2 — Index values, f_l, from added eccentricity and relationship to runout, F_r

Annex C
(informative)

Non-involute pin, ball, or plane (flank) artifact interpretation

C.1 Purpose

This annex provides examples of non-involute artifact interpretation. In practice, the known non-involute form is tested by an involute profile testing instrument which has been configured to generate a true involute form reference associated with a specified base circle. The theoretical deviations which should be measured by the instrument can be calculated and compared with the actual measured results.

The concept is to replace an involute shape by a simple geometry such as a straight line or circle, which can be produced to a higher accuracy. This enables the test to check probe condition, probe location and instrument gain.

C.2 Types of non-involute artifacts

Non-involute artifacts may take a variety of forms. The most common are plane artifacts (also known as flank artifacts, see Figure 19) and pin artifacts (see Figures 20 and 21). Another design is the ball artifact (see Figure 22). Plane artifacts consist of a flat surface feature which represents a plane that is parallel to, and offset from, the artifact axis of rotation. Pin artifacts consist of a pin feature which represents a cylinder with its axis parallel to and offset from the artifact axis of rotation. Ball artifacts consist of two ball features, one of which defines the artifact axis of rotation and the other the measured surface. Plane, pin and ball artifacts serve similar functions in calibration of involute profile testing instruments.

C.2.1 Non-involute artifact function and calibration

For a discussion of plane, pin and ball artifact function and calibration, see 6.4.2 to 6.4.5.

C.2.2 Probe tip effects

The calculations of non-involute artifact deviation from the specified involute must be compensated according to the vector deviations. Certification of spherical probe tip diameter is typically carried out separately from non-involute artifact certification measurements. However, the data must all be available for complete and accurate calculations of non-involute artifact deviation from the specified involute. Deviation of the probe tip diameter from the certified dimension will have only a very fractional effect upon the accuracy of the non-involute artifact test.

C.2.3 Measurement location

It may be desirable to limit testing of the plane and pin artifact to a specified axial location, in order to minimize the effects of manufacturing deviations. The ball artifact must be probed exactly at the equator of the ball.

C.3 Mounting reference features

Artifacts are normally mounted between centres on the involute profile test instrument. This is convenient and acceptable as are a variety of other possible configurations. However, since the physical orientation of the artifact to the instrument can affect test results, artifacts should be provided with appropriate reference surfaces to permit confirmation of proper mounting. Typically, this requirement is addressed by identifying truing diameter locations toward either end of the artifact. The amplitude and angular orientation of the runout characteristics of these reference surfaces must be included in the artifact certification data and confirmed as part of the involute profile test instrument calibration procedure.

Artifacts may also be constructed without provision for mounting between centres on the involute profile test instrument. Such artifacts must be provided with either two truing diameter locations near either end of the artifact or one truing diameter location and a truing band located on one face. Careful positioning of the artifact so as to minimize runout of the reference surfaces is required for this type of artifact. Artifacts of this type must have a circular chart documenting the amount and orientation of runout of these reference features included with the certification statement.

Ball artifacts need careful positioning of the ball centre, which defines the position of the axis of rotation if the instrument cannot compensate for eccentricity. The axis of rotation is defined by a line perpendicular to the axial datum surface, and passing through a ball centre.

C.4 Non-involute master interpretation

C.4.1 Recommended practice

Non-involute masters (plane, pin and ball masters) provide highly curved test traces which respond in an exaggerated manner to certain categories of test instrument variation. Included are measurement probe position variation, gain variation and hysteresis variation. It is best to restrict observation of test traces of non-involute masters to these characteristics.

The test instrument must achieve satisfactory performance in testing of involute masters before further refinement is attempted by use of non-involute masters. Furthermore, if certain types of adjustments are made to the instrument to improve non-involute master tests, retesting of the involute master will be required because of the interactive nature of such adjustments. Non-involute masters can be a valuable tool in the hands of a skilled gear metrologist, but they must be employed with caution.

C.4.2 Test trace interpretation

Four types of test instrument variation will be simulated in the following examples. Resultant traces will be presented for plane, pin and ball masters. Associated involute master traces will also be presented for additional reference. It is important to note that the various sources of instrument variation will be presented individually with other sources of instrument variation carefully adjusted to assure clarity of the example. In actual practice it is common for several, or all, sources of variation to exist simultaneously, rendering interpretation a complex task.

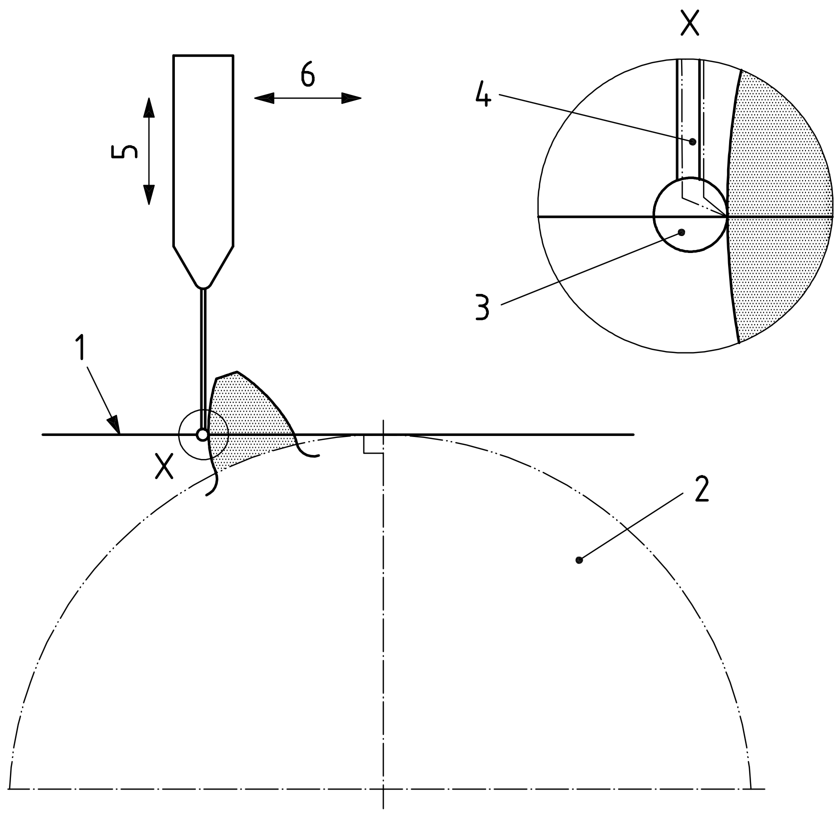
C.4.2.1 Probe base plane offset

In order to generate the specified involute, the contact point between the measurement probe and the master surface must lie within the plane tangent to the specified base cylinder. Variation of the probe location in a direction perpendicular to this plane will be referred to as probe base plane offset variation. Probe base plane offset occurs 90° from the direction of probe roll path offset described, see Figure C.1.

A common cause of this type of instrument variation is probe tip wear. Some instruments employ chisel-type probe tips which are designed to contact the involute profile at the sharp tip. Set up of this type of probe tip to the instrument involves positioning the end of the tip within the required plane. However, if the sharp chisel tip is worn, it may be relieved sufficiently to cause the side of the chisel rather than the end to contact the involute profile. This condition is best avoided by maintaining the sharpness of the chisel tip.

Both the plane and pin masters display negative trending traces from the start at zero degrees of roll until a low point or trend reversal occurs followed by a positive trend. Any variation in the probe base plane offset will cause the contact point between the probe and master to occur at a different diameter on the master at the start of the test. The negative trending region at the start of the test traces is quite sensitive to this. If the probe contacts a smaller diameter on the master, the amplitude of the negative portion of the trace will increase from the start to the trend reversal point. If the probe contacts a larger diameter, the amplitude will decrease.

Actually, if the starting point of the trace is fixed, it will appear that the whole trace is being driven down or carried up as the lead-in portion of the trace is thus lengthened or shortened.



Key

1 base tangent plane
2 base cylinder
3 ball probe
4 sharp pointed probe
5 probe base plane offset direction (see C.4.2.1)
6 probe roll path offset direction (see C.4.2.2)

Figure C.1 — Probe offsets

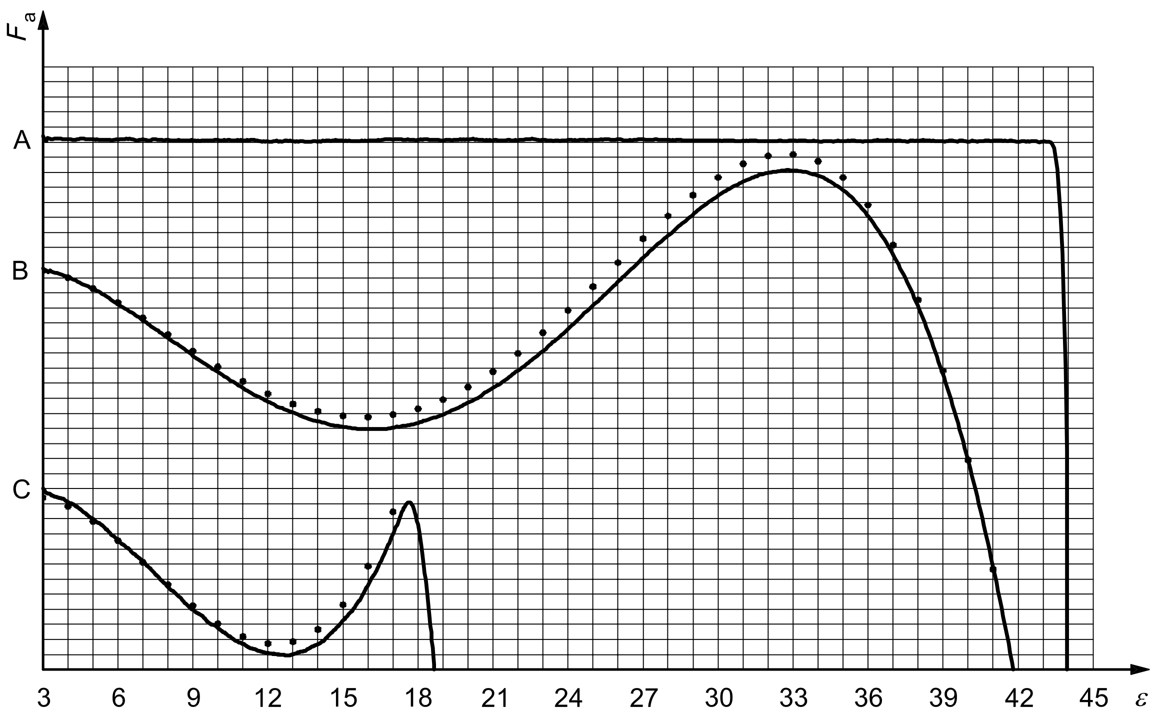
To correct this situation: move the probe out further from the centreline if the negative portion of the trace is longer than specified; move the probe in closer to the centreline if the negative portion of the trace is shorter than specified. The adjustment is relatively sensitive. A change of 38 mm is displayed in Figure C.2. This has resulted in up to a 5 µm change in the displacement of the plane master and pin master traces, see Figure C.2, traces B and C.

Note also that the adjustment has had no noticeable effect on the involute master, see Figure C.2, trace A. In cases of large variation of probe base plane offset, an involute slope variation may be encountered. Therefore, in the event of any adjustment to the probe base plane offset to improve non-involute master performance, a retest of the involute master must take place to assure that its slope performance was not adversely affected.

C.4.2.2 Probe roll path offset

As the measurement probe generates along the master feature from lower to higher diameters, it is moving tangential to the base cylinder within the plane of action. The amount of offset of the probe from the centreline where the plane of action contacts the base cylinder will determine the diameter at which the probe contacts the master. Variation of the probe offset in this direction will be referred to as the probe roll path offset variation. Probe roll offset occurs 90° from the direction of probe base plane offset described above, see Figure C.1.

A larger probe roll path offset results in contact at a higher diameter, while a smaller offset results in contact at a lower diameter. It is important to note that this category of instrument variation has no effect on the accuracy of the involute being generated. It only affects the accuracy of the degrees of roll scaling, causing correct involute test data to be shifted laterally out of location. In the presence of this type of error, plane and pin master traces also tend to be shifted sideways. However, since the traces trend significantly downward for the first portion of their length, the trace may also seem to be moved out of position vertically, thus emulating the type of trace characteristic encountered in the presence of a probe base plane offset variation. Interpretation of this type of variation can be challenging.



Dotted curves represents theoretical values.

Key

F_a 0,05 mm/div.

A involute master

B pin master

C plane master

Figure C.2 — Probe base plane offset

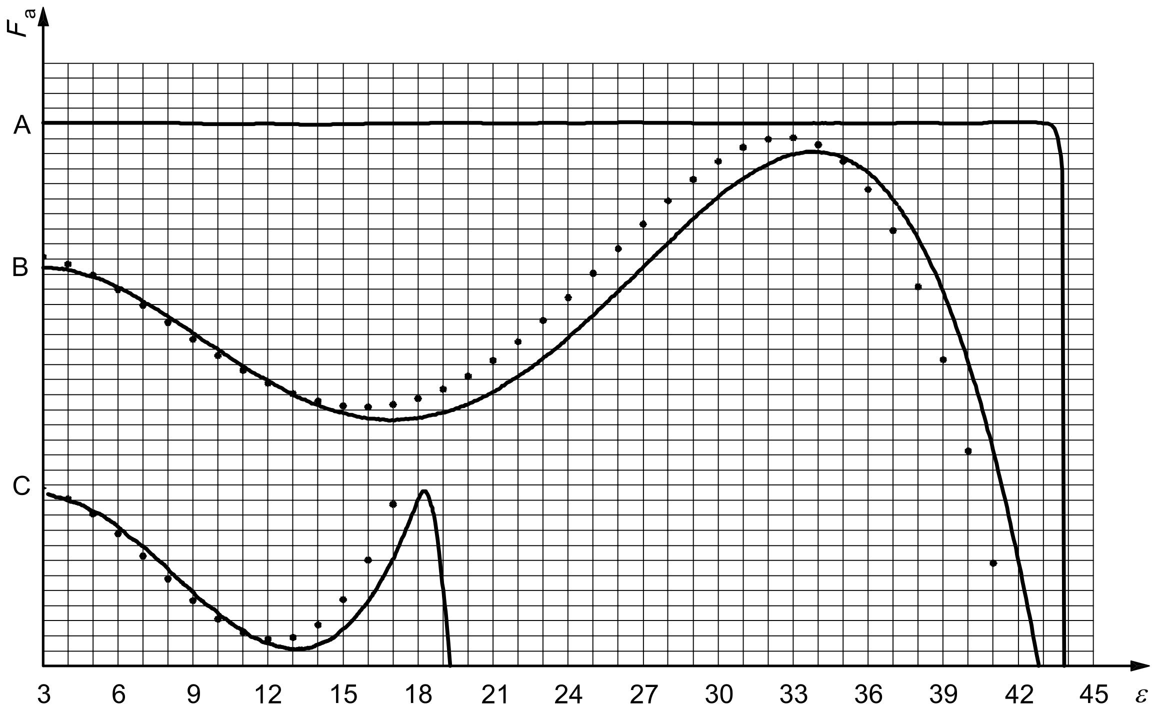
Relocation of the probe closer to the centreline will shift the trace higher along the degrees of roll scale. The negative trending lead-in portion of the trace may also tend to lengthen along the vertical scale causing an associated vertical shift in location. The opposite tendencies can be expected if the probe is moved farther from the centreline. The adjustment is not highly sensitive. A change of 760 µm was required to produce the changes displayed in Figure C.3.

Note that the involute master appears unaffected by the adjustment. In cases of large variation of probe roll path offset, apparent variation in the degrees of roll location of significant features such as the outside diameter drop-off may be encountered.

C.4.2.3 Gain

The gauging portion of the involute profile test instrument must be able to accurately measure the amount of variation it encounters during testing procedures. If the gauging tends to indicate more or less variation than that actually present, it is referred to as exhibiting gain variation.

A simple gain variation will tend to increase or decrease measured values by a percentage. Thus, measurements of small variations will include relatively small gain variations, while measurements of larger variations will include proportionately larger gain variations. Linearity variation is a subset of gain variation in which the ratio of measured variation to gain variation is not a fixed percentage. Detection of linearity variation requires more complex testing procedures than simple gain variation.



Dotted curves represents theoretical values.

Key

F_a 0,05 mm/div.

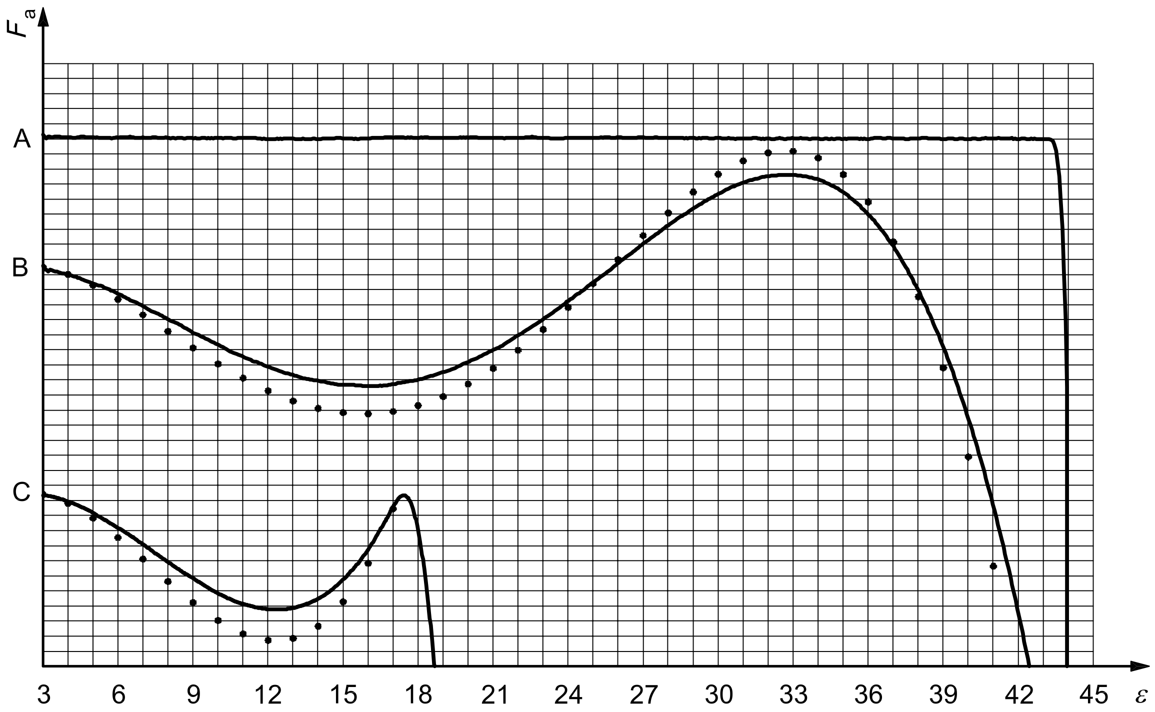
A involute master

B pin master

C plane master

Figure C.3 — Probe roll path offset

The characteristic trace of a pin master includes two reversals in the trend of the trace data which can serve to detect simple gain variation. If the amplitude of the trace from reversal to reversal is more or less than certified, an adjustment in gain is probably appropriate. Figure C.4, trace B, clearly displays the 17 µm gain adjustment.



Dotted curves represents theoretical values.

Key

F_a 0,05 mm/div.

A involute master

B pin master

C plane master

Figure C.4 — Gain

The characteristic trace of a plane master includes only one trend reversal between the start and outside diameter. It is therefore not considered an appropriate reference for this type of adjustment even though its trace will be affected by gain variation.

C.4.2.4 Hysteresis

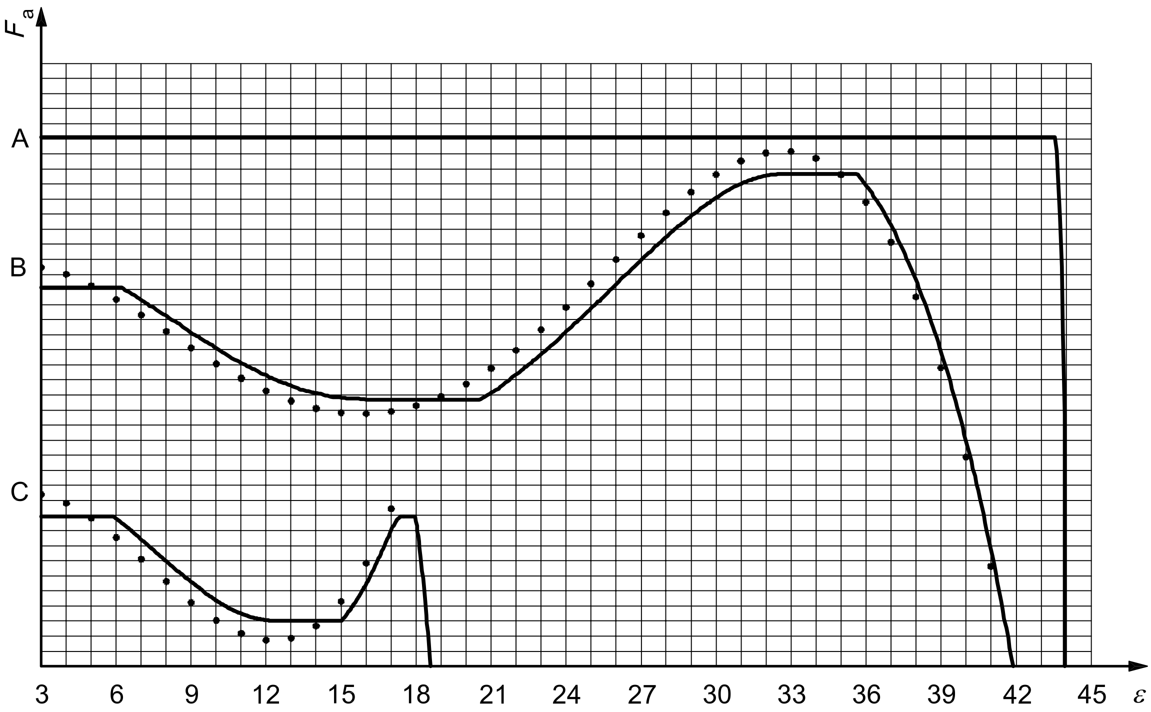
If precise measurements are to be made by the involute profile test instrument, its gauging must be appropriately sensitive to small amplitude variations. Gauging which tends to respond only to variations above a significant threshold is said to exhibit hysteresis variation.

Both plane pin and ball masters produce highly curved test traces which can serve as an aid to detecting hysteresis variation. In Figure C.5, traces B and C, it is clear that whenever a start of trend or reversal of trend is encountered, the gauging fails to respond to this variation until a threshold is passed. This characteristically results in improper flat spots in what should be a continuously curved trace.

Hysteresis causes involute trace A in Figure C.5 to be perfectly flat, since the actual deviation of the carefully manufactured master never exceeds the gauging sensitivity threshold. This could be mistaken as evidence of excellent instrument performance. But to the astute observer, the absolutely flat trace is an indication of significant test instrument hysteresis.

C.4.2.5 Slope and form variation

These two important types of involute profile test instrument variation are discussed in ISO/TR 10064-1. Information pertaining to slope and form variation is not included in the present clause because the involute master is considered a preferred reference for control of this type of instrument variation. However, it is important to be aware that any slope or form variation in involute master test traces will also affect non-involute master test traces in a very similar manner. Thus it is required that these types of test instrument variation be brought under control during testing of the involute master before beginning the non-involute master testing described in C.3.



Dotted curves represents theoretical values.

Key

F_a 0,05 mm/div.

A involute master

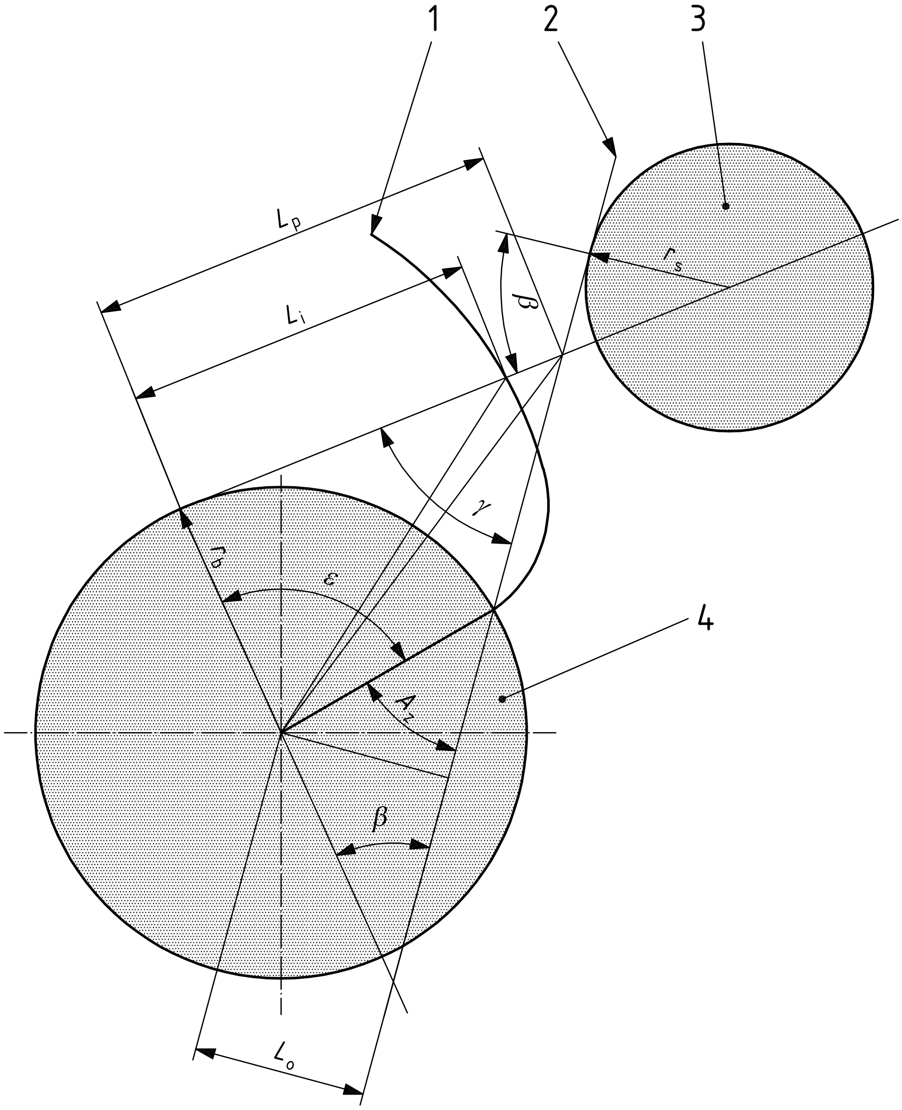
B pin master

C plane master

Figure C.5 — Hysteresis

C.5 Plane (flank) master calculations

The calculations involve a comparison of the intersections of a plane master and an involute master with a common line of action at selected roll angles. The starting position at zero degrees of roll places both the involute and the plane in intersection with the line of action at its point of tangency with the base circle. For the roll angle ε the length from the point of tangency with the base circle to the involute respectively to the plane is calculated, see Figure C.6. As the contact point of a spherical probe tip is normally not on the same tangent line, a correction needs to be made. This correction vanishes to zero for a chisel type probe tip.



Key

1 involute curve

2 base tangent plane

3 ball probe

4 base circle

Figure C.6 — Roll angle determination

C.5.1 Calculations for plane master

Given data:

r_b is the base circle radius;

r_s is the probe tip radius;

L_o is the distance from centre of base circle to plane;

ε is the angle of roll;

Δp_ε is the theoretical measured deviation between plane and involute.

$$A_z = \arcsin\left(\frac{L_o}{r_b}\right) \tag{C.1}$$

$$L_i = r_b\ \varepsilon\left(\frac{\pi}{180}\right) \tag{C.2}$$

$$\gamma = 360 - 180 - \varepsilon - \left(90 - A_z\right) \tag{C.3}$$

$$\gamma = 90 - \left(\varepsilon - A_z\right) \tag{C.4}$$

$$\beta = \varepsilon - A_z \tag{C.5}$$

$$L_p = \tan\beta\left(r_b + \frac{L_o}{\sin\beta}\right) \tag{C.6}$$

$$L_p = r_b \tan\beta + \left(\frac{L_o}{\cos\beta}\right) \tag{C.7}$$

$$\Delta p_\varepsilon = L_p - L_i + \left[\left(\frac{r_s}{\cos\beta}\right) - r_s\right] \tag{C.8}$$

$$\Delta p_\varepsilon = \left[r_b \tan\left(\varepsilon - A_z\right) + \frac{L_o}{\cos\left(e - A_z\right)}\right] - \left[r_b\ \varepsilon\left(\frac{\pi}{180}\right)\right] + r_s\left[\frac{1}{\cos\left(\varepsilon - A_z\right)} - 1\right] \tag{C.9}$$

Equation (C.9) describes the theoretical deviation curve between plane and involute form.

C.5.2 Plane master example

Plane master calculation example based on a typical 115 mm base circle.

Typical given data:

d_b = 115 mm Base circle diameter

r_b = $d_b/2$ = 57,5 mm Base circle radius

d_s = 1 mm Spherical probe tip diameter

r_s = $d_s/2$ = 0,5 mm Spherical probe tip radius

L_o = 9,233 mm Plane offset from centreline

Calculation:

$$A_z = \arcsin\left(\frac{L_o}{r_b}\right)$$

$$A_z = 9{,}2403\,°$$

ε°	0,0	0,5	9,2403	10,0	13,0
Δp_ε, µm	0,0066	–0,0212	–0,0401	–0,0392	–0,0137

For a chisel-type probe stylus we have r_s = 0,0 and get:

ε°	0,0	0,5	9,2403	10,0	13,0
Δp_ε, µm	0,0000	–0,0226	–0,0401	–0,0393	–0,0148

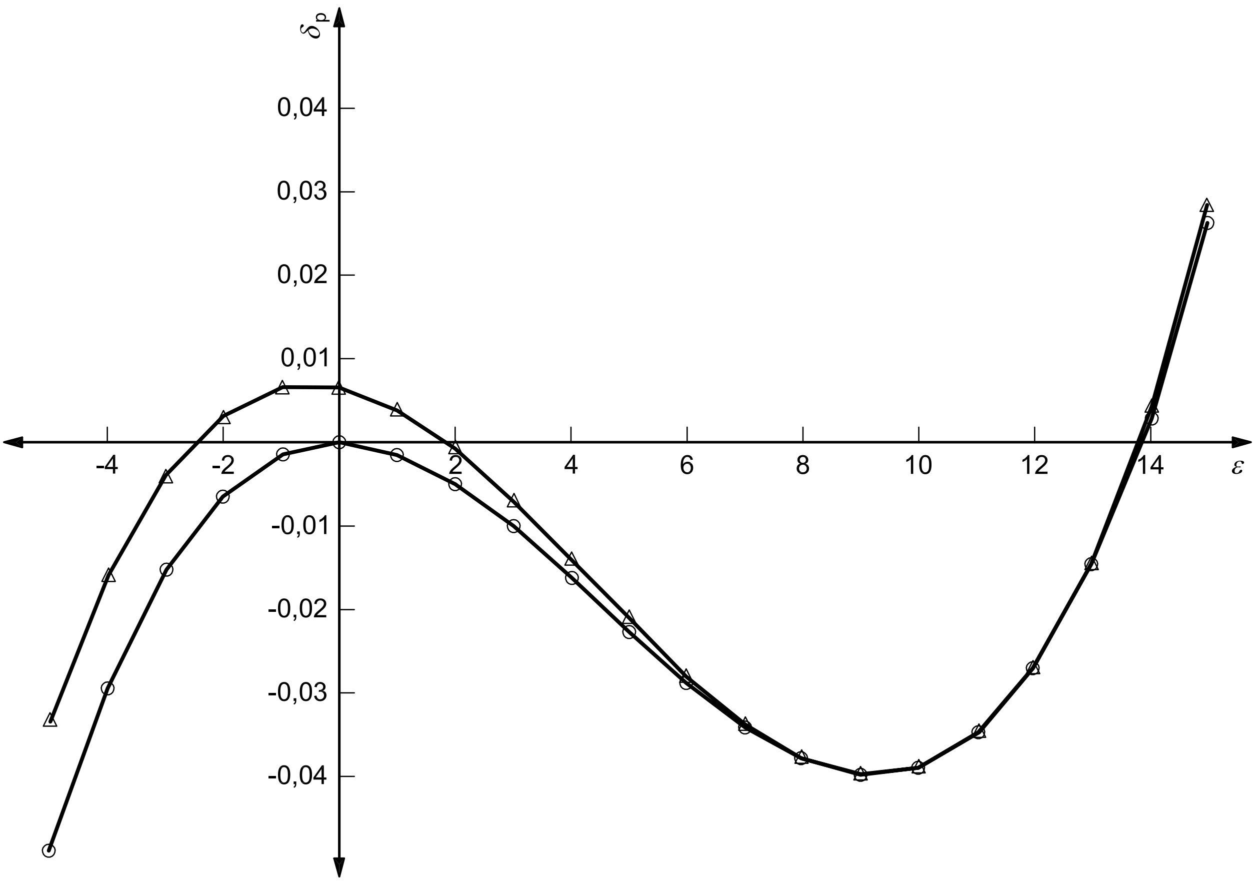


Figure C.7 — Plane master graph for r_s = 0,0 and r_s = 0,5

C.6 Typical pin or ball master calculations

The design of the radial setting of the pin or ball is not part of a calibration procedure for a gear measuring instrument. This parameter together with base diameter and pin/ball diameter determines the geometry of this type of non-involute master and must be known and certified from the master calibration.

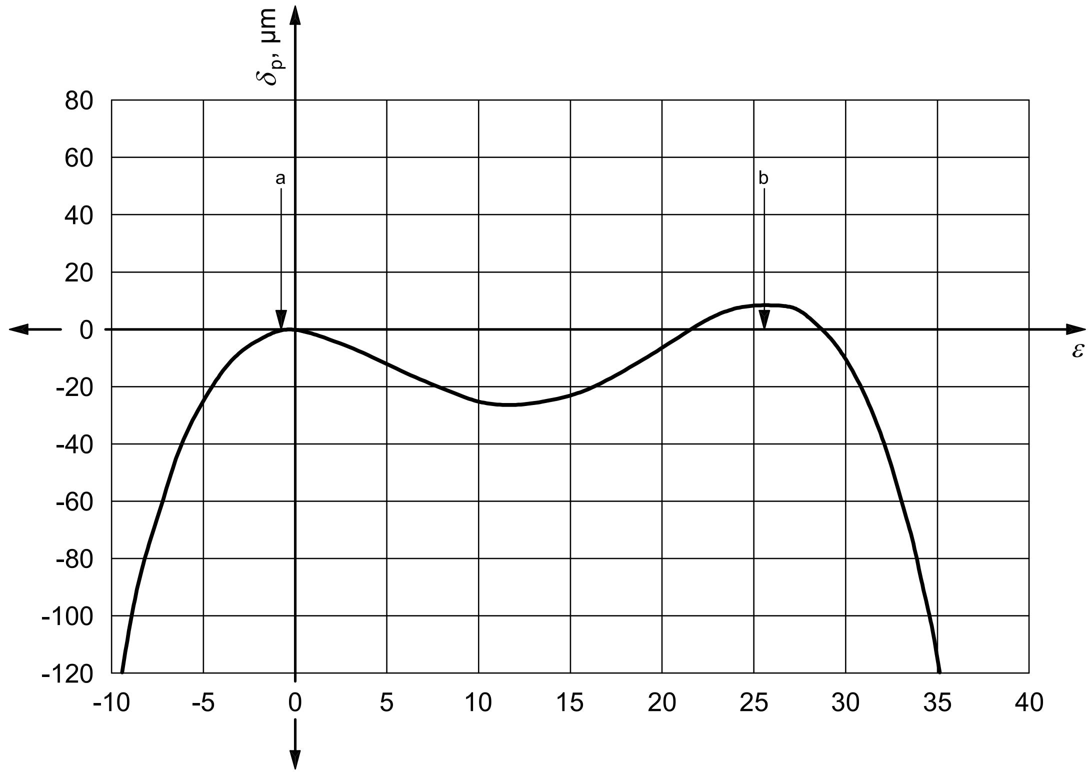
For a given target pin or ball radius, r_c, stylus tip radius, r_p, and base circle radius r_b, there is a simple relationship to define the positional radius, C, to produce an almost equal peak height of a camel-back form of output curve, see Figure C.8.

The equation is

$$C = 0{,}994\, r_b + 0{,}038\left(r_c + r_p\right) \qquad \text{(C.10)}$$

Equation (C.10) produces acceptable results when r_b/r_c is between 2,5 to 5,5. The roll-angle for the measurement in this case is wide enough related with actual tooth form checking.

See Figure C.9.



Key

a Peak A exists at rolling angle zero or negative, near point A, and receives strong influence of stylus tip radius.

b Peak B exists at larger positive rolling angle region, and receives strong influence from the setting value of base circle.

Figure C.8 — Pin or ball artifact output curve from a gear measuring instrument

C.6.1 Determination of theoretical curve for ball probe

C.6.1.1 Calculation for ball type probe tip

Given data:

r_b is base circle radius;

r_c is pin or ball radius;

r_p is stylus tip radius;

C is pin or ball centre distance;

ε is roll angle.

NOTE Angles are in degrees.

$$\tau = \arccos\left[\frac{r_b^2 + C^2 - r_c^2}{2\, r_b\, C}\right] \tag{C.11}$$

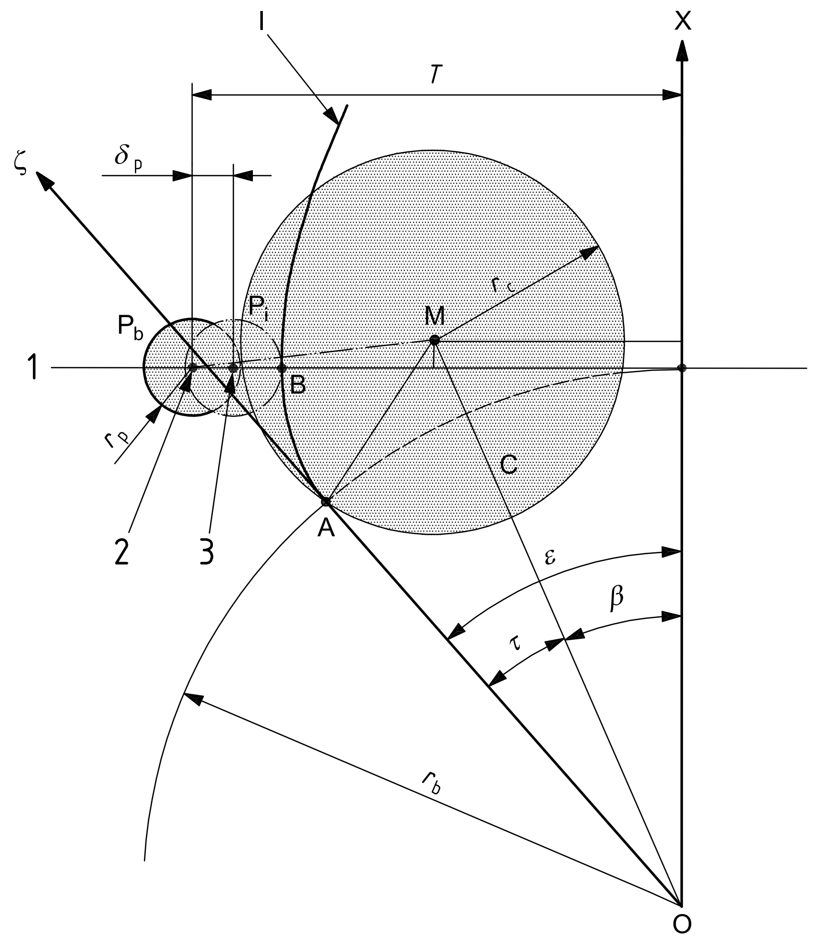
$$\beta = \varepsilon - \tau \tag{C.12}$$

$$T = \sqrt{\left(r_c + r_p\right)^2 - \left(C\cos\beta - r_b\right)^2} + C\sin\beta \tag{C.13}$$

$$\delta_p = T - \left[r_b\, \varepsilon\left(\frac{\pi}{180}\right) + r_p\right] \tag{C.14}$$

where

δ_p is the difference of pin or ball from involute using a ball probe.



Key

1 line of action
2 Stylus tip centre for contacting circle
3 Stylus tip centre for contacting involute
O centre of base circle (centre of rotation)
M centre of pin or ball
r_c radius of pin or ball
C distance between O and M
r_b radius of base circle
A crossing point of base circle with pin or ball periphery
I involute curve starting from point A
ζ axis from origin O through point A
X ordinate axis of gear checker
r_p stylus tip radius
B contact point of stylus tip to reference involute curve
P_i stylus tip centre, when stylus is on the involute
P_b stylus tip centre, when stylus is on the circle
T distance from point P_b to axis X
ε roll angle
τ angle < AOM
β angle < MOX
δ_p deviation of circular form from involute

Figure C.9 — Deviation of circular form from involute ($\varepsilon > 0$)

C.6.1.2 Example with ball type probe tip

For

r_b = 25 mm

r_c = 10 mm

r_p = 1 mm

C = 25,3036 mm

ε = 10°

$$\tau = \arccos\left[\frac{25^2 + 25{,}3036^2 - 10^2}{2(25)(25{,}3036)}\right] = 22{,}922\ 472\,°$$

β = 10° $-\tau$ = 12,922 472°

$$T = \sqrt{(10+1)^2 - (25{,}303\ 6\cos\beta - 25)^2} + 25{,}303\ 6\sin\beta = 5{,}336\ 124\ \text{mm}$$

$$\delta_p = 5{,}336124 - \left[25(10)\left(\frac{\pi}{180}\right) + 1\right] = -0{,}027\ 199\ \text{mm}$$

C.6.2 Example with chisel type probe tip

When using an involute tester with a chisel-type probe tip the ball radius r_p is to be set to zero in the formulae in C.6.1.

For

r_b = 25 mm

r_c = 10 mm

r_p = 0

C = 25,303 6 mm

ε = 10°

$$\tau = \arccos\left[\frac{25^2 + 25{,}3036^2 - 10^2}{2(25)(25{,}3036)}\right] = 22{,}922\ 472\,°$$

β = 10° $-\tau$ = 12,922 472°

$$T = \sqrt{(10)^2 - (25{,}303\ 6\cos\beta - 25)^2} + 25{,}303\ 6\sin\beta = 4{,}335\ 606\ \text{mm}$$

$$\delta_p = 4{,}335\ 606 - \left[25(10)\left(\frac{\pi}{180}\right)\right] = -0{,}027717\ \text{mm}$$

Figure C.10 shows the different measurements with ball or chisel tip. The upper curve is the resulting deviation for the probe tip radius r_p = 1 mm, the lower is for the chisel type with r_p = 0.

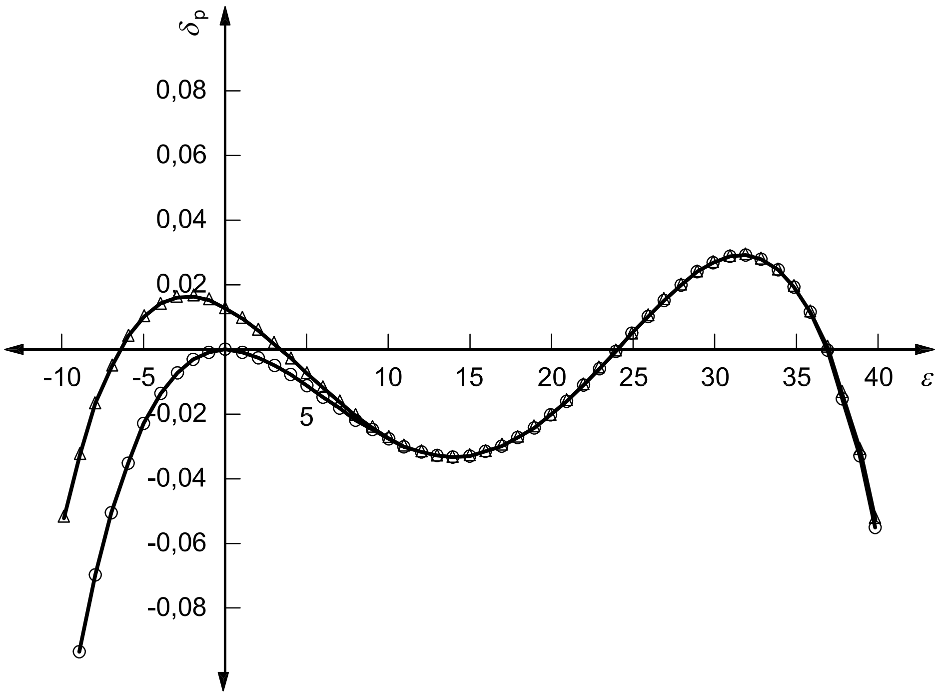


Figure C.10 — Different measurements with ball or chisel tip

C.6.3 Effects of systematic errors

In general, it is impossible to set the artifact without mounting errors on the gear checker to be calibrated. However, we can calculate the effect that mounting errors have on the profile measurement result.

Suppose the artifact is set with some setting errors in terms of (see Figure C.11):

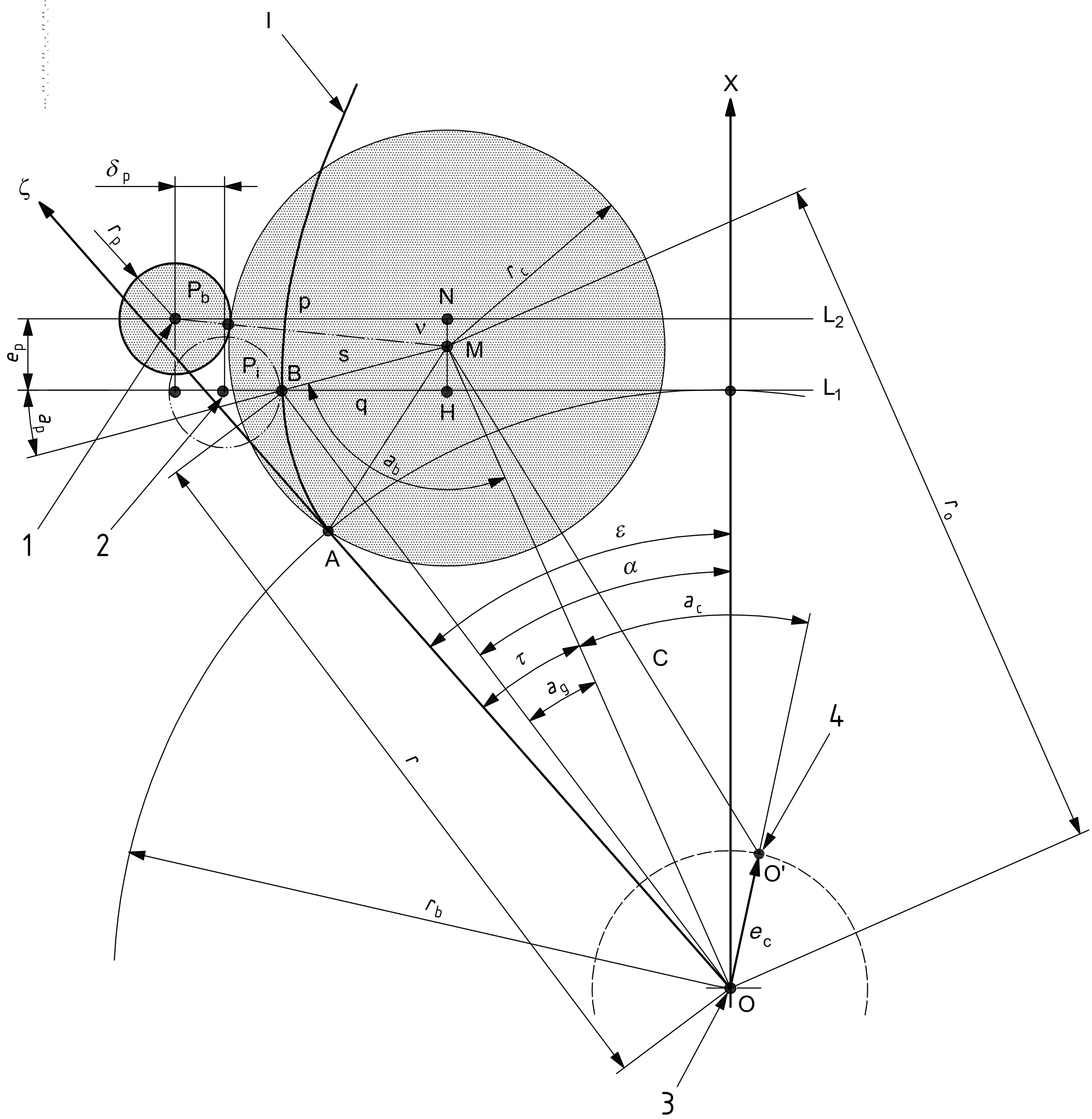
e_p is the off-set amount of stylus position from the line of action;

e_c is the off-set amount of artifact centre from the centre of rotation of the gear checker to be calibrated;

a_c is the off-set angle of artifact centre from the centre of rotation of the gear checker to be calibrated.

The following calculations show how these offsets can be taken into account for the determination of δ_p, i.e. the theoretically measured difference between involute and circle.

Figure C.11 shows the influence of the mounting errors on the results. It can give the user some guidance about allowable mounting errors when using the pin or ball artifact.



Key

1	stylus tip centre for contacting circle	e_p	distance between L_2 and L_1 (positive when line L_2 is on axis O side)
2	stylus tip centre for contacting involute	a_p	angle between line BM and L_1 (a_p being negative in Figure 5)
3	centre of base circle centre axis of pin or ball artifact	HN	cross point of perpendicular line through M to line $L_1$and L_2
		α	pressure angle at point B
O′	centre axis of pin or ball artifact	a_g	angle < BOM
e_c	eccentricity of artifact centre from axis of rotation	r	length BO
		s	length BM
a_c	angle < MOO′	a_b	angle < BMO
L_1	line of action for involute I by roll angle ε	ν	distance MN
L_2	line parallel to L_1, in which the centre of stylus tip P_b is included	p	distance PbN
		q	distance BH

Figure C.11 — Deviation of circular form from involute for systematic errors ($\varepsilon > 0$)

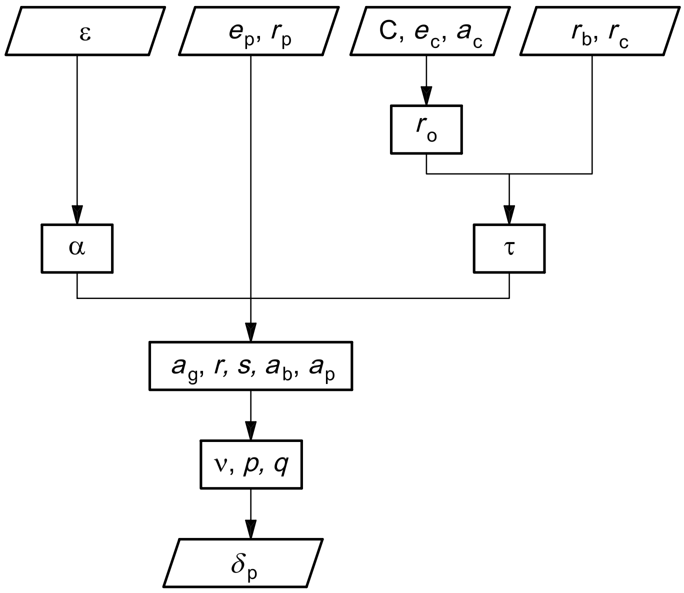


Figure C.12 — Flow chart for calculating δ_p, deviation of circle from involute

$$r_o = e_c \cos a_c + \sqrt{e_c^2 \cos^2 a_c + C^2 - e_c^2} \tag{C.15}$$

$$\tau = \arccos\left(\frac{r_b^2 + r_o^2 - r_c^2}{2 r_b r_o}\right) \tag{C.16}$$

$$\alpha = \arctan \varepsilon \tag{C.17}$$

$$a_g = \tau - \varepsilon + \alpha \tag{C.18}$$

$$r = \frac{r_b}{\cos \alpha} \tag{C.19}$$

$$s = \sqrt{r^2 + r_o^2 - 2r\, r_o \cos a_g} \tag{C.20}$$

$$a_b = \arccos\left(\frac{r_o^2 + s^2 - r^2}{2 r_o s}\right) \tag{C.21}$$

$$a_p = \frac{\pi}{2} - \tau + \varepsilon - a_b \tag{C.22}$$

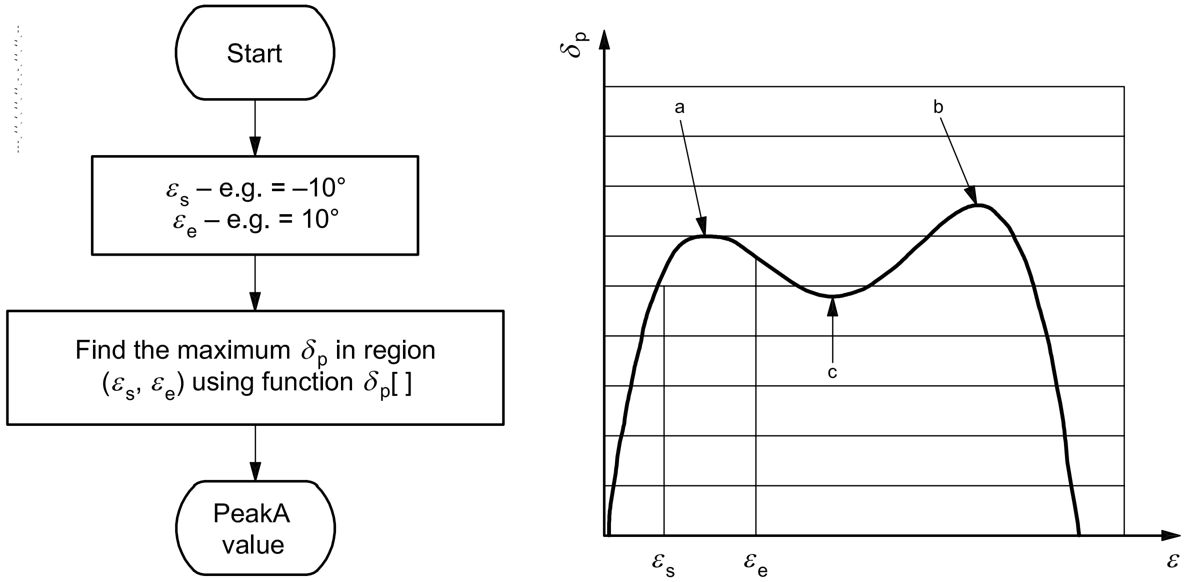
$$\nu = s \sin a_p + e_p \tag{C.23}$$

$$p = \sqrt{\left(r_p + r_c\right)^2 + \nu^2} \tag{C.24}$$

$$q = s \cos a_p \tag{C.25}$$

$$\delta_p = p - q - r_p \tag{C.26}$$

To find peak value at position A, etc., see Figure C.13.



The function δ_p[ ] is the set of equations from C.15 to C.26.

The interval values for the calculation, ε_s and ε_e, should be decided after checking the camel-back curve, in case that peak value searching fails.

Key

a Peak A.

b Peak B.

c Bottom height.

Figure C.13 — Calculation for peaks and bottom of the camel-back curve

Table C.1 — Numerical example of the δ_p values (mm)

ε (deg)						
	r_b (mm)	43,75	43,75	43,75	43,75	43,75
	r_c (mm)	12,7	12,7	12,7	12,7	12,7
	C (mm)	44	44	44	44	44
	r_p (mm)	0	0,5	0,5	0,5	0,5
	e_p (mm)	0	0	0,01	0,01	0,01
	e_c (mm)	0	0	0	0,01	0,01
	a_c (°)	0	0	0	0	90
–10		–0,187404	–0,155430	–0,151880	–0,151445	–0,151880
–9		–0,141376	–0,114496	–0,111248	–0,110920	–0,111248
–8		–0,103903	–0,081430	–0,078465	–0,078228	–0,078465
–7		–0,073882	–0,055214	–0,052517	–0,052358	–0,052517
–6		–0,050324	–0,034932	–0,032487	–0,032393	–0,032487
–5		–0,032335	–0,019752	–0,017544	–0,017503	–0,017544
–4		–0,019104	–0,008918	–0,006934	–0,006934	–0,006934
–2		–0,004037	0,002401	0,003976	0,003926	0,003976
–1		–0,000924	0,004084	0,005472	0,005413	0,005472
0		0,000000	0,003826	0,005037	0,004981	0,005037
1		–0,000765	0,002096	0,003143	0,003098	0,003143
2		–0,002766	–0,000681	0,000211	0,000489	0,000211
3		–0,005596	–0,004126	–0,003377	–0,003366	–0,003377
4		–0,008896	–0,007899	–0,007283	–0,007230	–0,007283
5		–0,012345	–0,011704	–0,011212	–0,011106	–0,011212
6		–0,015670	–0,015287	–0,014907	–0,014738	–0,014907
7		–0,018636	–0,018430	–0,018152	–0,017911	–0,018152
8		–0,021051	–0,020958	–0,020773	–0,020448	–0,020773
9		–0,022765	–0,022736	–0,022633	–0,022215	–0,022633
10		–0,023669	–0,023666	–0,023635	–0,023113	–0,023635
11		–0,023694	–0,023692	–0,023724	–0,023088	–0,023724
12		–0,022815	–0,022799	–0,022882	–0,022123	–0,022883
13		–0,021048	–0,021010	–0,021136	–0,020242	–0,021136
14		–0,018452	–0,018390	–0,018548	–0,017511	–0,018548
15		–0,015125	–0,015045	–0,015224	–0,014033	–0,015224
16		–0,011212	–0,011121	–0,011312	–0,009957	–0,011312
17		–0,006897	–0,006805	–0,006997	–0,005468	–0,006997
18		–0,002409	–0,002325	–0,002509	0,000796	–0,002509
19		0,001982	0,002049	0,001884	0,003789	0,001884
20		0,005963	0,006008	0,005872	0,007980	0,005872

Table C.1 (*continued*)

ε (deg)	r_b (mm)	43,75	43,75	43,75	43,75	43,75
	r_c (mm)	12,7	12,7	12,7	12,7	12,7
	C (mm)	44	44	44	44	44
	r_p (mm)	0	0,5	0,5	0,5	0,5
	e_p (mm)	0	0	0,01	0,01	0,01
	e_c (mm)	0	0	0	0,01	0,01
	a_c (°)	0	0	0	0	90
21		0,009179	0,009201	0,009105	0,011423	0,009104
22		0,011233	0,011238	0,011191	0,013730	0,011191
23		0,011688	0,011688	0,011700	0,014468	0,011700
24		0,010062	0,010081	0,010162	0,013168	0,010162
25		0,005836	0,005907	0,006068	0,009318	0,006068
26		–0,001551	–0,001382	–0,001132	0,002372	–0,001132
27		–0,012700	–0,012374	–0,012024	–0,008259	–0,012024
28		–0,028254	–0,027694	–0,027234	–0,023202	–0,027234
29		–0,048892	–0,048006	–0,047426	–0,043119	–0,047426
30		–0,075338	–0,074013	–0,073302	–0,068714	–0,073303
31		–0,108353	–0,106456	–0,105604	–0,100727	–0,105605
32		–0,148740	–0,146114	–0,145112	–0,139941	–0,145112
33		–0,197345	–0,193810	–0,192645	–0,187174	–0,192646
34		–0,255057	–0,250404	–0,249067	–0,243290	–0,249067
35		–0,322812	–0,316801	–0,315280	–0,309192	–0,315281
36		–0,401593	–0,393952	–0,392236	–0,385831	–0,392237
37		–0,492437	–0,482856	–0,480932	–0,474205	–0,480933
38		–0,596434	–0,584562	–0,582418	–0,575364	–0,582419
39		–0,714739	–0,700179	–0,697801	–0,690415	–0,697802
40		–0,848576	–0,830876	–0,828251	–0,820526	–0,828252

Bibliography

[1] ISO 701:1976, *International gear notation — Symbols for geometrical data*

[2] ISO 1122-1:1983, *Glossary of* gears — *Part 1:Geometrical definitions*

[3] AGMA TECHNICAL PAPER 93FTM6, *Effect of Radial Runout on Elemental Measurements*, by I. Laskin, Consultant; R.E. Smith, R.E. Smith & Co.; and E. Lawson, Mahr Corporation

[4] *Fundamental Statistical Process* Control, Automotive Industry Action Group, December, 1991

[5] *Journal of Quality Technology*, Volume 16, Nor. 4, October, 1984

[6] BEYER, W. et al. *Kreisförmige* Evolventennormale*, Qualitätstechnik*, Carl Hanser Verlag, München 1986

[7] KONDO, K., MIZUTANI, H. Measurement *Uncertainty of Tooth Profile by Master Balls*, VDI–BERICHTEN R.1665 (2002) PP.797–810

[8] Program of the Ministry of Economy, Trade and Industry for Standardization, FY2003 Report: *Artifact for nanometrological calibration of gear measuring instruments and calibration method based on it for the standardization*, National Institute of Advanced Industrial Science and Technology, Japan (AIST), March 2004

ICS 21.200

Price based on 89 pages