TECHNICAL REPORT

ISO/TR 10064-1

Second edition
2017-07

Code of inspection practice —

Part 1: Measurement of cylindrical gear tooth flanks

Code pratique de réception —

Partie 1: Mesure des flancs dentaires cylindriques

Reference number
ISO/TR 10064-1:2017(E)

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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by ISO/TC 60, *Gears*.

This second edition cancels and replaces the first edition (ISO/TR 10064-1:1992), which has been technically revised. It also incorporates the Technical Corrigendum ISO/TR 10064-1:1992/Cor. 1:2006.

The following changes have been made:

— the contents have been updated to correspond with ISO 1328-1:2013;

— additional material has been added on the proper setup and use of measuring machines, and how the measurement results can be used to determine the corrective steps needed to improve the gear tooth flank tolerance class.

A list of all parts in the ISO/TR 10064 series can be found on the ISO website.

Code of inspection practice —

Part 1: Measurement of cylindrical gear tooth flanks

1 Scope

This document supplements ISO 1328-1:2013. It provides a code of practice dealing with measurements on flanks of individual cylindrical involute gears, i.e. with the measurement of pitch, profile, helix and tangential composite characteristics. It describes measuring equipment, provides advice for gear measuring methods and for the analysis of measurement results, and discusses the interpretation of results.

Measurements using a double flank tester are not included (see ISO/TR 10064-2). This document only applies to involute gears.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, symbols and abbreviated terms

For the purposes of this document, the following terms, definitions, symbols and abbreviated terms apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

NOTE The symbols and terms used throughout this document are in basic agreement with the symbols and terms given in ISO 701 and in ISO 1122-1. In all cases, the first time that each symbol is introduced, it is defined and discussed in detail. See Table 1. Abbreviated terms are given in Table 2.

Table 1 — Symbols and definitions

Symbols[a]	Definition	Units	First use
a	tip point	—	Figure 31
b	face width	mm	Figure 37
C_f	profile control point	—	Figure 31
d	reference diameter	mm	Formula (4)
d_a	tip diameter	mm	14.3.2.1
$d_{a\,eff}$	effective (measured) tip diameter	mm	Figure 29
d_b	base diameter	mm	Formula (6)
$d_{b\,eff}$	effective base diameter	mm	14.2

[a] Symbols used for deviations of individual element measurements from specified values are composed of lower case letters "f" with subscripts (exceptions include f_e, f_1 and f_2) whereas symbols used for "cumulative" or "total" deviations, which represent combinations of several individual element deviations, are composed of capital letters "F" also with subscripts. It is necessary to qualify some deviations with an algebraic sign. A deviation is positive when, for example, a dimension is larger than optimum and negative when smaller than optimum.

[b] These deviations can be + (plus) or − (minus).

Table 1 *(continued)*

Symbols[a]	Definition	Units	First use
d_M	measurement diameter	mm	6.2.3.2
d_{Nf}	start of active profile (SAP) diameter	mm	Formula (8)
d_y	individual inspection diameter (measurement diameter)	mm	Figure 29
F_a	tip form point (where tip break starts)	—	Figure 31
F_{is}	total single flank composite deviation	µm	11.1
F_p	total cumulative pitch deviation	µm	9.3.1
F_{pi}	individual total cumulative pitch deviation	µm	9.3.8
F_{pk}	sector pitch deviation over *k* pitches	µm	9.3.7
F_r	radial runout	µm	6.2.5
F_α	total profile deviation	µm	Figure 14
F_β	total helix deviation	µm	Figure 37
f_α	difference between the actual and nominal pressure angle	degrees	9.1.4
$f_{\alpha m}$	mean pressure angle deviation	degrees	14.3.1
f_b	base circle deviation (difference between the actual and nominal base diameter)	mm	9.1.4
f_{bm}	mean base diameter deviation	mm	14.3.1
f_e	eccentricity between gear axis and axis of gear teeth	µm	Figure 34
$f_{f\alpha}$	profile form deviation	µm	Figure 14
$f_{f\beta}$	helix form deviation	µm	Figure 37
$f_{f\beta T}$	helix form tolerance	µm	8.3.1
$f_{H\alpha}$	profile slope deviation[b]	µm	Figure 14
$f_{H\alpha m}$	mean profile slope deviation[b]	µm	9.1.5
$f_{H\alpha i}$	individual profile slope deviation[b]	µm	9.1.5
$f_{H\beta}$	helix slope deviation[b]	µm	6.4
$f_{H\beta i}$	individual helix slope deviation[b]	µm	9.2.5
$f_{H\beta m}$	mean helix slope deviation[b]	µm	9.2.5
$f_{H\beta mt}$	mean helix slope deviation, in the transverse plane and tangent to the measurement diameter[b]	µm	Formula (37)
f_i'	tooth-to-tooth single flank composite deviation without removal of the long term component	µm	11.2.2
f_{is}	tooth-to-tooth single flank composite deviation after removal of long term component	µm	11.1
f_l'	variance of the long period component over one revolution	µm	11.2.2
f_p	single pitch deviation[b]	µm	8.4.3
f_{pzm}	mean lead deviation[b]	mm	14.4.1
f_{pbnm}	mean normal base pitch deviation[b]	µm	14.2.1
f_{pbn}	normal base pitch deviation[b]	µm	6.2.4
f_{pbni}	individual normal base pitch deviation[b]	µm	14.1
f_{pb}	single pitch deviation[b], normal base	µm	8.4.3
f_{pbt}	single pitch deviation[b], transverse base	µm	Formula (19)

[a] Symbols used for deviations of individual element measurements from specified values are composed of lower case letters "*f*" with subscripts (exceptions include f_e, f_1 and f_2) whereas symbols used for "cumulative" or "total" deviations, which represent combinations of several individual element deviations, are composed of capital letters "*F*" also with subscripts. It is necessary to qualify some deviations with an algebraic sign. A deviation is positive when, for example, a dimension is larger than optimum and negative when smaller than optimum.

[b] These deviations can be + (plus) or − (minus).

Table 1 *(continued)*

Symbols[a]	Definition	Units	First use
f_{pi}	individual single pitch deviation[b]	µm	Figure 42
f_{p2i}	individual double pitch deviation[b]	µm	9.3.8
f_{ui}	individual adjacent pitch difference[b]	µm	9.3.8
f_{u2i}	individual adjacent double pitch difference[b]	µm	9.3.8
$f_{w\alpha}$	undulation wave height in profile direction	µm	Figure 74
$f_{w\beta}$	undulation wave height in helix direction	µm	Figure 74
f_{α}	pressure angle deviation[b]	degrees	9.1.4
$f_{\alpha mn}$	mean normal pressure angle deviation[b]	degrees	14.2.1
$f_{\alpha mt}$	mean transverse pressure angle deviation[b]	degrees	14.2.1
f_{β}	helix angle deviation[b]	degrees	9.2.4
$f_{\beta m}$	mean helix angle deviation[b]	degrees	9.2.4
g_{α}	length of path of contact	mm	Figure 65
h_{cy}	chordal addendum to an individual measurement diameter	mm	Figure 29
h_{y}	radial distance from tip to an individual measurement diameter	mm	Figure 29
k	number of pitches in a sector	—	5.7
L	left flank	—	5.3
L_{α}	profile evaluation length	mm	Figure 14
$L_{\alpha c}$	functional profile length	mm	14.3.2.2
$L_{\alpha e}$	base tangent length to start of active profile	mm	Figure 14
L_{β}	helix evaluation length	mm	8.3.1
l	left hand helix	—	5.4
m_{n}	normal module	mm	Formula (1)
N	pitch number	—	5.6
N_{f}	start of active profile point on line of action	—	Figure 31
n	number of deviation values included in the mean	—	9.1.5
p_{b}	base pitch	mm	8.4.3
p_{bn}	normal base pitch	mm	Formula (1)
p_{bt}	transverse base pitch	mm	Formula (16)
p_{m}	true position pitch[b]	µm	14.1
p_{z}	lead of the helix	mm	Formula (36)
$p_{z\,eff}$	effective lead	mm	14.4.1
R	right flank	—	5.3
r	right hand helix	—	5.4
s	undulation weighting factor	mm	Figure 80
s_{cy}	chordal tooth thickness at an individual inspection diameter	mm	Figure 29
s_{n}	normal circular tooth thickness at the reference diameter	mm	Formula (12)
s_{yn}	normal circular tooth thickness at an individual inspection diameter	mm	Figure 29
z	number of teeth	—	6.2.3.2
z_{M}	number of teeth in master indexing worm wheel	—	Formula (22)

[a] Symbols used for deviations of individual element measurements from specified values are composed of lower case letters "*f*" with subscripts (exceptions include f_e, f_1 and f_2) whereas symbols used for "cumulative" or "total" deviations, which represent combinations of several individual element deviations, are composed of capital letters "*F*" also with subscripts. It is necessary to qualify some deviations with an algebraic sign. A deviation is positive when, for example, a dimension is larger than optimum and negative when smaller than optimum.

[b] These deviations can be + (plus) or − (minus).

Table 1 *(continued)*

Symbols[a]	Definition	Units	First use
z_1	number of teeth on driving gear	—	Figure 61
z_2	number of teeth on driven gear	—	Figure 61
$\alpha_{50\,\%}$	Gauss parameter	—	Formula (24)
α_{Mt}	transverse pressure angle at the measurement diameter	degrees	10.3.9
α_n	normal pressure angle	degrees	Formula (1)
$\alpha_{n\,eff}$	effective normal pressure angle	degrees	14.2.1
α_t	transverse pressure angle	degrees	Formula (5)
$\alpha_{t\,eff}$	effective transverse pressure angle	degrees	14.2.1
α_{yn}	normal pressure angle at an individual inspection diameter	degrees	8.2.3
α_{yt}	transverse pressure angle at an individual inspection diameter	degrees	Formula (11)
α_{Mt}	transverse pressure angle at measurement diameter	degrees	10.3.9
β	helix angle	degrees	Formula (4)
β_b	base helix angle	degrees	Formula (17)
β_{eff}	effective helix angle at the standard pitch diameter	degrees	14.4.1
$\beta_{M\,eff}$	effective helix angle at the measurement diameter	degrees	14.4.1
β_y	helix angle at an individual inspection diameter	degrees	Formula (10)
ε_γ	total contact ratio	—	11.3.4.2
λ_g	undulation wavelength	mm	Figure 74
λ_α	undulation wavelength in profile direction	mm	Figure 74
λ_β	undulation wavelength in helix direction	mm	Formula (22)
ξ	involute roll angle	degrees	Figure 14
ξ_a	involute roll angle to the tip diameter	radians	Formula (7)
ξ_{Nf}	involute roll angle to the start of active profile diameter	radians	Formula (8)
ξ_y	individual inspection roll angle	radians	Formula (9)
θ	angular position of gear	radians	Figure 61
$\Delta\theta$	angular gear position deviation	radians	Figure 61
I	reference face	—	5.3
II	non-reference face	—	5.3

[a] Symbols used for deviations of individual element measurements from specified values are composed of lower case letters "*f*" with subscripts (exceptions include f_e, f_1 and f_2) whereas symbols used for "cumulative" or "total" deviations, which represent combinations of several individual element deviations, are composed of capital letters "*F*" also with subscripts. It is necessary to qualify some deviations with an algebraic sign. A deviation is positive when, for example, a dimension is larger than optimum and negative when smaller than optimum.

[b] These deviations can be + (plus) or − (minus).

Table 2 — Abbreviated terms

	Definition	First use
3D	three dimensional	6.2.6
CAD	computer aided design	6.2.6
CMM	coordinate measuring machine	6.1
CNC	computer numerically controlled	6.1
CT	computer tomography	6.2.6
GCM	gear cutting machine	8.3.3
GMM	gear measuring machine	6.1

4 General considerations

4.1 Background

The purpose of this document is to provide background information that will assist with understanding the requirements, implementation and effectiveness of the gear measurements needed to establish the gear classifications defined in ISO 1328-1. This information will assist those involved in gear design and specification, gear manufacture and gear measurement processes. It includes background information and guidance on good measurement practice and addresses the interpretation of measurement results to identify common causes of gear manufacturing errors. Improved knowledge of gear measurement processes enhances the value of investments in measuring equipment.

When producing multiple identical gears in a large batch, it is rarely necessary or economical to measure all possible deviations on all the gears manufactured. Stable manufacturing processes allow a relatively small number of samples to be measured and still ensure that the required tolerance class is maintained. Certain elements may not significantly influence the function of the gear under consideration. However, some gear manufacturing processes are known to increase the risk of significant variation in tooth geometry in a single gear and thus require additional measurements to verify gear geometry parameter tolerances have been achieved. Some guidance is provided when this is necessary, but it remains the responsibility of the manufacturer of the gears to assure that the gears satisfy the specified requirements, such as those in ISO 1328-1. It is recommended that measuring plans be agreed upon between the manufacturer and the purchaser.

4.2 Required inspection information

All necessary information should be provided to the operator(s) of the measuring equipment. The information required will vary depending on the type of measurement(s). Most measurement processes require basic gear and blank data, such as number of teeth, pressure angle, helix angle, module, tip diameter, root diameter, face width, design profile, design helix, etc. Certain measuring tasks require additional information. For example, to measure profile, the profile control diameter and start of tip break must be provided. Minimum requirements are defined in ISO 1328-1 but it is the responsibility of the gear designer to ensure the specification provides sufficient information for the manufacturer to develop a measurement strategy that is suitable for the subject gears.

4.3 Measurement selection

4.3.1 Substitution of measurement methods

Inspection may be carried out using a number of methods. In some cases, some measurements may be substituted for others. For example, single flank composite measurement may be substituted for pitch measurement, or radial composite measurement may replace radial runout measurement. However, such substitutions may only be done with agreement between the manufacturer and the purchaser. See ISO 1328-1:2013, Table 4.

A number of factors should be considered when selecting the measurements, including the tolerance class required, size of the gear, manufacturing cost, and most important, the application of the product gear.

4.3.2 First piece inspection

It may be possible to verify that the manufacturing process is correct by inspecting only the first piece of a batch, allowing the inherent accuracy of the process to assure subsequent parts meet the required tolerance class.

4.3.3 Sampling and statistical process control

The deviations from the design shape of the gear that result from the manufacturing process are dependent on the production process used. When the process is proven capable of producing the required tolerance class (e.g. when using statistical methods), sampling inspection may be utilized. Many factors may influence the sample size and frequency; foremost among these should be the assurance that the required tolerance class of the parts is met.

The variability of the measuring process contributes to the perceived variability of the manufacturing process. For more information, see ISO 22514-7.

To achieve statistical compliance, the manufacturing deviations must be smaller than the specified tolerance. In some cases, for very accurate gears, the use of statistical process control is not possible due to the uncertainty in the measurements.

5 Conventions and measurement positions

5.1 General

When measuring gear teeth, specific reference is made to right flanks, left flanks, pitches, teeth or combinations of these.

5.2 Datum axis

Specification of the design profile, design helix, and design pitch requires definition of an appropriate reference axis of rotation, called the datum axis. It is defined by specification of datum surfaces. See ISO/TR 10064-3.

The datum axis is the reference for measurements and associated tolerances. The location and orientation of the measurement diameter circle are determined by this axis.

Ideally, the surfaces used to construct the datum axis, the surfaces used to locate the gear for manufacturing, and the functional surfaces that define the gear axis of rotation in its final assembly will all be the same. In practice, this is often not the case. For example, shaft type parts are often manufactured and inspected using centres to define the datum axis. In cases where the inspection, manufacturing, and/or functional datum surfaces are different, these surfaces should be coincident with each other to a level of accuracy sufficient to assure the final positioning of the gear is adequately represented during measurement.

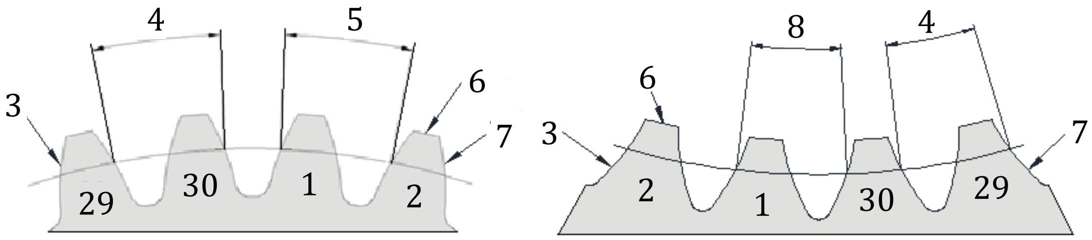
When a rotary table is used, the gear being measured should be oriented so that its datum axis is coincident with the axis of rotation of the measuring instrument. In the case of mounting the gear between centres, care should be taken to assure that the mounting arbor, if used, is in good condition, and the centres are clean and concentric with the datum surfaces of the gear. In the case of computer controlled measuring instruments, if the measuring program is capable of mathematically correcting the errors resulting from off axis mounting condition, then it may be possible to mount the gear with some deviation to the instrument's axis of rotation.

5.3 Left or right flank

It is convenient to choose one face of the gear as the reference face and to denote it with the letter "*I*". The other non-reference face might be termed face "*II*".

For an observer looking at the reference face, so that the tooth is seen with its tip uppermost, the right flank is on the right and the left flank is on the left.

Right and left flanks are denoted by the letters "R" and "L", respectively. See Figure 1.



a) External gear

b) Internal gear

Key

1	Tooth 1	6	tip
2	Tooth 2	7	right flank
3	left flank	8	1L = pitch number 1, left flank
4	30R = pitch number 30, right flank	29	Tooth 29
5	2L = pitch number 2, left flank	30	Tooth 30

Figure 1 — Notation and numbering for external and internal gears

5.4 Left hand or right hand helical gears

The helix of an external or internal helical gear is referred to as being right hand or left hand. The hand of helix is denoted by the letters "r" and "l", respectively.

The helix is right hand (left hand) if, when looking from one face, the transverse profiles show successive clockwise (counter-clockwise) displacement with increasing distance from an observer. See Figure 2.

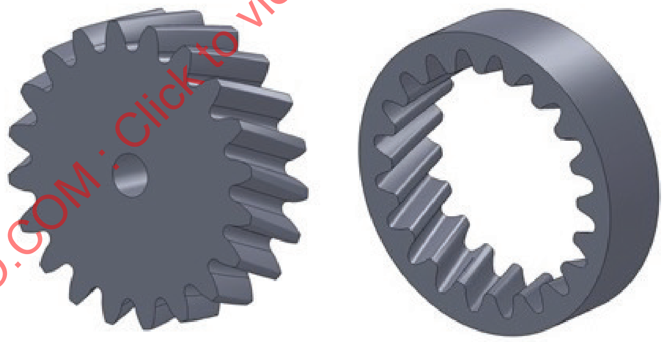


Figure 2 — Right hand gears, external and internal

5.5 Numbering of teeth and flanks

Looking at the reference face of a gear, the teeth are numbered sequentially in the clockwise direction. The tooth number is followed by the letter R or L, indicating whether it is a right or a left flank. For example, "Flank 30 R". See Figure 1.

5.6 Numbering of pitches

The numbering of individual pitches is related to tooth numbering as follows: pitch number "N" lies between the corresponding flanks of teeth numbers "N-1" and "N"; with a letter R or L, it is indicated whether the pitch lies between right or left flanks. For example, "Pitch 30 R" (see Figure 1).

NOTE Pitch 1 lies between the last and first tooth. Therefore, sector gears have no pitch 1; they start with pitch number 2.

5.7 Number of pitches "k" in a deviation symbol subscript

The subscript "k" in a deviation symbol denotes the number of consecutive pitches to which the deviation applies.

In practice, a number is substituted for "k", for example, F_{p3} indicates that a given cumulative pitch deviation refers to three pitches.

6 Types of measuring equipment and principle

6.1 General

The analytical measurement of gears, also known as individual or elemental measurement, includes the measurement of helix, profile, pitch, radial runout and tooth thickness deviations. Measurements are made by positioning a contacting probe at the theoretical position where the gear flank should be relative to the datum axis and measuring any deviation. This can be performed by a number of different types of measuring devices including:

— coordinate measuring machines (CMM, with appropriate software), illustrated in Figures 3 and 4;

— traditional mechanical gear measuring machine (GMM), illustrated in Figure 5;

— computer numerically controlled (CNC) gear measuring machines (GMM), illustrated in Figure 6 and 7;

— in-process CNC measuring stations mounted on a machine tool, illustrated in Figure 8;

— portable measuring devices, illustrated in Figures 9, 17 and 18;

— portable gear measuring machines which can be mounted on machine tools or rotary tables to measure pitch and radial runout of the tooth space on large gears, as illustrated in Figures 10 and 11.

NOTE Portable measuring arms typically cannot achieve the same level of uncertainty as can be achieved by other measuring devices.

These methods generally involve scanning the probe over the tooth flank in a continuous manner.

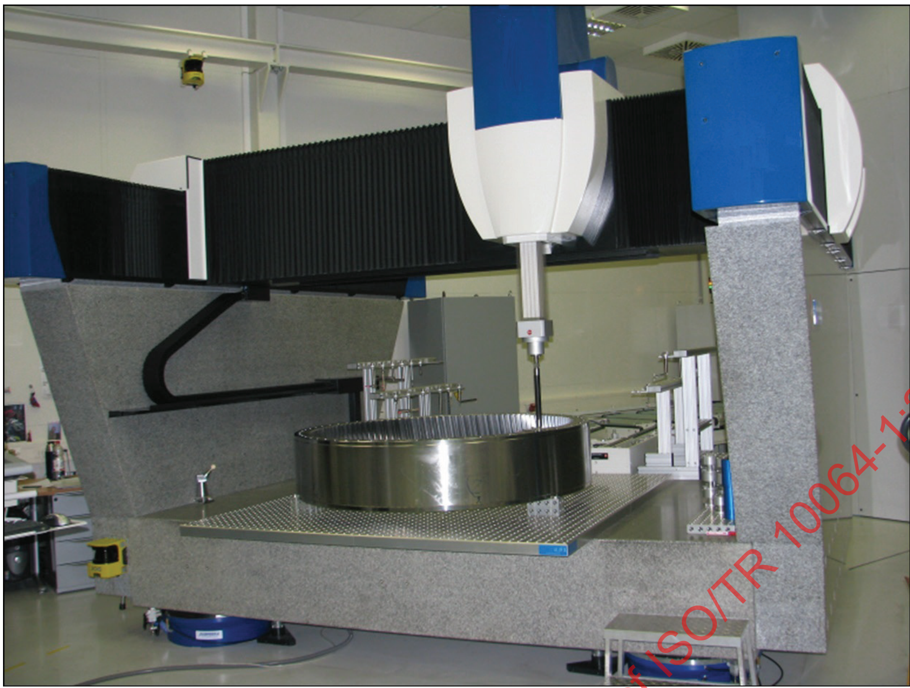


Figure 3 — Large coordinate measuring machine (CMM) used for helix, profile, pitch, radial runout and tooth thickness measurement

Figure 4 — Small CMM used for helix, profile, pitch, radial runout and tooth thickness measurement

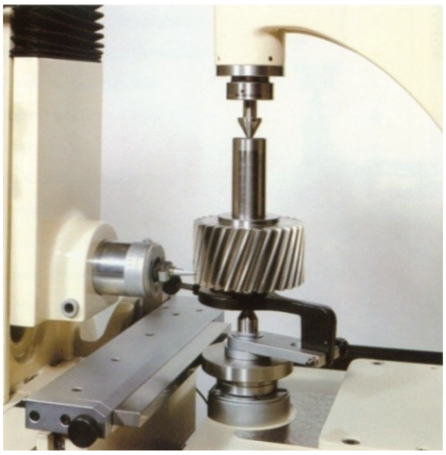
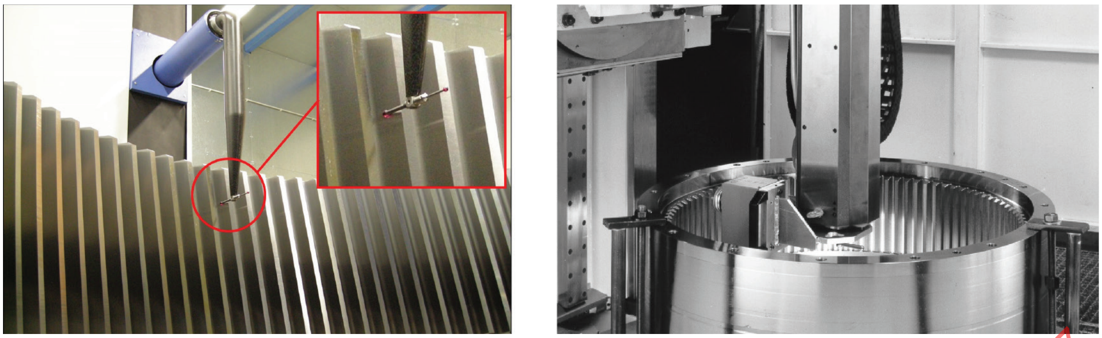


Figure 5 — Traditional GMM mechanical base disc profile and helix measuring machine

a) Workpiece mounted directly to rotary table **b) Workpiece located between centres on a rotary table**

Figure 6 — CNC GMM using the generative method of measuring profile and helix deviations and the capability to measure pitch, radial runout and tooth thickness



NOTE Profile is measured by scanning in X-Y coordinates only and the rotary table used to position the gear in the correct position for access by the probe.

Figure 7 — Two examples of non-generative internal gear profile measurement on a 4-axis GMM

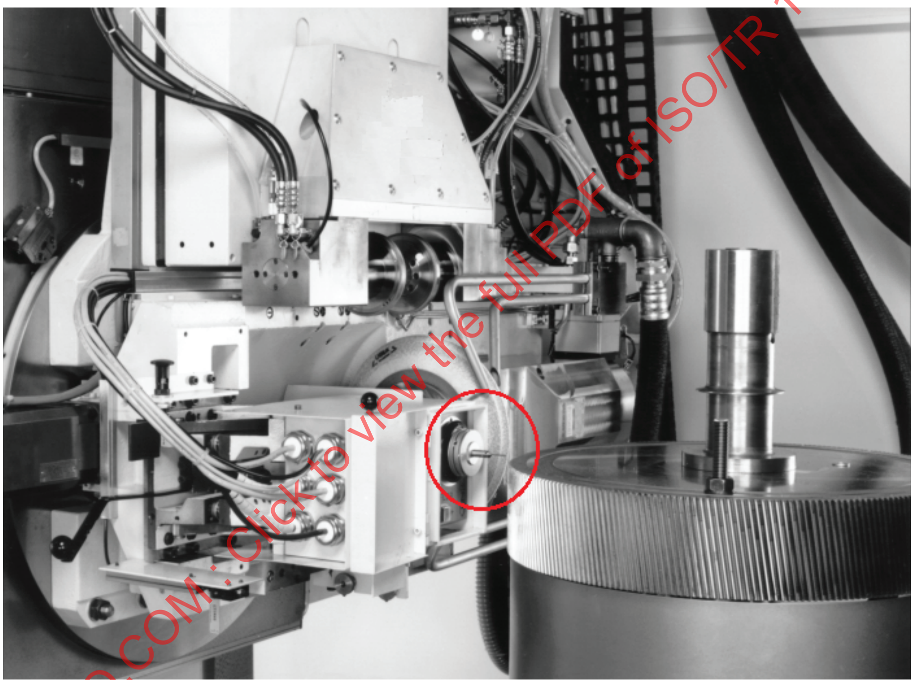
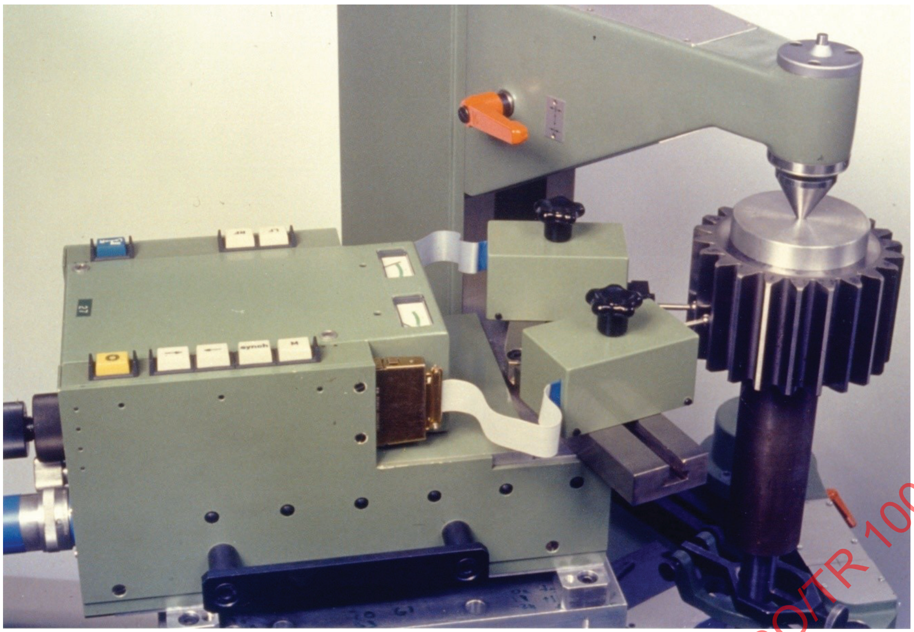


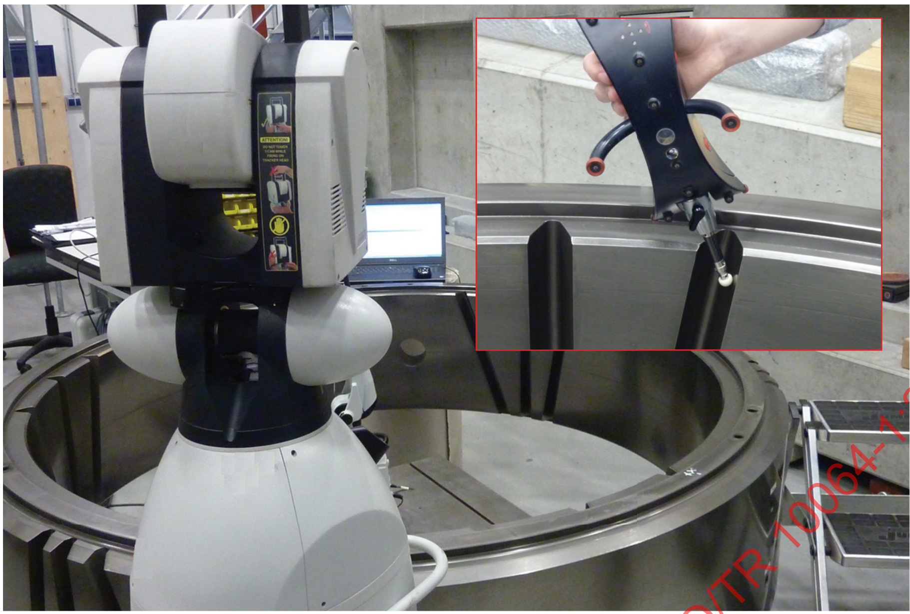
Figure 8 — In-process measurement with a CNC measuring station mounted on a grinding machine



NOTE Commonly used for large gears when independent measuring machines are not available.

Figure 9 — Portable pitch measuring equipment suitable for mounting adjacent to a machine tool rotary table (mounted on a measuring machine in this image)

Figure 10 — Portable measuring arm with gear artefact



NOTE A laser tracker determines the distance and position of a hand-held device in a local coordinate system. Result is the centre position of the probing tip.

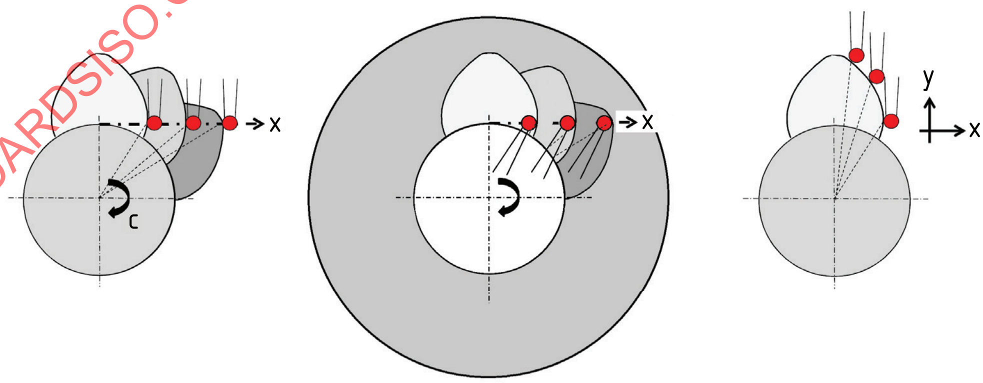
Figure 11 — Measurement of a large gear artefact with a laser instrument

Measuring machines can use two methods for profile and helix, as illustrated in Figure 12.

Generative method: The generative method creates the theoretical involute or helix with a combination of simultaneous rotation of a rotary axis and translation of a linear axis.

Non-generative method: Measurement of the involute and helix by scanning the surface with a three axis measuring machine [usually with three linear (orthogonal) axes but some machines use two linear axes and rotary axis]. Collectively, these can be considered as non-generative profile methods.

GMM that use the generative method for external gears often use a non-generative method for internal gears to minimize the risk from interference of the stylus shaft with the internal tooth tip (see Figure 12, middle sketch). The measurement methods are summarized in Table 3.



a) Generative profile measurement external gear

b) Generative profile measurement internal gear

c) Coordinate (non-generative) profile measurement

Figure 12 — Profile measurement methods

Table 3 — Summary of measurement methods

Machine type	Figure for an example	Principle	Internal (I) and/or external (E) gear	Number of axes	Comments
CMM	3 and 4	Non-generative	E and I	3 linear orthogonal	An additional rotary table may be used to minimize the number of measuring probes required.
Traditional mechanical GMM	5	Generative	E and I	3 linear orthogonal and 1 rotary axis	Machines require a base disc (fixed diameter or variable diameter using a mechanism).
CNC GMM	6 and 7	Generative and non-generative	E and I	2 or 3 linear orthogonal and 1 rotary axis	Most use the generative method for profile measurement but at larger diameters, change to non-generative because of either limitations in linear axis length or rotary table encoder accuracy. For internal gears, often, the non-generative method is used since the generative method may have interference with the stylus.
Machine tool based measuring station	8	Non- generative for profile	I and E	2 linear orthogonal and 1 rotary axis	Normally use the machine tool rotary axis as the datum axis.
Portable CMM, including measuring arms	10	Non-generative	E and I	3 axis coordinate system	Generally require an auxiliary datum surface.
Portable dedicated profile measurement	28	Non-generative	E	2 linear axes	Generally locate on the gear teeth themselves and require the measurement of tooth thickness to establish a datum.
Portable pitch measurement	9 and 17	Pitch only	E and I (less common)	1 linear axis and 1 rotary axis	Measures adjacent pitch with a two-probe system and relies on a machine tool rotary table to provide the datum axis. Commonly used for large gears.
Portable base pitch instrument	18	Base pitch only	E and I (less common)	Single axis	Uses the teeth as a datum to measure adjacent base pitch deviation. If set with a reference test piece or gauges, may be used to find mean base pitch deviation.

6.2 Measurement methods

6.2.1 Generative measurement methods

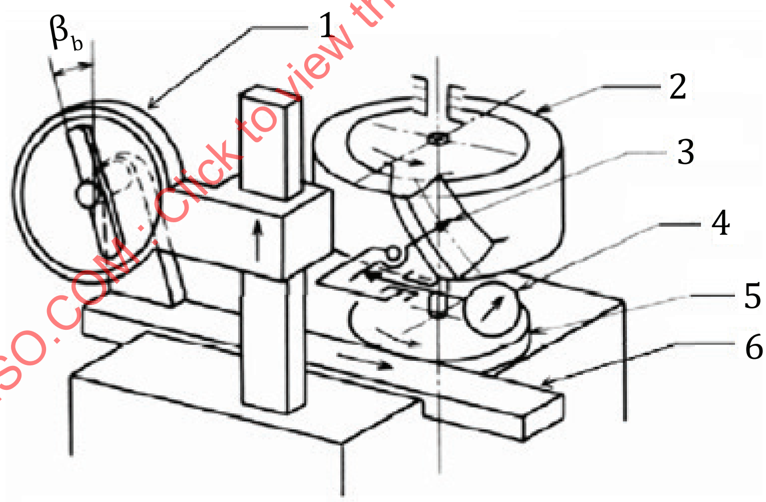
Generative methods measure tooth geometry deviations from a generated theoretical geometry. Involute profile testing involves generating a theoretical involute at the measuring probe with the relative motion of the machine axes. During such tests, the contact points between the stylus and the tooth surface are constrained within the plane of action (base tangent plane, a line tangent to the gear base cylinder used to define the involute profile). See Figures 12 and 13. Generative helix testing is carried out according to generation of the theoretical helix. Generative pitch testing involves rotational positioning of the gear according to ideal, equally spaced tooth locations. Profile and pitch measurements take place in the transverse plane, the plane of the involute curve.

On unmodified involute helicoid tooth flanks, the point and angle of contact between the 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. Although either a spherical or a sharp stylus may be used, a sphere is normally used because it allows the measurement of other features such as datum axis definition and tip and root diameter.

The generative principle was first used in mechanical base disk GMM and is still the preferred method in CNC machines.

The profile results from a generative measurement along the line of action (which is a base tangent line). ISO 1328-1 specifies that measurement points should be uniformly distributed along this line. This is achieved with even increments in roll angle or length of roll. Note that this data spacing requirement means the radial locations of the data are non-linear.

Figure 13 illustrates how the generative measurement principle was applied in the construction of a traditional mechanical gear measuring machine. The base circle disc (which is the same size as the gear base diameter) is located on the machine spindle and the straight edge contacts the disc. The stylus is set on the tangent line of the base circle disc. To measure the involute profile, the stylus generates a theoretical involute by the translation and the resulting rotation of the machine spindle along the base tangent line (without sliding between the disc and the straight edge). Thus, the stylus scans across the profile in the transverse plane. For helix measurement, the vertical movement of the stylus is controlled by the helical guide connected to the machine spindle; it generates a base helix by the rotation of the machine spindle.



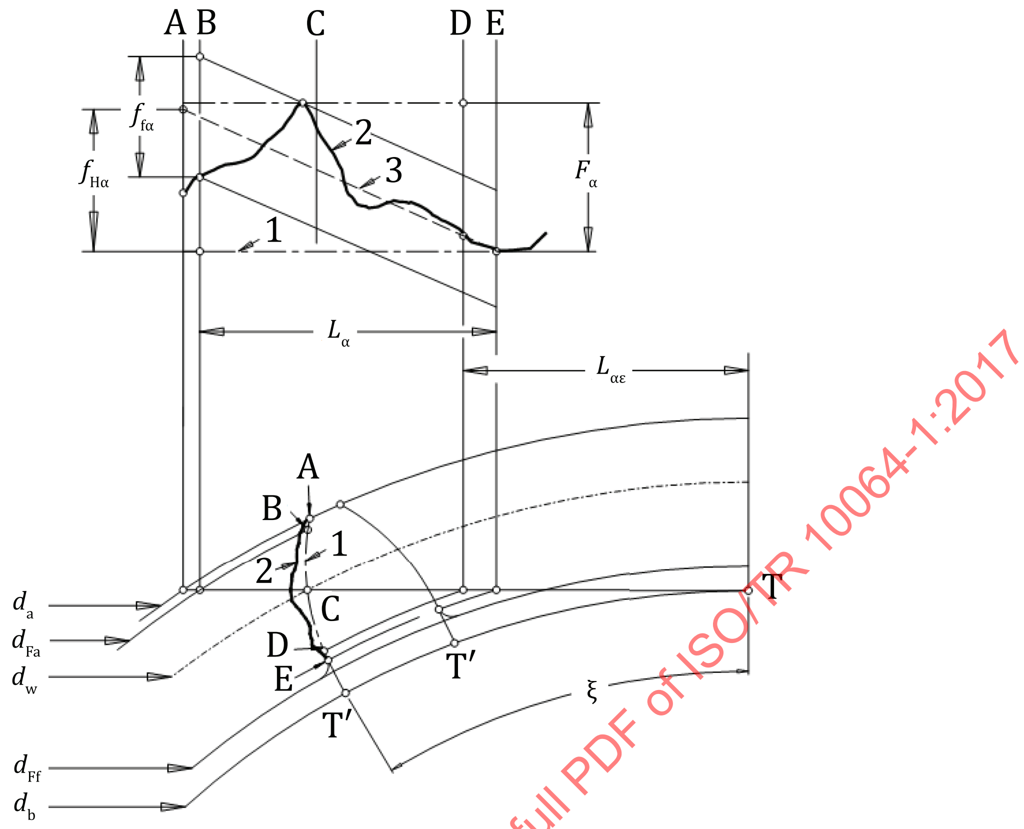
Key

1	helix guide mechanism	4	indicator
2	gear being measured	5	base circle disk
3	stylus	6	straight edge

Figure 13 — Generative helix and profile measuring device

The resulting profile trace is illustrated in Figure 14.

The traditional manual GMM requires three orthogonal linear axes and a rotary axis and thus, CNC GMM that use the generative principle require the same four axes.



Key

1	design profile
2	measured profile
3	mean profile line
A	tip circle point
B	start of tip break (chamfer)
C	pitch point
D	start of active profile
E	start of profile control
T	start of roll (point of tangency of transverse base tangent)
T′	origin of involute
F_{α}	total profile deviation
$f_{f\alpha}$	profile form deviation
$f_{H\alpha}$	profile slope deviation
B-D	active profile
B-E	usable profile
L_{α}	profile evaluation length
$L_{\alpha\varepsilon}$	base tangent length to start of active profile
ξ	involute roll angle (shown to point C)

Figure 14 — Tooth profile and profile diagram

6.2.2 Non-generative measurement methods

Generative measurement methods typically are not used with CMM and, due to probe interference risk or the required roll length being too large, they are sometimes not used for internal gears in four axis CNC GMM. In the non-generative method, the tooth flank geometry is considered as a series of points, each with a set of three dimensional coordinates. A calculation is needed to convert from the probe tip centre to the flank surface, and this must be done along a normal to the flank. A spherical stylus tip should be used for these measurements. During measurement, the points of contact between the spherical stylus tip and the tooth flank will vary substantially around the tip. Therefore, the sphericity influences measurement accuracy and both probe datum and the non-uniform stiffness of the probe stylus will affect measurement result accuracy if not properly compensated.

The data should be evenly spaced along the line of action (which is a base tangent line). ISO 1328-1 specifies that measurement points should be uniformly distributed along this line. This is achieved with even increments in roll angle or length of roll. Note that this data spacing requirement means the radial locations of the data are non-linear.

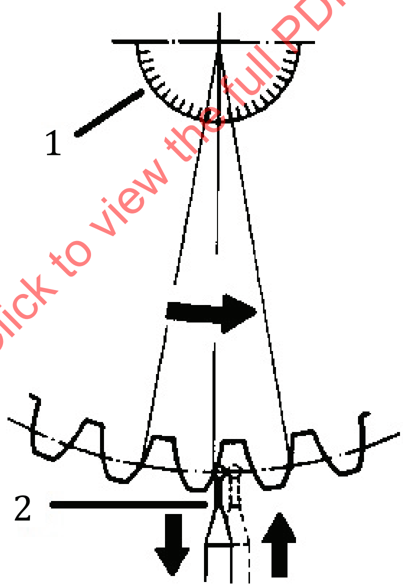
6.2.3 Pitch measurement methods

6.2.3.1 General

Pitch parameters can be measured by two principles. The indexing (single probe) method measures the location of each tooth around a gear, relative to a datum such as an angular encoder. This method is used on CNC GMM, in-process CNC measurement stations and CMM. The pitch comparator (two-probe) method compares the distances between adjacent tooth flanks to the distance between an initial reference pair of adjacent tooth flanks. This method is used on portable pitch measuring devices such as those illustrated in Figure 9.

6.2.3.2 Single probe method with rotary table

The indexing (single probe) device uses an angular datum such as a rotary encoder with a CNC controlled rotary drive to precisely rotate the gear by an angular increment equal to its pitch, or 360°/z (where z is the number of teeth) (see Figure 15). The degree of the device's precision should be consistent with the tolerance class and diameter of the gear.



Key

1 encoder

2 probe

Figure 15 — Pitch measurement using a rotary encoder as an angular datum

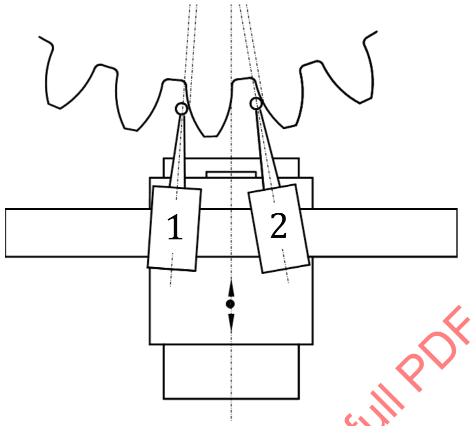
The gear is mounted with its datum axis coincident with the rotational axis. The single probe should be oriented to contact the tooth flanks at the measurement diameter, d_M, and to gather measurements in the specified measurement direction. The gear is incrementally rotated around its datum axis and the single probe moves in and out on a precision slide and stop, measuring each successive tooth flank position, relative to the angular datum. This process is repeated until every tooth has been measured.

It is common practice to complete this series of measurements by taking a final measurement on the initial reference tooth, thereby closing the circle. Ideally, this would produce a second measurement value of zero for the first tooth, as was set at the beginning of the process. Excessive deviation of this second measurement value from zero indicates a problem with the measurement.

Cumulative pitch or index and adjacent pitch deviations are calculated in accordance with ISO 1328-1.

6.2.3.3 Two-probe pitch comparator

The gear should be mounted with its datum axis coincident with the pitch comparator's rotational axis. The first probe acts as a datum for the measurement. The second probe measures the variation in position of the second tooth relative to the first tooth, from which single pitch variation is calculated. The device is adjusted to indicate zero while the probes are contacting the randomly selected initial pair of teeth (see Figure 16). Care is required to assure that the two probes contact at the same diameter.



Key

1 datum probe

2 measuring probe

Figure 16 — Two-probe pitch comparator

The two probes should be oriented to contact the adjacent tooth flanks within the same transverse plane, at the measurement diameter, d_M. As the gear is rotated around its datum axis, the pitch comparator moves in and out on a precision slide and stop, measuring each successive adjacent tooth pair. This process is repeated until every adjacent pair of teeth has been measured.

Most two-probe devices include analysis software which calculates the average pitch deviation, and subtract this value from the measured data to calculate single pitch deviations. Cumulative pitch deviations are calculated by summing the single pitch deviations. Most devices allow the results to be printed. This procedure is then repeated on the other flank.

6.2.3.4 Measurement without rotary table

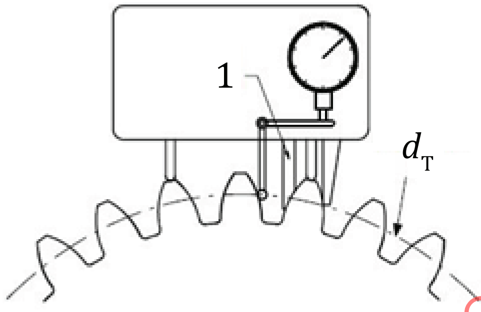
When measuring without a rotary table, the probe tip (single probe) or the probe tip configuration (several probe tips) moves around the gear and probes each point at the measurement diameter. See Figures 3 and 4.

6.2.4 Hand-held pitch measuring devices

Hand-held pitch measuring instruments, such as those illustrated in Figures 17 and 18, do not measure pitch relative to a datum axis. Therefore, they cannot be used to determine compliance with the tolerances defined in accordance with ISO 1328-1. However, when mutually agreed upon by the manufacturer and the purchaser, they may be used to measure either circular pitch or base pitch.

The normal base pitch parameter provides a localized composite observation of gear tooth pitch deviations. It is localized in that the observation is made only at a single point on the tooth flank. It is composite in that it combines the effects of involute profile, helix, and pitch at different contact diameters into a single observation that directly relates to the gear's ability to achieve smooth, conjugate meshing action with its mate.

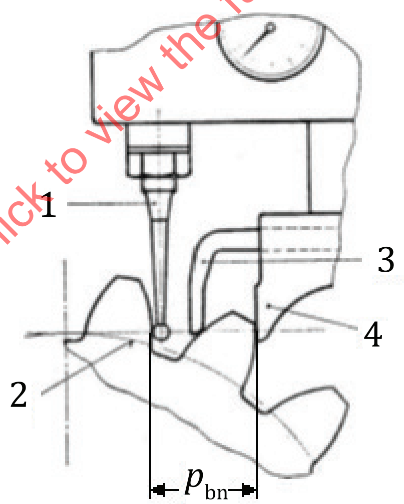
Hand-held base pitch measuring instruments can either be set to directly measure the deviations from the theoretical normal base pitch, with the aid of a suitable gauge, or set to reference a randomly selected initial pair of adjacent teeth. If the instrument is adjusted to the specified normal base pitch of a gear prior to commencing measurements, it can provide an observation of normal base pitch deviation, f_{pbn} (see 14.2).



Key

1 spring loaded

Figure 17 — Hand-held two-probe pitch measuring instrument



Key

1 measuring feeler

2 base circle

3 counter support

4 anvil

Figure 18 — Base pitch measurement, two-probe device

The normal base pitch can be calculated by using Formula (1):

$$p_{bn} = m_n \pi \cos \alpha_n \qquad (1)$$

where

p_{bn} is the normal base pitch, mm;

m_n is the normal module, mm;

α_n is the normal pressure angle, degrees.

The two measurement probes of the device are oriented to contact adjacent tooth flanks within a base tangent plane. In practice, this involves rocking the device through the possible range of contact of the measuring probe with the tooth flank while observing the measurement indicator. The observed minimum deviation of the indicator will occur at the point of contact corresponding with a base tangent plane. It is important to ensure that the points of contact of the probes do not lie in zones with profile or helix modifications, especially when measuring deviations from the theoretical normal base pitch.

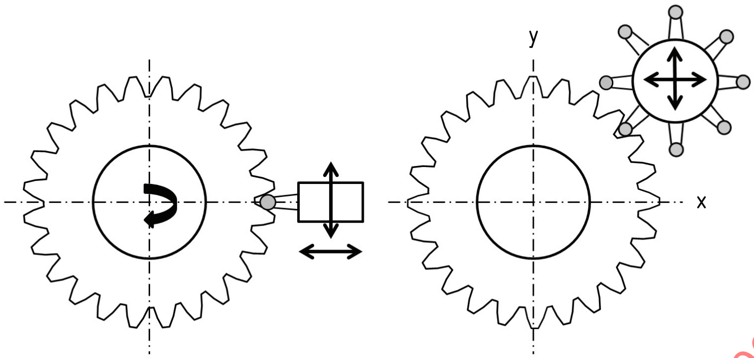
The normal base pitch measurement device is applied successively to each pair of teeth with each indicator measurement recorded. This process is repeated until every adjacent pair of teeth has been measured.

6.2.5 Radial runout measurement

Radial runout is defined as the runout of the tooth space relative to the datum axis of the gear. It is either measured directly by a single ball contacting the left and right flanks of a tooth space simultaneously or calculated indirectly from the measurement of pitch deviations separately on left and right flanks and the theoretical radial position of a ball in two flank contact. It may also be determined by measurements over a cylinder or anvil (shaped like a single tooth of a mating rack) placed in the tooth spaces. Although all these methods produce valid measurement results, it is likely that these results will be slightly different because of flank form deviations, small differences in measurement position, and, when a cylinder or anvil is used, averaging along the line of contact between the cylinder or anvil and the tooth flanks. For non-symmetric teeth, the runout measurement process should be agreed upon between the manufacturer and the purchaser.

The probing sphere or cylinder with an appropriate diameter is moved inside the tooth space until two-flank contact is realized. The diameter of the ball or cylinder or the anvil size should be chosen to contact at the measurement diameter. In cases where interference with the root diameter would occur, a ball or cylinder with a flat should be used. Depending on the device and the gear parameters, the measurement can be produced with or without a rotating table by means of an axis parallel probe or a star-probe. In the case where a star-probe is used, it is necessary to always use an eight star-probe because of the contact conditions. See Figure 19. The gear may also be rotated while supported by "V" blocks on the datum surfaces.

The use of other methods, such as dual flank composite measurement, to estimate radial runout F_r does not meet the requirements of ISO 1328-1.



a) Runout test with rotating table (four axis) and axis parallel probe

b) Runout test without rotating table (three axis) with star-probe

Figure 19 — Radial runout measurement

6.2.6 Computer tomography methods for small gears

Very small gears, even those with module <0,1 mm, made of plastic or titanium can be measured with dimensional computer tomography (CT) using x-rays. The result is a cluster of 3D points. See Figure 20 for an example where pitch is measured in the transverse plane and four teeth are measured for profile and helix on both flanks. The gear measurement is executed in three steps. The surface of the point cluster (voxels) is determined first. In a second step, the datum surfaces are measured on a system similar to a CAD system. Then the gear coordinate system can be established and the gear is measured in the same way as on a CMM. The difference is that the physical surface is not touched with a probe pin but instead the virtual calculated surface of the part is measured.

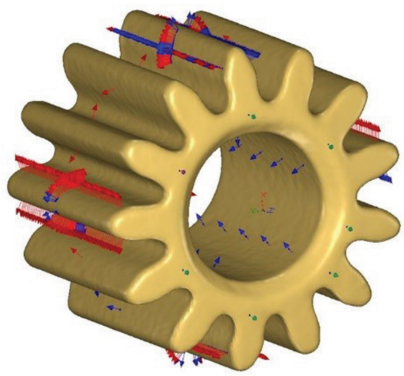


Figure 20 — Small gear measured with computer tomography showing virtual traces on the flanks

6.2.7 Optical devices for small spur gears

For very small spur gears, it is common practice to use optical devices. With image processing, the tooth edge and the bore along the upper face can be determined. After an appropriate selection of measured points, the standard gear profile evaluation can be executed. Intersection of a circle with the gear flank contours gives the pitch points.

6.3 Calibration of equipment

All measurement processes include random and systematic errors which affect the measurement result. The likely size of the errors is estimated using simple statistical analysis to characterize the process measurement uncertainty.

Methods of estimating measurement uncertainty are defined in ISO 18653. Also, ISO/TR 10064-5 and ISO 22514-7 provide more guidance and examples for calculating measurement uncertainty. The procedures are based around a comparison of measurements from a measuring process and a comparison with calibration values from an accredited calibration laboratory. It is recommended that all measuring processes used for inspecting gears have measurement uncertainty evaluated and used when considering compliance with tolerance specifications.

See 7.1 for recommendations on implementation and evaluation processes.

6.4 Tooth thickness, differences between CNC/CMM and manual measurement

There are several methods for the manual measurement of tooth thickness. They all measure tooth thickness indirectly and therefore tend to produce different values of tooth thickness.

Common methods include:

— measurement over or between balls or pins: this can be done on all but very large gears;

— span measurement: it is often very convenient, but helical gears may not have sufficient unmodified face width for span measurement;

— measurement over blocks (rack shaped artefacts): appropriate blocks are required;

— a special gear tooth caliper may be used where the gear outside diameter is used as the datum. With this method, the distance from the outside diameter to the edges of the jaws of the caliper defines where the normal chordal tooth thickness is measured. All of these methods have some uncertainty. However, a gear tooth caliper has additional uncertainty due to its reliance on the outside diameter of the gear, and the potential for slight rounding of the caliper tips giving false readings.

The manual tooth thickness measurement methods inherently measure in the normal plane at the points of contact. With the exception of a measurement over one ball or pin to the datum axis or a chordal measurement that has been corrected to the radius from the datum axis to the tip of the individual tooth being measured, the manual measurement methods do not reference the datum axis and so do not include the effect of tooth radial runout.

It is important to recognize the fundamental difference between tooth thickness measurement methods that reference the datum axis and those that are independent of the datum axis. Measurements taken in relation to the datum axis determine the functional tooth thickness and can be used to directly predict backlash. Therefore, use of measurement methods that reference the datum axis can be advantageous to closely control backlash. To predict backlash during the design stage, when specifying a tooth thickness measuring method that is independent of the datum axis, such as most of the manual methods, it is necessary to know the total composite tolerances of both mating parts. The total composite tolerances may be estimated from elemental tolerances for this purpose, but such estimations introduce some additional uncertainty.

On a CNC/CMM device, the exact position at the flank in the normal plane, relative to the datum surface, can be probed, at least in principle. But in most cases, the pitch measurement points, which are in a transverse plane, are used to determine the tooth thickness. In case of a helical gear, the points which define the normal tooth thickness are not in a transverse plane but more in a normal plane. Starting from the measured pitch points in a transverse plane, the tooth thickness points are calculated using the unmodified involute flank, ignoring deviations like profile slope deviation, $f_{H\alpha}$, helix slope deviation, $f_{H\beta}$, and crowning plus all other surface deviations. The tooth thickness result is influenced in proportion to the size of the deviations. Tooth thickness specifications should clearly indicate if the tooth thickness value is in the transverse, normal or axial plane, and is a circular arc or chordal thickness.

There are measurement strategies available on some CMM which allow the thickness measurement at the correct positions in the normal plane but these features are seldom used.

When it is known that the only measurement of tooth thickness will be on a CNC/CMM device, then it is best to just specify on the drawing the transverse circular tooth thickness and avoid mention of any of the manual methods of measurement.

6.5 "In-process" gear measurement on manufacturing machines

There is considerable time and effort involved in measuring gears. This is particularly the case when the gears are large as they take a long time to set up. Furthermore, if the gear has to be re-worked, then the measurement process will have to be repeated.

Some machine tools have an in-process measuring station mounted adjacent to the cutting tool which allows the gear to be inspected without removing it from the rotary table. See Figure 8. There are some potential problems with this approach, for example, ensuring that the gear blank is correctly mounted on the work table and is not distorted by clamping. But if it is used in conjunction with a conventional gear inspection machine, there can be significant benefits in terms of reduced process time. It is also useful for monitoring some aspects of grinding wheel performance.

However, it should be realized that since the measuring equipment uses the same datum axis as the manufacturing process, some deviations may not be detected. Mounting errors (radial runout of the gear blank) will not be apparent in the measurement results and temperature effects can also cause geometry deviations unless the machine can properly compensate to the reference temperature of 20 °C. Some measuring stations allow the measurement results to be adjusted by means of profile and helix geometry compensation by comparing measurements to those obtained from an independent measuring machine.

Use of in-process measurement stations can be subject to agreement between the manufacturer and the purchaser and should be calibrated with workpieces validated by a dedicated measuring machine.

6.6 Gear mounting

It is necessary to mount the gear on the measuring device in a way that allows access to all surfaces of interest, i.e. the tooth flanks and the datum surfaces. The mounting should be stable to avoid rocking but it should also avoid a deformation of the gear by fixture forces. Naturally, a displacement of the gear under probing forces is not permitted. In most cases, the gears are mounted between centres or in a multi-jaw chuck.

Mounting in a multi-jaw chuck: This type of mounting can be used for nearly all types of gears. On a chuck with four jaws, rocking is often an issue. But also in the case of three jaws, rocking will occur when the contact surfaces are not parallel to the gear axis. On ring gears with small wall thickness, a deformation can occur and will be visible from the radial runout and pitch measurement graphical results.

Mounting between centres: This type of mounting is only usable for external gears. It allows good access to the bearings or reference surfaces; rocking or deformation is no problem. It is critical that the centre of the tailstock cone is coaxial with the rotary table. Also, the centres on the part should be coaxial with the datum axis. If the reference surfaces on a mandrel are used without further mathematical alignment, then the parts may not meet required tolerance classification.

Mounting of large ring gears: A large ring gear with a relatively small thickness of the ring body will bend under its own weight between the support points. Therefore, it is good practice to measure profile and helix only above the support points.

Mounting of very long pinions: Some GMM use an upper support bearing on very long shafts; however, care is required to ensure that the bearing does not introduce additional errors. For very long pinions with no possibility for vertical mounting, the pinion can be mounted horizontally if appropriate software and hardware are available for alignment and measurement.

Gear datum radial runout correction: Many CNC GMM and CMM are equipped to measure and compensate gear blank mounting errors on the measuring machine. It is recommended that the gear mounting surface or bearing journal surfaces are used to define the datum axis. The required number of data points to minimize errors caused by datum surface form deviations should be established by testing.

6.7 Example output format from a CNC GMM

6.7.1 General

An example result from a CNC GMM is provided in Figure 21 for profile and helix and Figure 22 for pitch, radial runout and tooth thickness to illustrate some of the information that is required for a measurement and analysis. The figures also identify key information that can be used to analyse the results. Other valid formats are frequently used.

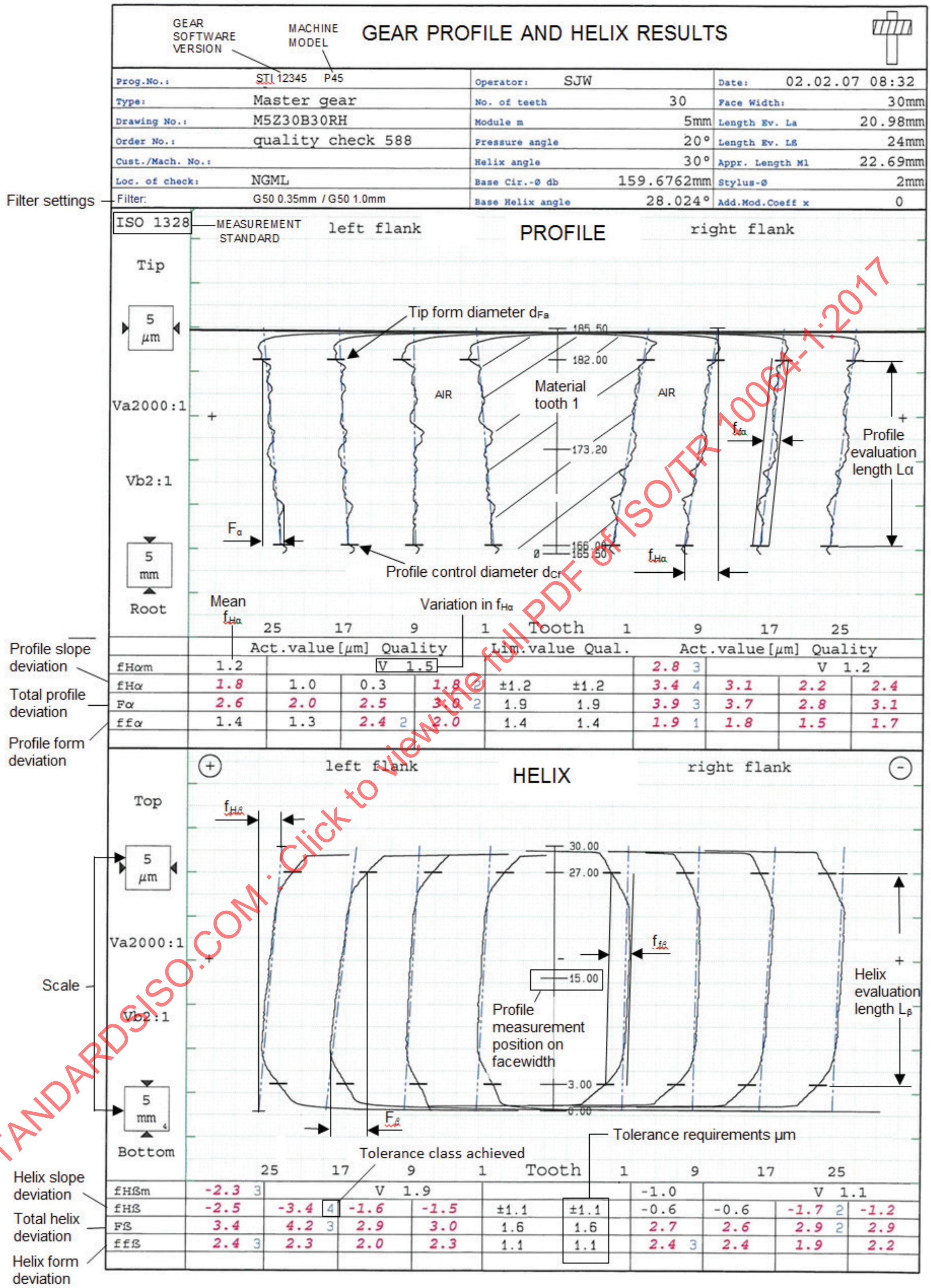


Figure 21 — CNC GMM example result for profile and helix, with comments added

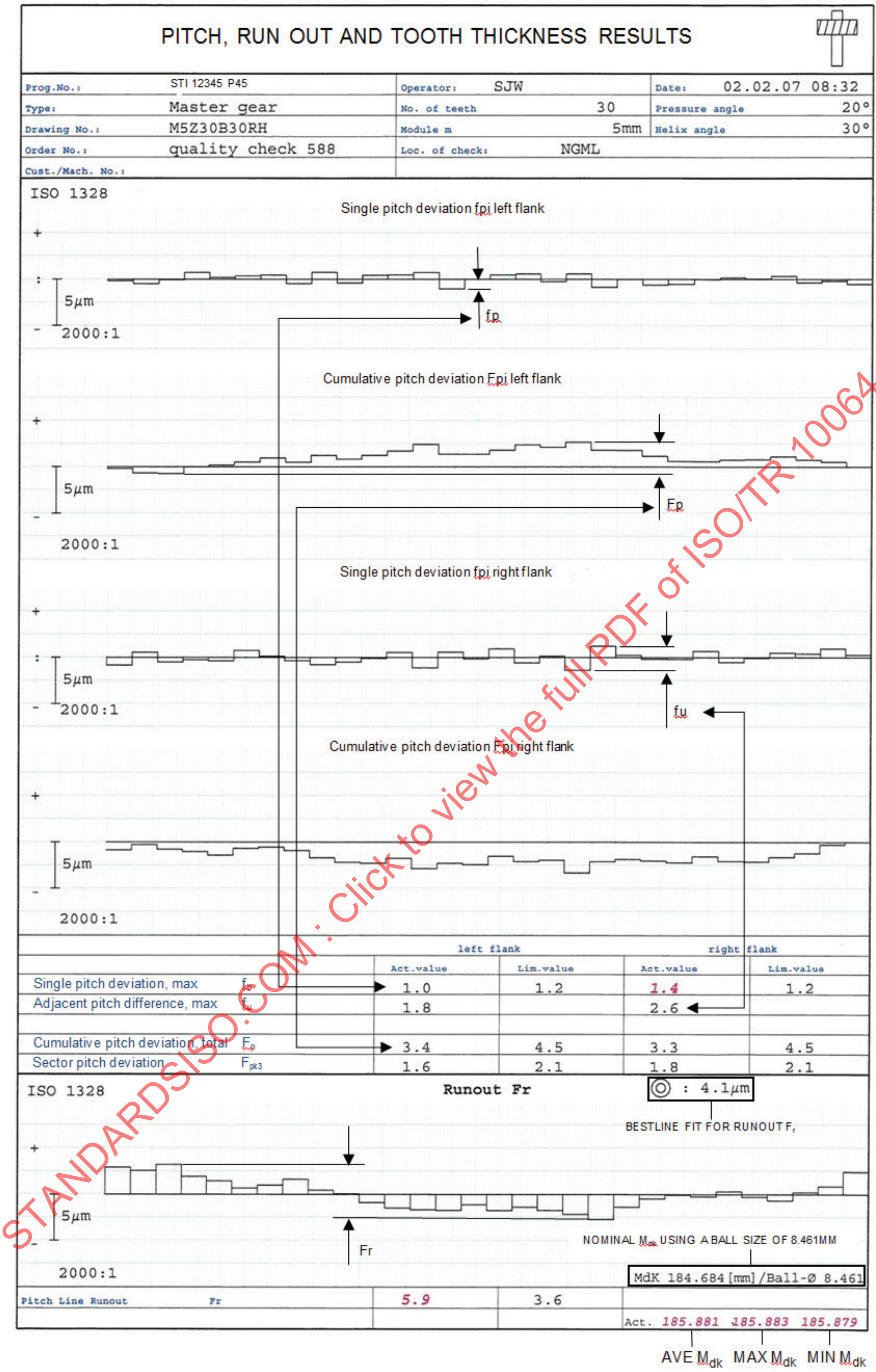


Figure 22 — CNC GMM example result for pitch and radial runout, with comments added

6.7.2 Example evaluations of modified helices and profiles

An example result from CNC GMM for helix measurement with linear end relief is provided in Figure 23. The measurement result has three evaluation ranges — the middle is an unmodified helix. Between the end relief area and the unmodified helix, there is a transition zone. This zone is not considered in the evaluation of either the unmodified helix or the end relief. It is needed to allow for manufacturing tolerances on length and amount of end relief. Lack of a transition zone could change the evaluated form deviation. The end of the evaluation length for end relief is indicated on both face sides (upper and lower end of each trace) to avoid tooth chamfering influencing the evaluation results.

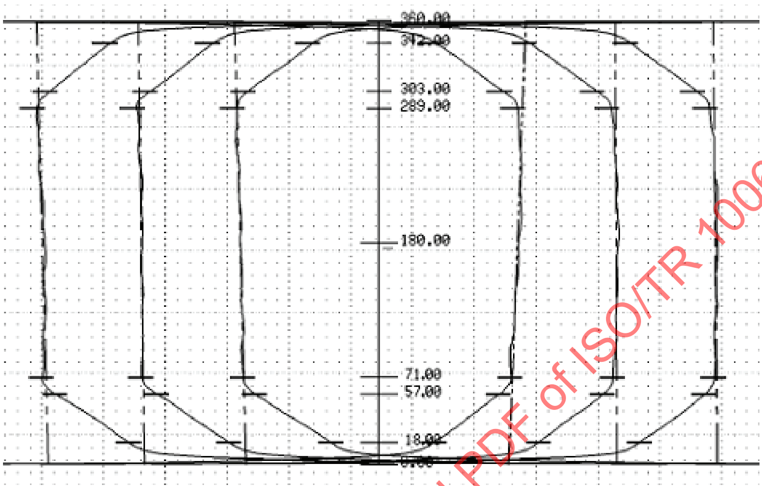


Figure 23 — Helix with end relief, evaluated with linear regression and transitional zones

Figure 24 provides an example result from CNC GMM for helix measurement with non-linear end relief. The measurement result has also three evaluation ranges—unmodified helix in the middle and end relief on both sides. A transition zone between the end relief and the unmodified helix is not required because the non-linear end relief begins tangential to the centre portion of the helix. The evaluation zone ends before both face sides to avoid an influence of the tooth chamfering on the evaluation of the end relief.

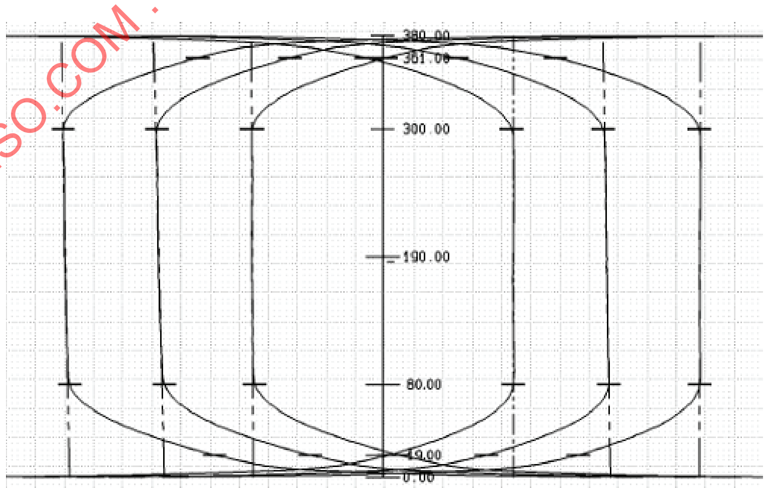


Figure 24 — Helix with end relief, evaluated with parabolic regression and without transition zones

An example result from CNC GMM for profile measurement with linear tip and root relief is provided in Figure 25. The middle zone has an unmodified profile. As with the helix, transition zones are necessary because of manufacturing tolerances in length and amount of tip and root relief. Also, the evaluation length ends prior to the tip or root so that form deviation is not effected by tip chamfering or by start of fillet. Below the start of active profile, a certain profile length should be recorded to check that no interference will occur when the tooth is in mesh.

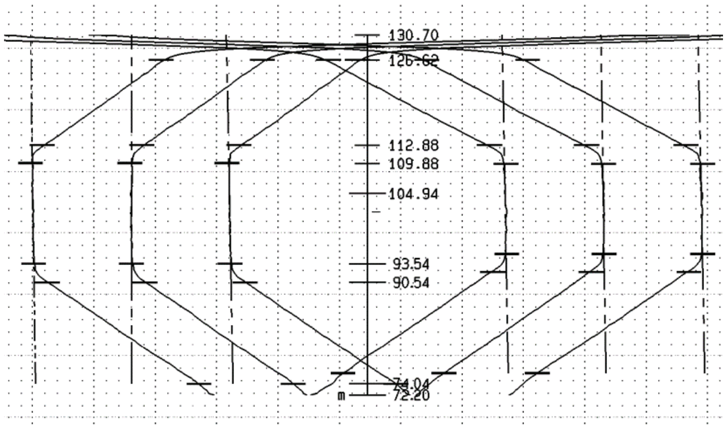


Figure 25 — Profile of an external gear with linear tip relief, root relief and transition zones

An example result from CNC GMM for profile measurement with non-linear tip relief is provided in Figure 26. The gear has two evaluation ranges—the unmodified profile and the non-linear tip relief. A transition zone between the tip relief and the unmodified profile is not required as the start of the non-linear tip relief is tangential to the centre portion of the profile. Below the start of active profile, every gear should have sufficient profile length recorded to check that no interference will occur when the tooth is in mesh.

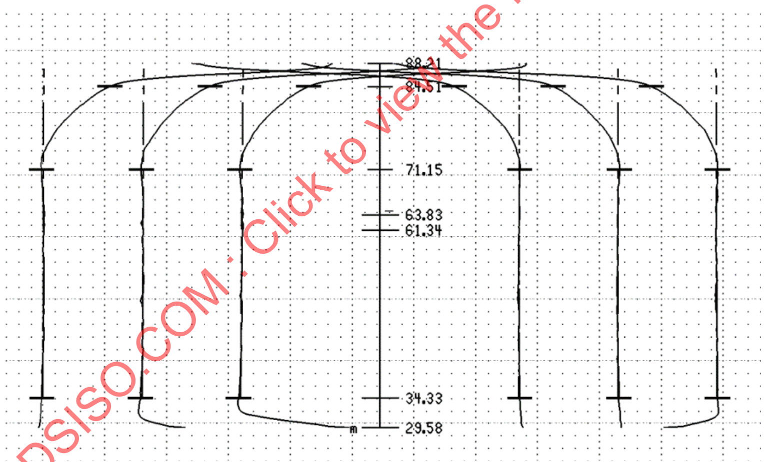


Figure 26 — Profile of an external gear with non-linear tip relief without transition zones

7 Recommended measurement procedure and good measurement practice

7.1 Measurement procedure

Any gear measurement process can indicate deviations which appear similar to those introduced from the manufacturing process. An example is radial runout of the gear blank or a tailstock alignment error which can occur during manufacturing or during the inspection processes. The inspection results look identical. Applying good measurement practice minimizes the risk from rejecting gears which would otherwise comply with the specification or accepting gears which fail to meet the specification.

The procedures that follow apply to CMM, CNC, and GMM. Inspection devices integrated into machine tools and portable inspection machines may require additional investigations to ensure measurements are valid for the proper evaluation of the tolerance class.

The following should be considered prior to gear measurement.

— Environment: it is recommended that the temperature of the measuring machine and workpiece should be 20 °C, or results compensated to this temperature. In all cases, the workpiece and the machine should be at a stable temperature. Temperature compensation should be used. Any temperature gradient will affect the accuracy of profile, helix and tooth thickness measurement and thus the validity of results. Refer to ISO/TR 10064-5 for guidance on temperature control and quantifying the effect that temperature deviations have on measurement results. It is also recommended that measuring machines are located in a clean environment to minimize the risk of contamination and extend the measuring machine life.

— Calibration: it is recommended that the measurement uncertainty of the measuring process is assessed using procedures defined in ISO 15530-3 or ISO 18653 and recommendations in the supporting document ISO/TR 10064-5. If measurement uncertainty is to be considered when interpreting compliance to a tolerance specification, the method of implementing this should be agreed between the manufacturer and the purchaser. Different options are presented in ISO/TR 10064-5. Also, see ISO 22514-7 for additional information and more detailed procedures.

  Formulae (2) and (3) should be used to calculate uncertainty; the uncertainty equations in ISO 18653:2003 should not be used.

$$U_{95} = k\sqrt{u_{\mathrm{m}}^2 + u_{\mathrm{n}}^2 + u_{\mathrm{g}}^2 + u_{\mathrm{w}}^2 + e^2} \qquad (2)$$

$$U_{95c} = k\sqrt{u_{\mathrm{m}}^2 + u_{\mathrm{n}}^2 + e^2} \qquad (3)$$

  See ISO 18653 for symbols and definitions.

— Measuring machine condition: tooling used to mount gears (e.g. centres, drivers, etc.) should be clean and free from damage. Indicators used to align gears (or the gear measuring machine) should be calibrated and have a discrimination of 1 µm or better, and any location fixtures need to be clean and free from damage.

Recommended measurement procedure:

a) Check that the correct probe is selected and calibrated, that the probe tip is small enough to measure the required control diameter and is suitable for measuring the datum surfaces if required. While measuring the gear teeth, the probe (or probe cluster when applicable) should not be changed. The frequency of probe re-calibration depends on the measurement requirements and measuring machine type.

b) Check that the measuring machine has been calibrated within the prescribed period. The machine should be regularly verified with a gear artefact or master gear with a traceable calibration certificate. The frequency of these checks will vary depending on environment, machine condition and required measurement performance. Intervals of once per week for low volume up to once per day for higher volume are commonly applied in industry. The date of each calibration should be recorded and made available to the purchaser. The required frequency of calibration should be verified by testing with calibrated master gears or workpieces.

c) Clean the gear teeth and the mounting surfaces. Check to see that all the teeth were cleaned up (properly machined) during the finishing operation, if appropriate. Verify the gear is free from nicks, burrs or corrosion.

d) It is recommended that the gear be removed from any manufacturing fixture before final inspection to avoid errors caused by radial runout of the gear blank on the mounting fixture.

e) The proper selection of datum axis is important for accurate gear measurement. Unless otherwise stated on the gear drawing, the datum axis should be defined by measuring the functional datum surfaces that will define the gear orientation in service.

   1) Measuring instruments with rotary tables: verify that runout of datum surfaces is small if no correction for gear blank mounting errors is used (5 µm or less for most applications) and record the mounting deviation on the record sheet.

   2) Measuring instruments with rotary tables and datum surface runout correction or measuring instruments without a rotary table: define the datum axis by probing the datum surfaces (two circular elements or a circular element and a transverse plane element). It is recommended that the minimum number of equally spaced points used be validated by testing because the required number depends on the measuring machine performance and form deviations of the datum surface (see note following point j).

f) Measure three or four teeth (left and right flanks) evenly spaced around the gear for helix and profile deviations. Measure profile deviations at approximately mid-face width and helix deviations at the measurement diameter, d_M, in accordance with ISO 1328-1.

g) When the gear is manufactured by processes which are known to cause variation in helix deviations with radial location or profile deviations across the face width, it is recommended that additional profile and helix measurements be made to verify the constancy of the active gear flank over the tooth range. The variations can be caused by manufacturing processes such as moulding processes or form grinding resulting in twist. The additional profile measurements are often done near the start and end of the helix evaluation range, while the additional helix measurements are done near the ends of the profile evaluation range.

h) Measure all teeth, left and right flanks, for cumulative pitch, adjacent pitch and radial runout deviation (if specified) at mid-face width and at the measurement diameter, d_M, in accordance with ISO 1328-1.

i) Evaluate all the results and compare them to the limit values. If one or more parameters are outside the limit values, the gear fails its tooth flank class specification. Guidance on measurement uncertainty and compliance with specification is provided in ISO/TR 10064-5.

j) Additional measurements such as topographical measurements on a single tooth or helix and profile measurements on all teeth are recommended when it is important to understand the causes of manufacturing errors or when developing a measurement strategy for processes likely to cause significant variation in flank deviations from tooth to tooth.

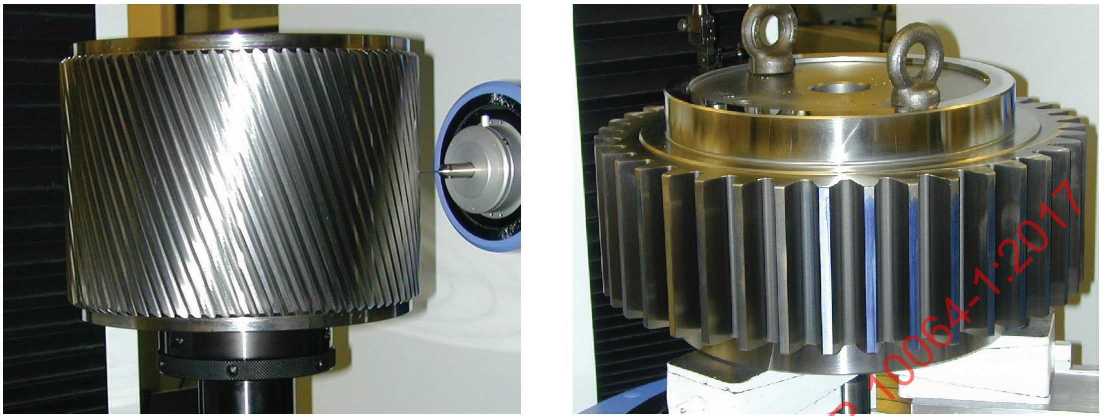
NOTE Many measuring instruments have options to define the gear datum axis by measuring the teeth themselves either by measuring pitch (radial runout) deviations or tooth flanks. This is not appropriate for defining gear classification in accordance with ISO 1328-1 because radial runout effects are not included in the evaluation. Therefore, unless specifically specified on the gear drawing, do not establish the gear datum axis from measurements on the teeth. An exception is the measurement of splines where the teeth themselves are the reference.

7.2 Probe problems when measuring aluminium parts

It has been observed that when measuring parts made of aluminium with a contacting probe or stylus, particles may adhere to the probe tip which will affect results. One successful strategy to prevent this is to spray the surface with oil before measuring, then clean the workpiece after the measurement.

7.3 Suitable artefacts for calibration of measuring machines

ISO 18653 recommends the use of “workpiece-like” artefacts which are artefacts that are similar to the product gears to be inspected with the measuring machine. The artefacts are used for helix, profile, pitch, radial runout and tooth thickness calibration purposes. These should be similar in size and weight to make the calibration process similar to the product gear measurement process. Measuring machines are commonly supplied with gear artefacts which are used to demonstrate the machine measurement capability. Although these can be used to assess measurement uncertainty, significant differences between workpiece and artefact geometry reduce the validity of this process. Examples of "workpiece-like" artefacts are illustrated in Figure 27 where the gear artefacts are identical to the geometry of the workpieces.



a) Helical gear

b) Spur gear

Figure 27 — "Workpiece-like" artefacts

It is recommended that for verification of the measuring machine, gear artefacts with known deviations and similar surface finish to workpieces should be used. If not manufactured from stable tool steel, the calibration interval should be selected to reflect the stability of the artefacts. See ISO 15530-3.

8 Inspection procedures for gears that are too large for gear inspection machines

8.1 General

In most cases, GMM or CMM are used to verify if gears meet the specified ISO 1328-1 classification. These may include portable measuring arms or laser based equipment that is suitable for even the largest gears. However, when inspection machines are not available for large gears, with agreement between the manufacturer and the purchaser, the criteria and measurement practices described in this clause may be used.

8.2 Profile inspection using portable device

8.2.1 Disassembly of segments

Although it is preferable to perform inspections on fully assembled gears, if the part is assembled from segments, it may be disassembled for measurements.

8.2.2 Measurement by portable gear inspection device using coordinates

Some of these devices are mounted with respect to the gear teeth, and thus they do not reveal deviations from the datum axis. They measure the profile as a series of coordinates. The device should be calibrated on parts that have already been inspected on a gear measuring machine. For transportable devices, care should be taken in their mounting and adjustment on the gear to be inspected. Incorrect adjustment will lead to abnormal profile slope deviations ($f_{H\alpha}$) (positive on one flank and negative on the other flank). In this case, a check should be carried out by measuring the base pitch. Figure 28 illustrates a portable profile measuring device which is located on the tooth flanks.

Repeatability should be checked and the measuring uncertainty quantified. Refer to ISO/TR 10064-5 for further information.

NOTE Some portable instruments do not measure profile and helix deviations relative to the datum axis of the gear and thus, the effect of radial and axial datum runout deviations is not included.

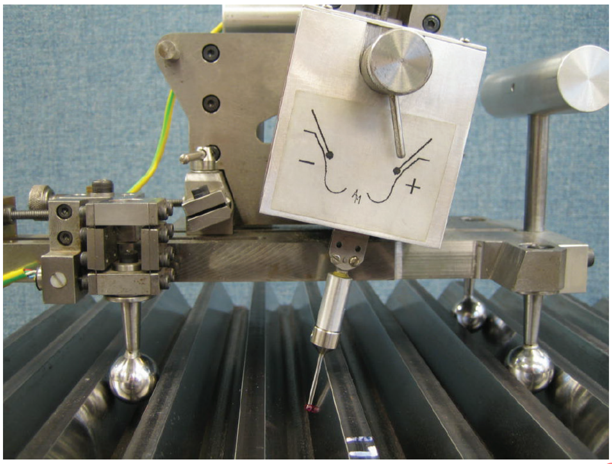
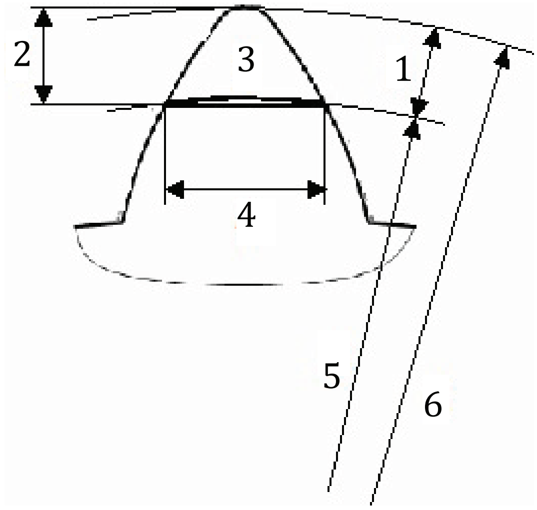


Figure 28 — Close-up of profile measuring device for large gears

8.2.3 Profile inspection by gear tooth caliper

The total profile deviation can be approximated using measurements taken with a gear tooth caliper at several radial locations on the tooth (see Figures 29 and 30). The suitability of a gear tooth caliper should take account of the reading inaccuracy of this device.

Since the measured deviations are equally distributed on each of the tooth flanks, it is not possible to accurately dissociate the actual deviations on each of the profiles.



Key

1 radial distance, h_y
2 chordal addendum, h_{cy}
3 circular thickness, s_{yn}
4 chordal thickness, s_{cy}
5 measurement diameter, d_y
6 effective (measured) tip diameter, $d_{a\ eff}$

Figure 29 — Addendum and chordal tooth thickness

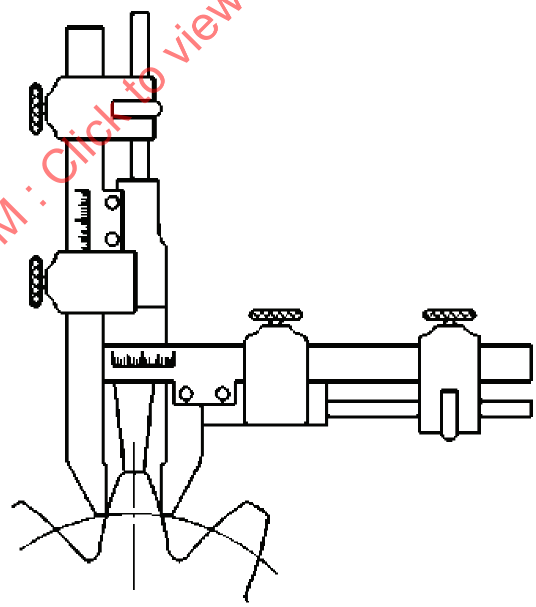


Figure 30 — Gear tooth caliper

For a better interpretation of this inspection, it should be complemented by a measurement of the actual base pitch. By comparing it with the theoretical base pitch, this measurement enables the profile slope deviation, $f_{H\alpha}$, to be partly taken into account.

After converting the measurements to the transverse plane, the total profile deviation is calculated by subtracting the theoretical value calculated for a design profile from the value of the chordal thickness, and then by redistributing the deviation equally on the two flanks.

It is recommended that for closer compliance with ISO 1328-1, the deviation should be multiplied by cos (α_{yn}) where (α_{yn}) is the pressure angle at an individual inspection diameter.

The recommended minimum number of measurements is 12, equally distributed by involute roll angle, ξ, over a height corresponding to the evaluation length and taken at a constant axial position. The following calculations should be performed using the measured tooth thickness of the gear.

The roll angles at the tip and start of active profile can be found with Formulae (4) to (8):

$$d = \frac{z m_n}{\cos\beta} \quad (4)$$

$$\alpha_t = \tan^{-1}\left\{\frac{\tan\alpha_n}{\cos\beta}\right\} \quad (5)$$

$$d_b = \frac{z\, m_n}{\cos\beta}\cos\alpha_t \quad (6)$$

$$\xi_a = \tan\left(\cos^{-1}\frac{d_b}{d_{a\,eff}}\right) \quad (7)$$

$$\xi_{Nf} = \tan\left(\cos^{-1}\frac{d_b}{d_{Nf}}\right) \quad (8)$$

where

z is the number of teeth;

β is the helix angle;

d is the reference diameter, mm;

α_n is the normal pressure angle;

α_t is the transverse pressure angle;

d_b is the base diameter, mm;

$d_{a\,eff}$ is the tip diameter, mm;

d_{Nf} is the start of active profile (SAP) diameter, mm;

ξ_a is the roll angle to the tip diameter, radians;

ξ_{Nf} is the roll angle to the start of active profile diameter, radians.

The difference between the roll angles at the tip and start of active profile is divided by the desired number of measurements minus 1, then repeated subtraction from the roll angle at the tip diameter will give the evenly spaced roll angles where the chordal measurements should be taken. These roll angles can be converted to diameters using Formula (9):

$$d_y = \frac{d_b}{\cos\left(\tan^{-1}\xi_y\right)} \quad (9)$$

where

d_y is an individual inspection diameter, mm;

ξ_y is an individual inspection roll angle, radians.

The local helix angle, transverse pressure angle, normal tooth thickness, chordal addendum and chordal tooth thickness can now be found for each inspection diameter shown in Formulae (10) to (15):

$$\beta_y = \tan^{-1}\left\{\frac{d_y}{d}\tan\beta\right\} \tag{10}$$

$$\alpha_{yt} = \cos^{-1}\left(\frac{d_b}{d_y}\right) \tag{11}$$

$$s_{yn} = d_y\left(\frac{s_n}{d\cos\beta} + \mathrm{inv}\,\alpha_t - \mathrm{inv}\,\alpha_{yt}\right)\cos\beta_y \tag{12}$$

$$h_{cy} = \frac{d_{a\,eff} - d_y\left(\cos\left(\frac{s_{yn}\cos\beta_y}{d_y}\right)\right)}{2} \tag{13}$$

$$s_{cy} = \sqrt{\left(s_{yn}\sin\beta_y\right)^2 + \left(d_y\sin\left(\frac{s_{yn}\cos\beta_y}{d_y}\right)\right)^2} \tag{14}$$

$$\alpha_{yn} = \tan^{-1}\left\{\tan\alpha_{yt}\cos\beta_y\right\} \tag{15}$$

where

β_y is the helix angle at an individual inspection diameter, degrees;

α_{yt} is the transverse pressure angle at an individual inspection diameter, degrees;

s_n is the normal circular tooth thickness at the reference diameter, mm;

s_{yn} is the normal circular tooth thickness at an individual inspection diameter, mm;

h_{cy} is the chordal addendum to an individual inspection diameter, mm;

s_{cy} is the chordal tooth thickness at an individual inspection diameter, mm;

α_{yn} is the normal pressure angle at an individual inspection diameter, degrees.

On large gears, the difference between the normal and chordal tooth thickness is usually very small, but it is recommended that the chordal tooth thickness always be calculated.

NOTE These formulae are only for external gears.

An example of the calculations for chordal thickness measurements is presented in Tables 4 to 6 (input values are highlighted).

Table 4 — Gear data

	Symbol	Value	Units
Module	m_n	40	mm
Pressure angle, normal	α_n	25° = 0,436 332	radians
Helix angle	β	0° = 0,000 000	radians
Number of teeth, pinion	z	134	—
Profile shift coefficient	x	0	—

Table 5 — Calculations

Tooth thickness, normal circular	s_n	62,832	mm
Reference diameter	d	5 360,000	mm
Transverse pressure angle	α_t	0,436 33	radians
Base circle diameter	d_b	4 857,810	mm
Helix angle at d_y	β_y	0,000 000	radians

Table 6 — Results

	d_y mm	ξ_y radians	β_y radians	α_{yt} radians	s_{yn} mm	h_{cy} mm	s_{cy} mm
Tip	5 440	0,504 04					
1	5 425,83	0,497 53	0,00	0,461 67	31,68	7,13	31,68
2	5 411,81	0,491 01	0,00	0,456 43	38,52	14,16	38,52
3	5 397,94	0,484 50	0,00	0,451 17	45,17	21,12	45,17
4	5 384,22	0,477 99	0,00	0,445 88	51,65	28,01	51,65
5	5 370,65	0,471 47	0,00	0,440 57	57,96	34,83	57,96
6	5 357,23	0,464 96	0,00	0,435 22	64,09	41,57	64,09
7	5 343,97	0,458 45	0,00	0,429 85	70,04	48,24	70,04
8	5 330,86	0,451 93	0,00	0,424 46	75,83	54,84	75,83
9	5 317,91	0,445 42	0,00	0,419 04	81,45	61,36	81,45
10	5 305,11	0,438 91	0,00	0,413 59	86,91	67,80	86,90
11	5 292,48	0,432 39	0,00	0,408 11	92,20	74,16	92,19
SAP	5 280	0,425 88	0,00	0,402 61	97,33	80,45	97,32

8.3 Inspection of helix form deviation

8.3.1 Inspection of helix form deviation on the gear cutting machine

For spur gears, this inspection may be carried out using a dial gauge mounted on the tool spindle and linked to a continuous graphic recorder. The straightness of the slide should be checked with a calibrated straightness measurement standard.

If the helix angle is not zero, the differential of the machine should be used.

The deviation is measured with a minimum of 10 equally spaced points on the evaluation length, L_β. It should be evaluated with the helix form tolerance, $f_{f\beta T}$.

8.3.2 Straightness inspection using a cylinder

This inspection may only be carried out on spur gears.

A ground cylinder is used whose diameter enables it to be tangent to both the right and left flanks of a tooth space. The flank-cylinder contact points should be approximately at mid-tooth depth.

The cylinder length should equal the face width inspected plus at each end sufficient length for handling the cylinder.

The cylindricity of the cylinder should be less than approximately 10 % of the helix form tolerance, $f_{f\beta T}$.

Form deviation is assessed in relation to the mark left on the gear tooth by the cylinder previously coated with Prussian blue. The deviation values are measured using "precision feeler gauges" slipped in between the cylinder and the gear tooth flank in the unmarked zones. The recommended minimum size of the precision feeler gauge is 0,04 mm.

8.3.3 Inspection of the tooth contact pattern

Contact marking tests provide a method of verifying helix consistency. When agreed between the manufacturer and the purchaser, contact marking tests can replace individual helix measurements.

Inspection of the tooth contact pattern should be carried out in accordance with ISO/TR 10064-4.

The tooth contact check should be done with single flank contact. This is often done by bringing the gears into tight mesh contact, then separating them by a few millimetres.

For the contact pattern check, three different roll tests can be done. In order of preference, they are:

— on gear cutting machine (GCM), fixed centre distance;

— with crane, pinion on top, roll check;

— with crane, gear on top, roll check.

Results obtained through the three different tests are practically equivalent.

Blueing application: blueing is applied on the roughest surface (generally the gear).

Apply blueing uniformly on the whole surface of both tooth flanks on a minimum of five consecutive teeth.

Among these teeth, two of them will be covered with a thicker coat of blue to help contact pattern evaluation.

Test realization: A minimum of three teeth have to go through the gear mesh on both flanks.

Test records: Documentation is done by use of transparent and self-adhesive plastic films. They are applied to the teeth and then transferred to paper. After application of the film to paper, the result may be recorded with a colour photograph for storage.

The helix form modifications and deviations of the pinion have to be known.

Small variations in backlash around the nominal value have no influence on the tooth contact pattern.

Typical tooth contact patterns are given in ISO/TR 10064-4.

8.4 Inspection of the pitch

8.4.1 Calculation of pitch

The transverse base pitch is the length of the normal common to two consecutive corresponding apparent flanks. It is also the length of the base circle arc between two points where these two profiles touch the base circle.

$$p_{bt} = d_b \frac{\pi}{z} \tag{16}$$

The normal and transverse base pitches are related by Formula (17):

$$p_{bn} = p_{bt} \cos\beta_b \tag{17}$$

The actual distribution of the load between the teeth of meshing gears requires appropriate inspection of the variation of the base pitch of the two parts making it up.

This is especially important when the parts should be interchangeable.

The theoretical value of the actual base pitch depends on the actual module and the actual pressure angle. See Formula (18).

$$p_{bn} = \pi m_n \cos\alpha_n \tag{18}$$

NOTE Given the production deviations of the tip diameter of girth gears, inspection of the circular pitch using a device that takes this diameter as reference is not advised. It is replaced by the base pitch inspection.

8.4.2 Inspection using an automatic device on the cutting machine: inspection of the single circular pitch and the cumulative pitch deviation

Portable automatic pitch inspection devices are two-probes pitch comparators (see Figures 9 and 16).

Measurement of the pitch deviations using a two-probe pitch comparator should occur in a stress free and unclamped state.

The two probes should be positioned at the same distance from the gear axis and in the same plane normal to the axis (transverse plane). The direction of the probes displacement should be tangential to the measuring circle. As the exact radial distance is difficult to assess, such comparators are seldom used to check the true values of transverse pitches. Thus, the most suitable use of these devices is the determination of pitch deviations.

Some pitch comparators are equipped with a table that advances the probes at a constant radial distance, approximately at mid-tooth depth.

The gear under inspection turns slowly, either continuously or intermittently around its axis, and the probes on the table are moved in and out of the gauging position.

Based on the single pitch deviations, these devices are capable of calculating for each flank the cumulative pitch deviation for one revolution.

Depending on the application, the cumulative pitch deviation can be measured for a cumulative pitch number (k pitches) or for all the teeth. In the latter case, it advantageously replaces the gear radial runout deviation, which is not representative of the gear action and is not a required measurement.

8.4.3 Manual inspection: inspection of base pitch, p_b, and base pitch deviations, f_{pb}

In practice, a portable comparator is used for the measurement of the normal base pitch deviations. The principle of such an instrument is shown in Figure 18. By using an appropriate gauge, the comparator is calibrated to measure directly the deviations from a theoretical base pitch.

During the measurement of the base pitch, the contact points with the instrument's probes should not be located in zones where the profile and/or helix have been modified.

When the gear is manufactured in sections, pitch deviations should be measured across every joint in addition to measurements within the sections.

The following relationship is used to convert to the standardized single pitch deviation, f_p:

$$f_p = \frac{f_{pbt}}{\cos \alpha_t} \tag{19}$$

When a girth gear is made in several parts, it is recommended that the inspections be carried out with the part placed on a reference surface. This is to avoid introducing deviations, especially at the faces on either side of the joints.

Measurement of the base pitch deviation does not enable the cumulative pitch deviation to be determined.

8.5 Measuring tooth thickness

See ISO 21771 for tooth thickness measurement calculations.

8.6 Measuring gear radial runout and axial runout of reference surfaces

The radial and axial runout inspection of the reference surfaces of the part is carried out on a cutting machine before machining.

The reference surfaces and diameter are defined by the manufacturer of the gear and indicated on drawings.

At the user's request, these same inspections may be carried out after unclamping the fixing clamps of the gear on the cutting machine.

The readings are given for information purposes. The measured deviations should be less than the requested tolerances after mounting on site.

9 Measurement analysis — Profile, helix, pitch and radial runout

9.1 Profile

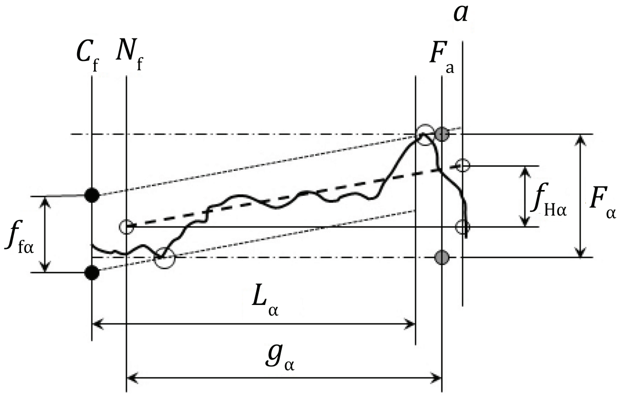
9.1.1 Profile deviation

Profile deviation is the difference between the specified and the measured profile of the gear. Unless profile modifications are specified, the shape of the profile in the transverse plane is an involute curve. ISO 1328-1 specifies the direction of tolerance for profile deviations to be within the transverse plane, tangent to the base circle.

Amplified traces of the profile inspection test results should be presented on charts that are graduated for rolling path length, degrees of roll, or diameters. They should also be labelled for magnification, filter wavelength and number of evaluation points in conformance with the specification.

Any point along the profile diagram can be related to a diameter (radius), a base tangent length and an involute roll angle. See Formula (9) and ISO 21771.

Figure 14 shows a sample tooth profile and the relation to the corresponding profile trace, together with the appropriate terms. Details of terms, definitions and concepts concerning the profile trace are provided in ISO 1328-1. Figure 31 shows a typical profile inspection chart.



Key

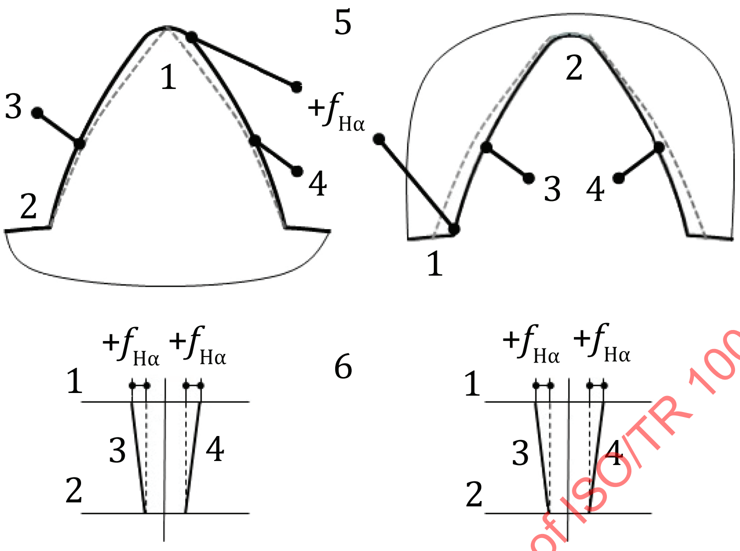
————————	measured profile	Points on line of action	
– — — — — — –	mean profile line	C_f	profile control
—.—.—.—.—	facsimile of design profile	N_f	start of active profile (SAP)
————————	facsimile of mean profile line	F_a	tip form, where tip break starts
		a	tip

Figure 31 — Typical profile inspection chart

9.1.2 Profile deviation diagram

An unmodified involute profile with no deviations will be charted as a straight line. Deviations of the curve from a straight line represent, in magnified form, deviations of the actual profile from an unmodified involute. Profile modifications introduced by the designer create the “design profile” which will also appear as departures from the straight line, but these are intentional. It may also be helpful to chart deviations from design profile in addition to the traditional chart of deviations from an unmodified involute.

Excess material on the profile is considered a plus deviation, while insufficient material is considered a minus deviation (see Figures 32 and 33). In addition, these charts are valuable for determining profile characteristics such as tip break, undercut and tip or root relief.



a) External gear　　b) Internal gear

Key

1 tip
2 root
3 left flank
4 right flank
5 tooth cross sections
6 profile charts

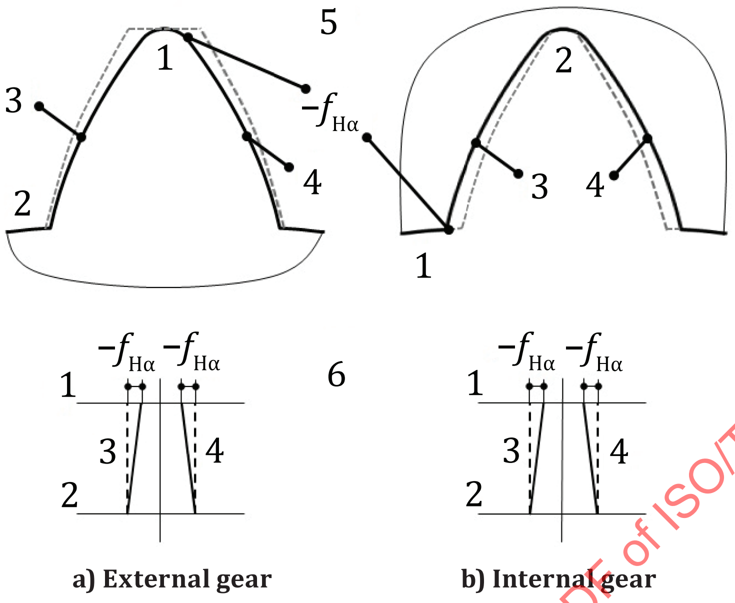
– – – – – – design tooth shape, unmodified involute
———— measured tooth shape

Figure 32 — Gear with excess material at tip (decreased pressure angle)

9.1.3 Evaluation of profile diagrams

Depending on flank tolerance class specified, it may only be necessary to measure total profile deviation, F_{α}. See ISO 1328-1:2013, Clause 4.

The profile slope deviation, $f_{H\alpha}$, and the profile form deviation, $f_{f\alpha}$, are determined by superposing the mean profile line onto the diagram as shown in ISO 1328-1:2013, Figures 4 to 8. Allowable values of $f_{H\alpha}$ and $f_{f\alpha}$ can be calculated in accordance with ISO 1328-1.



Key

1 tip
2 root
3 left flank
4 right flank
5 tooth cross sections
6 profile charts

– – – – – – – design tooth shape, unmodified involute
———— measured tooth shape

Figure 33 — Gear with minus material at tip (increased pressure angle)

9.1.4 Algebraic signs of $f_{H\alpha}$, f_b and f_α

For the proper interpretation of measurement results, it is necessary to define algebraic signs to the deviations and calculate numerical values.

f_α is the difference between the actual pressure angle and nominal pressure angle.

f_b base circle deviation is the difference between the actual base diameter and nominal base diameter.

According to ISO 1328-1, the profile slope deviation, $f_{H\alpha}$, is termed positive and the corresponding pressure angle deviation, f_α, is termed negative when the mean profile line rises towards the tooth-tip end of the diagram, as shown in Figure 32. In Figure 34, both positive and negative slopes, caused by eccentricity of mounting on the gear generating machine, are shown.

If the slopes, seen in the profile diagrams of mating gears, are equal and have the same sign, the deviations are mutually compensating. This applies to both external and internal gears.

9.1.5 Mean profile slope deviation, $f_{H\alpha m}$

Slope deviations of individual profiles can be caused by eccentricity due to inaccuracies of manufacturing or inspection set-up. Such deviations will vary around the gear. The use of mean profile slope deviations cancels out the influence of eccentricity on individual profile traces.

The effect of eccentricity on profile slope and the determination of mean profile slope deviation are illustrated in Figure 34.

Calculating the mean profile slope deviation is a step towards the correction of manufacturing processes or other suitable action.

For all practical purposes, it is usually sufficient to calculate the arithmetic mean of the profile slope deviations by calculating the average of the deviations measured on three or more corresponding flanks of equally spaced teeth around the gear circumference according to Formula (20):

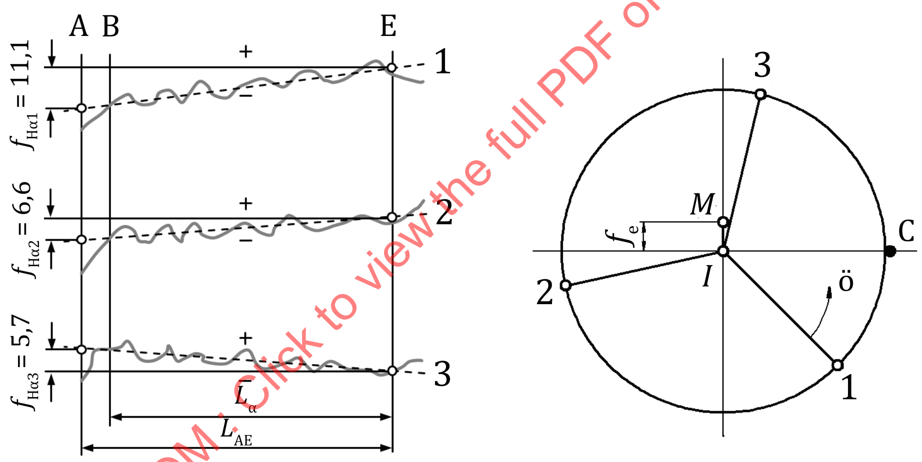
$$f_{H\alpha m} = \frac{1}{n}\left(f_{H\alpha 1} + f_{H\alpha 2} + \cdots + f_{H\alpha n}\right) \qquad (20)$$

where

$f_{H\alpha m}$ is the mean profile slope deviation, µm;

$f_{H\alpha i}$ are the individual profile slope deviations, i can have values from 1 to n, µm;

n is the number of profile slope deviation values included in the mean.



$$f_{H\alpha m} = \frac{1}{3}(-11,1 - 6,6 + 5,7) = -4\ \mu m$$

Key

M axis of rotation of the gear on the machine tool

I axis of rotation of the gear on the inspection apparatus

C position of tool or profile measuring probe

1, 2, 3 positions of the teeth from which the profile traces were obtained (at 45°, 165°, 285°) and relevant profile traces

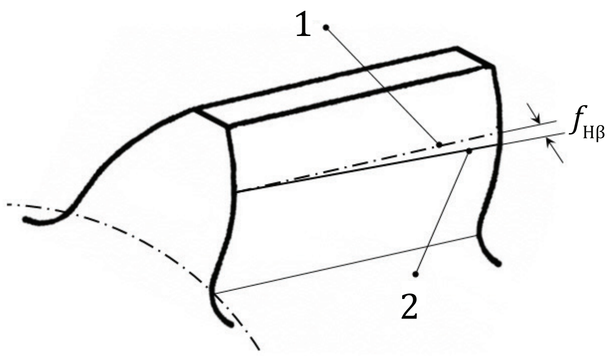
Figure 34 — Mean profile slope deviation, $f_{H\alpha m}$

9.2 Helix

9.2.1 General

Helix is the lengthwise shape of the tooth flank across the face from one end to the other. The theoretical helix of a helical gear is contained on the surface of a cylinder concentric with the datum axis at the intersection of that cylinder with the tooth flank. The theoretical helix of a spur gear is a straight line parallel to its rotating axis.

Helix deviation is the difference between the specified and the measured helix of the gear (see Figure 35). ISO 1328-1 specifies the direction of tolerance for helix deviation to be within the transverse plane, tangent to the base circle.



Key

1 measured helix

2 design helix

Figure 35 — Helix deviation

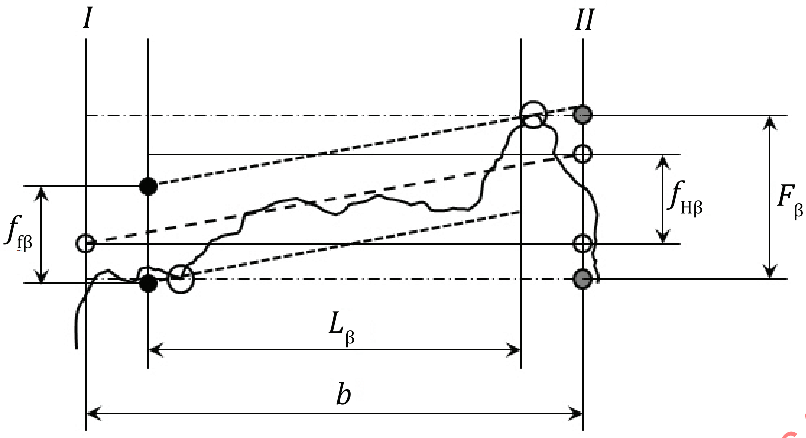
9.2.2 Helix deviation diagram

An unmodified helix with no deviations will be charted as a straight line. Deviations of the curve from a straight line represent, in magnified form, deviations of the actual helix from an unmodified helix. Helix modifications introduced by the designer create the design helix; they are intentional departures from the unmodified helix. It may also be helpful to chart deviations from design helix in addition to the traditional chart of deviations from an unmodified helix.

Excess material on the helix is considered a plus deviation while insufficient material is considered a minus deviation. In addition to identifying the location and magnitude of the helix deviation, these charts are valuable for determining helix characteristics such as edge rounds, crowning, and end relief.

Reference to right hand and left hand helices can be indicated by means of the letters “r” and “l” or the symbols + and –, respectively.

In Figure 36, a typical example of a helix diagram shows the helix deviations of a tooth flank of which the design helix is an unmodified helix. Had the design helix been crowned, end relieved or otherwise modified, traces representing it would be appropriately formed curves.



Key

————————	measured helix
— — — — — — —	mean helix line
—.—.—.—.—	facsimile of design helix
_ _ _ _ _ _ _ _ _ _	facsimile of mean helix line

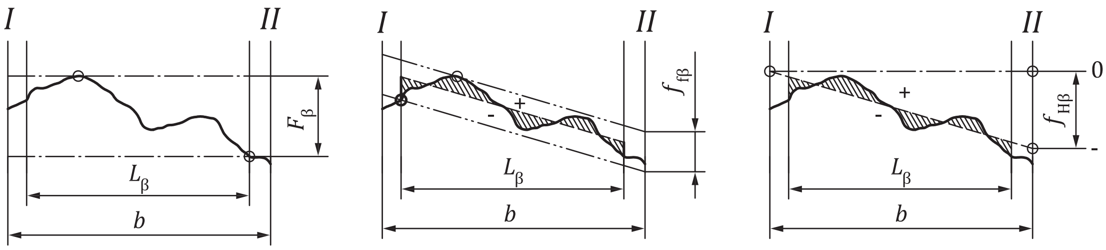
Figure 36 — Typical helix inspection chart

Details of terms, definitions and concepts concerning the helix trace are provided in ISO 1328-1.

The helix evaluation range, L_β, unless otherwise specified, is equal to the length of trace, reduced at each end by the smaller of two values: 5 % of the face width or the length equal to one module. This reduction is made to ensure that unintentional, slight end reliefs caused by some machining conditions are not normally included in the assessment of the deviation magnitudes intended for comparison with stringent tolerances. For assessment of the total helix deviation, F_β, and the helix form deviation, $f_{f\beta}$, excess material which increases the amount of deviation should be taken into account even if it is outside the helix evaluation range.

9.2.3 Evaluation of helix diagrams

Depending on the class specified, it may only be necessary to measure “total helix deviation”, F_β. See ISO 1328-1:2013, Clause 4. For flank tolerance classes 1 through 6, it is also mandatory to evaluate the “helix slope deviation”, $f_{H\beta}$, and the “helix form deviation”, $f_{f\beta}$. For this, it is necessary to superpose the “mean helix line” onto the diagram as shown in ISO 1328-1:2013, Figures 9 to 13. For reference, ISO 1328-1:2013, Figure 9 is reproduced here as Figure 37. Tolerance values $f_{H\beta T}$ and $f_{f\beta T}$ can be calculated in accordance with ISO 1328-1.



Key

b	face width	————	measured helix
F_β	total helix deviation	— · — · —	facsimile of design helix
$f_{f\beta}$	helix form deviation	— ·· — ·· —	facsimile of mean helix line
$f_{H\beta}$	helix slope deviation		
L_β	helix evaluation range		
I	reference face		
II	non-reference face		

Figure 37 — Helix diagram

9.2.4 Algebraic signs of $f_{H\beta}$ and f_β

Helix angle deviation, f_β, is the difference between actual helix angle and specified helix angle.

Helix slope deviation, $f_{H\beta}$, and the helix angle deviation, f_β, are to be reported with an algebraic sign. Helix angle deviation, f_β, is calculated in a manner similar to mean helix angle deviation, $f_{\beta m}$ (see 14.4.7).

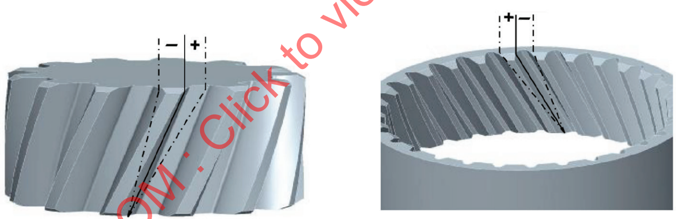


Figure 38 — Right hand helical gears showing plus and minus helix slope deviations, $f_{H\beta}$

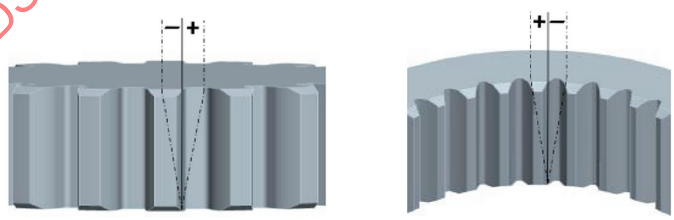


Figure 39 — Spur gears showing plus and minus helix slope deviations, $f_{H\beta}$

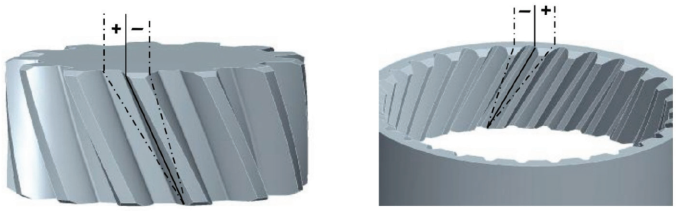


Figure 40 — Left hand helical gears showing plus and minus helix slope deviations, $f_{H\beta}$

According to ISO 1328-1, for helical gears, deviations are deemed to be positive ($f_{H\beta} > 0$ and $f_{\beta} > 0$) when the absolute values of the helix angles are larger than the design helix angle, and negative when smaller. The helix slope deviations of spur gears are deemed + (positive) if the measured helix is right hand and − (negative) if left hand. See Figures 38, 39 and 40.

NOTE In the past, the helix deviations of spur gears if other than zero were indicated by the subscripts “r” and “l”, instead of an algebraic sign, implying deviations in the sense of right or left hand helices, respectively.

In Figure 42, both positive and negative slopes, caused by eccentricity or wobble due to mounting on the gear generating machine, are shown.

If the helix slope deviation, $f_{H\beta}$, (assuming equal evaluation ranges) of the corresponding flanks of two mating gears is equal in magnitude and algebraic sign, the deviations are mutually compensating.

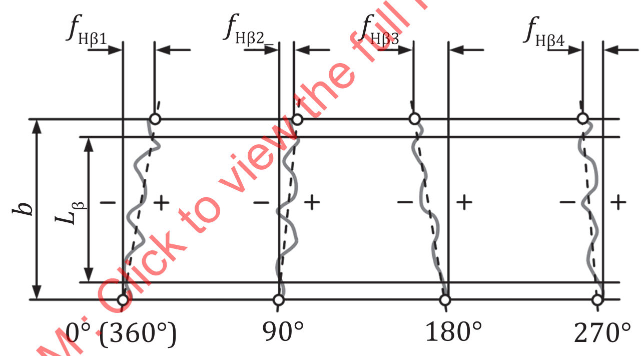


Figure 41 — Traces generated from four tooth flanks

9.2.5 Machine corrections based on mean helix slope deviation, $f_{H\beta m}$

For correction of machine tool settings or for matching the helix with a mating gear in a matched pair, determination of the mean helix slope deviation, $f_{H\beta m}$, of the gear is useful. If the helix slope deviations are either random or are fairly consistent, then the mean helix slope deviation may be used to correct the helix setting of the machine used to manufacture the gear. In the case of a matched set of mating gears where one has been manufactured and inspected, then the mean helix slope deviation may be used to adjust the manufacture of the other gear in the set. This will result in improved contact between the gears without the need to make corrections to the previously finished gear. Note that ISO 1328-1 does not apply to matched gear pairs.

If the helix slope deviation, $f_{H\beta}$, varies in a regular pattern around the circumference of a helical gear, then the datum axis of the gear was probably tilted, offset, or misaligned relative to the machine axis during either manufacture or inspection. See Figure 41. Tilting affects spur gears in the same manner, but offset (eccentricity) does not.

— Eccentricity: The variation of helix slope deviation caused by eccentricity (if within specified limits) is not normally detrimental to the operation of the gear.

— Tilting: Variation of helix slope deviation caused by misalignment of the gear teeth relative to the datum axis may affect the proper functioning of the gear. Tilting leads to poor load distribution. The helix slope deviations will cause the centre of contact pressure to shift axially back and forth with each revolution. This can, in turn, cause gear tooth damage. Therefore, attention should be drawn to this condition even if the deviations are within tolerance.

The mean helix slope deviation, $f_{H\beta m}$, is calculated by averaging the helix slope deviation, $f_{H\beta}$, observed on the corresponding flanks of three or more teeth equally spaced around the circumference of the gear. See Formula (21).

$$f_{H\beta m} = \frac{1}{n}\left(f_{H\beta 1} + f_{H\beta 2} + \cdots + f_{H\beta n}\right) \tag{21}$$

where

$f_{H\beta m}$ is the mean helix slope deviation, μm;

$f_{H\beta i}$ are the individual helix slope deviations, $_i$ can have values from 1 to n, μm;

n is the number of helix slope deviation values included in the mean.

A suitable mean value can be obtained from the helix diagrams of corresponding flanks of two diametrically opposite teeth. However, if the helix slope deviations vary around the gear, this will not always be disclosed unless traces of at least three equally spaced flanks are obtained.

9.3 Pitch

9.3.1 Pitch deviation

Single pitch deviation (f_p) and total cumulative pitch deviation (F_p) are elemental parameters relating to the accuracy of tooth locations around a gear. The following is a description of the measuring methods and a guide to the interpretation of the data generated by the measuring devices.

9.3.2 Pitch deviation measurement

Measurements for determining single pitch deviation (f_p) and total cumulative pitch deviation (F_p) are made:

— relative to the datum axis of the gear;

— at the measurement diameter, d_M;

— in the specified tolerance direction (within the transverse plane along the arc of the measurement diameter).

Measurements made in other directions need to be adjusted so that they are equivalent to measurements in the tolerance direction. This adjustment should be made before comparison of test results to tolerances.

Sector pitch deviation (F_{pk}) is an optional parameter described in ISO 1328-1:2013, Annex D. Measurements of sector pitch deviation are also expected to conform to the above requirements.

Pitch should be measured on both left and right flanks.

9.3.3 Relationships of pitch parameters and measuring methods

The relationships of pitch parameters using different measuring methods is illustrated in Figures 42 to 44.

Tooth number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Single probe readings, right flanks	0	3	4	7	8	7	4	2	0	−3	−7	−9	−10	−11	−10	−7	−4	−2
Cumulative pitch deviations	0	3	4	7	8	7	4	2	0	−3	−7	−9	−10	−11	−10	−7	−4	−2
Pitch number	18	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Single pitch deviations f_{pi} (calculated)	2	3	1	3	1	−1	−3	−2	−2	−3	−4	−2	−1	−1	1	3	3	2

NOTE 1 In practice, integer values are seldom encountered.

NOTE 2 Maximum magnitude of f_{pi} and minimum and maximum values for cumulative pitch deviations are shaded.

Figure 42 — Sample table with hypothetical deviation values obtained by indexing (single probe) device

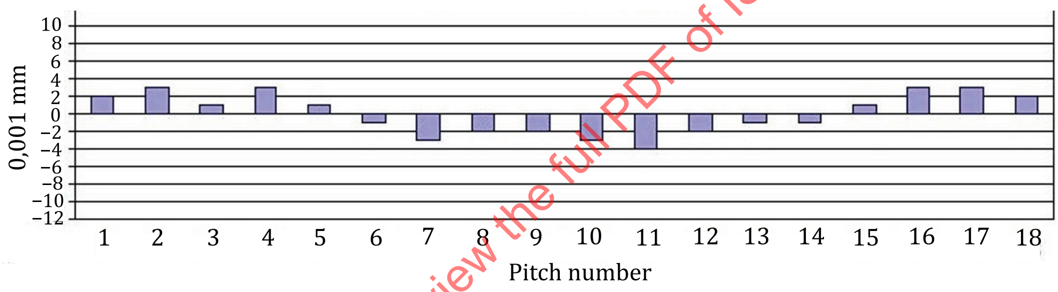


Figure 43 — Sample graphic representation of single pitch deviations, f_p

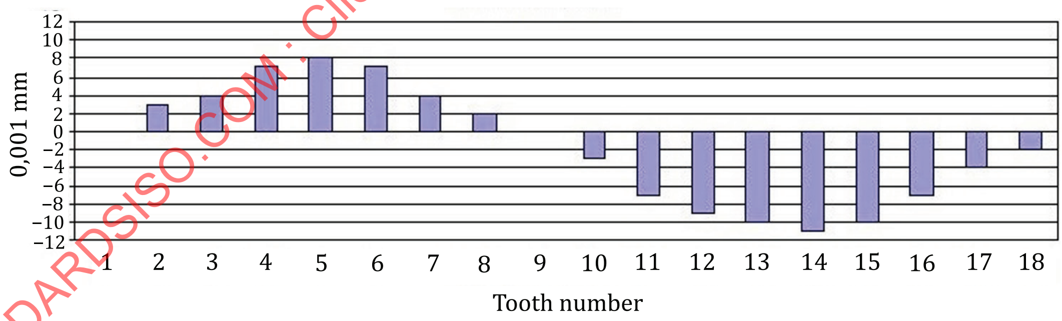


Figure 44 — Sample graphic representation of cumulative pitch (index) deviations

9.3.4 Calculation of cumulative pitch (index), F_p

If the indicator always reads plus material as a plus reading and the gear is indexed counter-clockwise (teeth are numbered clockwise), then the right flank measurement values provided by the indexing (single probe) pitch measurement device can be used directly as the plus and minus values of index for each tooth of the gear (see Figure 42). Left flank single probe measurement values should be multiplied by −1 to produce the correct plus and minus index values. Other pitch parameters may then be calculated from that data.

9.3.5 Calculation of single pitch, f_{pi}

Individual single pitch deviation values, f_{pi}, are the differences between adjacent index values. Subtraction of each successive pair of index values produces the values of single pitch deviation for each adjacent pair of tooth flanks of the gear. See Clause 5 for specified tooth numbering, pitch numbering, and flank naming conventions.

Single pitch deviation value number 1 is equal to the index value of the last tooth subtracted from the index value of the first tooth. Single pitch deviation value number 2 is equal to the index value of the first tooth subtracted from the index value of the second tooth, and so on.

9.3.6 Calculation of total cumulative pitch deviation, F_p

The total cumulative pitch deviation, F_p, is equal to the difference between the most positive and the most negative index value for the complete gear. See Figure 45.

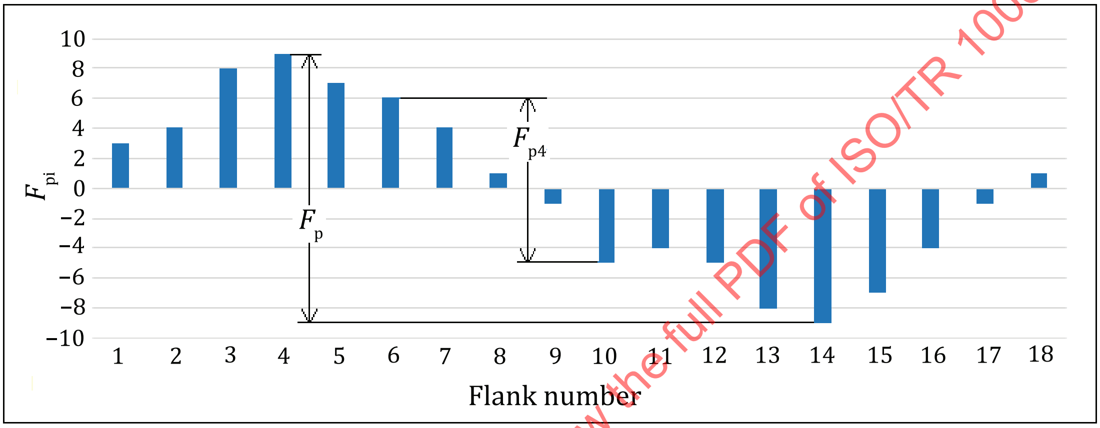


Figure 45 — Cumulative pitch, F_p, and sector pitch over four teeth, F_{p4}

9.3.7 Calculation of sector pitch deviation, F_{pk}

Calculation of the sector pitch deviation, F_{pk}, is presented in ISO 1328-1:2013, Annex D. An example for F_{pk} is shown in Figure 45 where subscript k is equal to four.

9.3.8 Segment gear measurement

A gear is called segmented if it consists of a single segment or if one or several teeth or spaces are missing. The effect on the pitch evaluation is best explained by an example. Consider a gear with 40 teeth and one missing tooth, tooth number 10. The pitch is measured in a clockwise order. Obviously, the cumulative pitch has no value on tooth 10. But the individual pitch has no value at tooth 10 and tooth 11. That is because tooth 11 has no preceding tooth to calculate the difference. The adjacent pitch has three missing values because it is created out of the differences of individual pitch deviations. Therefore, individual cumulative pitch deviation, F_{pi}, has no value at tooth 10, individual single pitch deviation, f_{pi}, has no value at teeth 10 and 11, and individual adjacent pitch difference, f_{ui}, has no value at teeth 10, 11, and 12.

On special gearing where each second tooth is missing, no f_{pi} and no f_{ui} values can be calculated at all. Such gear has only F_{pi} values. To get information about the behaviour in between the teeth, the parameters f_{p2i} and f_{u2i} can be created, which means that only every second tooth is used.

9.4 Radial runout, determining eccentricity

9.4.1 Measuring principle

Relative to the gear reference axis, the radial runout, F_r, of gear teeth is the difference between the maximum and the minimum radial positions of a suitable ball, anvil, cylinder or prism, which is placed successively in each tooth space.

If a ball, cylinder, or anvil (a piece shaped like a single tooth of a mating rack) that contacts both sides of a tooth space is used, the tolerance in ISO 1328-1 may be applied.

Alternatively, radial runout, F_r, may be calculated from left and right pitch measurements on a CMM or GMM, provided the probe diameter contacts at the measurement diameter specified on the drawing.

The size of the item used for the measurement should be selected such that it contacts the tooth at approximately mid-tooth depth and it should be placed at mid-face width (see ISO 21771 for the calculation of ball diameter).

9.4.2 Evaluation of measurement

9.4.2.1 Radial runout, F_r

The radial runout, F_r, is referenced to the datum axis and is equal to the algebraic difference between the maximum and minimum values of the radial deviation measured in accordance with ISO 10064-2:1996, 5.3. It is composed of roughly twice the eccentricity, f_e, together with superimposed effects of pitch and profile deviations of the gear (see Figure 46).

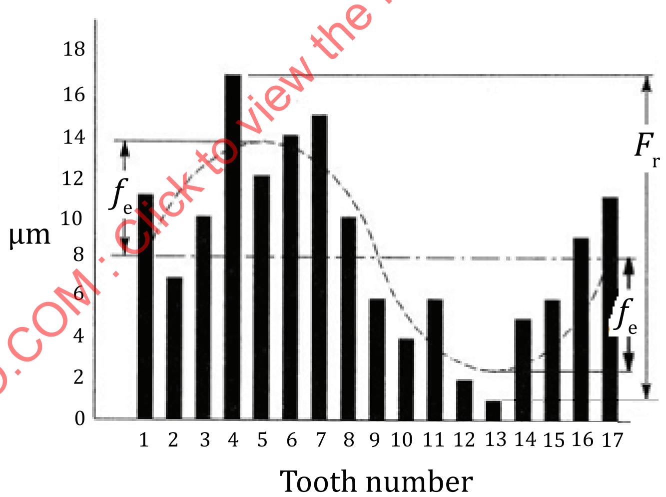


Figure 46 — Radial runout diagram of a gear with 16 teeth

9.4.2.2 Eccentricity, f_e

A diagram showing measured radial runout is shown in Figure 46. The sinusoidal component of the curve roughly drawn by hand or calculated by the least squares method indicates (in the plane of measurement) the eccentricity of the teeth to the reference axis by an amount f_e. When the runout is caused mainly by eccentricity, then the maximum pitch deviation is approximately 90° + α_t on the left flanks and 90° – α_t on the right flanks from the high point of runout.

10 Interpretation of profile, helix, pitch and radial runout results

10.1 Interpreting measurement results

The measurement of profile, helix, pitch and radial runout provides data that can be used to identify the potential causes of the measured deviations. Before diagnosing a manufacturing problem using this information, it is vital that potential sources of measurement error are eliminated. For example, measurements which show radial or axial runout merely indicate that the measurement axis is not the same as the production axis and can easily be caused by an error in the measurement set-up. Careful control and measurement of mounting errors and simply removing the gear from its mounting fixture before repeating the inspection will provide confidence in measurement results.

10.2 Procedure for interpreting measurement results

The following procedure provides a robust method of evaluating and interpreting gear measurement results. Examples of measured deviations are provided for guidance.

a) Use all the information available to diagnose the cause of the deviations (helix, profile, pitch and radial runout deviations and tooth thickness).

b) Helix and profile error visual examination:

   1) Review all teeth measured (left flanks and right flanks).

   2) Use slope parameters to detect trends.

      i) Generally consistent slope deviations between the measured teeth at regular intervals indicate the same manufacturing error is present on all teeth and thus, the tooling or setup is the predominant cause of deviations. Example error sources include alignment, tool setting or dressing errors, re-grinding faults on hobs and shaping cutters, cutting tool runout, temperature effects, elastic deflection from cutting forces, mould cavity errors due to shrinkage or cavity shape errors.

      ii) Deviations that vary from tooth to tooth in a cyclic manner over measured teeth at regular intervals are generally due to blank mounting errors, in the case of machine cut gears. Example error sources include axial or radial runout of the blank on the production machine (or measuring machine), radial runout of the teeth and gear blank from previous operations, mould cavity concentricity errors, mould shrinkage variation.

c) Pitch and radial runout deviation visual examination:

   1) Review all the available evaluated parameter values and deviation charts.

   2) Examine the shape of the deviations. Smooth sine waves are generally caused by radial runout or concentricity errors during either final machining or measurement process.

   3) Review the phase of the high points on the cumulative pitch deviations.

      i) If the high points of the sine waves are out of phase by approximately two times the transverse pressure angle, then the deviation is likely to be due to blank radial runout.

      ii) If the high points are in phase, the deviation is due to an indexing error on the manufacturing machine spindle or from the previous operation when checking shaved or honed gears. Examination of radial runout deviation should show no significant sine wave once per revolution error in this case.

   4) Review the cumulative pitch deviation charts to identify repeating patterns of pitch deviations that may cause excessive noise. The deviations may be within tolerance but still cause excessive noise and vibration in service. Possible causes of repeating pitch deviation patterns include multi-start hob errors, spindle drive errors or grinding wheel dressing errors.

10.3 Recognition of common manufacturing errors

10.3.1 General

The following examples illustrate common manufacturing errors and discuss the potential causes of error both from manufacturing and measuring processes. The results are from measurements taken on actual gears and thus, they are typical of what is seen in a production environment.

10.3.2 Example of a profile with pressure angle deviation

Examination of the left and right flank profile deviations in Figure 47 shows a consistent error from root to tip indicating minus metal at the tip. The mean left flank profile slope deviation $f_{H\alpha m}$ is −23,1 µm and varies between −22,4 µm and −23,5 µm. The mean right flank profile slope deviation $f_{H\alpha m}$ is −24,4 µm and varies between −23,8 µm and −24,7 µm. Consistent profile errors indicate they are caused by a common error source. 14.3.1 provides a method to calculate the deviation in base diameter and pressure angle deviation from the mean deviation, $f_{H\alpha m}$.

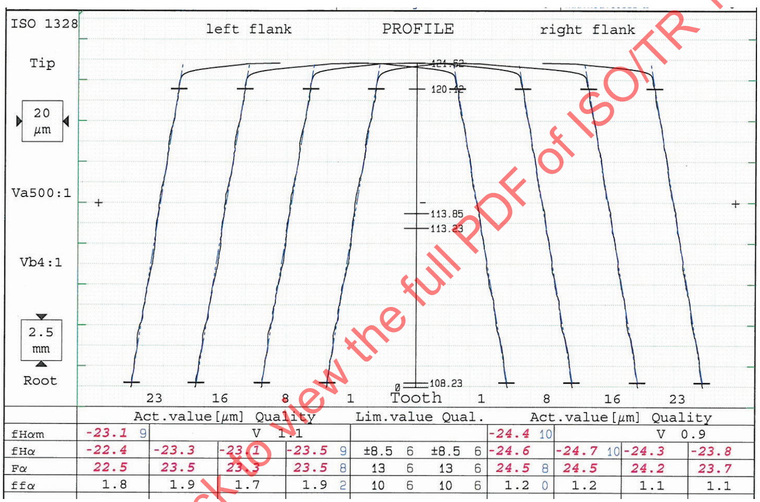
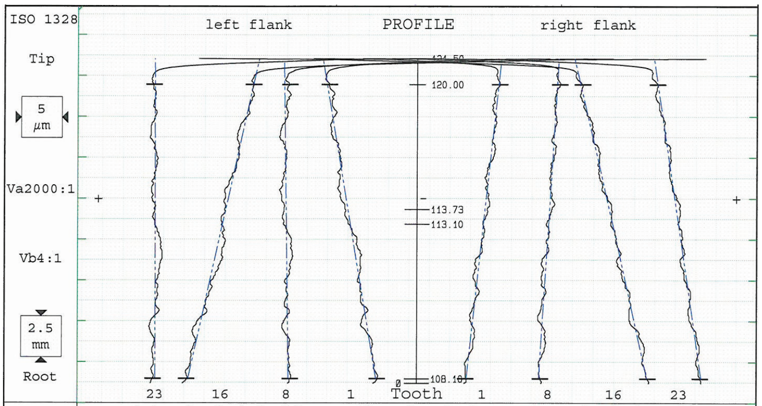


Figure 47 — Consistent profile slope deviations

The most likely cause is a tooling problem. For machine cut or ground gears, this could be an error in dressing the grinding wheel or hone. For hobbing or shaping processes, it could be caused by an error in cutting tool manufacture or an error when the tool is re-sharpened. In moulded gears, this could indicate an error in the mould cavity caused by the manufacturing process or shrinkage as the gear cools. Measurement errors can also cause this effect. Programming of measuring instruments with the wrong module or pressure angle or selecting the wrong size base disc on manual instruments will cause these errors. Temperature errors will also affect the profile slope deviations in this manner (see ISO/TR 10064-5 to quantify these effects).

10.3.3 Example of profile deviations with varying pressure angle deviation

Examination of the left flank profile deviations in Figure 48 shows a varying profile slope deviation between four teeth measured at 90° intervals. The mean left flank profile slope deviation $f_{H\alpha m}$ is −0,3 µm and varies between −7,9 µm and +6,1 µm. The mean right flank profile slope deviation $f_{H\alpha m}$ is −1,9 µm and varies between −8,2 µm and +3,9µm. The mean profile deviations are small and thus, the tooling errors and tooling runout are not the primary fault here. The deviations vary and thus, the most likely cause of the deviations is radial runout of the gear blank. The radial runout effect varies cyclically around the gear depending on the phase of the runout with respect to the four teeth samples randomly at 90° intervals. What cannot be established is whether the runout occurs from the measurement process or the manufacturing process. All that is clear is that there is a difference between the measurement axis and the manufacturing axis. Careful measurement and verification of runout of the datum axis will eliminate the measurement process from this. Note that radial runout or incorrect datum axis definition on measuring instruments has the same effect. With traditional mechanical base disc instruments, runout of the base disc has the same effect as radial runout of the gear, and thus this should also be checked.

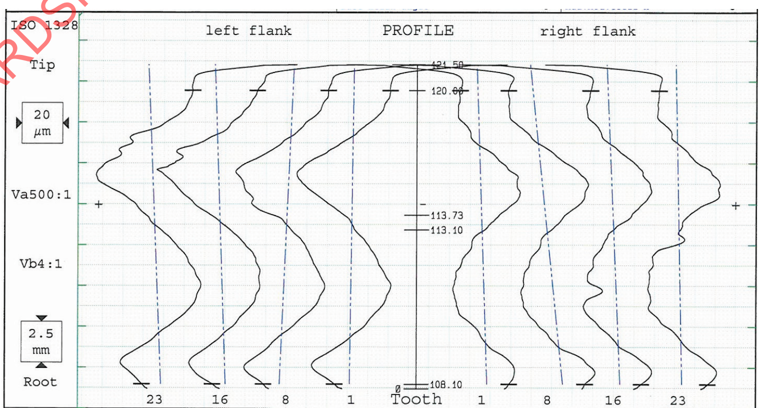


	Act.value [µm] Quality				Lim.value Qual.		Act.value [µm] Quality			
fHαm	-0.3 0	V 14.0					-1.9 2	V 12.1		
fHα	0.1	-7.9 6	0.6	6.1	±8.5 6	±8.5 6	3.9	2.2	-8.2 6	-5.4
Fα	1.7	8.2 5	1.7	6.1	13 6	13 6	4.2	2.6	8.3 5	5.6
ffα	1.7	1.8 1	1.6	1.6	10 6	10 6	1.1	1.2 0	1.2	1.1

Figure 48 — Example of varying profile slope deviation

10.3.4 Hob runout or shaping cutter deflection

Examination of the profile deviations in Figure 49 shows that the mean left flank profile slope deviation $f_{H\alpha m}$ is +0,8 µm and varies between +5,8 µm and −6,2 µm while the right flank mean $f_{H\alpha m}$ is −7,3 µm and varies between −3,2 µm and +15 µm. The form of these deviations is consistent between left and right flanks and is the predominant deviation. The deviation is the same for four teeth measured at 90° intervals and thus, radial or axial blank runout is not contributing to this deviation. If the same deviation is present on all teeth, tooling related problems are the most likely cause. In this case, a hobbing process was used to make the gear. Errors in manufacturing the hob could cause this profile deviation and the cutting tool should be measured to verify that it is not at fault. However, an accurate cutting tool (hob) mounted with excessive radial runout can also cause these deviations. Note that differences between left and right flank deviations generally result from the combination of the hob (axial and radial) runout deviations that are resolved differently because of the pressure angle of the tool flanks. Other causes of this type of deviation include variations in elastic deflection of the hob shaft during the cutting process. Shaping cutters may also show this type of form deviation due to variation in deflection of the cutter shaft.



	Act.value [µm] Quality				Lim.value Qual.		Act.value [µm] Quality			
fHαm	0.8 0	V 12.0					-7.3 6	V 11.8		
fHα	5.8	5.0	-6.2 6	-1.6	±8.5 6	±8.5 6	-4.8	-15.0 8	-6.3	-3.2
Fα	51.4 10	50.6	45.1	46.2	13 6	13 6	32.6	42.8 10	33.3	35.5
ffα	49.2	50.5 11	46.1	46.8	10 6	10 6	34.2	38.5 10	35.5	36.6

Figure 49 — Example of effect on profile of either hob radial runout or deflection of the hob arbor

10.3.5 Consistent mean helix slope deviation

Examination of the left and right flank helix deviations in Figure 50 shows a consistent slope deviation across the face width. The left flank shows plus metal at the end marked “top” on the deviation chart and the right flank shows minus metal at the same end. Deviations from a vertical straight line are deviations from the helix. The mean left flank helix slope deviation $f_{H\beta m}$ is −34,4 µm and varies between −32,1 µm and −36,1 µm over the four teeth spaced at 90° intervals. The mean right flank helix slope deviation $f_{H\beta m}$ is −35,2 µm and varies between −32,0 µm and −37,2 µm over the four teeth spaced at 90° intervals. The helix deviations are consistent, which indicates they are caused by a common error source at each tooth equally spaced at 90° intervals. 14.4.7 provides a method to calculate the deviation in helix angle from the mean slope deviation, $f_{H\beta m}$. The primary error is a consistent mean slope deviation but the small variation in slope is consistent with axial runout or wobble during manufacturing or measurement processes.

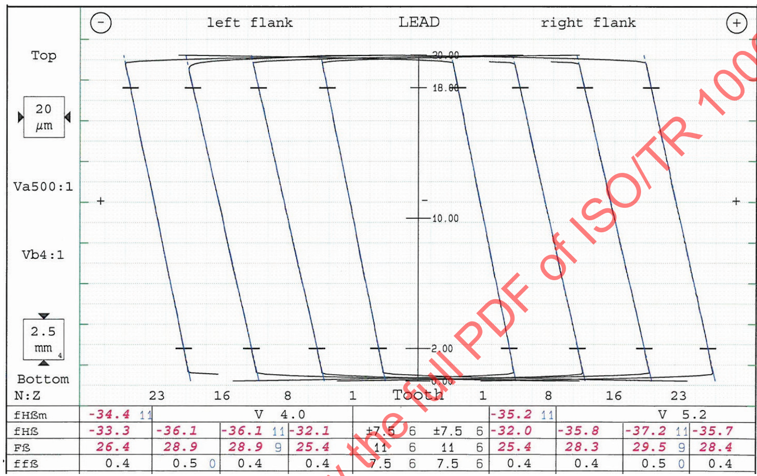


Figure 50 — Example of a helix deviation with consistent mean slope deviation

The mean helix deviation could be caused by an alignment error in the manufacturing machine tailstock, wrong helix programmed or a fundamental axis alignment error. Helix deviations can also be caused by temperature deviations (see ISO/TR 10064-5 to quantify temperature effects). Measuring machine alignment errors, helix specified or temperature effects during measurement can have similar effects. The risk of these occurring is minimized by routine alignment tests and the use of calibrated artefacts to verify measuring machine performance.

10.3.6 Helix slope variation

Examination of the left and right flank helix deviations in Figure 51 shows clear variation in helix slope deviation of around 19 µm (left flank) and 16,4 µm (right flank) over four teeth spaced at 90° intervals. The mean helix deviations are very low, around 2 µm. The primary error is the variation in slope deviation and is commonly caused by axial runout (sometimes called swash error) during either the manufacture or measurement processes. This can also be caused by radial runout in helical gears because of the different angular position of the tooth across the face width. Careful control of radial runout in the measurement process will minimize the risk of this occurring during measurement, but the selection of the wrong datum surfaces for defining the measuring datum axis will cause similar deviations. Again, it is the variation in results which show this is caused by blank mounting errors.

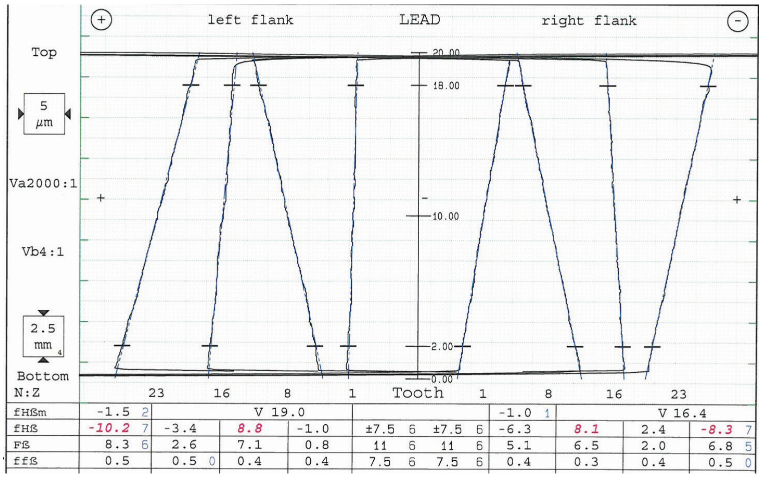


Figure 51 — Variation in helix deviation

10.3.7 Profile control diameter not achieved

Figure 52 is an example of where the gear teeth have not fully cleaned up in the root of the right flank. The right flank profile deviations show that neither the profile control diameter nor the SAP has been achieved during finish grinding. This could be due to the wrong hob or excessive protuberance on the cutter or due to uneven stock removal from each flank after heat treatment. The key point is that the profile deviations are consistent on four teeth spaced at 90° intervals (both left and right flanks) and thus, the cause is likely to be a set-up or tooling error.

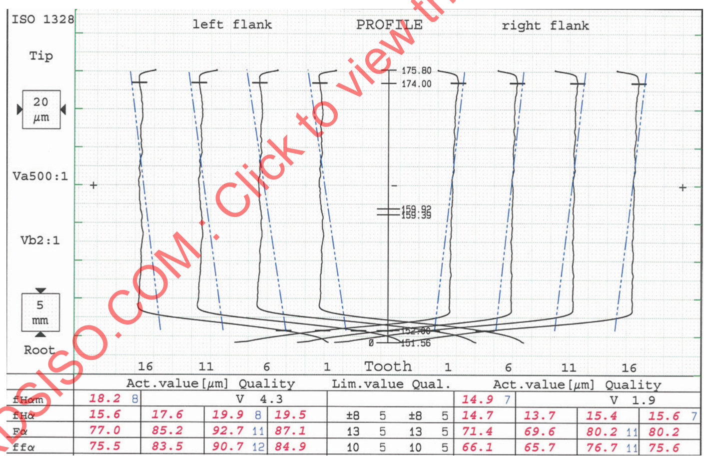
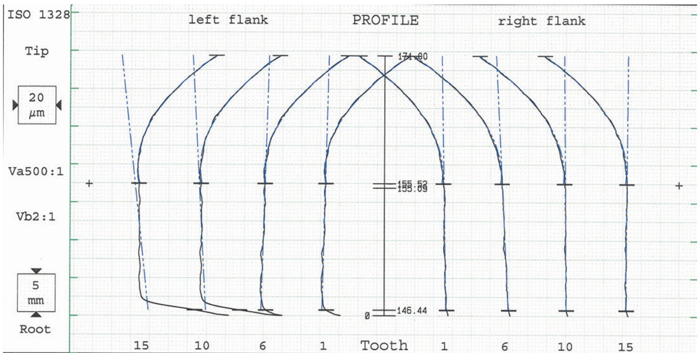


Figure 52 — Non-clean up during grinding processes

10.3.8 Variation in profile non-clean up and profile control diameter not achieved

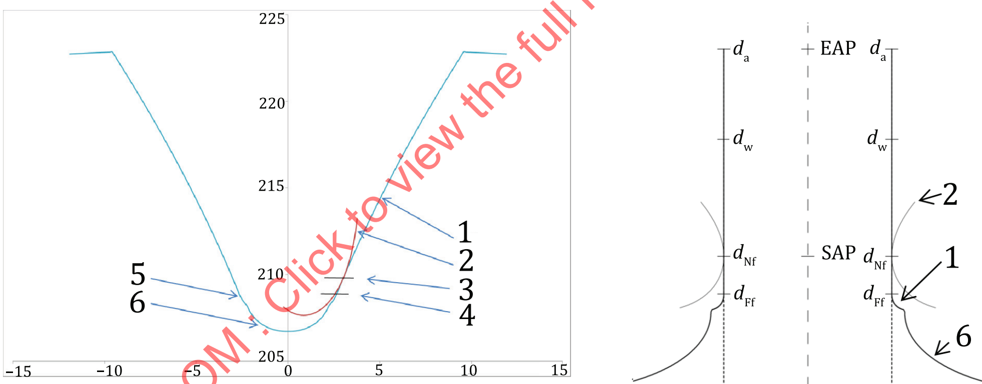
Figure 53 shows flank clean up variation for profile on the left flank. Teeth 1 and 6 meet the control diameter requirements. Teeth 10 and 15 do not and are out of specification. Observe that the flank trace below the profile control diameter shows variation in metal condition. This variation indicates a difference in mounting error between hobbing and grinding operations. In addition, the right flanks have all met the profile control diameter requirements (cleaned up). They show no variation in metal condition below the profile control diameter. This indicates uneven stock division at the start of the grinding process as well as excessive errors in mounting between operations.



	Act.value [µm] Quality				Lim.value Qual.		Act.value [µm] Quality			
fHαm	1.7 1	V 9.1					-1.1 0	V 3.9		
fHα	7.0 5	3.5	-2.1	-1.7	±8 5	±8 5	-1.2	-3.3 3	-0.6	0.6
Fα	29.6 8	21.1	2.9	2.7	13 5	13 5	1.9	3.7 2	1.1	1.2
ffα	27.8 8	20.3	3.6	3.3	10 5	10 5	1.2	1.3 0	0.8	1.0
fKo	-50.1	-46.1	-41.7	-42.8	-45±5	-45±5	-44.0	-43.9	-45.2	-44.2
R/T-φ [mm]	132.707						171.045			

Figure 53 — Variation in start of involute caused by radial runout, uneven stock

Figures 54 and 55 present a tooth contour manufactured without protuberance and ground on the flank only. In this case, consideration should be given to the tip curve of the mating gear. The grinding process should ensure sufficient distance between the mating gear tip curve and the tooth contour (see Figure 54). There, the generated length of involute is sufficient and the mating gear tip curve has no interference with the tooth contour.



a) Tooth profile

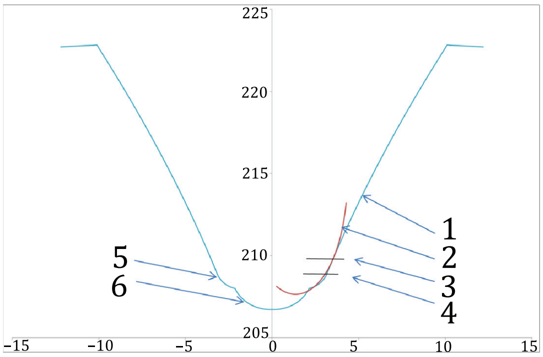
b) Profile chart

Key

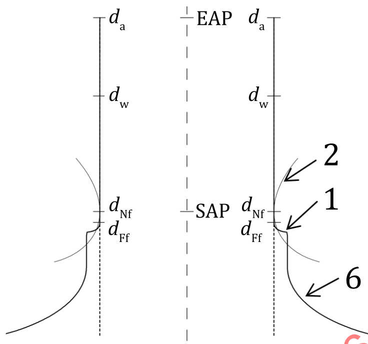
1 tooth contour
2 mating gear tip trace
3 start of active profile
4 start of involute
5 grinding fillet
6 root fillet

Figure 54 — Tooth profile that has no interference with mating gear tip trace

If the distance between mating gear tip curve and tooth contour is not sufficient, interference during mesh will occur (see Figure 55). There, the mating gear tip curve has interference with the tooth contour after grinding, although the generated length of involute is sufficient for the active profile. Those conditions will lead to noise excitations.



a) Tooth profile



b) Profile chart

Key

1 tooth contour
2 mating gear tip trace
3 start of active profile
4 start of involute
5 grinding fillet
6 root fillet

Figure 55 — Tooth profile with interference of mating gear tip trace

10.3.9 Pitch results with radial runout of the gear blank

When an otherwise perfect gear has an eccentric bore, as in Figure 46, and it rotates about the axis of the bore, the radial runout, F_r, will approximately equal 2 f_e. Eccentricity causes single pitch deviations around the circumference of the gear with a maximum value of f_{pt} = 2 f_e [sin (180°/z)/cos α_{Mt}]. The resulting cumulative pitch deviation also has a sinusoidal form, with a maximum value of F_p = 2 f_e/cos α_{Mt}. The angle between the maximum cumulative pitch deviation and the maximum radial runout is approximately 90° + α_t on the left flanks and 90° − α_t on the right flanks. Radial runout caused by eccentricity results in a variation in backlash and accelerations and decelerations due to pitch deviations.

The results in Figure 56 show the cumulative pitch results have a cyclic once per revolution sine wave characteristic which is commonly caused by radial runout. The deviation is identical whether runout occurs during the measurement process or when it occurs during the manufacturing process. Examination of the cumulative pitch deviations in 10.3.2 shows that the high points of the sine wave deviations are displaced by a phase angle of two times the transverse pressure angle, which in this case is approximately by 40°. The calculated radial runout plot confirms the runout.

10.3.10 Pitch with indexing deviations

Indexing deviations while form cutting, shaving or power honing teeth can create a gear in which all tooth spaces are of equal size, resulting in no runout, while substantial pitch and cumulative pitch deviations are present.

Results in Figure 57 illustrate this. The large cumulative pitch deviation sine wave peaks on left and right flanks are in phase and thus, the deviations cannot be caused by blank radial runout. This is confirmed by the radial runout deviations which are small. It may be caused by an indexing deviation of the rotary table drive. But it is also common in shaving and honing processes where the pitch deviations introduced during the hobbing process are not removed by the finishing process.

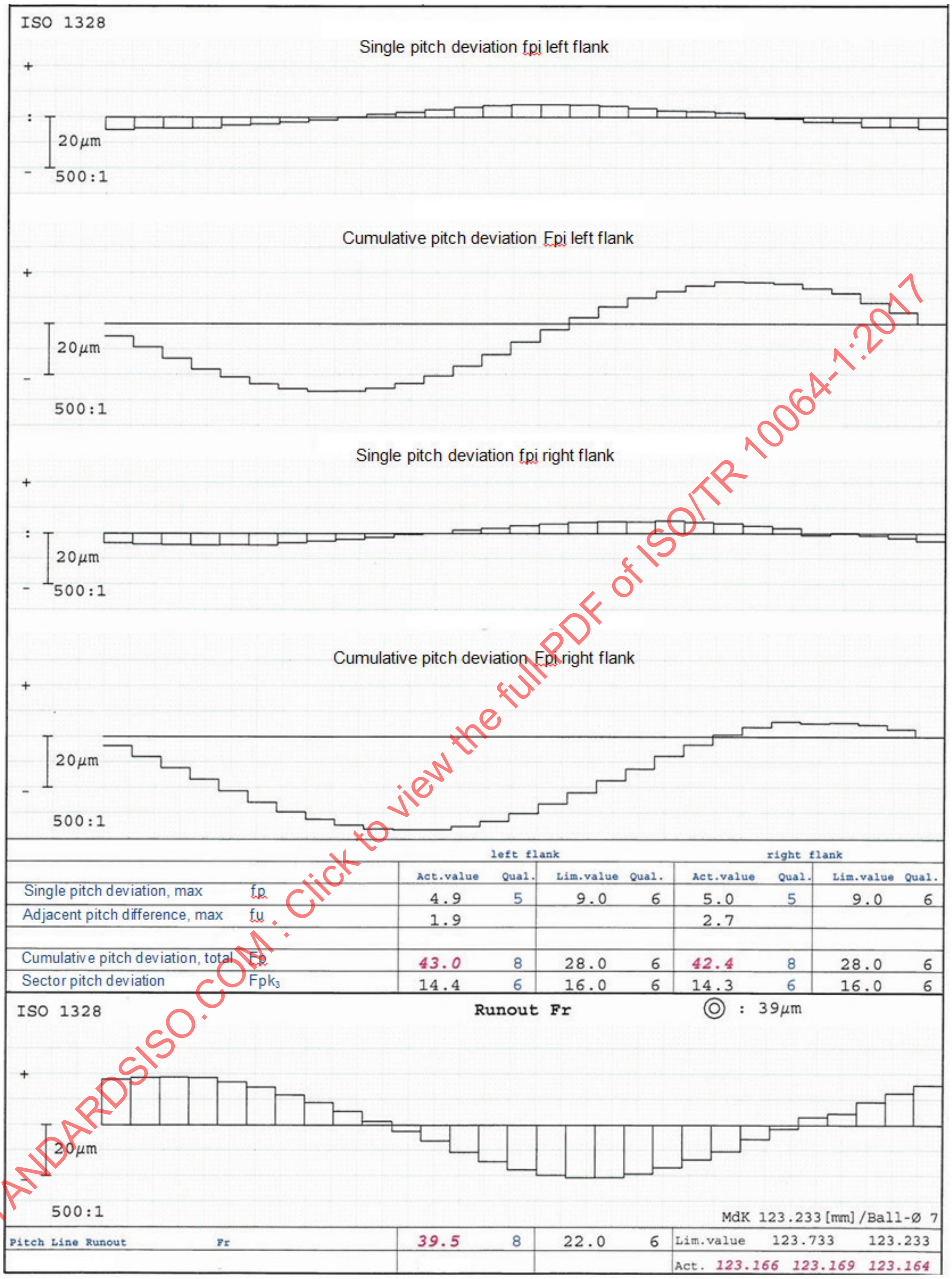


Figure 56 — Gear blank radial runout deviation and influence on adjacent cumulative pitch results

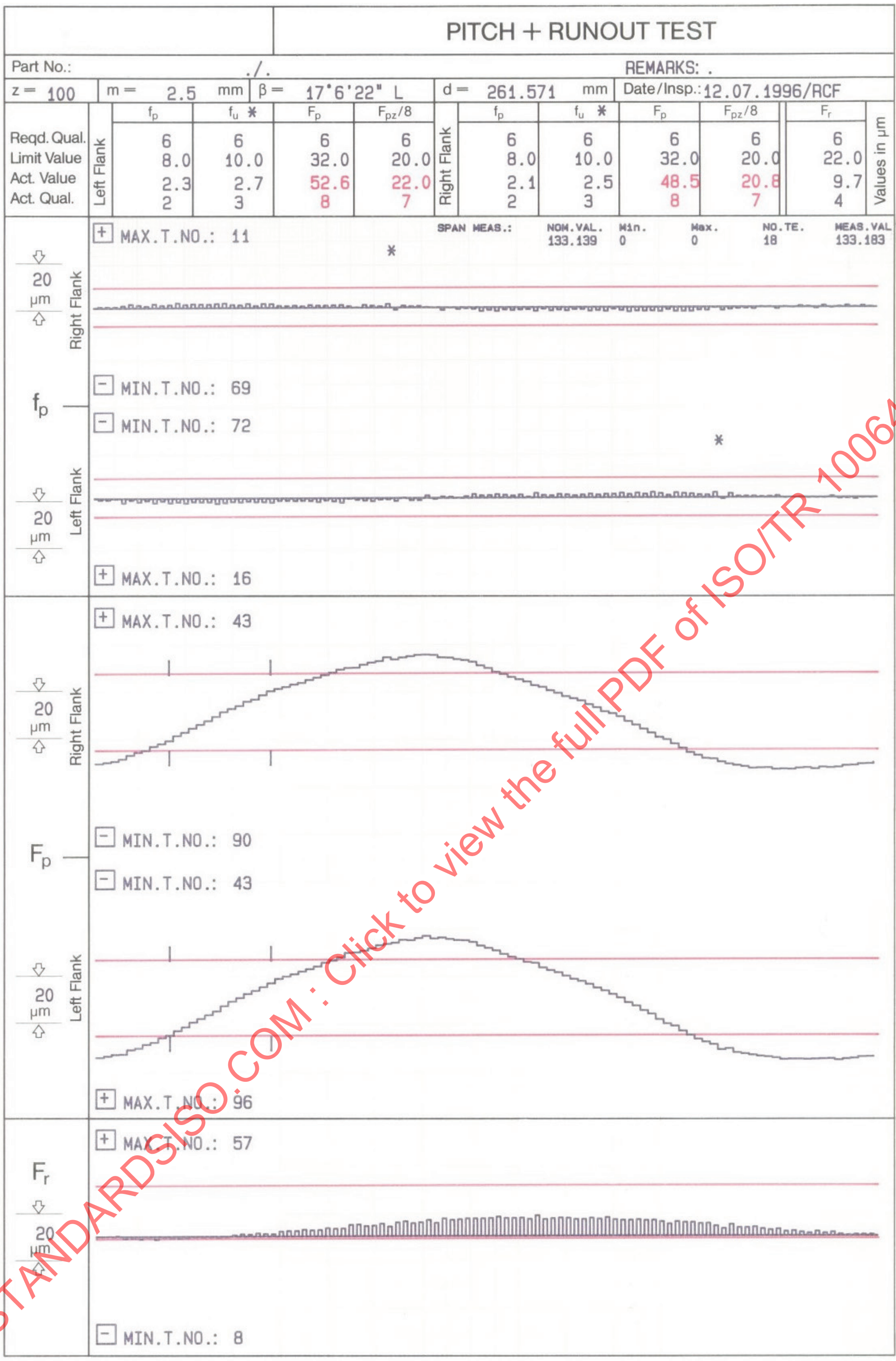
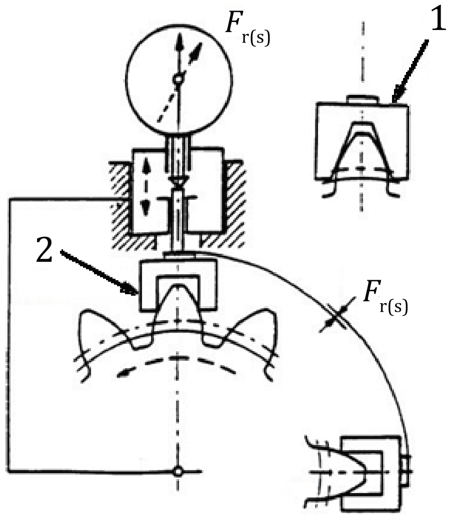


Figure 57 — Example of an indexing deviation on cumulative pitch and radial runout

To reveal this condition on the gear, a modified radial runout check can be applied using a "rider" as a probe (see Figure 58). The reason why this check detects the effect of the pitch deviations is that here, the pitch deviation results in tooth thickness deviations, which a rider indicates as a radial change when contacting both flanks. This type of gear measurement is not included in ISO 1328-1.



Key

1 rider type A

2 rider type B

Figure 58 — Measurement of radial runout of the teeth with a rider

10.3.11 Pitch with repeating deviation patterns that may cause noise

Figure 59 shows a repeating adjacent pitch deviation pattern that has occurred during manufacture. This type of deviation is likely to cause excessive noise and vibration in operation. Typical causes of these deviations are multi-start hobs with thread pitch deviations or deviations caused by the rotary table drives on machine tools.

11 Single flank composite testing

11.1 Single flank composite testing principle

Tangential (single flank) composite testing can provide valuable information about the transmission error of a gear, a pair of gears, or an entire gear train. Transmission error is the deviation of the position of a driven gear from the position that the driven gear would occupy if all the gears involved in the measurement were geometrically perfect. It should be noted that gears with modified flanks will show deviations during an unloaded single flank test that are different from the deviations that will exist when the gears are loaded.

Recorded diagrams of single flank composite measurements generally include short period components corresponding to successive cycles of tooth engagement, superposed on long period components associated with complete revolutions of each of the meshing gears.

ISO 1328-1 provides tolerances for two characteristics of transmission error (without applied load between the gear pair) for individual product gears measured with a master gear, total single flank composite deviation, F_{is}, and tooth-to-tooth single flank composite deviation, f_{is}.

The following is a description of the measuring methods and a guide to interpretation of the data generated during single flank measurement:

a) individual gears measured with a master gear;

b) a pair of product gears.

Single flank testing of more than a single mated pair of gears is the assessment of the kinematics of a gear transmission. This is not considered to be within the scope of this document or ISO 1328-1.

11.2 Single flank composite test

11.2.1 Single flank test setup

For measurement of single flank composite deviations, two gears are mounted, with backlash, at an appropriate centre distance. Contact should occur only on one set of corresponding flanks. Rotating synchronously with each gear is a device capable of measuring angular motion; these are typically rotary optical encoders (gratings and reader head assemblies), but may be rotary accelerometers or velocity transducers. If both flanks are to be tested, two tests must be run.

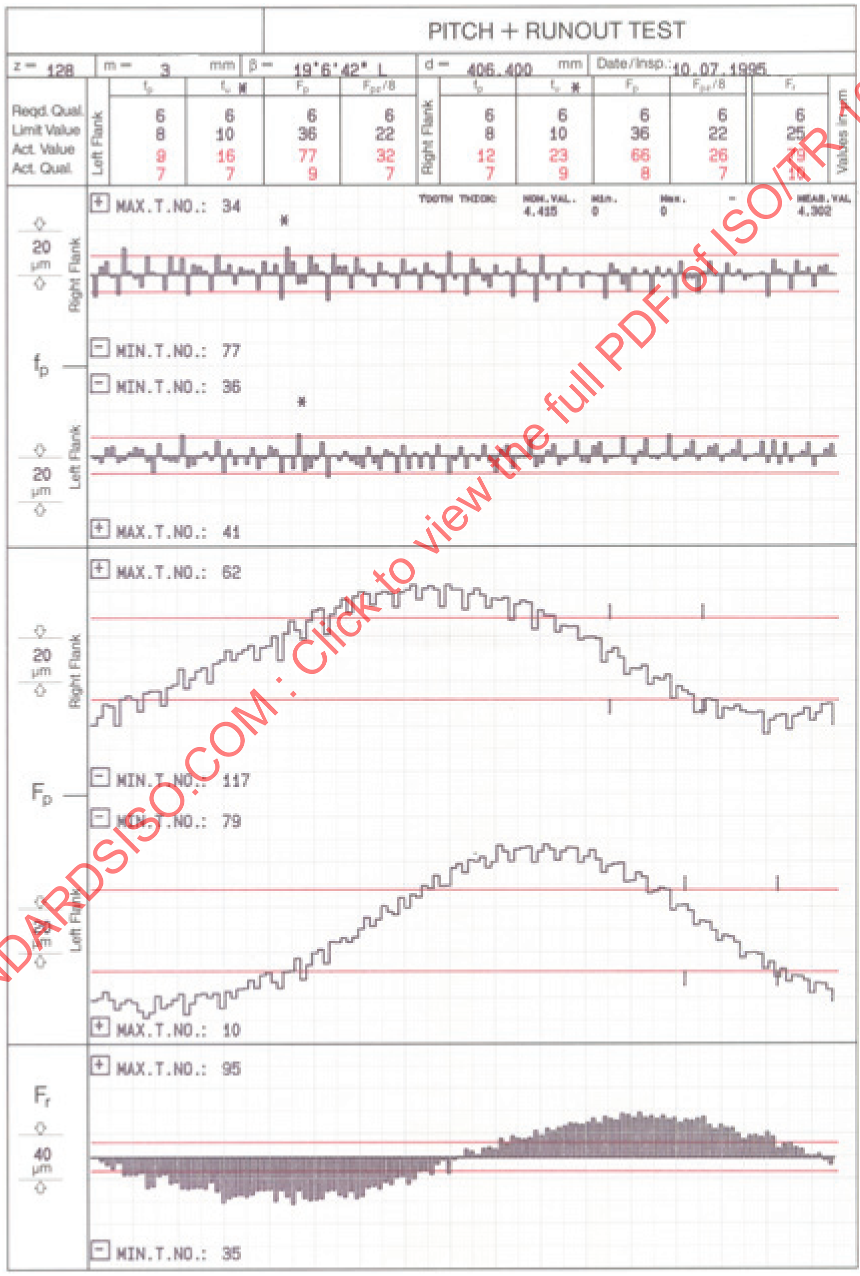
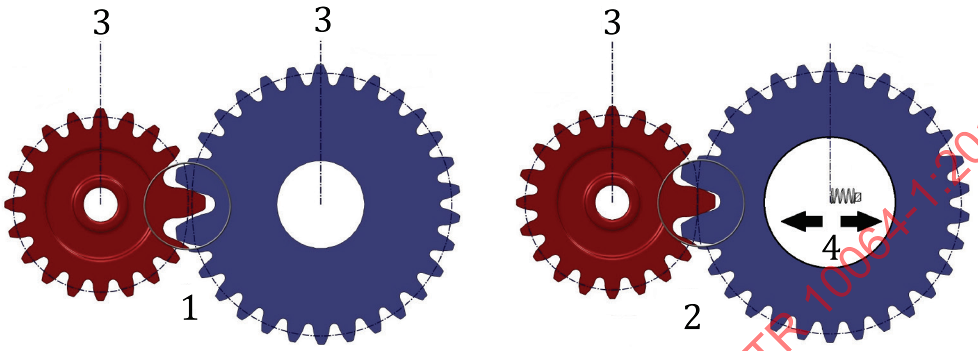


Figure 59 — Single and cumulative pitch deviations with repeating patterns

Figure 60 shows the principle of single flank testing and double flank testing. For single flank testing, the rotational movements are measured; for double flank testing, the centre distance variation is measured. A schematic of a single flank measuring device is presented in Figure 61.

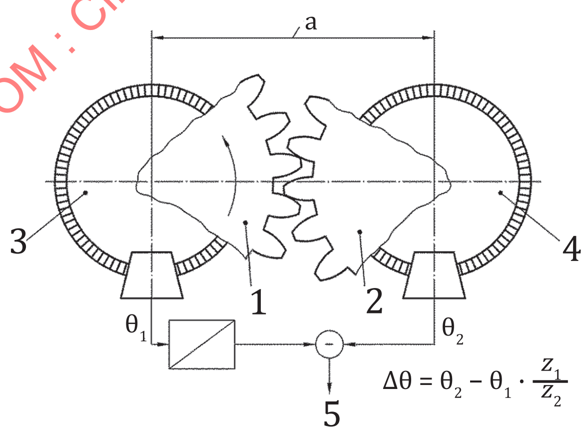


Key

1 single flank test (with backlash)
2 double flank test (no backlash)
3 fixed position
4 floating (movable) centre

NOTE Meshing teeth enlarged for clarity.

Figure 60 — Principle of single flank and double flank composite gear testing



Key

1 driving (master) gear
2 driven (product) gear
3 rotary encoder of driving gear
4 rotary encoder of driven gear
5 calculation of transmission error
a Fixed centre distance.

Figure 61 — Schematic of a single flank measuring device

Single flank composite measurements are performed with tooth flank contact maintained, under very light load, and with low angular velocities. During measurement, one gear acts as the driver, rotating the other gear. During rotation, the angular positions of the driven gear relative to the driver are measured, taking the ratio of the number of teeth into account. The angular deviations from nominal are recorded either on a strip chart or into digital storage on a computer for one complete revolution of the product gear being measured. See 11.4 for single flank measurement of product gear pair. The results generated reflect the combined elemental deviations (profile, helix, pitch) of both gears. To compare the angular readings to the tolerances provided in ISO 1328-1, they should first be converted to linear values at the measurement diameter specified. If no measurement diameter is specified, the conversion should be done at the reference diameter.

Before starting the single flank composite measurement, it is very important that:

— the spindle runout is minimized;

— the tooth flanks have been adequately cleaned;

— the gears are properly aligned and set up with minimum eccentricity to the spindle axis.

Tangential composite deviations of heavily loaded gears can also similarly be checked when a suitable rig is available. Under these conditions, recorded deviations are influenced by load induced tooth deformations, by mesh stiffness variation, and, depending on the speed of rotation, by impact effects, as well as by imperfections of tooth geometry. The loaded test will also include effects from the bearings and housing deformations resulting from load. Tolerances for measurement under load are not covered by ISO 1328-1.

11.2.2 Single flank composite deviations

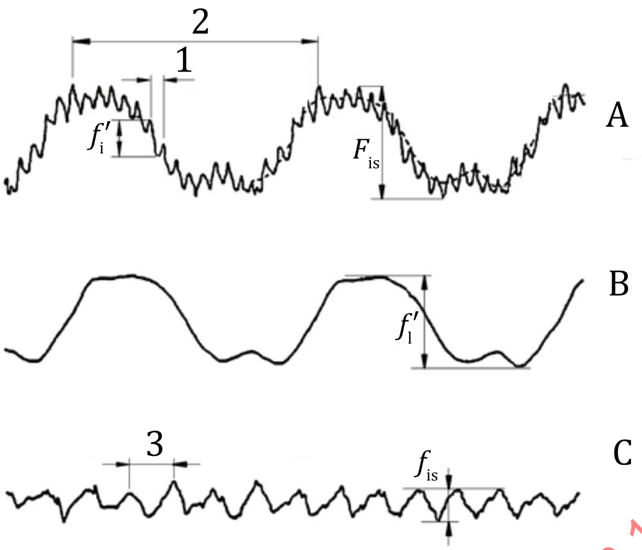
Total single flank composite deviation, F_{is}, is the maximum measured transmission error range when the gear wheel is moved through one complete revolution. See Figure 62, Key A.

Tooth-to-tooth single flank composite deviation with long term component removed, f_{is}, is the value of the greatest measured transmission error over any one pitch (360°/z) after removal of the long term component (low pass filter) when the gear is moved through one complete revolution. See Figure 62, Key C.

The long term component may be found by using a moving average (rectangular filter) with a window length equal to 10 % of the number of teeth. This has been found to be generally applicable to all size gears.

The variance of the long period component over one complete revolution achieved by using a low pass filter is described by parameter f_l'. See Figure 62, Key B.

Tooth-to-tooth single flank composite deviation before removal of long term component, f_i', is the value of the greatest measured transmission error over any one pitch (360°/z) without removal of the long term component when the gear is moved through one complete revolution. See Figure 62, Key A.



Key

1 single pitch of tooth meshing
2 one wheel revolution
3 single pitch of tooth meshing
A total signal of tangential composite deviation
B long period component obtained by using a low pass filter
C short period component obtained by subtracting low pass curve

Figure 62 — Single flank composite diagram with long period and short period deviation components

11.3 Single flank measurement with master gear

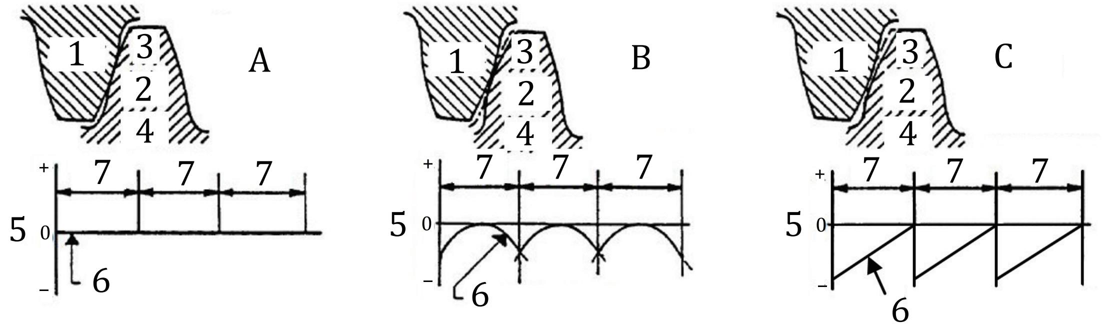
11.3.1 Master gear requirements

For single flank measurement of individual product gears, a master gear of known accuracy (calibrated) and specifically designed to mesh with the product gear to be inspected should be used. Attention should be paid to the fact that the tolerance class of the master gear will influence the measurement of product gears. However, when the flank tolerance class of the master is at least four classes better than the required class of the product gear, inaccuracies of the master are often ignored.

11.3.2 Influence of profile deviations

The assumption that the master gear is perfectly accurate implies that the generated single flank composite deviation diagram represents only the combined deviations of the tooth elements of the product gear.

Figure 63 shows schematically single flank composite recordings of three consecutive cycles of tooth engagement of a master gear and product gear. Each corresponds to a different tooth profile. The first is unmodified and faultless, the second being progressively modified from mid-depth towards each limit of the active profile (barrelling), and the third with negative profile slope deviation (modified pressure angle).



Key

1 master gear
2 product gear
3 tip
4 root
5 angular displacement
6 angular motion curve
7 one angular pitch
A perfect conjugate tooth shape
B modified tooth shape (profile with barrelling)
C modified tooth shape (modified pressure angle)

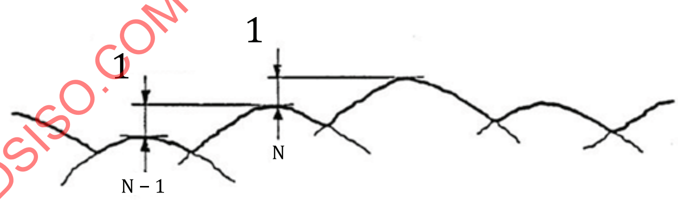
Figure 63 — Angular motion curves from tooth modification

It should be noted that diagrams of single flank composite measurements do not merely reflect influences of profile deviations revealed by individual measurements made on a few teeth, but may be influenced by contact with excess material on the working surfaces of the teeth of the product gear. On helical gears, axial overlap may significantly influence results (see 11.3.4).

11.3.3 Influence of pitch deviations

Each single pitch deviation introduces a local tangential component, which will show on the single flank composite diagram as a displacement of the corresponding profile generated component of the diagram.

The schematic diagram in Figure 64 illustrates the influence of single pitch deviations, f_{pt}, on the single flank composite diagram. While single pitch error can increase the tooth-to-tooth deviations as shown in Figure 64, it generally is not possible to determine the single pitch error from single flank results.



Key

1 single pitch component

Figure 64 — Influence of single pitch deviation diagram of a spur gear

11.3.4 Influence of helix deviations

11.3.4.1 General

A helix slope deviation that is constant in magnitude and sign (i.e. is similar for every tooth) results in consistent localized contact in the mesh. This does not substantially influence the single flank composite deviations of spur gears. The single flank composite deviations of helical gears, however, may be adversely affected by a constant helix slope deviation. This is due to the different nature of the path of contact of helical gears. This effect increases with overlap ratio if the overlap ratio is greater than one.

When helix slope deviations vary in magnitude and/or sign around a product gear, the contact location will vary around the gear. This condition may adversely affect single flank composite deviations of both spur and helical gears.

11.3.4.2 Spur gears

A single flank composite deviation diagram generated from a master gear and product gear combination is composed of successive curves representing for the most part the profile deviations, as shown in Figure 65. The traces at the top of this figure represent those of a test with a perfect master gear. Single-pair and two-pair tooth engagements and the single flank composite deviation diagram during a complete cycle of tooth engagement are clearly illustrated. It can easily be recognized that the maximum length of the single-pair tooth contact path is realized when the contact ratio, ε_γ, is equal to one. As the contact ratio increases, this length reduces and when the contact ratio is equal to or greater than two, there is no single-pair tooth contact at all.

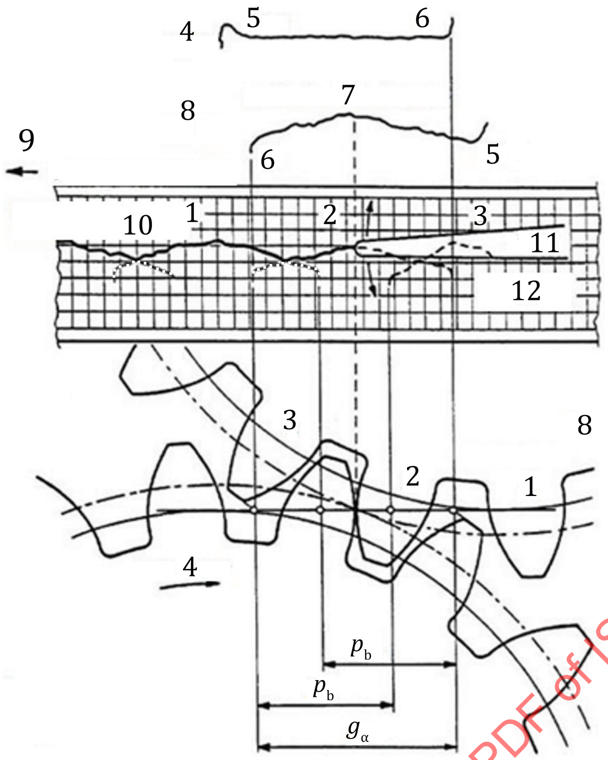
In order to derive the maximum amount of useful data, the teeth of the master gear should be made as deep as is consistent with adequate tooth tip width. This enables checks to be made at extended centre distance such that the contact ratio is unity and other checks to be made with the centre distance so adjusted that the “in-service” working flanks are fully explored.

11.3.4.3 Helical gears

When the total contact ratio, ε_γ, is less than two, the meshing conditions for a helical gear are similar to those of a spur gear with a contact ratio, ε_α, less than two, in which case, all of the above comments concerning spur gears apply equally to such a helical gear.

When the total contact ratio, ε_γ, exceeds two, which is normally the case for helical gears, the short period components which represent profile irregularities are smoothed to some extent because in general, simultaneous contact takes place on two or more tooth pairs.

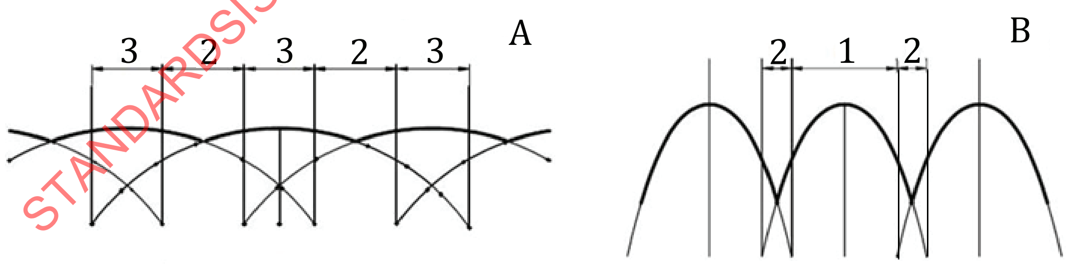
Diagrams in Figure 66 with the two cases “A” (generated from helical gears) and “B” (from spur gears) illustrate the difference between the ways in which the influence of the overlapping teeth of the two types combine.



Key

1	tooth number
2	tooth number
3	tooth number
4	master gear
5	root
6	tip
7	profile deviation diagrams
8	product gear
9	direction of paper feed
10	tangential composite deviation
11	stylus
12	profile component
p_b	base pitch
$g_α$	length of path of contact

Figure 65 — Effect of contact transfer on the profile component in a tangential composite deviation diagram (spur gears)



Key

1, 2, 3	number of tooth pairs in mesh
A	diagram for helical gears
B	diagram for spur gears

Figure 66 — Influence of overlap ratio

11.4 Single flank measurement of product gear pair

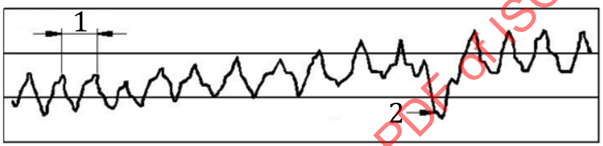
11.4.1 Differences between tests with a master gear and between two product gears

The single flank tooth-to-tooth and total composite deviations involving a mated pair of product gears are termed "transmission deviations of a gear pair". To fully explore the complete spectrum of the deviations, it is necessary to continue rotation until the complete meshing period of both gears has been explored. The number of revolutions of the smaller gear that is required corresponds to the number of teeth in the larger member divided by the largest factor common to both members.

Analysis is similar to that described in 11.3 for a product gear with a master gear, except that the deviations should be calculated based on the complete meshing period of both gears rather than on a single revolution of the product gear. See ISO 1328-1:2013, Figure F.2.

11.4.2 Identification and location of defects

The measurement of tangential composite deviations facilitates the identification and location of defects (nicks or burrs) which may degrade the smoothness of transmission. For example, as indicated in the diagram in Figure 67, the presence of a defective tooth can readily be seen.



Key

1 one pitch

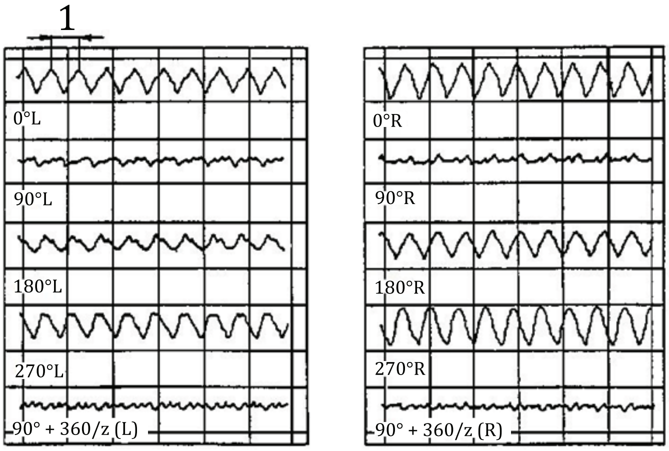
2 damaged tooth

Figure 67 — Part of tangential composite deviation diagram — Interpretation example

11.4.3 Selective meshing of gears

In some exceptional cases involving mated pairs of gears with equal numbers of teeth or other integer ratios, special steps can be taken to ensure that optimum performance is realized. Such gears can be meshed to best advantage by re-meshing the gears with a phase shift of 90° to find the quadrant in which single flank composite deviations are smallest. Following this, the process is repeated by re-meshing the gears with phase shifts less than 90° in order to find the optimum meshing phase.

In Figure 68, diagrams are shown which were generated from a pair of gears at the different phases of mesh indicated. It is quite evident that the single flank composite deviation diagrams for the left flanks and right flanks are not the same. It may be necessary to choose an intermediate meshing position that provides the best compromise solution if a high degree of transmission accuracy is needed for both directions of rotation.



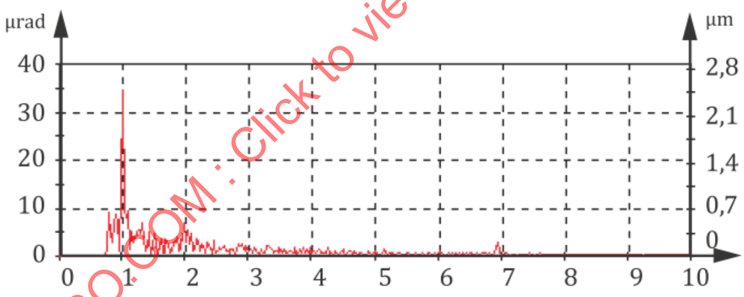
Key

1 one gear revolution

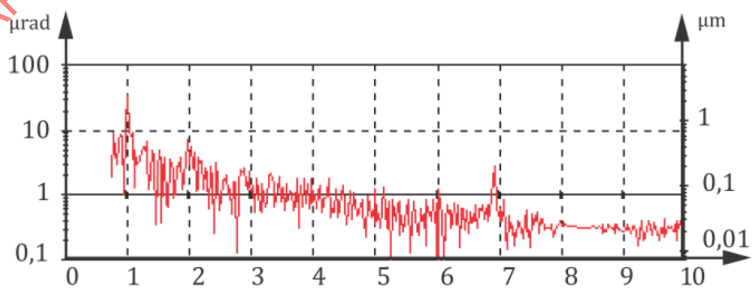
Figure 68 — Tangential composite deviation diagrams showing influence of mesh relocation

11.5 Data analysis by the Fourier transform method

Composite deviations are mainly used to evaluate the gear tolerance class. However, it may be desirable to carry out additional analysis for diagnostic purposes, such as noise potential or manufacturing process monitoring. In such cases, more comprehensive data analysis is necessary. Figure 69 shows the Fourier transformed deviations. The amplitude is drawn against the harmonic numbers "n". Sharp peaks can be seen at the mesh frequency and the second order mesh frequency.



a) Order of tooth mesh frequency (linear scale for amplitude)



b) Order of tooth mesh frequency (log scale for amplitude)

Figure 69 — Fourier transformed single flank composite deviations

It should be borne in mind that gear noise and vibration spectra may include significant components at one or more of the sub- and higher harmonics of the tooth meshing frequency.