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Geometrical product specifications (GPS) — Decomposition of geometrical characteristics for manufacturing control

Spécification géométrique des produits (GPS) — Décomposition des caractéristiques géométriques pour la maîtrise de la fabrication

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Foreword

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This document was prepared by Technical Committee ISO/TC 213, *Dimensional and geometrical product specifications and verification*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document is a geometrical product specifications (GPS) standard and is to be regarded as a fundamental GPS standard (see ISO 14638). It influences indirectly chain link E of the chains of standards of geometrical characteristic (size, distance, form, orientation, location and run-out) in the general GPS matrix model as graphically illustrated in Table A.1. The measurement as given in chain link E is decomposed to evaluate quantity values of a geometrical characteristic, and to define manufacturing adjustment values, not to manage the conformance of a workpiece.

The ISO GPS matrix model given in ISO 14638 gives an overview of the ISO GPS system of which this document is a part. The fundamental rules of ISO GPS given in ISO 8015 apply to this document and the default decision rules given in ISO 14253-1 apply to specifications made in accordance with this document, unless otherwise indicated.

For more detailed information on the relationship of this document to other standards and to the GPS matrix model, see Annex A.

The geometrical specification, as defined in ISO 1101, allows the evaluation of conformance or non-conformance by defining a limit value for a geometrical characteristic as a univariate characteristic (non-signed value). This evaluation alone does not provide the information necessary to adjust machine tools parameters to maintain the production of conforming workpieces. The goal of decomposition of the measurement result is to isolate parameter values that can be used to adjust the manufacturing process. This document uses simple examples to illustrate the fundamental principles.

This document defines a number of independent characteristics obtained by decomposition that are intended to assist with adjusting and evaluating the manufacturing process.

In statistical analysis the mean value and standard deviation are used to calculate capability indices. In the case of a position tolerance, for example the location of a hole, which applies in a plane perpendicular to the axis of the hole, the position characteristic is two times the radial distance between the centre of the hole and its theoretically exact location. Capability indices based on the mean value and standard deviation of this characteristic do not properly reflect the capability of a manufacturing process. Instead, the position characteristic could be decomposed according to the kinematic arrangement of the manufacturing process. If the axis of the hole is manufactured using a machine with linear X- and Y-axes, the position characteristic could be decomposed into an X-component and a Y-component and the studies of capability could be calculated based on these components so that they properly reflect the capability of the manufacturing process.

Geometrical product specifications (GPS) — Decomposition of geometrical characteristics for manufacturing control

1 Scope

This document describes principles and tools to control a manufacturing process in accordance with a GPS specification. For this purpose a set of one or more complementary, independent characteristics (size, form, orientation, and location characteristics independent to each other) that correlate to the manufacturing process parameters and to the manufacturing process coordinate system established from the manufacturing datum system are used.

This document describes the concept of decomposition of the macro-geometrical part of the GPS specification. It does not cover the micro-geometry, i.e. surface texture.

The objective of the decomposition presented in this document is to define correction values for manufacturing control or to perform a statistical analysis of the process.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

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

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

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

3.1
univariate characteristic
characteristic represented by a single scalar variable

EXAMPLE   A global size characteristic is a univariate characteristic.

3.2
collected characteristic
C
set of a *univariate characteristic* (3.1) and the multivariate characteristic required to derive it (see 3.3)

EXAMPLE   For a position specification, the median line of a hole is constrained by a cylindrical tolerance zone with a diameter of 0,4 mm. The global univariate characteristic result is 0,5 mm (out of tolerance). The decomposition of the location in two directions (X, Y) at a given height is given by the multivariate characteristic result (+0,15; +0,2). The collected characteristic combines the global result and its decomposition.

			Result of evaluation mm
Collected characteristic	Univariate characteristic		0,5
	Observed deviation		0,25
	Multivariate deviations	X	+0,15
		Y	+0,2

Note 1 to entry: A collected characteristic is a set of more than one independent variable and the final result from this set of variables, e.g. C (A, G_F, G_S, G_O, R_X, R_Y, R_Z, G_L, T_X, T_Y, T_Z). See Table 1 for an example.

Note 2 to entry: A collected characteristic is a vector.

3.3
decomposition
<manufacturing> operation establishing a multivariate characteristic from a *univariate GPS characteristic* (3.1)

Note 1 to entry: The purpose of the decomposition for manufacturing is to define a multivariate characteristic that consists of a set of variables, each of which is related to a manufacturing process parameter (See 5.2).

3.4
location point
defined point on the reference feature used to locate a geometrical feature

3.5
real orientation vector
V_{AO}
unit vector defining the orientation of the extracted feature from the situation feature of the associated feature in a specified Cartesian system

3.6
nominal orientation vector
V_{TO}
unit vector defined from the situation feature of the nominal feature in a specified Cartesian system

3.7
angular deviation set
$V_{\Delta O}$
vector having components which are the angles defined in a specified Cartesian system allowing the transformation of the *real orientation vector* (3.5) into the *nominal orientation vector* (3.6)

3.8
actual location vector
V_{AL}
vector defining the location of the extracted feature from the origin of a specified Cartesian system to the *location point* (3.4) of the situation feature of the associated integral feature

3.9
theoretical location vector
V_{TL}
vector defined from the origin of a specified Cartesian system to a location point of a situation feature of the nominal geometrical feature (integral, or derived)

3.10
deviation location vector
$V_{\Delta L}$
vector defined as the difference between the actual location vector (3.8) and the theoretical location vector (3.9)

Note 1 to entry: The components of the deviation location vector defined on the X-axis, Y-axis, and Z-axis of the specified Cartesian system are designated as T_X, T_Y, T_Z.

4 Symbols

The list of symbols is given in Table 1.

Table 1 — Symbols

Symbol	Description
C	Generic symbol of a collected characteristic, which is a vector
A	Actual value of the specified GPS characteristic
O	Actual value of the orientation GPS characteristic
G_F	Independent form characteristic
G_S	Independent global size characteristic
G_O	Independent orientation characteristic, corresponding to the effect of the angular deviation (R_x, R_y, R_z) in length unit by considering the orientation deviation defined from the restricted associated feature
G_L	Independent location characteristic, corresponding to the effect of the linear deviation (T_x, T_y, T_z) considering the location deviation of the reference feature of the orientation characteristic from the theoretically exact location
V_{AO}	Real orientation vector for the extracted feature in the coordinate system
V_{TO}	Nominal orientation vector for the nominal feature in the coordinate system
$V_{\Delta O}$	Angular deviation set from the theoretically exact orientation in the coordinate system
V_{AL}	Actual location vector for a specific point defined from extracted feature in the coordinate system
V_{TL}	Theoretical location vector for a specific point defined on the nominal feature in the coordinate system
$V_{\Delta L}$	Deviation location vector from the theoretically exact location in the coordinate system
R_X, R_Y, R_Z	Rotation angle components around axes of the coordinate system
T_X, T_Y, T_Z	Components of $V_{\Delta L}$ which are the translation deviations from the theoretically exact location of the location point
NOTE A geometrical GPS characteristic is defined in ISO 25378 as a "zone characteristic".	

5 Principles

5.1 General

A GPS specification is a condition (a tolerance) applied on a univariate characteristic.

In particular for a geometrical tolerance, this characteristic can include several types of independent deviations (size, form, orientation and location) and other kinds of deviation parameters (angle deviations, location deviations). To control the manufacturing process, these deviations shall be separated. This document presents a way to perform this separation for a geometrical specification, giving inputs to corrections to manufacturing process parameters. The decomposition of a GPS characteristic yields the components of the collected characteristic. These shall be measurable quantities. These components can be independent GPS characteristics (form, size, orientation and location) or components from which rotation or translation parameters reflecting the kinematics of the manufacturing process can be derived.

Typically, the univariate characteristic of a GPS specification is defined from a set of distances between an input feature (the toleranced feature) and a reference feature or a set of sizes. This definition is the primary model of decomposition for the GPS specification, having these n distances as the independent variables. Therefore if the specification is verified on a feature using for example 1 000 points on the

surface, this primary model of decomposition would result in 1 000 distances. However, these 1 000 distances cannot be used directly for manufacturing process corrections.

Three geometrical features shall be distinguished in this kind of operation: the extracted feature, its associated feature and the situation feature of the associated feature.

5.2   Decomposition process

The first step of the decomposition is to define the default form GPS characteristic of the toleranced feature (integral or derived), G_F [see Figure 2 d), Figure 3 d) and Figure 4 d)]. If the associated features are established by another association criteria than the default criteria (minimax – Chebyshev) then it shall be stated in the report of results of decomposition.

NOTE   The curve variation of form deviation can itself be analysed by decomposition (e.g. by Fourier analysis or modal discrete decomposition). It is not the intent of this document to describe this process of form decomposition.

To separate the signed orientation and location parameters, a coordinate system, for example a Cartesian system or a polar system, shall be defined for manufacturing purpose from the datum system attached to the manufacturing process. If the specification datum system does not lock all degrees of freedom, it shall be complemented by a secondary datum and/or a tertiary datum defined from the workpiece interface surfaces with the manufacturing machine.

The orientation parameters (R_X, R_Y, R_Z) expressed by $V_{\Delta\text{O}}$, shall be given in angular units.

The form characteristic (G_F), the independent size characteristic (G_S), the independent orientation characteristic (G_O), the location parameters (T_X, T_Y, T_Z) and the independent location characteristic (G_L) shall be given in linear (length) unit.

The independent size characteristic, (G_S), only applies to features of size or to a non-feature of size on which an offset can be applied and which changes its nominal shape. For a feature of size, it is defined as the difference between the size of the direct associated integral feature and the nominal size. For a non-feature of size on which an offset can be applied, the size deviation parameter defines the observed offset from the nominal shape.

The direction vector of the form reference feature allows establishing the transfer angles (R_X, R_Y, R_Z) from the geometrical specification Cartesian system. The relation between the manufacturing Cartesian system and the geometrical specification Cartesian system is used to define the correction to the manufacturing process. To evaluate the independent characteristic, the restricted associated feature shall be established by projecting the extracted feature onto the form reference feature.

The orientation reference feature is defined from the restricted associated feature. The independent orientation characteristic, (G_O), is evaluated as an orientation characteristic established from the restricted associated feature (corresponding to the extracted feature, see Figure 2 e), Figure 3 e), and Figure 4 e). The independent orientation characteristic can be decomposed in three angles (R_X, R_Y, R_Z).
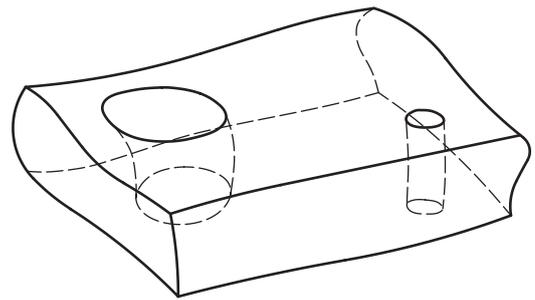
The independent location characteristic, (G_L), is the signed distance between the location reference feature and the orientation reference feature, at the location point (considered on the location reference feature). The independent location characteristic shall be described in the manufacturing Cartesian system. By default, it is the distance between the location point (belonging to the orientation reference feature) and its theoretical exact location (see Figure 4 f).

The independent location characteristic can be decomposed in three linear components (T_X, T_Y, T_Z).

Figure 1 a) presents a geometrical specification with datum system where the manufacturing datum system is considered identical to the specified datum system. Figure 1 b) illustrates the manufacturing result: the workpiece. Figures 1 c) to f) illustrate steps of the decomposition process of a specified geometrical characteristic.
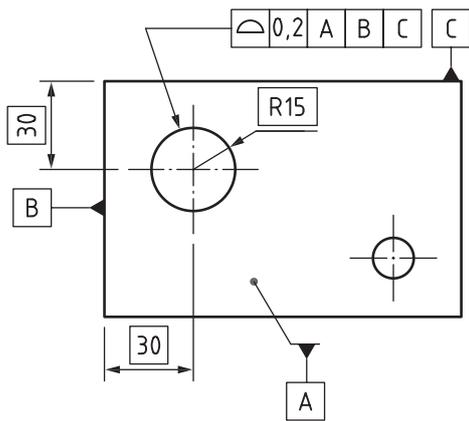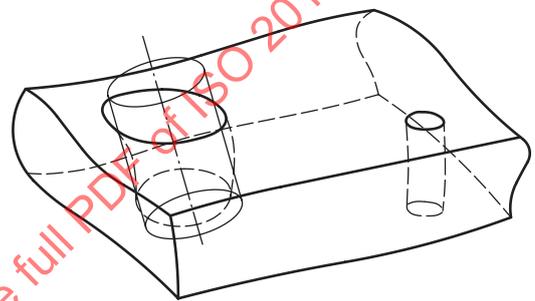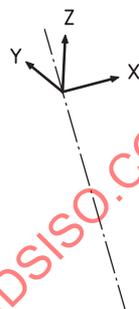
a) GPS specification

b) Workpiece
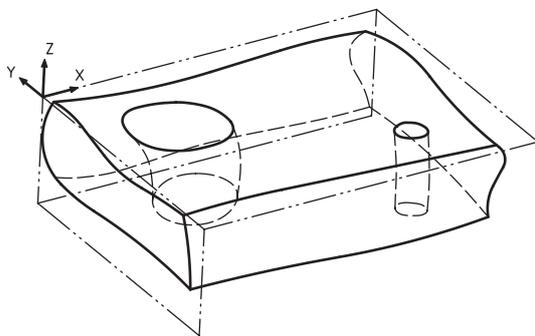
c) Step 1: datum system and Cartesian system (see Note 1)

d) Step 2: independent form and size characteristics (see Note 2)

e) Step 3: independent orientation characteristic (see Note 3)

f) Step 4: independent location characteristic (see Note 4)

NOTE 1   To determine the collected characteristic (see Table 4):

— the univariate characteristic is the result of the evaluation of GPS location specification.

— the multivariate characteristic is the result of the decomposition, i.e. the set of independent size, form, orientation, and location characteristic evaluations.

NOTE 2   After a first association, the evaluation of the size deviation parameter and of the form deviation is considered independently.

NOTE 3   The evaluation of the angular deviations is established from the situation feature of the previous associated feature from the datum A.

NOTE 4   The evaluation of the location deviations is established from the considered location point of the situation feature from the datum system A, B, C.

Figure 1 — Steps of manufacturing decomposition to geometrical specifications in macro geometry

Examples 1 to 3 and Figures 2 to 4 present and illustrate the components of collected characteristics for orientation specification or location specification.

EXAMPLE 1   A parallelism orientation characteristic applied in an intersection plane can be seen as a collected characteristic combining the form deviation and the angular deviation of the extracted integral line as shown in Figure 2, when it is assumed that the manufacturing fixture surface and datum feature K are the same.
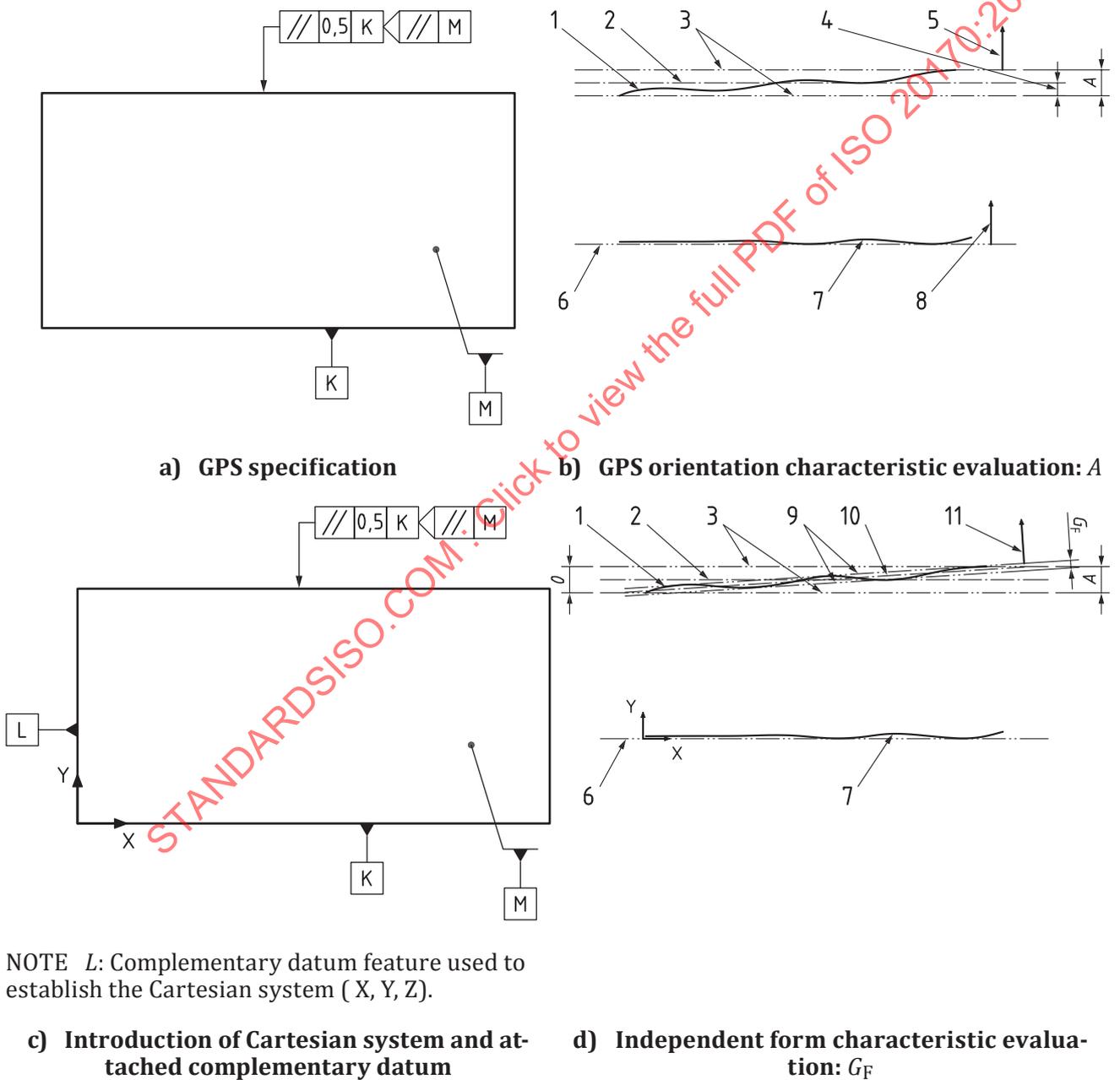
a) GPS specification   **b) GPS orientation characteristic evaluation:** A

NOTE L: Complementary datum feature used to establish the Cartesian system (X, Y, Z).

c) Introduction of Cartesian system and attached complementary datum   **d) Independent form characteristic evaluation:** G_F
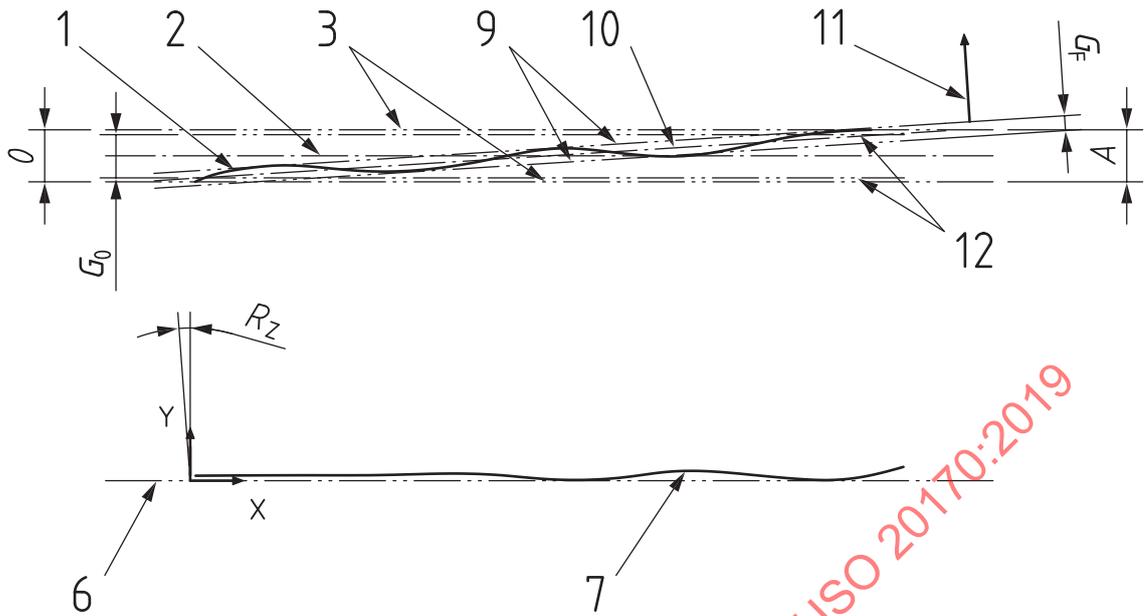
NOTE   In the case of orientation GPS characteristic, O is equal to A [distance between 3)].

e) Independent orientation characteristic: G_O [distance between 12)]

Key

|	
A	GPS characteristic of parallelism
O	actual value of orientation GPS characteristic (in this case $O = A$)
G_F	GPS characteristic of form
G_O	independent orientation characteristic
R_Z	angle deviation around Z-axis
1	toleranced feature: extracted integral surface
2	reference feature of 1) for orientation GPS characteristic which is the median feature of 3)
3	limits of minimum zone of orientation GPS characteristic with orientation constraint from 1)
4	maximum distance between 2) and 1)
5	normal vector from 2)
6	datum K
7	datum feature K
8	normal vector from 6)
9	limits of minimum zone for form
10	restricted associated feature, restricted by the projection of 1) on the median feature of 9) (reference feature for form GPS characteristic)
11	normal vector from 10)
12	limits of minimum zone of orientation GPS characteristic with orientation constraint for 10)

NOTE   The Cartesian coordinate system is established from a datum system.

Figure 2 — Illustration of decomposition of parallelism specification
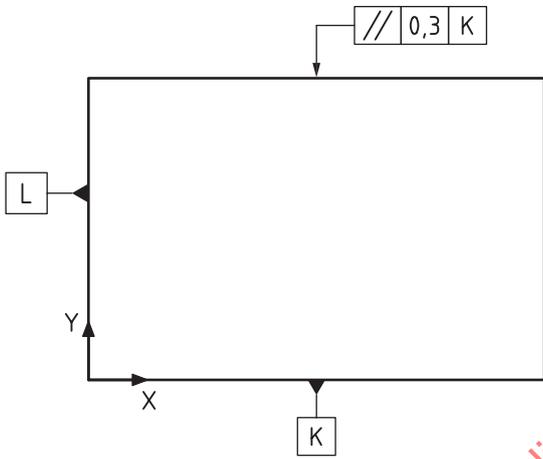
EXAMPLE 2   A parallelism orientation characteristic can be seen as a collected characteristic combining the form deviation and the angular deviation of the extracted integral surface as shown in Figure 3, when it is assumed that the manufacturing fixture surface and datum feature K are the same.
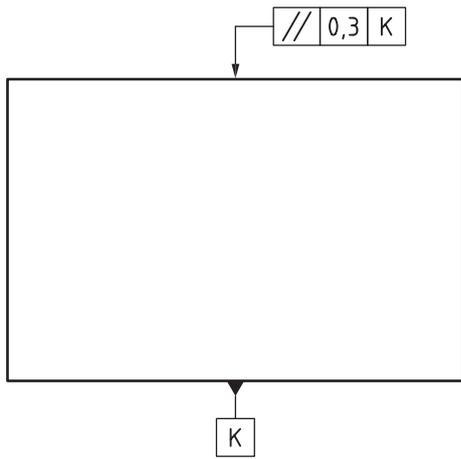
a) GPS specification
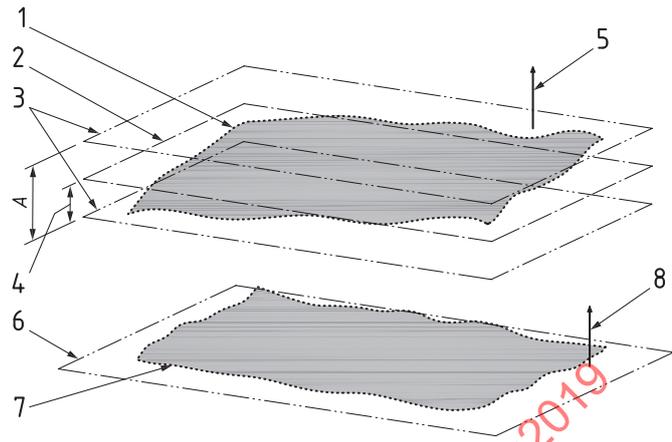
b) GPS orientation characteristic evaluation: A

NOTE L: Complementary datum feature used to establish the Cartesian system (X, Y, Z).

c) Introduction of Cartesian system and attached complementary datum

d) Independent form characteristic evaluation: G_F
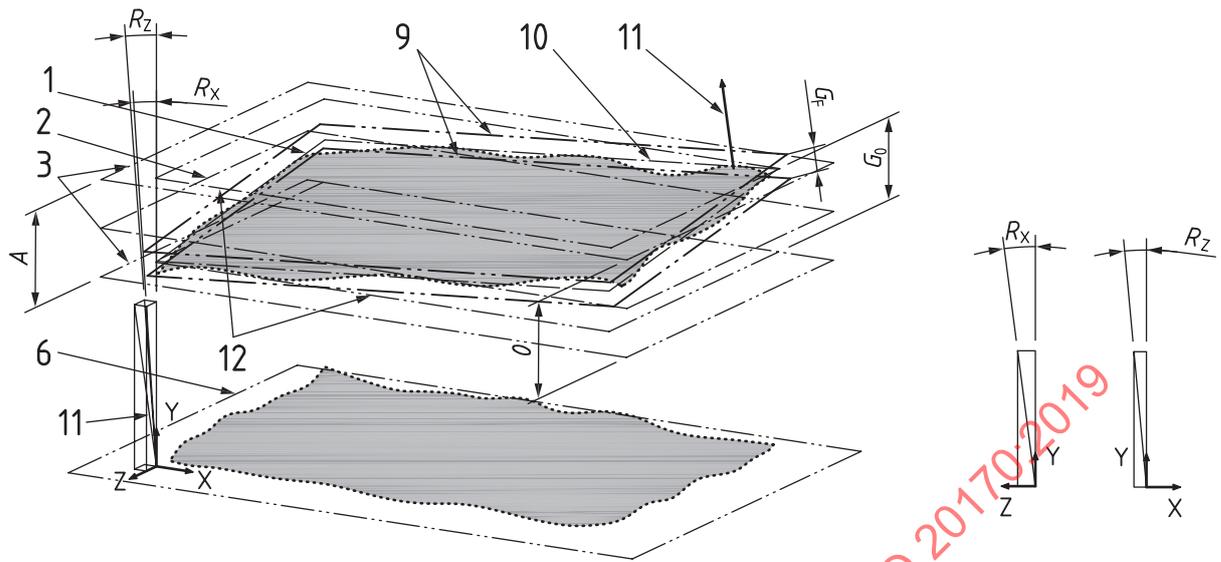
NOTE   In the case of orientation GPS characteristic, O is equal to A.

e) Independent orientation characteristic: G_O

Key

A GPS characteristic of parallelism

O actual value of orientation GPS characteristic (in this case $O = A$)

G_F GPS characteristic of form

G_O independent orientation characteristic

R_X angle deviation around X-axis

R_Z angle deviation around Z-axis

1   toleranced feature: extracted integral surface

2   reference feature of 1) for orientation GPS characteristic which is the median feature of 3)

3   limits of minimum zone of orientation GPS characteristic with orientation constraint from 1)

4   maximum distance between 2) and 1)

5   normal vector from 2)

6   datum K

7   datum feature K

8   normal vector from 6)

9   limits of minimum zone for form

10   restricted associated feature, restricted by the projection of 1) on the median feature of 9) (reference feature for form GPS characteristic)

11   normal vector from 10)

12   limits of minimum zone of orientation GPS characteristic with orientation constraint for 10)

NOTE   The Cartesian coordinate system is established from a datum system.

Figure 3 — Illustration of decomposition of parallelism specification

EXAMPLE 3   A position characteristic can be seen as a collected characteristic combining the form deviation, the angular deviation of the plane, and the location deviation of the plane as shown in Figure 4, when it is assumed that the manufacturing fixture surface and datum feature K are the same.
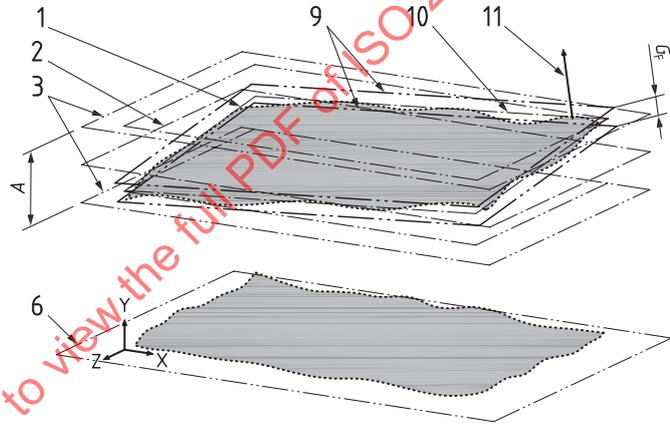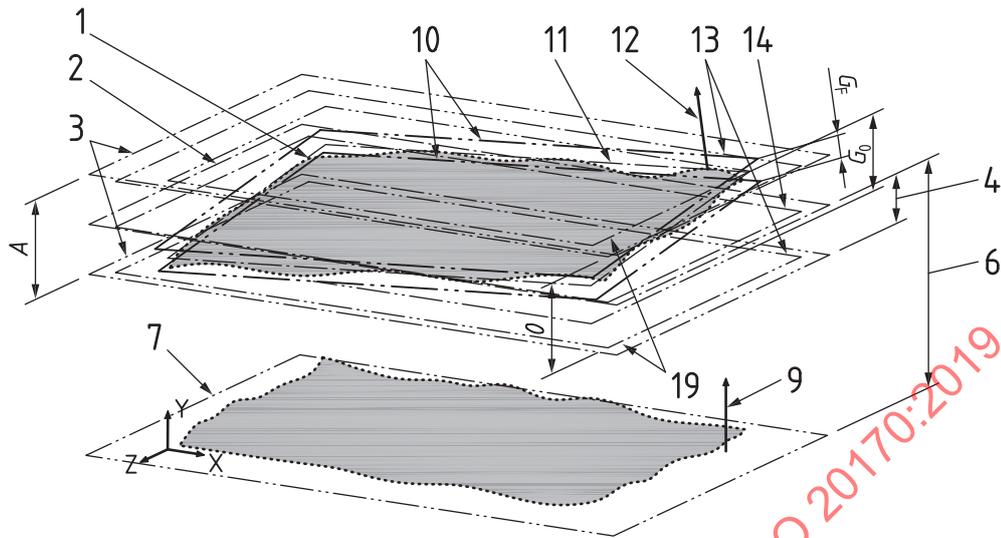
a) GPS specification

b) GPS location characteristic evaluation: *A*

NOTE   *L*: Complementary datum feature used to establish the Cartesian system (X, Y, Z).

c) Introduction of Cartesian system and attached complementary datum

d) Independent form characteristic evaluation: G_F **[deviation between 10]**

e) **Independent orientation characteristic:** G_O
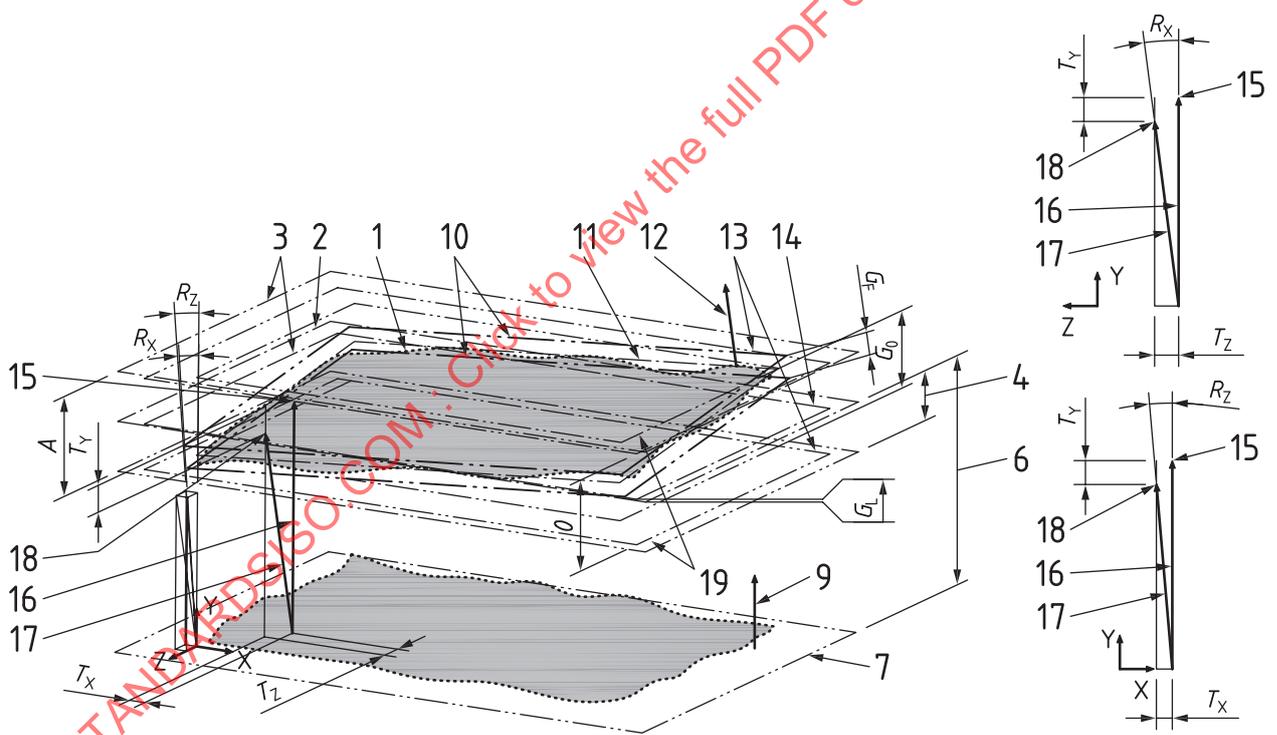
f) **Independent location characteristic:** G_L

Key

A	GPS characteristic of position
O	GPS characteristic of orientation
G_F	GPS characteristic of form, which is also the independent form characteristic
G_O	independent orientation characteristic, i.e. distance between the two planes // to datum which enclosed the restricted associated surface

5	normal vector from 2)
6	theoretical exact distance between 2) and 7)
7	datum K
8	datum feature K
9	normal vector from 7)
10	limits of minimum zone for form
11	restricted associated feature, restricted by the projection of 1) on the median feature of 10)

11

G_L	independent characteristic of position [deviation from 2) to 11)]		(reference feature for form characteristic)
R_x	angle deviation around X-axis	12	normal vector of the 11)
R_Z	angle deviation around Z-axis	13	limits of minimum zone of orientation GPS characteristic for 1)
T_x, T_y, T_z	translation deviation of the actual location point (18)	14	median feature of 13)
		15	theoretical location point
1	toleranced feature: extracted integral feature	16	theoretical location vector
2	reference feature of 1) for position GPS characteristic which is the median feature of 3)	17	actual location vector
		18	actual location point
		19	limits of minimum zone of orientation GPS characteristic for 10)
3	limits of minimum zone of position GPS characteristic with orientation and location constraint		
4	maximum distance between 2) and 1)		

Figure 4 — Illustration of decomposition of location specification

5.3 Determination of components of a collected characteristic

Depending on the property of the toleranced feature (invariance class, feature of size), it is possible to define in a Cartesian system:

— a form deviation (G_F) except for a toleranced feature which in an ideal feature (e.g. in case of projected tolerance);

— a size parameter (G_S) when the toleranced feature is a feature of size or when an offset can be considered from the nominal shape;

— up to three orientation parameters (R_X, R_Y, R_Z) depending on the invariance class of the toleranced feature;

— up to three location parameters (T_X, T_Y, T_Z) depending on the invariance class of the toleranced feature.

In addition, independent orientation and location characteristics can be defined to facilitate the decision to provide corrections on manufacturing process parameters.

If a local size characteristic is defined, then the result is not unique. In this case, the result interval is the interval limited by the minimum and maximum values of the set of local size characteristic values. If the size parameter is not applicable then the associated value is equal to "—".

When the chosen Cartesian system is the manufacturing coordinate system, then it is possible to define the orientation and location deviation parameters ($V_{\Delta O}, V_{\Delta L}$) from the nominal orientation vector and nominal location vector (V_{TO}, V_{TL}). To determine them, an associated feature shall be established from the extracted integral feature or from the extracted derived feature (depending on the toleranced feature). Its situation features (plane, straight line and/point) shall be considered as defined in Table 2.

Table 2 — Geometrical feature used to establish (actual, theoretical or deviation) orientation vector, or (actual, theoretical or deviation) location vector or to establish G_L

Invariance class	Set of situation features	V_{AO}, V_{TO}[a]	Location point used to establish $V_{\Delta L}$ or G_L
Planar	Plane	Vector perpendicular to the situation plane	Point of the situation plane, the nearest of the specified Cartesian system origin
Cylindrical	Straight line	Vector parallel to the situation straight line	Point of the situation straight line, the nearest of the specified Cartesian system origin
Spherical	Point	Impossible to define	Its location point
Revolute	Straight line + point[b]	Vector parallel to the situation straight line	Its location point
Prismatic	Plane + straight line [b]	Vector parallel to the situation straight line belonging to the situation plane	Point of the situation straight line, the nearest of the specified Cartesian system origin
Complex	Plane[b] + straight line[b] + point[b]	Vector perpendicular to the situation plane	Point[b]

a The orientation of the vector is defined from a situation feature of the geometrical feature. The orientation is considered positive out of the material.

b To be specified.

When the manufacturing datum system is not the same as the specification datum system, the result of the specification depends on the control of the toleranced feature and on the datum features themselves. To have an overview of the decomposition, it is necessary to decompose the GPS characteristics in the manufacturing datum system and to decompose the orientation and the location characteristics of each datum feature related to the datum system of the GPS specification.

If the purpose is to define statistical parameters to evaluate the manufacturing process performance, then the univariate characteristic is not sufficient. Instead, it should be considered as a collected characteristic to allow the statistical combination of the variation of each parameter. To control the manufacturing process, the univariate geometrical characteristic is not sufficient. Instead, it shall be considered as a multivariate characteristic, for example using the parameters (A, G_S, G_F, G_O, R_X, R_Y, R_Z, G_L, T_X, T_Y, T_Z). Some of these parameters may be zero by definition and can be omitted, depending on the specification.

For a form specification, the parameters G_O, R_X, R_Y, R_Z, G_L, T_X, T_Y, T_Z are not applicable and the associated value is equal to "—" and may be omitted.

For an orientation specification, the parameters G_L, T_X, T_Y, T_Z are not applicable and the associated value is equal to "—" and may be omitted.

5.4   Use of collected characteristics

To control the manufacturing process, the coordinate system shall be based on the features that interface with the manufacturing fixturing, not on the datum system defined in the geometrical specification. Each manufacturing step may require a different coordinate system. The collected characteristics shall be used to adjust manufacturing process parameters, by taking into account the impact of the differences between the specification datum system and the manufacturing datum system, to which it can be related.

If the datum system of the specification is not identical to the manufacturing datum system, then an analysis of the orientation and location of each datum of the specification datum system shall be done.

5.5 Presentation of a GPS or a collected characteristic results

5.5.1 General

The report of decomposition shall present not only the global results of the GPS characteristic, but also the components of the results of the collected characteristics (see Table 3).

NOTE   The decomposition parameters can be used for simulations of tolerance calculation.

Table 3 — Example of content of a measurement report for manufacturing process control

Specifi-cation No.	Univari-ate char-acteristic	Collected characteristics[a,b]										
		Multivariate characteristic										
		Form result in mm	Independent characteris-tic result in mm			Orientation angle in coordinate system in °			Location in coordinate system in mm		
	Global result in mm		Size result	Orien-tation result	Location result	R_X	R_Y	R_Z	T_X	T_Y	T_Z
	Uncer-tainty of global result in mm										
	A	U	G_F	G_S	G_O	G_L	R_X	R_Y	R_Z	T_X	T_Y	T_Z
1	0,026	0,002	0,001	—	0,015	0,005	0,012	−1,53	0,25	−0,005	0,000	0,000
2	0,062	0,003	0,031	—	0,011	0,009	0,01	1,03	−0,05	0,010	0,000	0,000

NOTE   "—" means "not applicable".

a   The values of the collected characteristic components are linked with an explanation of how the used coordinate system is established from the workpiece.

b   If the associated features are established by an association criteria other than the default criteria (minimax – Chebyshev) then it shall be stated in the report of results of decomposition.

EXAMPLE 1   Geometrical specification, illustrated in Figure 5, using a datum system which is identical to the manufacturing datum system.
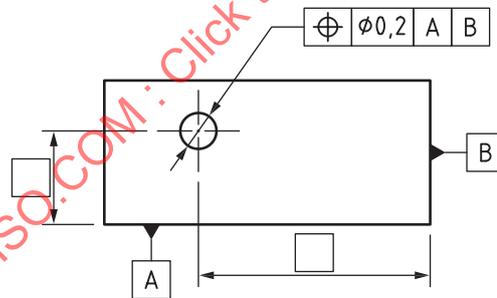
Figure 5 — Positional specification applied to an extracted derived line (extracted axis)

In EXAMPLE 1, the coordinate system is defined from the manufacturing datum system, and the most appropriate coordinate system is chosen, i.e. a Cartesian system. The primary axis of the coordinate system is a vector perpendicular to the primary datum. The secondary axis is built from the secondary datum. The tertiary axis is perpendicular to the two first vectors. To completely define the Cartesian system, the upper plane is defined as a complementary tertiary datum, enabling the definition of the origin of the coordinate system.

The toleranced feature is the extracted axis.

The specified characteristic includes the form, the orientation and the location of the toleranced feature.

The decomposition shall be carried out according to the following steps.

5.5.2 Decomposition steps

5.5.2.1 Manufacturing coordinate system

Define the coordinate system, based on a manufacturing related datum system, see Figure 6.

Depending on the manufacturing process, for example machining on a five-axis machine tool, the datum system used to establish the Cartesian system shall always consider the manufacturing process, but not necessarily the fixture of the workpiece in the manufacturing process.
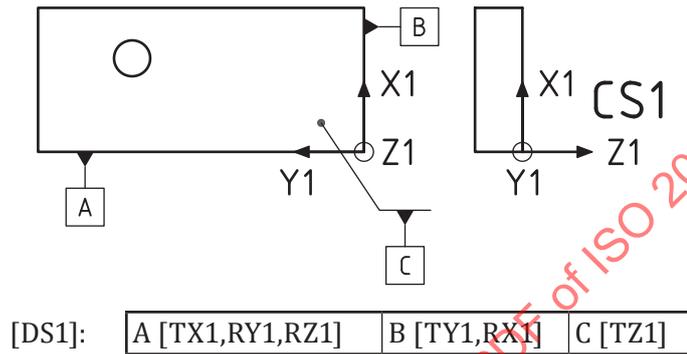
The global result shall remain related to the specification datum system.

[DS1]:   A [TX1,RY1,RZ1]   B [TY1,RX1]   C [TZ1]

Figure 6 — Description of a Cartesian system based on a datum system

5.5.2.2 Extraction of datum features

Extract the geometrical features, build the datum system and create the Cartesian system on the workpiece, see Figure 7.
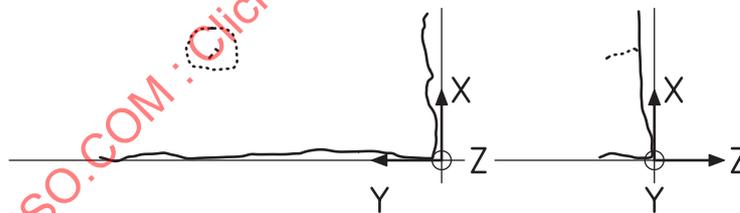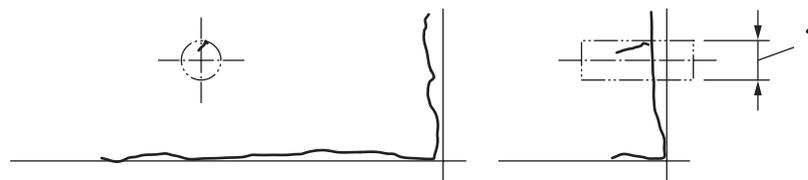

Figure 7 — Establishment of a datum system and a Cartesian system from the real workpiece

5.5.2.3 Global result of the GPS specification

Evaluate the result (*A*) of the geometrical specification (see Figure 8).


Key

1   global GPS characteristic result (*A*)

Figure 8 — Global result of a geometrical characteristic

5.5.2.4 Decomposition in different types of deviations
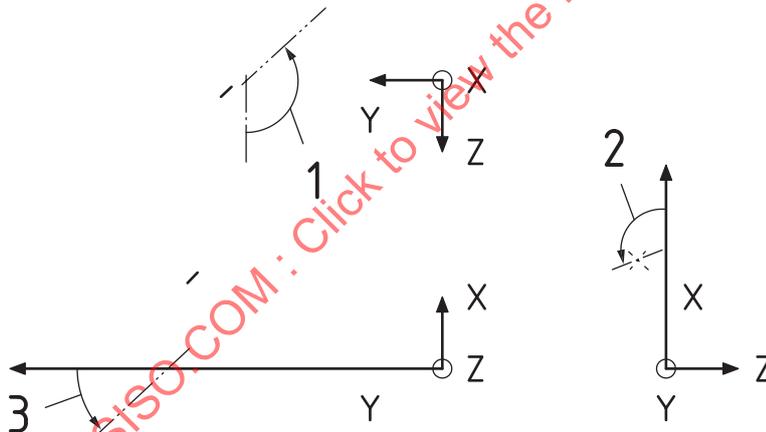
Separate the different types of deviation, see Figures 9 to 11.

a) Form (see Figure 9).

b) Size (not applicable in this case).

c) Orientation of the situation feature of the associated feature (see Figure 10).

d) Location of a specified point on the situation feature of the associated feature (see Figure 11).
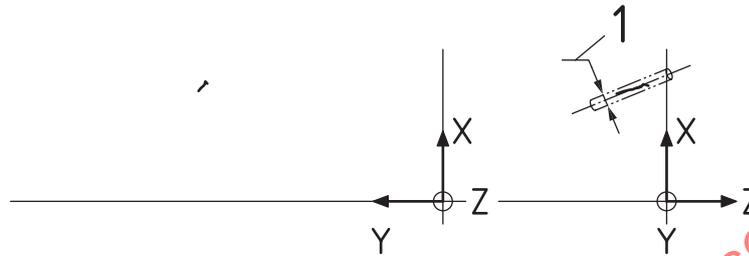
Key

1 form characteristic (G_F)

Figure 9 — Form characteristic deviation

Key

1 angular deviation around X-axis, R_x, used in $V_{\Delta O}$ (R_x, R_y, R_z)
2 angular deviation around Y-axis, R_y, used in $V_{\Delta O}$ (R_x, R_y, R_z)
3 angular deviation around Z-axis, R_z, used in $V_{\Delta O}$ (R_x, R_y, R_z)

Figure 10 — Independent orientation characteristic and angular