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Geometrical product specifications (GPS) — Filtration —

Part 31:
Robust profile filters: Gaussian regression filters

Spécification géométrique des produits (GPS) — Filtrage —

Partie 31: Filtres de profil robustes: Filtres de régression gaussiens

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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*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 290, *Dimensional and geometrical product specification and verification*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This second edition cancels and replaces the first edition (ISO 16610-31:2016), which has been technically revised.

The main changes compared to the previous edition are as follows:

— providing continuous Gaussian regression filters for open and for closed profiles;

— providing a normative iterative solution for continuous Gaussian regression filters.

A list of all parts in the ISO 16610 series can be found on the ISO website.

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 specification (GPS) standard and is to be regarded as a general GPS standard (see ISO 14638). It influences chain links C and E in the GPS matrix structure.

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 the specifications made in accordance with this document, unless otherwise indicated.

For more information on the relationship of this document to the filtration matrix model, see Annex C.

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

This document develops the terminology and concepts of robust Gaussian regression filters for surface profiles. It separates the large- and small-scale lateral components of surface profiles in such a way that the surface profiles can be reconstructed without altering. The robust Gaussian regression filter for surface profiles reduces the influence of protruding dales and hills. Depending on the selected nesting index and regression degree, robust Gaussian regression filters offer one method for F-Operation.

Geometrical product specifications (GPS) — Filtration —

Part 31:
Robust profile filters: Gaussian regression filters

1 Scope

This document specifies robust Gaussian regression filters for the filtration of surface profiles. It defines, in particular, how to separate large- and small-scale lateral components of surface profiles with protruding dales and hills.

The concept presented for closed profiles are applicable to the case of roundness filtering. Where appropriate, these concept can be extended to generalized closed profiles, especially for surface profiles with re-entrant features.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 16610-1,, *Geometrical product specifications (GPS) — Filtration — Part 1: Overview and basic concepts*

ISO 16610-20, *Geometrical product specifications (GPS) — Filtration — Part 20: Linear profile filters: Basic concepts*

ISO 16610-21, *Geometrical product specifications (GPS) — Filtration — Part 21: Linear profile filters: Gaussian filters*

ISO 16610-22, *Geometrical product specifications (GPS) — Filtration — Part 22: Linear profile filters: Spline filters*

ISO 16610-30, *Geometrical product specifications (GPS) — Filtration — Part 30: Robust profile filters: Basic concepts*

ISO/IEC Guide 99, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 16610-1, ISO 16610-20, ISO 16610-21, ISO 16610-22, ISO 16610-30, ISO/IEC Guide 99 and the following apply.

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

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

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

3.1
surface profile
line resulting from the intersection between a surface portion and an ideal plane

Note 1 to entry: The orientation of the ideal plane is usually perpendicular to the tangent plane of the surface portion.

Note 2 to entry: See ISO 17450-1:2011, 3.3 and 3.3.1, for the definition of an ideal plane.

[SOURCE: ISO 16610-1:2015, 3.1.2, modified — Note 2 to entry replaced.]

3.1.1
open profile
finite length *surface profile* (3.1) with two ends

Note 1 to entry: An open profile has a compact support, i.e. within a certain interval the height values of an open profile can be equal to any real number. Outside the interval, the height values of an open profile are set to zero.

[SOURCE: ISO 16610-1:2015, 3.7, modified — Note 1 to entry replaced.]

3.1.2
unbounded open profile
infinite length *surface profile* (3.1) without ends

Note 1 to entry: In this document, the term "unbounded" refers to the X-axis.

Note 2 to entry: The concept of the unbounded open profile is ideal and do not apply to real surface profiles.

3.1.3
closed profile
connected finite length *surface profile* (3.1) without ends

Note 1 to entry: A closed profile is a closed curve which is periodic with the finite period length L.

Note 2 to entry: A typical example of a closed profile is one from a roundness measurement.

[SOURCE: ISO 16610-1:2015, 3.8, modified — Note 1 to entry replaced and Note 2 to entry added.]

3.2
linear profile filter
profile filter which separates *surface profiles* (3.1) into large- and small-scale lateral components and is also a linear function

Note 1 to entry: If F is a function and X and Y are surface profiles, and if a and b are independent from X and Y, then F being a linear function implies $F(a\,X + b\,Y) = a\,F(X) + b\,F(Y)$.

[SOURCE: ISO 16610-20:2015, 3.1, modified — Definition and Note 1 to entry replaced.]

3.3
weighting function
function to calculate large-scale lateral components by convolution of the surface profile heights with this function

Note 1 to entry: The convolution (see ISO 16610-20:2015, 4.1) performs a weighted moving average of the surface profile heights. The weighting function, reflected at the X-axis, defines the weighting coefficients for the averaging process.

3.4
transmission characteristic of a filter
characteristic that indicates the amount by which the amplitude of a sinusoidal surface profile is attenuated as a function of its wavelength

Note 1 to entry: The transmission characteristic is the Fourier transformation of the *weighting function* (3.3).

3.5
cut-off wavelength
λ_c
wavelength of a sinusoidal surface profile of which 50 % of the amplitude is transmitted by the profile

Note 1 to entry: Linear profile filters are identified by the filter type and the cut-off wavelength value.

Note 2 to entry: The cut-off wavelength is the nesting index for linear profile filters.

[SOURCE: ISO 16610-20:2015, 3.5, modified — In Note 2 to entry "recommended" deleted.]

3.6
undulations per revolution
UPR
integer number of sinusoidal undulations contained in a *closed profile* (3.1.3)

Note 1 to entry: In this document, UPR is a frequency and is denoted by f.

3.7
cut-off frequency in undulations per revolution
f_c
frequency in UPR of a sinusoidal *closed profile* (3.1.3) of which 50 % of the amplitude is transmitted by the profile filter

3.8
robust profile filter
profile filter which separates *surface profiles* (3.1) into large- and small-scale lateral components and is insensitive against specific phenomena in the input data

Note 1 to entry: A robust profile filter is a nonlinear filter.

Note 2 to entry: See also ISO 16610-1:2015, 3.9.

Note 3 to entry: Outliers, scratches and steps are examples of specific phenomena. Further details can be found in ISO 16610-30:2015.

Note 4 to entry: In particular, the *robust Gaussian regression filter* (3.11) in accordance with this document reduces the influence of specific phenomena such as protruding dales and hills. Profile examples are given in Annex B.

3.9
biweight function of Beaton and Tukey
function used in M-estimation and defined by Formula (1)

$$\delta(\Delta z(x),c)=\begin{cases}\left[1-\left(\dfrac{\Delta z(x)}{c}\right)^2\right]^2 & \text{for } |\Delta z(x)|\le c\\ 0 & \text{for } |\Delta z(x)|>c\end{cases} \tag{1}$$

where

x	is the given x-coordinate;
$\Delta z(x)$	are heights depending on x;
c	is a scale value.

Note 1 to entry: The biweight function $\delta(\Delta z(x),c)$ of Beaton and Tukey is almost constant and equals nearly 1 for heights $\Delta z(x) \ll c$. For increasing heights $|\Delta z(x)|$, the biweight function of Beaton and Tukey approaches zero.

Note 2 to entry: The biweight function of Beaton and Tukey is related to the influence function $\psi(\Delta z(x))$ (see ISO 16610-30:2015) used in M-estimation as follows: $\psi(\Delta z(x))=\Delta z(x)\,\delta(\Delta z(x),c)$.

Note 3 to entry: See also ISO 16610-30:2015 and Reference [9].

3.10
regression filter
profile filter which based on a local polynomial modelling of the large-scale lateral component of a *surface profile* (3.1)

3.11
robust Gaussian regression filter
regression filter (3.10) based on the Gaussian weighting function and the *biweight function of Beaton and Tukey* (3.9)

4 Characteristics of the robust Gaussian regression filter for open profiles

4.1 General

In this clause, the ideal filtration of open profiles is considered. Since the robust Gaussian regression filter is nonlinear and no transmission characteristic by means of the Fourier transformation can be given, the generic term nesting index N_{i} is used as the filter parameter instead of cut-off wavelength λ_{c}. But in many cases of application, values for the cut-off wavelength λ_{c} used for linear filtration are also suitable as a nesting index N_{i} for robust filtration.

4.2 Filter equations

4.2.1 Determination of the large-scale lateral component

To determine the large-scale lateral component of an open profile, the robust Gaussian regression filter with degree p is defined by Formula (2):

$$w(x)=\begin{pmatrix}1 & 0 & \cdots & 0\end{pmatrix}\left(\int_{\Omega}\boldsymbol{v}_p^{\mathrm{T}}(x,u)\,\boldsymbol{v}_p(x,u)\,s(x,u)\,\mathrm{d}u\right)^{-1}\int_{\Omega}z(u)\,\boldsymbol{v}_p^{\mathrm{T}}(x,u)\,s(x,u)\,\mathrm{d}u \quad (2)$$

where

Ω	is the finite interval, expressed as a set, in which the open profile can be any real number;
x	is the given x-coordinate with $x\in\Omega$;
u	is the integration variable along the X-axis with $u\in\Omega$;
$z(u)$	is the open profile depending on u;
$\boldsymbol{v}_p(x,u)$	is the vector space of polynomials up to p^{th} degree depending on x and u;
$\boldsymbol{v}_p^{\mathrm{T}}(x,u)$	is the transpose of $\boldsymbol{v}_p(x,u)$;
$s(x,u)$	is the modified Gaussian weighting function depending on x and u;
$w(x)$	is the large-scale lateral component depending on x.

The vector space $\boldsymbol{v}_p(x,u)$ is defined by Formula (3):

$$\boldsymbol{v}_p(x,u)=\begin{bmatrix}1 & (x-u) & \cdots & (x-u)^p\end{bmatrix} \quad (3)$$

The modified Gaussian weighting function $s(x,u)$ is defined by Formula (4):

$$s(x,u)=\delta\big(z(u)-w(u),c\big)\,\frac{1}{\gamma N_{\mathrm{i}}}\,\mathrm{e}^{-\pi\left(\frac{x-u}{\gamma N_{\mathrm{i}}}\right)^2} \quad (4)$$

where

$\delta(\cdot)$ is the biweight function of Beaton and Tukey;

N_i is the nesting index;

γ is the filter constant;

c is a scale value.

The scale value c is defined by Formula (5):

$$c = \frac{3}{\sqrt{2}\,\mathrm{erf}^{-1}(0{,}5)} \operatorname*{median}_{u \in \Omega} |z(u) - w(u)| \approx 4{,}447\ 8 \operatorname*{median}_{u \in \Omega} |z(u) - w(u)| \qquad (5)$$

The definition for the scale value c is equivalent to three times the standard deviation, if $z(u) - w(u)$ has a Gaussian amplitude distribution.

For $p = 0, 1, 2$, the filter constant γ is defined by Formula (6):

$$\gamma = \begin{cases} \sqrt{\dfrac{\ln 2}{\pi}} \approx 0{,}469\ 7 & \text{for } p = 0, 1 \\ \sqrt{\dfrac{-1 - W_{-1}\left(-\dfrac{1}{2\,\mathrm{e}}\right)}{\pi}} \approx 0{,}730\ 9 & \text{for } p = 2 \end{cases} \qquad (6)$$

NOTE 1 erf^{-1} is the inverse error function.

NOTE 2 W_{-1} is the “Lambert W” function with branch -1 (see Reference [6]).

NOTE 3 The median of the absolute deviation $|z(u) - w(u)|$ is called MAD (see ISO 16610-30:2015, 3.5.2).

NOTE 4 See Clause 6.3 for an iterative solution of the robust Gaussian regression filter.

4.2.2 Determination of the small-scale lateral component

The small-scale lateral component of an open profile is determined by subtracting the large-scale lateral component of this open profile, Formula (2), from this open profile according to Formula (7).

$$r(x) = z(x) - w(x) \qquad (7)$$

where

x is the given x-coordinate;

$z(x)$ is the open profile depending on x;

$w(x)$ is the large-scale lateral component of the open profile depending on x;

$r(x)$ is the small-scale lateral component of the open profile depending on x.

4.3 Transmission characteristics

The modified Gaussian weighting function of the robust Gaussian regression filter depends on the heights of the open profile. Therefore, no transmission characteristics by means of the Fourier transformation can be given.