13th IMEKO TC10 Workshop on Technical Diagnostics
Advanced measurement tools in technical diagnostics for systems' reliability and safety
June 26-27, 2014, Warsaw, Poland

Toward improved performance in separation of roughness, waviness and form: ISO 16610 series

Marta Wiśniewska[1] Sabina Żebrowska-Łucyk[2]

[1] *Warsaw University of Technology, Faculty of Mechatronics, Institute of Metrology and Biomedical Engineering, 8 Św. A. Boboli Str., 02-525 Warszawa, Poland,*
Tel.: +48222348323, E-mail: martwisn@mchtr.pw.edu.pl
[2] *Warsaw University of Technology, Faculty of Mechatronics, Institute of Metrology and Biomedical Engineering, 8 Św. A. Boboli Str., 02-525 Warszawa, Poland,*
Tel.: +48222348323, E-mail: szl@mchtr.pw.edu.pl

Abstract- During recent years the surface texture measurement and analysis has become one of the most important fields of interest in modern metrology. So, the development of the new filtering methods, enabling to separate surface's components of different scale, should not be surprising. However, Gaussian linear filter, in spite of its significant drawbacks, remains the one and the only filter used by the vast majority of engineers in their professional performance. It is a result both of the chaos brought by the dozens of filtration algorithms proposed recently and the low consciousness of their advantages over the typical filters. Due to this, the ISO 16610 standard series has been devised. Its main aim is to promote recent advances in the surface texture filtration techniques and systematise knowledge about them. This paper reviews the set of standards concerning the profile (2D) filters discussed in this series: Gaussian, spline, wavelet and morphological ones. It also outlines main features and possible applications of these filtration algorithms.

I. Introduction

It is widely known that there is a profound impact of the surface texture on the performance of engineering objects. However, as measurements should not be performed in isolation from functional properties of examined surfaces, it is crucial to apply proper method of surface characterisation. For this reason not only have the new measurement techniques been devised, but also the new algorithms of signal analysis have been proposed. Most of them refer to the measured profile filtration performed in order to separate the surface geometry into basic components, differing in their scale of size: form, waviness and roughness.

However, the multiplication of the filtration algorithms proposed by the scientists and measuring instruments manufacturers is not reflected by their recognition among the industrial staff. It is due to the chaos brought by both by the dozens of filtration algorithms proposed recently and the subtleties differing them, which are not easily understood by non-scientists. What is more, many metrologists remain unaware of advantages of the latest filtration methods over typical ones such as Gaussian linear filter [1]. As a result, Gaussian filter remains, in spite of its significant drawbacks, the one and the only filter used by the vast majority of engineers in their professional performance.

In response to the increasing necessity for popularising and systematising knowledge about recent advancements in the surface texture filtration techniques, the ISO 16610 standard series has been published. The main aim of the paper is to outline crucial limitations of this set applicability. Also, the most important ambiguities prevailing in these documents will be presented.

Firstly, in spite of the efforts of the numerous scientists [2, 3], the main aim of this set of standards that is promoting new approaches towards filtration in surface characterisation, has not been achieved yet. It is due to the fact that the algorithms outlined in the standards are not implemented in most of commercially available software. Another problem, limiting the reach of these documents, is the fact that they are published in English and not translated into native languages. Also, a pace of introducing these standards by the national standardisation organisations is insufficient. In example, till the of May 2014 the PKN (Polish Committee for Standardization) has published just two standards from the series. In the same time there are thirteen parts of the series that have already been published by the ISO. Furthermore, fourteen others are under development.

To make matters even worse, the algorithms of filters presented in the series are complicated and understanding them properly requires knowledge of advanced mathematics. Due to this, the standards are not clear enough to be widely applied by industrial staff.

In order to evaluate the performance of each ISO 16610 filter, some algorithms have been implemented into the *ISO Filters 16610* software devised by the authors. This overview is limited to the standards concerning the profile (2D) filters [4]. Among the filtration methods taken into consideration there are not only linear, but also robust and morphological ones. What is more, the wavelet signal analysis will be mentioned. The figures showing filtration results presented in the paper are screen captures from this program.

II. Gaussian linear filter

Gaussian linear filter was standardised as soon as in the 1990s [5] and, in effect, it remains the best-known and the most popular filter used for digital processing of surface profiles. Due to this, Gaussian filter must have been described in the ISO 16610 series [6]. What is more, it has been chosen as the reference filter – performance of every newly devised filtration technique should be compared with the Gaussian linear one. A weighting function of the filter differs depending on the type of profile: open or closed, as presented below:

a) weighting function equation for an open profile:

$$s(x) = \begin{cases} \frac{1}{\alpha\lambda_c}\exp\left[-\pi\left(\frac{x}{\alpha\lambda_c}\right)^2\right] & \text{for } -L_c\lambda_c \le x \le L_c\lambda_c \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

b) weighting function equation for a closed profile:

$$s(x) = \begin{cases} \frac{f_c}{\alpha L}\exp\left[-\pi\left(\frac{xf_c}{\alpha L}\right)^2\right] & \text{for } -\frac{L_c L}{f_c} \le x \le \frac{L_c L}{f_c} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where:
x - is the distance from the centre (maximum) of the weighting function;
λ_c – the cut-off wavelength;
α - a constant to provide 50 % transmission characteristic at the cut-off λ_c;
L_c - a truncation constant;
f_c - the cut-off frequency in undulations per revolution;
L - the length of the closed profile.

This weighting function of a filter has slightly changed when compared with the earlier standardising documents: an introduction of truncation constant L_c has been recommended. Nevertheless, this difference does not affect effects of filtration in a significant way. It is claimed that the implementation error caused by change of L_c value should not exceed 0.76% [6]. However, in majority of cases this error is not greater than the hundredth parts of per mill. So, the necessity for introducing this constant seems to be doubtful.

Moreover, the way weighting function equations are presented may be misleading. For example, there is a "×" sign used as a multiplication symbol. Not only can it be easily mistaken for the distance *x* from the maximum of the weighting function, but it also does not follow the ISO recommendations concerning mathematical symbols usage [7]. In the paper, in order to avoid propagating misleading information, the formulas are presented in a correct way.

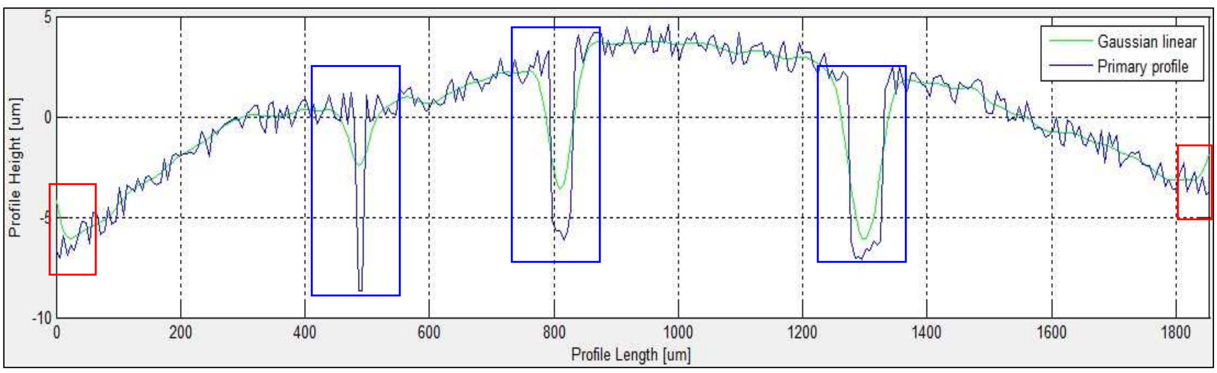

Figure 1. Original (primary) profile and the reference profile
obtained with the standard Gaussian filter (λ_c = 0.08 mm, L_c = 1)

In spite of its extensive popularity, Gaussian linear filter is not free from disadvantages. The most important among them is the significant impact of the outlying points (i.e. pores or scratches) on the filtration results, as it is presented in Fig. 1 (blue rectangles). If the primary profile is skewed or its nominal form is not removed before applying the filtering, the results may be visibly distorted, too.
Another serious drawback of Gaussian linear filter are *the end effects* – filtration errors observed at the ends of the open profile being filtered (Fig. 1, red rectangles). In order to avoid these profile distortions a longer profile should be taken. There are a few ways of performing so [8]. The most popular of them are: zero padding or linear extrapolation of a profile. Then, *the end effect regions* should be removed from a filtration response.

III. Spline linear filter

Spline linear filter has been proposed in 1996 [8] as a solution to the Gaussian linear filter major drawbacks. Not only have the end effects been eliminated (Fig. 2), but also it is applicable to every surface profile, including skewed ones. Moreover, this is an effective tool for filtering profiles with a random data spacing. Also, thanks to spline linear filter simplicity, the time of computations has been significantly reduced, when compared with Gaussian linear filter performance [3].
Spline linear filter equation is as follows [9]:

$$[I + \beta\alpha^2 P + (1 - \beta)\alpha^4 Q]w = z \tag{3}$$

where:
n – the number of extracted values of a profile;
z – vector of dimension *n* of the profile values before filtering;
w – vector of dimension *n* of the profile values after filtering;
I – matrix of ones with *n* rows and *n* columns;
P, Q – matrixes with *n* rows, *n* columns and values dependent on the type of profile;
the parameters:

$$\alpha = \frac{1}{2\sin\frac{\pi\Delta x}{\lambda_c}} \tag{4}$$

Δx – the sampling interval;
λc - the cut-off wavelength of a profile filter;
and $0 \leq \beta \leq 1$ (recommended value of tension parameter $\beta = 0$).
As it has been mentioned, the *P* and *Q* matrixes differ depending on the kind of profile. The recommended ones are respectively:

a) *P* and *Q* matrixes for an open profile:

$$\mathrm{P} = \begin{bmatrix} 1 & -1 & & & & & \\ -1 & 2 & -1 & & & & \\ & -1 & 2 & -1 & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & -1 & 2 & -1 & \\ & & & & -1 & 2 & -1 \\ & & & & & -1 & 1 \end{bmatrix} \quad \mathrm{Q} = \begin{bmatrix} 1 & -2 & 1 & & & & \\ -2 & 5 & -4 & 1 & & & \\ 1 & -4 & 6 & -4 & 1 & & \\ & \ddots & \ddots & \ddots & \ddots & \ddots & \\ & & 1 & -4 & 6 & -4 & 1 \\ & & & 1 & -4 & 5 & -2 \\ & & & & 1 & -2 & 1 \end{bmatrix} \tag{5}$$

b) *P* and *Q* matrixes for a closed profile:

$$\mathrm{P} = \begin{bmatrix} 2 & -1 & & & & & -1 \\ -1 & 2 & -1 & & & & \\ & -1 & 2 & -1 & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & -1 & 2 & -1 & \\ & & & & -1 & 2 & -1 \\ -1 & & & & & -1 & 2 \end{bmatrix} \quad \mathrm{Q} = \begin{bmatrix} 6 & -4 & 1 & & & 1 & -4 \\ -4 & 6 & -4 & 1 & & & 1 \\ 1 & -4 & 6 & -4 & 1 & & \\ & \ddots & \ddots & \ddots & \ddots & \ddots & \\ & & 1 & -4 & 6 & -4 & 1 \\ 1 & & & 1 & -4 & 6 & -4 \\ -4 & 1 & & & 1 & -4 & 6 \end{bmatrix} \tag{6}$$

.

It is worth-mentioning that in the ISO standard there is a slight ambiguity. A matrix of ones *I* and a scalar value of 1.0 have the same symbol (“1”). It may lead to misunderstandings and, therefore, the systematising role of standard documents is not fulfilled. In the paper, to assure the accuracy of the given formulas, two different symbols have been applied.

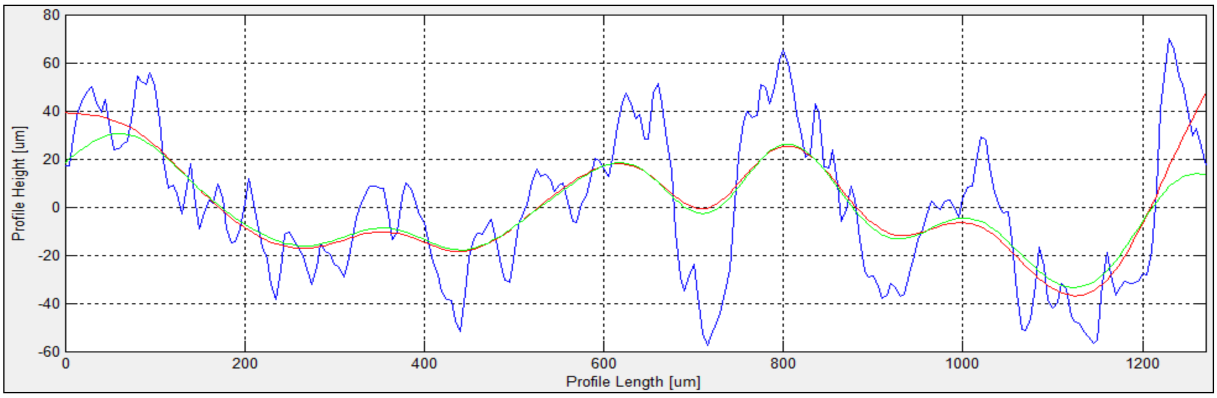

Figure 2. The profiles obtained with a use of Gaussian linear (green line, λ_c = 0.25 mm, L_c = 1) and spline linear (red line) filter (λ_c = 0.25 mm)

IV. Spline wavelets

Usage of the wavelet transform instead of the Fourier one is a completely new approach towards the surface texture characterisation. Thanks to combination of the advantages of spline linear filter and opportunity to separate the surface features of different scale simultaneously, comprehensive information about surface functional properties is given [10] (Fig. 3). However, as there is wide variety mother wavelets that can be applied, the filtration results are difficult to be interpreted. In effect, the range of possible applications of the spline wavelet filter has not been fully established yet.

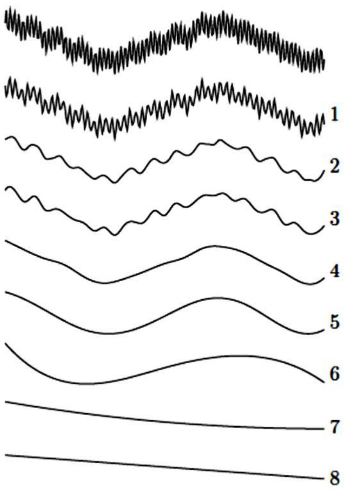

Figure 3. Spline wavelets [10]

V. Gaussian robust filter

The non-sensitivity to profile outliers is the most important advantage of the robust filters differing it from the linear ones (Fig. 4). However, the multi-iteration algorithm of filtration makes the computations both time-consuming and complicated. To make matters worse, not every symbol from the filter equation has been explained clearly in the standard [12]. For example, a few symbols representing vectors or matrixes are listed in bold type, whereas the others are not. What is more, this way of outlining non-scalar values is improper according to the ISO guidelines [7]. Furthermore, some symbols have not been explained at all (i.e. *l* and *k*). So, simplicity and non-ambiguity, which are essential features of each documents of the kind, are not ensured. It makes applying the recommendations of a standard without any additional research extremely difficult or even impossible.
Also, the results obtained with a use of Gaussian robust filter may differ significantly depending on a number

of iterations that has to be predefined. However, as neither scientific publications, nor the ISO standard [12] give any recommendations concerning this issue, further research in this field and, in consequence, some improvements of the ISO 16610 series are yet to be made.

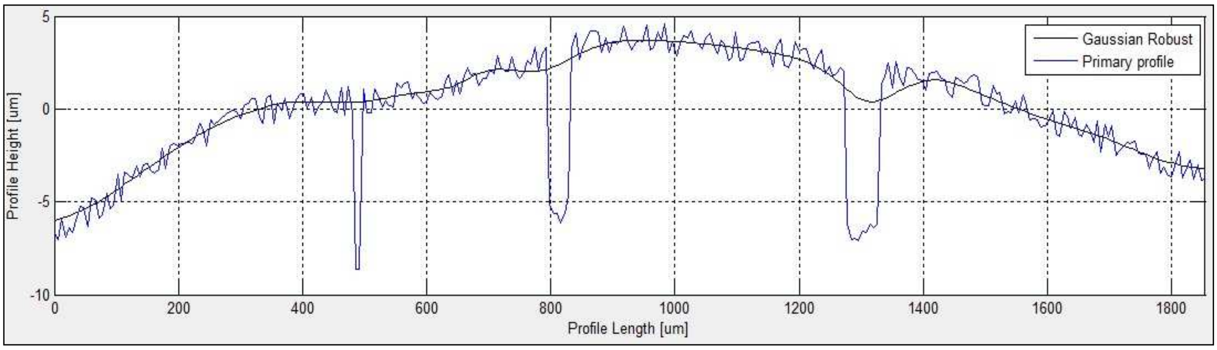

Figure 4. The profile acquired with a use of Gaussian robust filtration (λ_c = 0.25 mm, n = 6 iterations applied)

VI. Morphological filters

When the envelope system of the surface texture characterisation has been proposed in the 1950s, the computer engineering has not been popularised yet. In effect, this way of surface properties evaluation could not have been practically applied, as it demands complicated and multi-step computations. It has resulted in the decades-lasting underrating of this approach. As these hardware limitations have been eliminated, a use of the surface profile envelope for surface properties evaluation has staged a comeback and resulted in development of the morphological filters [13].

These filters are not applicable to separating the components of a different scale from the surface profile, but they let us understand mechanical properties of a surface better than ever before. Despite all possible applications of the morphological filters have not been outlined yet, it has already been realised that they are a useful tool to predict the performance of mechanical parts, as they may simulate contact phenomena effectively [14].

The primary operations of morphological filtration are dilation and erosion. The origin of the structuring element (disk or horizontal line) is positioned at every point of the profile and their Minkowski sums are calculated. So, the output of this operation is a profile, which consists of the extreme values collected at each sampling point. Closing and opening filters, which are secondary morphological operations, are computed by applying dilation and erosion in a specified sequence. Opening is obtained by applying the erosion followed by the dilation, whereas closing is conducted by applying the dilation followed by the erosion.

The results obtained with a use of morphological filters of different types are presented in Fig. 5.

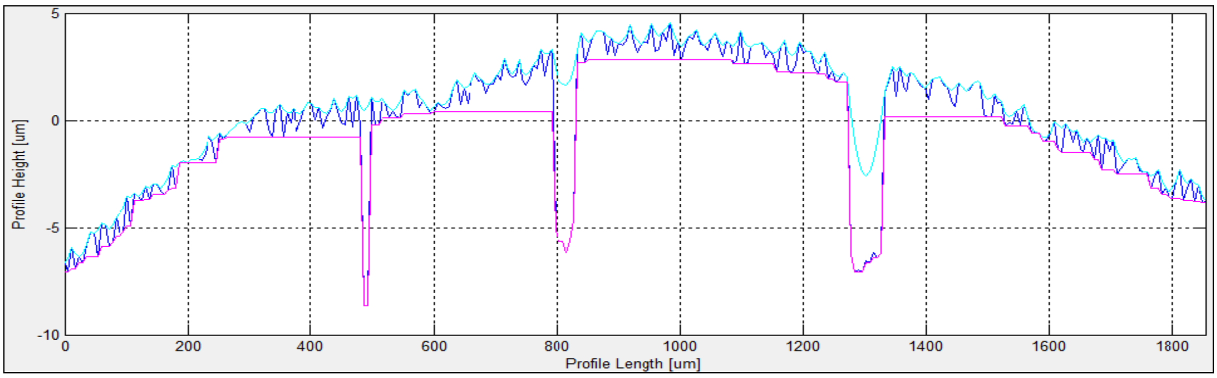

Figure 5. Profiles obtained with a use of morphological filters: a) cyan - closing filter, disk (R = 0.1 mm) used as a structuring element; b) magenta - opening filter, horizontal line (R = 0.1 mm) used as a structuring element

VII. Conclusions

Introduction and development of the ISO 16610 series reflects the metrologists' increasing interest in the surface topography measurements and analysis. The variety of the filters described in this set of standards makes it a comprehensive tool to systematise knowledge on filtration of surface profiles and popularising it among the engineers. Nevertheless, the efforts, taken by the authors to implement the algorithms practically, have proved that there are still some improvements to be made.

Firstly, as it has already been mentioned, the description of algorithms may be unclear for majority of engineers. Insufficient or even lack of explanations of some symbols being used in the formulas presented in the series makes the understanding of the standards entirely more difficult.

Also, as the authors' study has shown, the nomenclature used in the ISO 16610 documents is incoherent with the one introduced in the standards that had been published before [15,16]. One of such terms is a *profile filter*, which is defined as *filter which separates profiles into longwave and shortwave components* (ISO 4287:1997) or *operator consisting of a filtration operation for use on a surface profile* (ISO/DIS 16610-1). To make matters worse, a definition of *profile filter* proposed in ISO 4287:1997 and *linear profile filter* introduced in the ISO 16610 series [17] are one and the same.

What is more, some definitions are repeated within a new set of standards, whereas the others are not. There is no clear explanation for this non-uniformity. Also, repetition of definitions in each standard makes the aim of the standards referring to the basic filtration concepts (i.e. ISO/DIS 16610-1) doubtful. An extreme example of reprising the same term many times is *cut-off wavelength*. It has been already been repeated at least four times. Moreover, *cut-off* value is defined variously depending on a standard. In example, it may refer both to *wavelength of a sinusoidal profile of which 50 % of the amplitude is transmitted by the profile filter* [6,17] and *nesting index* [9].

Last but not least, the ISO 16610 series is not free of mistakes. In example, the robust spline filter equation cannot be solved. Thus, it has neither been implemented in the *ISO Filters 16610* software developed by the authors, nor presented in the paper.

References

[1] S. Lou, W. Zeng, X. Jiang, P.J. Scott, "Robust Filtration Techniques in Geometrical Metrology and Their Comparison", *International Journal of Automation and Computing*, vol. 10(1), pp. 1-8, 2013.

[2] P. Dobrzański, P. Pawlus, "Digital filtering of surface topography: Part I. Separation of one-process surface roughness and waviness by Gaussian convolution, Gaussian regression and spline filters", *Precision Engineering*, vol. 34, pp. 647-650 2010.

[3] J. Raja, B. Muralikrishnan, Shengyu Fu, "Recent advances in separation of roughness, waviness and form", *Precision Engineering*, vol. 26, pp. 222-235, 2002.

[4] ISO/DIS 16610-1. Geometrical product specifications (GPS) -- Filtration -- Part 1: Overview and basic concepts.

[5] ISO 11562:1996. Geometrical Product Specifications (GPS) -- Surface texture: Profile method -- Metrological characteristics of phase correct filters.

[6] ISO 16610-21:2011. Geometrical product specifications (GPS) -- Filtration -- Part 21: Linear profile filters: Gaussian filters.

[7] ISO 80000-2:2009. Quantities and units -- Part 2: Mathematical signs and symbols to be used in the natural sciences and technology.

[8] ISO 16610-28. Geometrical product specifications (GPS) -- Filtration -- Part 28: Profile filters: End effects.

[9] ISO/TS 16610-22:2006. Geometrical product specifications (GPS) -- Filtration -- Part 22: Linear profile filters: Spline filters.

[10] ISO/TS 16610-29:2006. Geometrical product specifications (GPS) -- Filtration -- Part 29: Linear profile filters: Spline wavelets.

[11] M. Krystek, "ISO filters in precision engineering and production measurement", PTB, Braunschweig 2010.

[12] ISO/TS 16610-31:2010. Geometrical product specifications (GPS) -- Filtration -- Part 31: Robust profile filters: Gaussian regression filters.

[13] ISO/DIS 16610-40. Geometrical product specifications (GPS) -- Filtration -- Part 40: Morphological profile filters: Basic concepts.

[14] S. Lou, X. Jiang, P.J. Scott, "Applications of Morphological Operations in Surface Metrology and Dimensional Metrology", *14th International Conference on Metrology and Properties of Engineering Surfaces*, Taipei 2013.

[15] ISO 4287:1997. Geometrical Product Specifications (GPS) -- Surface texture: Profile method -- Terms, definitions and surface texture parameters.

[16] ISO 4288:1996. Geometrical Product Specifications (GPS) -- Surface texture: Profile method -- Rules and procedures for the assessment of surface texture.

[17] ISO/DIS 16610-20. Geometrical product specifications (GPS) -- Filtration -- Part 20: Linear profile filters: Basic concepts.