X. International Colloquium on Surfaces

X. Internationales Oberflächenkolloquium

Chemnitz (Germany) Jan. 31 - Feb. 02, 2000

Proceedings & Posters - Vorträge & Poster

herausgegeben von

M. Dietzsch, H. Trumpold

Shaker Verlag
Aachen 2000

Development of a robust Gaussian regression filter for three-dimensional surface analysis

S. Brinkmann, H. Bodschwinna, H.-W. Lemke
Institute for Measurement and Control, University of Hanover, Germany

1. Introduction

Determination of a reference plane is essential to evaluation of the technical surfaces in particular of their roughness. Micro geometrical properties can have significant influence on the quality of products. This reference plane serves as a basis for quantitative analysis of surface roughness and takes direct effect on the calculation of roughness parameters. The reference plane represents here the spatial structure of waviness and long wave form components.

The three-dimensional robust Gaussian regression filter, developed by the Institute for Measurement and Control, is a powerful method for the calculation of this reference plane. This filter was worked out within the scope of SURFSTAND, a research project on the subject "The Development of a Basis for 3D Surface Roughness Standards" supported by the European Community. Starting point was the standardised 2-dimensional profile filter of ISO 11562 [1] and the modified Gaussian regression filter developed by Seewig [2,3]. Applying the regression approach instead of convolution no margin problem emerges. That means the full measured length respectively the measured area can be evaluated without running in and running out effects of the filter. Due to the use of a robust algorithm this filter can additionally be employed with plateau like surfaces, for example plateau honed cylinder liners.

The effect of the robust algorithm on the evaluation of roughness is examined using the bearing area ratio curve. It will be demonstrated that the robust filter is the better choice when it comes to approximation of the plateauness of functional stratified surfaces. It remains neutral with for example turned or ground surfaces.

2. Concept of the 3-dimensional Gaussian regression filter

2.1. 2-dimensional Gaussian regression filter

For better clarity in the following the formulation of the 2-dimensional Gaussian regression filter is briefly explained before the 3-D regression filter will be deduced.

Up to now the industrial practice was exclusively characterised by the 2-dimensional contact stylusinstruments. In order to separate roughness from waviness and long wave form components the so called Gaussian filter according to ISO 11562 is nowadays world wide established. The filter mean line derives from the convolution of the measured surface profile with the symmetrical Gaussian bell curve as the weighting function. Shifting of the weighting function is equal to a sliding averaging, whereby loss of data emerges from running in and -out of the filter. Consequently the reading of the measured length is shortened. Using the following regression approach the filter method can be modified in a way that enables the evaluation of the marginal areas too [2,3,4]:

$$\int_0^{lt} \left(z(\xi) - w(x)\right)^2 \cdot s(x-\xi) \cdot d\xi \rightarrow \underset{w(x)}{\text{Min}} \qquad (1)$$

In this formulation $z(\xi)$ are the measured profile values, $w(x)$ is the value of the reference or mean line and $s(x-\xi)$ is the Gaussian weighting function.

Figure 1 shows the filter concept. A measured surface profile with the filter mean line is plotted. Up in the outline for one selected position of x the Gaussian bell curve is demonstrated. Below the profile the minimisation approach is visualised. For each position of the bell curve the level z of a horizontal line w(x=ξ) is varied in such a way that the weighted error square is minimized. For the selected position the black point marks the reference.

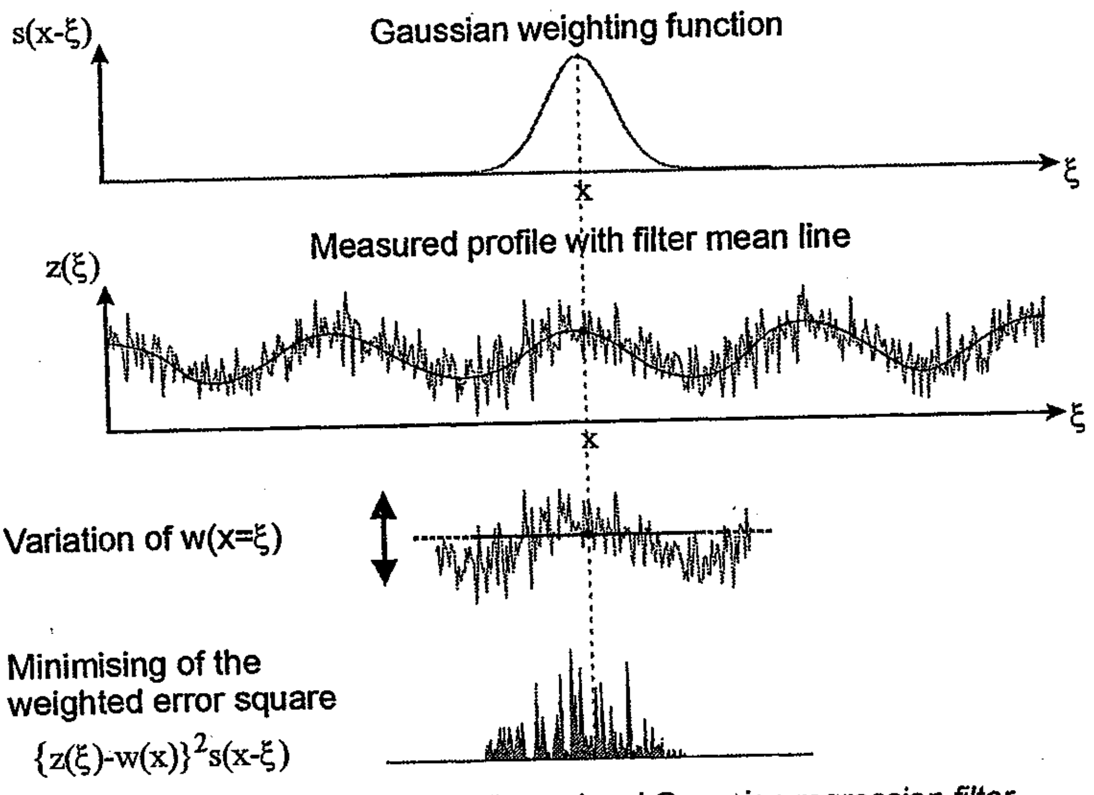


Figure 1: Concept of the 2-dimensional Gaussian regression filter

As mathematical conclusion of this minimising problem from equation (1) the mean line $w(x)$of the Gaussian regression filter can still be described as convolutional integral

$$w(x)=\int_0^{lt} z(\xi)\cdot s_{reg}(x-\xi)\cdot d\xi \quad \text{with} \quad s_{reg}(x-\xi)=\frac{s(x-\xi)}{\int_0^{lt} s(x-\xi)\cdot d\xi} \tag{2}$$

but with the adjusted weighting function $s_{reg}(x-\xi)$ for the Gaussian regression filter. The area enclosed by the function $s_{reg}(x-\xi)$ is always scaled to one. For locations of x outside the marginal areas $\lambda co < x < lt-\lambda co$ the weighting function $s_{reg}(x-\xi)$ is equivalent to the Gaussian weighting function $s(\xi)$ of the standardised filter in ISO 11562.

2.2. 3-D Gaussian regression filter

For the filtering of micro topographies as recorded with 3-D stylus instruments or optical measuring devices like interferometers the formulation from equation (1) is to be extended by another dimension [2,5]:

$$\int_0^{lty}\int_0^{ltx} \left(z(\xi,\eta)-w(x,y)\right)^2\cdot s(x-\xi,y-\eta)\cdot d\xi\cdot d\eta \rightarrow \underset{w(x,y)}{\text{Min}} \tag{3}$$

As weighting function for the Gaussian probability density function the following equation is being applied:

$$\begin{aligned} s(x-\xi,y-\eta) &= \frac{1}{2\pi\cdot\lambda co_x\cdot\lambda co_y\cdot\Lambda_{LP}^2}\cdot\exp\left(-\frac{(x-\xi)^2}{2\cdot\left(\lambda co_x\cdot\Lambda_{LP}\right)^2}-\frac{(y-\eta)^2}{2\cdot\left(\lambda co_y\cdot\Lambda_{LP}\right)^2}\right) \\ &= s(x-\xi)\cdot s(y-\eta) \end{aligned} \tag{4}$$

The minimising problem from equation (3) led to a convolution integral for the calculation of the reference plane as well:

$$\begin{aligned} w(x,y) &= \frac{\int_0^{lty}\int_0^{ltx} z(\xi,\eta)\cdot s(x-\xi)\cdot s(y-\eta)\cdot d\xi\cdot d\eta}{\int_0^{ltx} s(x-\xi)\cdot d\xi\cdot\int_0^{lty} s(y-\eta)\cdot d\eta} \\ &= \underbrace{\int_0^{lty}\underbrace{\int_0^{ltx} z(\xi,\eta)\cdot s_{reg}(x-\xi)\cdot d\xi}_{\text{Filtering along x}}\cdot s_{reg}(y-\eta)\cdot d\eta}_{\text{Filtering along y}} \end{aligned} \tag{5}$$

As demonstrated in equation (5), a function value of the reference plane $w(x,y)$ is being calculated by first carrying out a weighted averaging in x-direction followed by another one in y-direction. The outcome is, that the 3-D Gaussian regression filter can be put down to the 2-dimensional filter described under paragraph 2.1, and it can utilise nearly the same computing algorithms. Combined to $s_{reg}(x-\xi,y-\eta)$ the two weighting functions from equation (5) come out to:

$$s_{reg}(x-\xi,y-\eta)=\frac{s(x-\xi)}{\int_0^{ltx} s(x-\xi)\cdot d\xi}\cdot\frac{s(y-\eta)}{\int_0^{lty} s(y-\eta)\cdot d\eta}=s_{reg}(x-\xi)\cdot s_{reg}(y-\eta) \qquad (6)$$

In Figure 2 the shape of s_{reg} for three selected positions over the measured surface is demonstrated. At position 1 the weighting function lies midst of the measured surface and takes on a rotationally symmetrical form. Position 2 and 3 show how the appearance of the weighting function changes in the marginal areas since it is asymmetrically cut off. The condition of the enclosed volume always equalling one applies for any position of the weighting function.

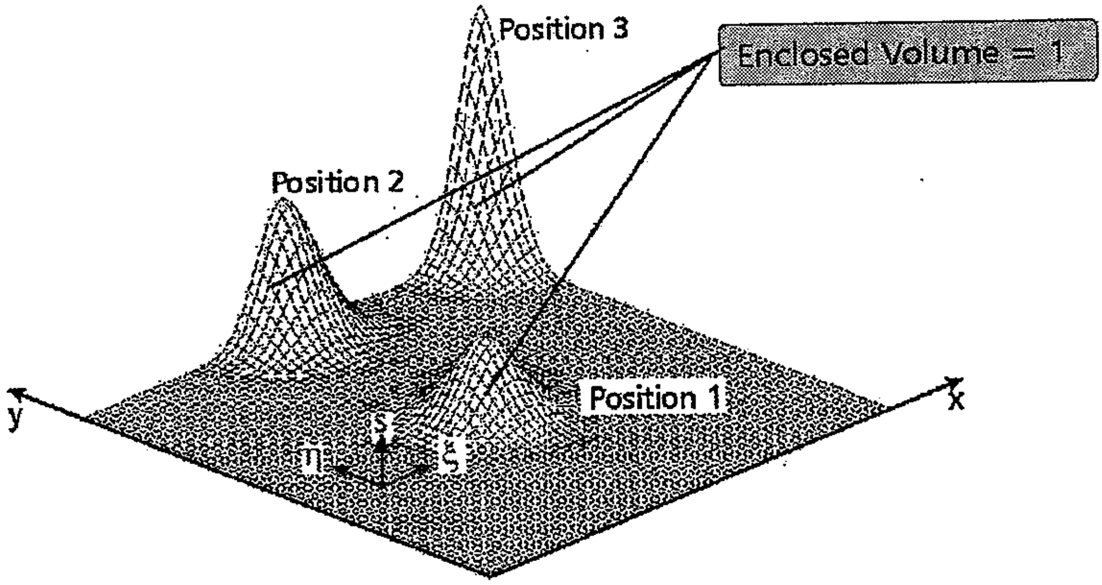


Figure 2: Shape of the weighting function of the 3-dimensional filter [5]

In order to determine the transfer function $S(\lambda co_x,\lambda co_y)$ the range $0.5\cdot\lambda co_x \le x \le ltx-0.5\cdot\lambda co_x$ and $0.5\cdot lco_y \le y \le lty-0.5\cdot lco_y$ is looked at. Taken any wave front with a wavelength λ_r, two new wave fronts with the wavelengths $\lambda_x=\lambda_r/\cos(\varphi)$ and $\lambda_y=\lambda_r/\sin(\varphi)$ can be put down. Because of the integrals in equation (6) $\int_0^{ltx} s(x-\xi)\cdot d\xi \cong 1$ and $\int_0^{lty} s(y-\eta)\cdot d\eta \cong 1$ the transfer function $S(\lambda co_x,\lambda co_y)$ is found to be the Fourier transform of the weighting function of equation (4)

$$S(\lambda co_x,\lambda co_y)=\exp\left(-2\pi^2\cdot\Lambda_{LP}^2\cdot\left(\lambda co_x{}^2\cdot\cos^2(\varphi)+\lambda co_y{}^2\cdot\sin^2(\varphi)\right)/\lambda_r^2\right). \qquad (7)$$

For two different limiting wavelengths λco_x and λco_y the damping of the transfer function depends on the direction of the wave front. For $\lambda co_x = \lambda co_y = \lambda co_r$ the damping is independent of the direction of the wave front:

$$S(\lambda co_r) = \exp\left(-2\pi \cdot \Lambda_{LP}^2 \cdot \lambda co_r^{\,2} / \lambda_r^2\right). \tag{8}$$

The choice of the two cut-off wavelengths is of great importance for sensible adjustment of the filter. If the texture of the surface does not follow a certain direction determined by the manufacturing process, as for example with a sandblasted specimen, the two wavelengths can be equal. But if the surface texture does have a visible direction like a turned or milled surface, the cut-off wavelength must be adjusted according to the direction of the waviness.

3. Robust Algorithm

A filter is being called "robust", as far as so called "outliers" do not lead to a distorted surface roughness. So for example either drag lines or profile peaks can be declared as outliers. Defective spots in optical measuring of the micro topography can be referred to as outliers too and may not affect the calculation of the reference plane. Without additional techniques the Gaussian filter cannot really be called robust [2].

From the field of statistics an algorithm can be taken that extends the Gaussian regression filter described in paragraph 2 to a robust filter [6,7]. Basis for the robust filter is the extension of the arrangement from equation (3) by an additional vertical weighting $\delta(x,y)$ of each measuring point. Mathematically the definition of this weighting function results from using the Beaton-function within a generalised regression arrangement [2,4].

This leads to the following new formulated minimising problem:

$$\int_0^{ltx}\int_0^{lty} \left(z(\xi,\eta) - w_i(x,y)\right)^2 \cdot \delta_i(\xi,\eta) \cdot s(x-\xi, y-\eta) \cdot d\xi \cdot d\eta \rightarrow \underset{w_i(x,y)}{\text{Min}} \tag{9}$$

As labelled in the equation with the index i, the robust algorithm is mathematically being accomplished by an iteration that leads to the reference plane by knowledge of the previous filtering. The algorithm is shown in fig. 3 as a flowchart.

In the first step the reference level is being calculated by the Gaussian regression filter. In this case $\delta = 1$ applies to all weights. Then the median of the absolute values $|r_i(x,y)| = |z(x,y) - w_i(x,y)|$ is being determined. The weights δ calculated by equation (10) girdle the first filter level with a weighting band for all surface ordinates. The parameter c_B is here the limit count of the robust algorithm given by the Beaton function.

$$\text{First step:} \quad \delta_1(x,y)=1$$

$$\text{i-th iteration:} \quad \begin{cases} \delta_{i+1}(x,y)=\left(1-\left(\frac{r_i(x,y)}{c_B}\right)^2\right)^2 & \text{for } \left|\frac{r_i(x,y)}{c_B}\right|<1 \\ \delta_{i+1}(x,y)=0 & \text{otherwise} \end{cases} \quad (10)$$

In order to assess the value limit count c_B without the influence of outliers the median has proofed to be effective [2]. It is estimated c_B by :

$$c_B = 4.4 \cdot \text{Median}\left|z(x,y)-w(x,y)\right| \quad (11)$$

That means the weights are being adjusted in such a way that the surface ordinates lying close to the calculated filter level get the maximum weight of one. The other ordinates further away than 4.4 times the median get a weight of zero.

These iterations are executed until the reference plane between two iteration steps barely changes anymore. The change of the median between two iteration steps is taken as a measure for this. If the change is smaller than a given tolerance the iterations are being stopped.

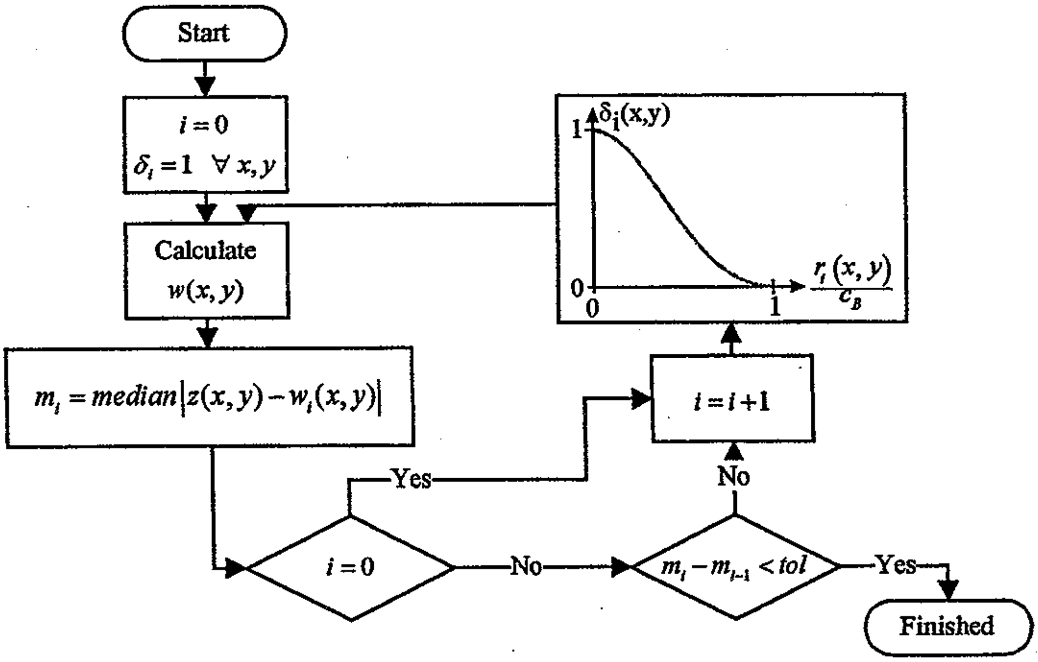


Figure 3: Robust Algorithm for the 3D Gaussian Regression Filter

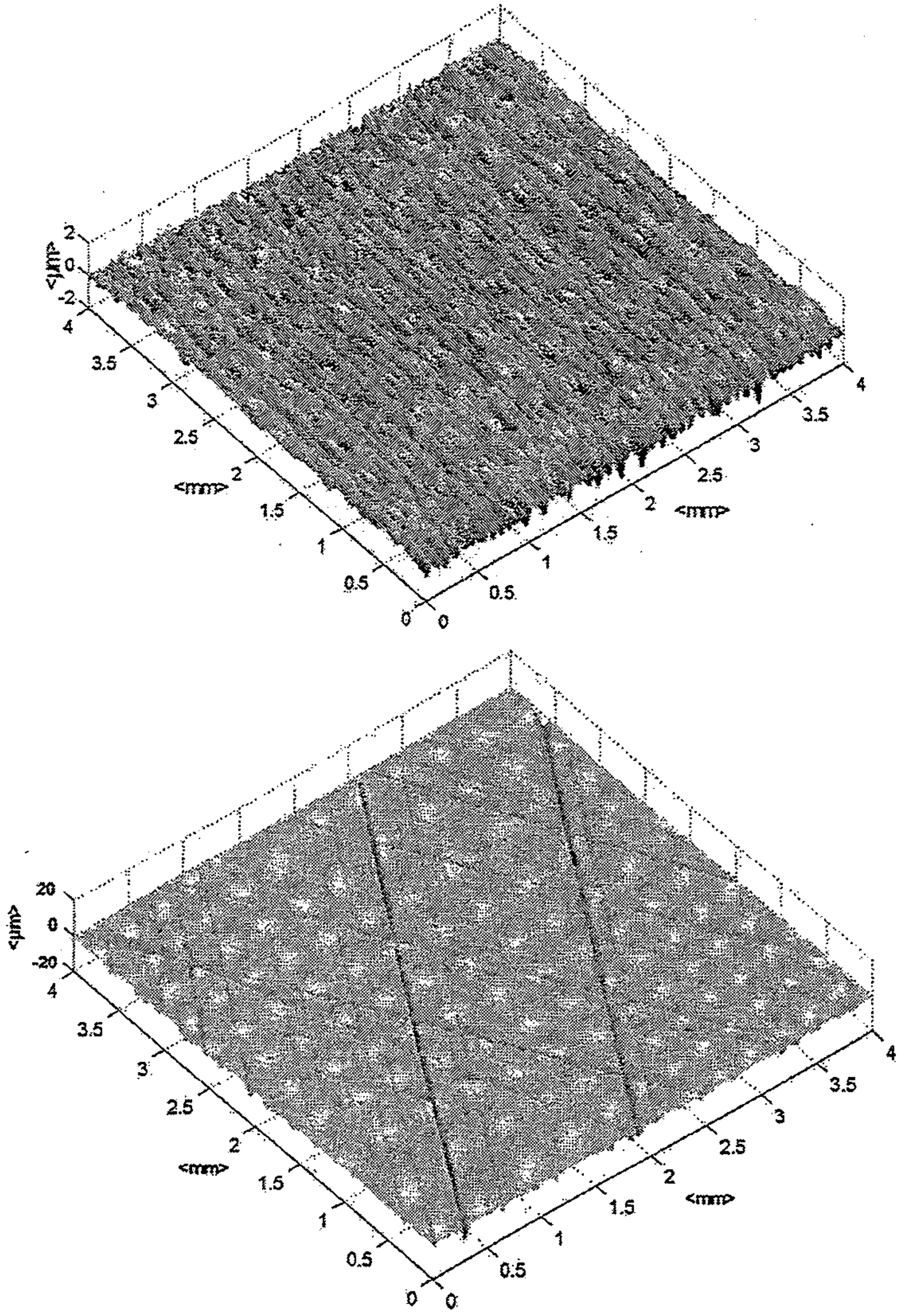


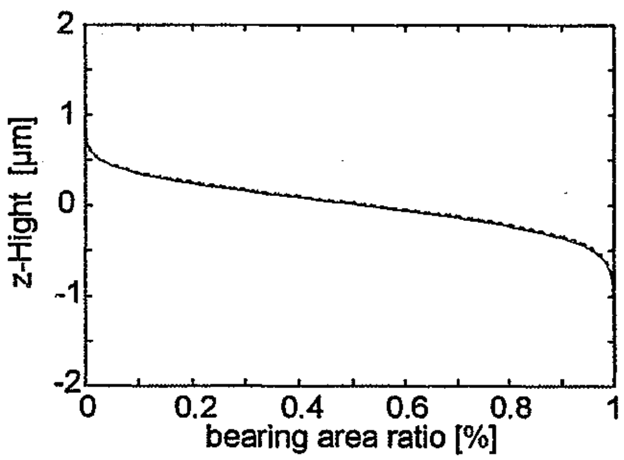
Figure 4: a) ground surface b)plateau honed surface

4. Effects of the robust Gaussian regression filter on surface parameters

The following two different types of surfaces are discussed in order to examine the effect of the robust filter in contrast to the non robust Gaussian filter. The first surface is a ground surface with an approximately symmetric amplitude distribution. The second surface is a plateau honed surface with an asymmetric amplitude distribution and a consequently distinct plateau. Figure 4 shows the plots of these two surfaces after applying robust filtering. For both surfaces the measured area is 4 mm × 4 mm and a cut-off wavelength $\lambda co_x = \lambda co_y = 0.8$ mm is used.

The effect of the robust filter becomes most distinct by the change of the bearing area ratio curve of the two surfaces. In the Figures 5 and 6 the curves for the non robust and for the robust filter and some significant surface parameters are plotted.

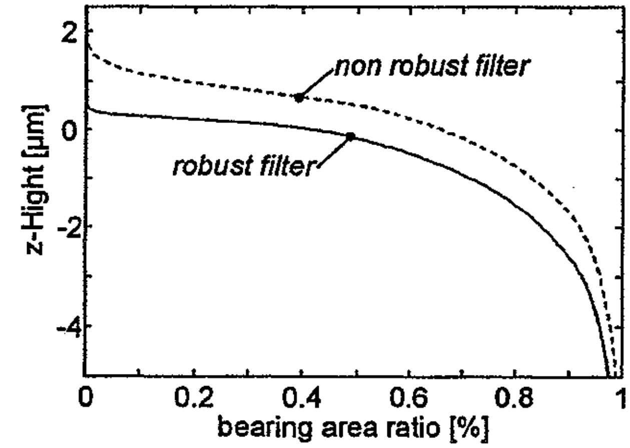
Looking first at the ground surface (Figure 5) the resulting bearing area ratio curves of the both filters lie on top of each other. The robust filter produces nearly the same filter mean plane as the non robust filter. Also the surface parameters hardly show any changes. Therefore the evaluation of such a surface is possible utilising both filters.



		Non robust filter	Robust filter
S_a	[µm]	0.2	0.2
S_t	[µm]	5.3	5.4
S_{sk}		-0.31	-0.32
S_{ku}		3.65	3.69
S_{bi}		0.70	0.70
S_{ci}		1.32	1.32
S_{vi}		0.14	0.14
S_m	[µm³/mm²]	14.2 e3	14.9 e3
S_c	[µm³/mm²]	0.33 e6	0.33 e6
S_v	[µm³/mm²]	41.4 e3	41.4 e3
S_{pk}	[µm]	0.91	0.92
S_k	[µm]	0.74	0.74
S_{vk}	[µm]	0.61	0.57

Figure 5: bearing area ratio curve and surface parameters for the ground surface

In contrast to the ground surface the analysis of the plateau honed surface is very sensitive to the applied filter. As demonstrated in Figure 6 the position and the form of the bearing area ratio curves for the two filters are different. The curve corresponding to the robust filter lies below the one of the non robust filter and is flater within the core area. This indicates that the robust filter leads to a better approximation of the plateau. Parameters illustrating this effect which characterise the form of the roughness amplitude distribution are the skewness S_{sk} and kurtosis S_{ku}. Other significant changes can be seen when transferring the parameter of DIN 4776 [8,9], developed by Bodschwinna, to 3-D surface analysis. The parameter $S_k$characterising the flat core region drop significantly. Looking at the peaks and valleys the volume parameters S_m, S_c, S_v and the index parameters S_{bi}, S_{ci}, S_{vi} proposed by Stout et al. [10,11] show an expected change. The peak and core parameters drop while there is barley change to the valley parameters.



		Non robust filter	Robust filter
S_a	[µm]	1.0	1,.0
S_t	[µm]	15.7	15.7
S_{sk}		-2.1	-2.2
S_{ku}		9.0	9.4
S_{bi}		1.07	1.28
S_{ci}		0.73	0.56
S_{vi}		0.21	0.22
S_m	[µm³/mm²]	17.7 e3	4.3 e3
S_c	[µm³/mm²]	0.87 e6	0.77 e6
S_v	[µm³/mm²]	0.29 e6	0.31 e6
S_{pk}	[µm]	0.59	0.84
S_k	[µm]	1.58	0.93
S_{vk}	[µm]	3.58	3.62

Figure 6: bearing area ratio curve and surface parameters for the plateau honed surface

The influence of the robust filter gets most distinct looking at a profile trace taken from the plateau honed surface (Figure 7). One can clearly make out that the non robust filter cannot represent the plateau whereas the robust filter provides a good closeness.

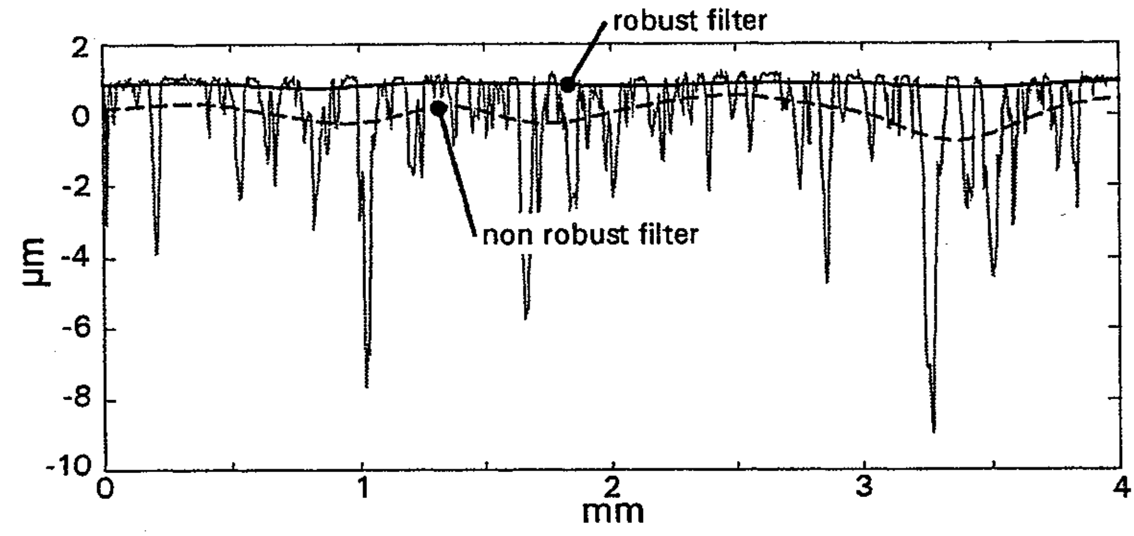


Figure 7: Profile plot with the filter mean lines of the robust and non robust filter

5. Summary

The 3-dimensional robust Gaussian regression filter can be used to access the surface roughness of any engineered surfaces. With its regression approach it is able to handle even smaller measured areas because there is no loss of data in the marginal areas. The robust algorithm is especially designed for stratified functional surfaces, but in contrast to DIN 4776 respectively ISO 13565 [12] this filter can also cope with peaks on a the measured surface. The mean plane of this filter gives a good estimation of the waviness and long wave form components and it is extremely useful as reference plane for the calculation of roughness parameters.

6. References

[1] ISO 11562 (1996): Geometrical Product Specification (GPS) – Surface Texture – profile method – Metrological characteristics of phase correct filters

[2] SEEWIG, J.: Praxisgerechte Signalverarbeitung zur Trennung der Gestaltabweichungen technischer Oberflächen, Disseration, Universität Hannover, eingereicht November 1999

[3] BODSCHWINNA, H., SEEWIG, J.: Verbesserung des phasenkorrekten Filters nach E DIN ISO 11562 zur Trennung von Rauheit, Welligkeit und langwelligen Formabweichungen, DIN-Tagung Geometrische Produktspezifikation und –prüfung (GPS), Leinfelden-Echterdingen, 9./10.Feb. 1998

[4] BODSCHWINNA, H.: I: Oberflächenmesstechnik zur Beurteilung und Optimierung technischer Funktionsflächen, Habilitation, Universität Hannover, 1998

[5] INSTITUTE FOR MEASUREMENT AND CONTROL, UNIVERSITY OF HANNOVER: 3D Filtering Techniques for Functional Surfaces, First Year Progress Report of the European Project "SURFSTAND", The Development of a Basis for 3D Roughness Standards, 1999

[6] HAMPEL, F.: Robust Statistics, John Wiley & Sons, New York, 1985

[7] CLEVELAND, W.S.: Robust Locally Weighted Regression and Smoothing Scatterplots, Journal of the American Statistical Association, Vol. 74, No. 368, 1979, pages 829-836

[8] BODSCHWINNA, H.: Funktionsgerechte Rauheitsmessung, Technische Rundschau 28, 1988, p. 36-40

[9] DIN 4776 (1990): Kenngrößen Rk, Rpk, Rvk, Mr1, Mr2 zur Beschreibung des Materialanteils im Rauheitsprofil

[10] STOUT, K.J., SULLIVAN, P.J., DONG, W.P., MAINSAH, E., LUO. N, MATHIA, T., ZAHOUANI, H.: The Development of Methods for the Characterisation of Roughness in three Dimensions, ISBN 0-7044-1313-2

[11] UNIVERSITY OF HUDDERFIELD: Characterisation and Feature Extraction for Multi-Scalar Surfaces, First Year Progress Report of the European Project "SURFSTAND", The Development of a Basis for 3D Roughness Standards, 1999

[12] ISO 13565(1996): Geometrical Product Specification (GPS) – Surface texture – Profile method – Characterisation of Surface having stratified functional properties