Characterization of form deviations on technical surfaces through structure function analysis

Beñat Gutiérrez-Cañas Pazos*, Claas Falldorf*, Ralf B. Bergmann*,**

*BIAS - Bremer Institut für Angewandte Strahltechnik, Klagenfurter Str. 2, 28359 Bremen, Deutschland
**Universität Bremen, Fachbereich 01: Physik/Elektrotechnik and MAPEX Center for Materials and Processes, 28359 Bremen, Deutschland

mailto: gutierrez@bias.de

The structure function (SF) describes averaged squared height differences as a function of the relative distance between associated positions. As a tool for the statistical analysis of surface structures, the SF is used in this work to quantify form deviations in accordance with DIN 4760 and for the efficient detection of surface features on technical surfaces.

1 Introduction

Reliable methods for the quantitative detection of form deviations are essential for quality assurance. A convenient method for this purpose is offered by the structure function (SF). It describes averaged squared height differences as a function of the relative distance of the associated positions. The SF is a multifunctional tool for the statistical analysis of raw shape data and can be used for any apertures and geometries. It enables the identification of local and global characteristics in the spatial frequency and thus the extraction of relevant parameters for the characterization of technical surfaces. This paper presents the SF as an alternative evaluation method for the characterization of roughness, shape deviations and periodic profiles according to DIN 4760. In addition, a method for the efficient detection of surface features by coordinated parameter selection is shown. The SF is thus a novel useful tool for a holistic characterization of technical surfaces.

2 Definition of the structure function

The SF was originally defined by Kolmogorov for the statistical investigation of turbulence represented by velocity distributions [1]. Here, however, the SF $S(s)$ is used to analyze height data z and, in the one-dimensional case, it describes the mean squared height difference for value pairs (z_i, z_{i+s}) as a function of the separation s by

$$S(s) = \frac{1}{N-s} \sum_{i=1}^{N-s} (z_i - z_{i+s})^2 \qquad (1)$$

with $i = [1, N]$, N being the size of the array. The separation s represents the relative distance between the points under consideration. In contrast to Fourier-based evaluation methods, the SF is clearly defined in the spatial domain and simple units allow an intuitive evaluation of the results. In general, the SF reproduces periodicities on the surface and shows a high sensitivity for roughness differences.

In the two-dimensional case, i.e. for the two-dimensional description of surfaces, a vector-type scan with $\vec{s} = (s_x, s_y)$ allows for the definition of the *Area Structure Function* $S(s_x, s_y)$. It describes analogously for any pairs of points $(x, y), (x + s_x, y + s_y)$ the squared height difference, averaged over all $x \leq m$, $y \leq n$ and is given by

$$S(s_x, s_y) = \frac{1}{m \cdot n} \sum_{x,y=1}^{m,n} \left(z_{x,y} - z_{x+s_x, y+s_y}\right)^2 \qquad (2)$$

with $m = M - s_x$ and $n = N - s_y$ respectively for an image with size $M \times N$ and (s_x, s_y) as the relative separation of the points under consideration. Inherently, the two-dimensional SF provides direction-dependent data on height differences, whereby anisotropy is preserved.

Another possibility to characterize two-dimensional height data is offered by a parallelized, multidirectional construction $S(s)$ of the SF. Here, for a separation s_i the values are averaged across all possible directions (s_x, s_y) with $\sqrt{s_x^2 + s_y^2} = s_i$, resulting in an one-dimensional representation. However, this does not reproduce anisotropy, which is why multidirectional evaluation is particularly suitable for surfaces with statistically distributed properties or characteristics such as roughness. For that case, an advantage of the SF is that via the separation parameter s the sensitivity for discrete frequencies can be determined. Therefore, the separate frequency regimes for roughness, waviness and shape errors can be considered.

3 Characterization of form deviations

3.1 Surface roughness

Multidirectional evaluation of the SF is suitable for the evaluation of surface roughness. Due to the large data basis, this evaluation method yields low-noise results and a high sensitivity that allows for the discrimination of even very small roughness differences. The maximum separation s_{max}, which is still assigned to the roughness regime, corresponds

DGaO Proceedings 2024 – http://www.dgao-proceedings.de – ISSN: 1614-8436 – urn:nbn:de:0287-2024-A033-9
submitted: 23.07.2024 – published: 12.08.2024

to the cutoff wavelength λ_c according to DIN EN ISO 4288. Fig. 1 shows the results of $S(s)$ for two RUGO test surfaces [2] that belong to the same roughness class N2. As can be clearly seen in Fig. 1, the SF-measurement shows a significant difference between the samples that is neither reflected by the roughness class nor by the almost identical Sa-values, although the higher SF values correspond to higher mean height differences and therefore higher roughness. Roughness characterization using the SF thus offers the possibility of defining new characteristic roughness values or also carrying out functional evaluations of surfaces, e.g. to characterize tool wear.

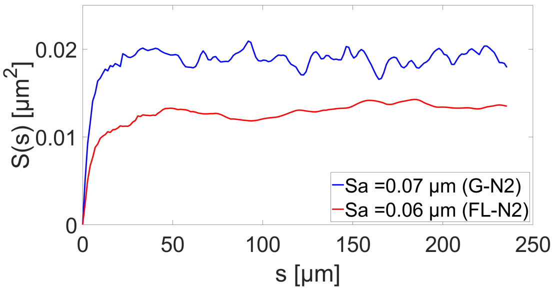

Fig. 1 *Multidirectional evaluation of the structure function (SF) easily visualizes small roughness differences. The higher SF values correspond to higher mean height differences and therefore higher roughness.*

3.2 Periodic profiles

For the characterization of periodic surface structures the linear SF (LSF) can be used. The two-dimensional data is evaluated row-wise in the x-direction and column-wise in the y-direction, and thus enables the determination of the surface periodicity and its orientation dependent structure. The determination of the periodicity (e.g. of the groove spacing RSm) follows from the minima of the LSF. These are per definition located exactly on the wavelength of the input function. In addition, the mean ordinate of the periodic structure relative to the rest of the surface follows from the prominence of the first minimum.

Fig. 2 shows the results of the LSF for a surface machined with a friction tool. Here, the row-wise evaluation along a line section yields a periodicity of $RSm = 223$ px with a prominence of $(0{,}16 \pm 0{,}10)\,\mu\mathrm{m}^2$, which results in a mean ordinate of $\sqrt{0{,}16\,\mu\mathrm{m}^2} = 0{,}4\,\mu\mathrm{m}$.

3.3 Detection of surface features

To detect surface features, the 4D correlation function $\chi(x, y, s_x, s_y)$ can be defined as

$$\chi(x, y, s_x, s_y) = (z(x, y) - z(x + s_x, y + s_y))^2, \quad (3)$$

which describes on a meta level all possible correlations via finite differences for each location (x, y).

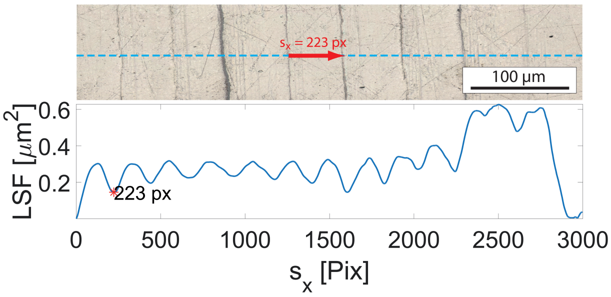

Fig. 2 *By linear evaluation of the structure function along a line section, the periodicity is determined as $RSm = 223$ px and the corresponding mean ordinate as $\sqrt{0{,}16\,\mu\mathrm{m}^2} = 0{,}4\,\mu\mathrm{m}$.*

By scanning selected separations $\vec{s_j}$, maxima can be found in the correlations, which provide the location, average depth and extent of surface features. The selection of separations corresponds to the shape of the feature being searched for. The position (x_0, y_0) at which a maximum average value for $\chi(\vec{s_j})$ is found, provides the position of the feature. Fig. 3 shows a result for the detection of a feature with a "L"-shape. The data points framed in red stand for control separations $\vec{s_c}$, which are used to differentiate from other features (e.g. a rectangle). This feature detection method may also be implemented efficiently with shear interferometry, whereby the measured shear correlations can be used directly, without performing a full shape measurement.

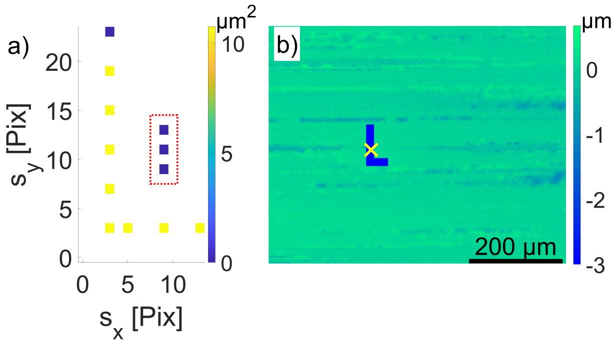

Fig. 3 *By measuring the correlations by means of finite differences according to the "L"- shape searched for (**a**), the position (yellow) of surface features can be determined with pixel accuracy (**b**).*

4 Acknowledgments

The authors thank the Deutsche Forschungsgemeinschaft (DFG) for funding the project Strukturfunktion 2, grant number 288038549.

References

[1] A. N. Kolmogorov, “Dissipation of Energy in Locally Isotropic Turbulence,” Akademiia Nauk SSSR Doklady **32**, 16 (1941).

[2] “Surface Roughness Standard,” `https://www.edmundoptics.de/f/surface-roughness-standard/12888/`.