Reduction of the end-effect in surface texture analysis

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Abstract. The edge-effect in the filtering of the results of surface topography measurements is presently one of the most significant and radical challenges in surface texture assessments. Errors in data analysis are next to measurement problems the most affecting factor of the accuracy for the results obtained. This paper investigates reduction of the edge-filtering-effect of cylinder liner surface textures. Different edge-robust data analysis methods were applied and compared with commonly-used procedures, e.g. those available in commercial software of measurement equipment like various regression Gaussian filters. It was assumed that some of surface topography features are more vulnerable for their false estimation when they are edge-locates and their size (depth, width, section) might be a potentially decisive factor in selecting a correct procedure. The influence of the proposed methods on the selected surface topography parameters (from ISO 25178 standard) calculation and their comparison with the typically used procedures (e.g. Gaussian regression filter) was also comprehensively studied. It was found that some of the digital filters, commonly recommended for commercial software of measuring equipment, did not always provide consistent or direct results when textures with relatively large valleys were carefully examined.

1. Introduction

Accuracy of measurement of surface topography is fraught with many factors which can cause errors that can be roughly classified into systematic and variable errors [1]. Errors in surface metrology, in general, can be also divided into errors caused by the environment [2], measuring instruments [3], software [4], measuring methods [5] and measuring objects [6]. Errors also occur when raw measured data is processed and such errors can be classified as errors of applied procedures [7] or errors in parameter computing [8]. Surface texture, especially if shows tribological behaviour, is often analysed after removal of irrelevant components, e.g. form, waviness, noise; morphological properties of the surface were also carefully considered [9] for turned [10, 11] or milled [12, 13] textures.

Many papers discussed extraction of form or waviness. Besides, unwanted elements of surface geometry are commonly referred to as waviness according to inadequacy in the manufacturing process. There were many algorithms and procedures dedicated to extraction of form or waviness, e.g. regular [14] and robust Gaussian filters [15], least-square or bi-square fitted polynomials [16], the some ‘robust’ for outliers approach [17], spline functions or filters [18], envelope [19] and morphological [20] operations or wavelets [21].

One of the most pressing issues is how to efficiently reduce the end effect in surface metrology. The edge-effect, often defined as an ‘edge-filtering’ problem, especially when a characterisation of functional properties of engineering surfaces is considered, can be specified as a distortion of measurement results when filtering (removing irrelevant features, e.g. form or waviness) is applied. This
severe disadvantage was countervailed by various procedures, e.g. a recursive implementation of Gaussian filters [22], an approach based on assuming periodic boundaries [23], the valley excluding scheme [24] or the machine learning-based surface extrapolation method [25]. Nonetheless, there is still a grave problem with an edge-characterisation of surface texture with some features, e.g. dimples, valleys, oil reservoirs, scratches. The effect of dimple size and distribution was carefully studied for two-process topographies [26] when its influence on both wear in lubricated sliding [27] and characteristics of the Strieber curve [28] was considered. Edge-location was also examined by comparing various robust data processing techniques [29]. A plateau-valley separation method can be also valuable to analyse two-process textures containing dimples [30, 31].

This paper compares the application of various generally-used, available in commercial software, algorithms, e.g. regression Gaussian or robust regression Gaussian filters [32] with envelope [33, 34] and morphological [35] filters.

2. Materials and methods

Two-process textures with additionally burnished dimples of relatively large sizes in some cases were analysed by the envelope (EF) or morphological (MF) filtering methods. The results were compared with those received by the commonly-used procedures, e.g. regular (GRF) and robust Gaussian regression filter (RGRF), the least-squared fitted polynomial plane of 2nd (Poly2) or 4th (Poly4) degree, the regular polynomial plane of 2nd (P2-VEF) or 4th (P4-VEF) degree based on the valley excluding the method presented previously in reference [24].

The surface topography was measured by a stylus instrument, Talyscan 150, with a nominal tip radius of about 2 μm and a height resolution of 10 nm. The measured area was 5 mm by 5 mm (1000 x 1000 measured points). The sampling interval was 5 μm. For the minimisation of the edge-effect of the filtering, the measurement results were provided by areal (3D) and profile (2D) analyses. The surface was levelled after the measurement process.

Some of the textures (profiles) were also assessed by an enlarged detail (extraction) analysis to make the differences in the results more clear and unequivocal. The paper discusses how the minimisation of the end-effect problem is impacted by the proposed algorithms (EF or MF) and how the values of selected surface topography parameters (from ISO 25178 standard) are impacted by a reduction of the edge-effect, specifically by an analysis of feature distribution.

3. Results and discussions

3.1. The edge-effect in surface topography measurements

Usually, for a characterisation of surface textures, especially those with tribological performance, one of the primary data processes is to extract and then remove form and waviness from raw measured results. This type of surface topography components are commonly removed with filters based on the Gaussian functions, e.g. GRF or RGRF. Such filtering methods were presented as exceedingly valuable methods to characterise functional surfaces with tribological performance.

The issue of edge-effect in surface filtering is particularly evident in the characterisation of textures containing deep features, e.g. dimples, scratches, valleys in general. In some cases, width of such features was also very significant; nonetheless, it was not the focus of this work.

It was found that the application of various Gaussian filters (GRF or RGRF) caused a distortion of edges of the analysed details, which is visible by the eye-view assessments of the contour map plots presented in figure 1 (a and b). This fact can also be deduced from the enlarged exaggeration of deep features when filtering was applied in accordance with the polynomial analysis. It was found in the previous research that the some-features (e.g. dimple) excluding approach caused a minimisation of errors in the computing surface topography parameters. Further, the distortion of valleys decreased when the exclusion scheme was accomplished according to the regular least-squared fitted polynomial algorithm, however, the influence of the polynomial degree was not studied in this paper.
Taking into consideration the distribution of surface features (valleys in particular), it was reasonably assumed that the dimples located on the edge or near the edge (usually when the distance between the feature and the edge of the assessed element was smaller than the valley width) of the analysed detail, the distortion increased, in most instances enormously.

![Contour map plots of the cylinder liner texture with wide dimples after the form extraction and removal by the methods of: GRF (a), RGRF (b), Poly2 (c) P2-VEM (d), Poly4 (e) and P4-VEM (f).]

3.2. Proposals of the edge-separation of surface texture features by morphological or envelope filtering
To reduce both the end-effect and distortion of edge-located features, the morphological and envelope filtering methods were proposed and compared with regular procedures. Our research shows that the polynomial approaches (least-square fitted and those with excluding some deep/wide wholes), the ones
using an extraction of features, dimples in particular, caused a smaller exaggerations of valleys, and even more the out-of-dimples areas were more flattened (their $Sq$ value was smaller).

The regular polynomial plane of 2nd or 4th order results from a reduction of oil capacity; the value of $Sv$ parameter usually decreases by from 10 to 30% according to the proposed polynomial plane with the extraction of selected features, dimples in general. Moreover, it is clear from from the eye-view of the contour map plots in figure 2 that the analysed detail seems to be more flattened (b, d), especially in the out-of-valley areas; the form and waviness were removed more thoroughly.

\begin{align*}
\text{(a)} & \quad Sq = 9.51 \, \mu m, \\
& \quad Sp = 12.7 \, \mu m, \\
& \quad Sv = 31.6 \, \mu m, \\
& \quad Sz = 44.4 \, \mu m, \\
& \quad Sa = 6.72 \, \mu m, \\
& \quad Sk = 1.88 \, \mu m, \\
& \quad Spk = 2.4 \, \mu m, \\
& \quad Sv = 3.06 \, \mu m \\
\text{(b)} & \quad Sq = 9.92 \, \mu m, \\
& \quad Sp = 10.7 \, \mu m, \\
& \quad Sv = 34.6 \, \mu m, \\
& \quad Sz = 45.3 \, \mu m, \\
& \quad Sa = 7.08 \, \mu m, \\
& \quad Sk = 1.89 \, \mu m, \\
& \quad Spk = 2.4 \, \mu m, \\
& \quad Sv = 3.06 \, \mu m \\
\text{(c)} & \quad Sq = 8.72 \, \mu m, \\
& \quad Sp = 24.3 \, \mu m, \\
& \quad Sv = 31.8 \, \mu m, \\
& \quad Sz = 56.1 \, \mu m, \\
& \quad Sa = 5.94 \, \mu m, \\
& \quad Sk = 1.89 \, \mu m, \\
& \quad Spk = 2.39 \, \mu m, \\
& \quad Sv = 3.04 \, \mu m \\
\text{(d)} & \quad Sq = 10.5 \, \mu m, \\
& \quad Sp = 10.8 \, \mu m, \\
& \quad Sv = 38.1 \, \mu m, \\
& \quad Sz = 48.9 \, \mu m, \\
& \quad Sa = 7.5 \, \mu m, \\
& \quad Sk = 1.89 \, \mu m, \\
& \quad Spk = 2.4 \, \mu m, \\
& \quad Sv = 3.05 \, \mu m
\end{align*}

**Figure 2.** Contour map plots of the details and their selected surface topography parameters extracted from the cylinder liner surface with two separate dimples, located at the edge of the analysed element. The details are processed by the Poly2 (a), P2-VEM (b), Poly4 (c) and P4-VEM (d) schemes.
MF or EF caused a smaller distortion (flatness) of oil pockets, located mainly at (near) the edge of the analysed detail. Moreover, in comparison with the methods based on the polynomial plane (Poly2, Poly4, P2VEM and P4VEM), the values of parameters describing a valley part of the surface ($S_v$ and $S_vk$) increased by around 30% for some cases. Besides, if all the presented filtering algorithms are considered, MF and EF seem to give the most encouraging results for the eye-view analysis of the contour map plots (figure 3). Firstly, the edge-effect of filtering was reduced (c, d) and secondly, GRF and RGRF caused the removal of form/waviness only in the centre of the considered detail (a, b), although MF or EF minimised the distortions of end-filtering results. Selection between MF and EF can be adequately decided when the given profile is assessed (figure 4).

![Figure 3](image_url)

**Figure 3.** Contour map plots of the details, and their selected surface topography parameters, extracted from the cylinder liner surface with two separate dimples, located at the edge of the analysed element; the details were processed by GRF (a), RGRF (b), MF (c) and EF (d); cut-off = 0.8 mm.
Figure 4. Profiles of the detail extracted from the cylinder liner texture and processed by the methods of GRF (a), RGRF (b), Poly2 (c), P2-VEM (d), Poly4 (e), P4-VEM (f), MF (g) and EF (h); cut-off = 0.8 mm.
The methods of P2-VEM (d), P4-VEM (f) and MF (g) caused a distortion of the edge-dimple areas – convex for polynomial form approximation and concave for morphological operations (the profile descriptions were indicated by the arrows in the mentioned figure). Both exaggerations are not desirable in the extraction of the selected surface features so it seems reasonable to suggest the EF method for a removal of irrelevant features such as form and waviness from surface textures.

4. Conclusions
Removal of form and waviness from results of surface topography measurements requires a thorough assessment of effects received after processing raw measured data. If a procedure is incorrectly selected, tribological behaviour of analysed details can be falsely estimated. This can be even more disadvantageous than if properly made parts were classified as a lack and rejected. Many regular algorithms, included in commercial software of measuring equipment (e.g. Gaussian regression filter, robust Gaussian regression or least-square fitted polynomial plane of nth degree) can cause errors in edge-areas of assessed elements. Moreover, it was previously found that areal form removal can be radically affected by the distribution effect of some of the features located in the considered surface detail.

It was suggested to remove the form of cylinder liner topographies containing oil reservoirs with a prime focus to the minimisation of distortion of the dimples. The exaggeration of the considered features should be detected by areal (3D) and profile (2D) evaluations. From the analysed procedures, the envelope filter provides quite promising results as against conventional (commonly-used) approaches.

The effect of distribution of deep/wide features, e.g. dimples, scratches, valleys in general on areal form removal should be closely studied in further research by an assessment of the density of the detail considered; and the influence of form-separation schemes on values of surface topography parameters should always be taken into account. Additionally, an analysis of the impact of the dimple area on evaluating the usage of the algorithm provided can be especially relevant in future studies.

Acknowledgements
This paper was prepared with financial support from the project no. 2013/09/N/ST8/04333 from National Science Center.

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