Detection of measurement noise in surface topography analysis

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Abstract. Various types of measurement noise detection from the results of surface topography measurements are presented and compared. The types of considered surface textures are: honed, turned, ground, laser-melted, milled, composite, ceramic and isotropic topographies. The measurements are carried out using the stylus (Talyscan 150) or non-contact – optical (white light interferometer Talysurf CCI Lite) equipment. It was assumed that for certain stratified textures, power spectral density assessment would be sufficient, otherwise, the multi-threaded analysis was required. It was also found that certain frequency errors in measurement can be readily detected with profile analysis. Nonetheless, when measurement noise amplitudes are relatively small, e.g. root mean square height (Sq) < 10%, then the isometric view detection is nearly impossible. For the detection of high-frequency measurement noise, the power spectral density analysis is required; for this type of texture, the high-frequency measurement noise surface (HFNS) is described using the regular spline filter. It is indicated that the HFNS should be observed if the machining marks are visible in the isometric view. Secondly, accurately defined HFNS should contain only the high-frequency rather than low-frequency details.

1. Introduction
Surface topography measurement, especially of “engineering textures,“ is fraught with numerous factors, which can be defined or divided according to various criteria. One of them is a classification by errors resulting from internal (e.g. drivetrains operation) and external factors (e.g. vibrations or temperature fluctuations) [1]. Nonetheless, the classification of surface texture measurement errors specified for high-precision engineered surfaces should be more precisely considered. Uncertainty in measuring might be caused by the environment, measuring equipment, the measured object, software and measuring method errors. Other types of measurement uncertainty are: errors typical for the measuring method, errors obtained during data processing [2], errors caused by the digitisation process [3] and other errors [4].

Surface topography measurement errors are commonly defined as measurement noise, or simply noise [5], which can be generated e.g. by aperiodic stochastic vibration. Random factors during the cutting process can also affect noise distribution throughout the entire frequency domain. Moreover, machined surface topography, which is often contaminated with heavy noise [6], is known to contain complex frequency components that might be the source of valuable feedback for the machining process as well as the tool path errors. The errors in the measurement of surface topography increase substantially along with the rising complexity of analysed detail [7].
The de-noising process is usually proposed in the frequency domain. To date, a number of frequency-based algorithms have been proposed for the extraction of irrelevant features from surface textures, e.g. Gaussian approaches and their modifications [8-10], wavelet transform procedures [11], spline filters [12], morphological [13] or envelope [14] approaches and other algorithms [15]. However, the detection of measurement noise from the results of raw measured data has not yet been widely investigated (especially in the high-frequency domain since low-frequency noise was previously studied [16]).

Typical stylus errors (noise) are conventionally represented using mechanical filtering of the stylus tip [17]. Another type of measuring equipment – optical instruments – applied for measurements of areal topographies, can be particularly sensitive to noise presence, especially in scanning applications [18]. In surface topography measurement, the detection and the reduction of the high-frequency errors (HFE) seem to be particularly important. False indication of surface topography parameters (caused by a non-proper extraction of irrelevant features, e.g. form, waviness or noise) can result in the rejection of properly made parts. Therefore, in this paper, different types of noise detection methods are discussed and proposed.

2. Materials and methods
The following types of surface topographies were analysed: honed, turned, ground, laser-melted, milled, composite, ceramic or isotropic. The measurements were carried out by stylus instrument Talyscan 150 with a ±2 µm nominal tip radius, height resolution 10 nm, or white light interferometer Talysurf CCI Lite (height resolution 0.01 nm). The measurement area was 5 mm by 5 mm (1000 x 1000 measured points) for the stylus approach or 3.35 mm by 3.35 mm (1024 x 1024 points) for the non-stylus equipment. The sampling interval and spacing were 5 µm and 3.27 µm, respectively.

The methodology of measurement noise detection from the raw measured data involved several different procedures. Firstly, the out-of-feature areas of the surface were studied using prior results. The out-of-feature analysis is based on the selection of regions (profiles) of a measured detail and correlating them with the noise detected in the measurement results. Although the procedure enables analysing the effect of feature distribution (e.g. dimple size or location [19]) on the measurement noise occurrence, the issue was outside the present scope.

Other techniques employed in the reported investigations were Power Spectral Density (PSD) and the Autocorrelation Function (ACF) graphs. PSD in its two-dimensional is a common measure of surface roughness in related standards for surface texture [20]. The high-frequency measurement noise surfaces (HFNS) were also defined by S-separation (removal of surface texture components from the raw measured data with application of the S-operator [21]). The influence of measurement noise detection on the values of surface topography parameters (from ISO 25178 standard) was also taken into account.

3. Results and discussions

3.1. Problems with measurement noise detection
Measurement noise, especially HFE, can be discerned by observation of a measured detail. Figure 1 presents examples of a milled texture measured at different speed using the stylus approach. The noise occurrence is represented in the areal (3D) (a, b) or profile (2D) (c, d) isometric analysis. One of the proposals for measurement noise definition is to characterise the surface texture with the PSD. Reduction of PSD variance is recommended [22] when the surface texture is considered.

From the analysis of PSD graphs, it can be seen that measurement noise frequencies (HFE in particular) cannot be directly observed (detected). For various measurement conditions (e.g. measurement velocity [23]) the differences in the PSD graphs were negligible or non-existent (Figure 1, g, h). Similar problems were observed for honed, turned, ground or laser-melted details. For ceramic and composite topographies, the HFE were detected, but the differences were similarly hard to follow (usually almost negligible).

It was directly observed that increasing the measurement velocity resulted in the rise in surface topography parameters. The HFE presence caused an overestimation of height and feature parameters,
especially in the Spd (peak density) parameter. Neither of the analyses, i.e. the values of surface topography parameters nor an isometric view of contour map plots, produced a conclusive outcome in the detection of the measurement errors in the high-frequency domain.

\[ \text{Sq} = 0.772 \text{ mm}, \; \text{Sp} = 5.15 \text{ mm}, \; \text{Sv} = 8.58 \text{ mm}, \; \text{Sz} = 13.7 \text{ mm}, \; \text{Sa} = 0.587 \text{ mm}, \; \text{Spd} = 163 \text{ \(1/\text{mm}^2\)}, \; \text{Spc} = 25.1 \text{ \(1/\text{mm}\)} \]

\[ \text{Sq} = 0.943 \text{ mm}, \; \text{Sp} = 6.45 \text{ mm}, \; \text{Sv} = 8.76 \text{ mm}, \; \text{Sz} = 15.2 \text{ mm}, \; \text{Sa} = 0.734 \text{ mm}, \; \text{Spd} = 766 \text{ \(1/\text{mm}^2\)}, \; \text{Spc} = 101 \text{ \(1/\text{mm}\)} \]

Figure 1. Contour map plots (a, b), parts of profiles (c, d), parameters (e, f), and the areal PSDs (g, h) of a milled texture measured by stylus instrument with a various speed: 0.2 mm/s (left column) or 1 mm/s (right column).

3.2. Feature-based separation of measurement noise

It was found that feature occurrence (e.g. deep/wide scratches, dimples, valleys in general) has a considerable impact on the measurement noise (especially HFE) detection. Therefore, for more precise measurement noise assessment, the out-of-valley or “machining-mark-tracking” analysis was employed.
The out-of-valley analysis extracts the surface area with no valleys. The out-of-valley extraction can be replaced by the valley extraction method [24] should all the measured area need to be considered.

Figure 2 compares the valley and out-of-valley isotropic profiles. It was assumed that in profiles not exhibiting extensive valleys, the detection of measurement noise with PSDs was facilitated. Therefore, in textures containing extensive deep and broad, elements, HFE detection should be accomplished with out-of-feature characteristics.

Another method is based on tracking of the machining marks on the analysed detail. This approach can be exceedingly valuable for periodic textures, e.g. turned or ground topographies. Figure 3 presents the application of this method was presented for the ground surface. It was assumed that "machining-mark-tracking" method gave more direct results in the PSD-detection of HFE. Small-scale frequencies (high-frequencies) were more visible on the PSD graphs designated for extractions received with the proposed scheme than for vertical or horizontal profiles.

Both methods (out-of-dimple and "machining-mark-tracking") depend on the precise extraction of features. A detailed analysis of profiles cannot provide a thorough evaluation when 3D detail (out-of-feature) or 2D profile ("machining-mark-tracking") are selected without due diligence. Consequently, in-depth surface measurement and analysis require both accurate visual analysis and exact extraction of detail (profile) from an analysed surface.

**Figure 2.** A profile containing a dimple (a) and out-of-valley profile (b) (with their corresponding PSDs), extracted from an isotropic surface measured with speed equal to 0.8 mm/s.
Figure 3. "Machining-mark-tracking" method with profile assessment: measured ground detail (a) and vertical (b) or machining-mark-trace (d) profiles with their corresponding PSDs (c and e).

3.3. Reduction of measurement errors with the application of spline filter

The proposal for the measurement noise reduction is based on the characterisation of (spline) filtration results received with the S-scale (S-operator application). The spline filter is a commonly used algorithm for surface filtration (available in the commercial software) [25]. To reduce the HFE, the regular spline filter [26] with a cut-off value equal to 0.025 mm was applied. It was assumed that S-filtering results, defined as an HFNS should contain only the pre-filtered frequencies. In the considered example, the HFNS should contain high-frequency components as a dominant frequency.

From the isometric view analysis of HFNS contour map plots (Figure 4), it emerged that when measurement noise amplitude was relatively small (usually the value of Sq of the received HFNS was smaller than 10% of Sq value of measured surface), then the HFNS contain some non-noise features,
e.g. reservoirs (a), scratches (c, e) or other. Simultaneously, it can be concluded that not only the irrelevant features were removed by the spline filter and that the measurement noise amplitude in the obtained raw measured data was also relatively small.

**Figure 4.** The HFNS received by spline filtration, defined for composite (a, b), milled (c, d) and honed surfaces (e, f) measured with 0.1 mm/s (a, c, e) and 0.7 mm/s speed (b, d, f).
It is tentatively suggested that to reduce the measurement noise, in particular the HFE, with the filtering method should contain the analysis of the received S-separated components, occurring as a result of measurement noise. In particular, the analysis of the presented HFNS may be worth considering. Nonetheless, a careful selection of the filter and its bandwidth should be conducted.

4. Conclusions
The detection of measurement noise is fraught with many factors that affect the accuracy of the analysis. In this paper, some suggestions were presented for the selection of measurement noise separation procedure; their application can improve accuracy in the extraction of irrelevant features from the results of surface topography measurements.

The results from the study indicate that the out-of-feature detail (profile) analysis ought to be employed when describing the surfaces containing relatively deep/wide/extensive dimples/scratches/valleys. This particularly applies to measurement noise detection with power spectral density techniques. Furthermore, the feature-based extraction of profiles (machining mark tracking) might be of value when periodic (largely non-isotropic) textures are considered.

It was also found that the detection of measurement noise is significantly hampered by a small measurement noise amplitude (designated in relation to the root mean square height of the measured surface), even though the measurement noise amplitude was not the primary research objective of this paper.

The high-frequency measurement error reduction can be achieved by the application of a regular spline filter. It, however, requires precise filtration of results (received by the S-operator separation). The obtained high-frequency measurement noise surface should contain only the irrelevant (in the raw measured data) components, that is no machining marks should be found on this detail.

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