euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020

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Mathematical approach to the validation of surface texture filtration software

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Abstract

We introduce a novel method for the validation of surface texture filtration. The method utilises a combination of a mathematically defined surfaces and an accurate evaluation of the linear Gaussian filter transmission characteristic function to produce a mathematically traceable reference pair suitable for the performance assessment for surface texture analysis software. The method is suitable for both profile and areal surfaces and filtration methods. We showcase the method with two example reference pairs; one profile and one areal, which are used to demonstrate how the performance of a surface texture analysis software package can be assessed. Results are presented for a variety of Gaussian filter options, including end effect removal widths and end effect management.

Surface texture, Areal parameters, Profile parameters, Filtration

1. Introduction

The analysis of surface texture is an important aspect of surface topography characterisation in the field of precision manufacturing [1,2]. Surface texture can have a significant effect on a part via the mechanical interaction between it and its environment. Attributes such as friction and wear can impact the overall lifetime of a component and contribute toward energy consumption and efficiency [3,4].

Surface texture analysis is usually performed using surface texture field parameters; numerical descriptors of a surface that provide statistical information about the distribution of heights across a measured area [1,5,6]. Obtaining meaningful surface texture parameters from a surface topography measurement is achieved by first performing adequate filtration operations in order to extract a finite spatial frequency band from the surface measurement data. Appropriate a priori knowledge is required to determine the scale-limited surface relevant to the application at hand, enabling efficient and effective analysis.

Surface texture analysis software is used to perform filtration operations, nevertheless, it is important that such software is validated against reference values. The current state of the art uses reference software, developed by National Metrology Institutes, to calculate parameter values for a given input surface topography dataset against which software-obtained values can be compared [7-9]. However, these reference software packages are developed using similar numerical, discrete-based algorithms as commercial software and, therefore, are subject to the same sources of error. Previous work has compared the output parameter values of different reference software packages and shown significant variations in the results [10]. These differences justify the need for an alternative approach to surface texture analysis software validation.

Previous work has addressed the calculation of areal surface texture parameter values using a mathematical foundation [11,12]. By defining a surface analytically, surface texture parameter values can be obtained that are accurate and mathematically traceable. These mathematically defined parameter values can then be used as traceable references against which software can be compared.

The work presented in this paper continues from the previous work by applying the same mathematical approach to the filtration operations required prior to parameter calculation. A technique is presented that enables the creation of mathematically traceable reference pairs; one pre-filter analytical surface and one post-filter analytical surface, that can be used as reference surfaces that assess the performance of software implemented filtration operations. This paper focusses on the linear areal and profile Gaussian filters [13,14].

2. Reference pairs

In order to assess the performance of filtration operations in software, it is necessary to analyse the outputs of such operations. This can be achieved by providing the software with a known input and comparing the result with a known output value. This is known as using a reference pair.

2.1. Input mathematical surface

The first component of the reference pair is the input reference. This is an analytical mathematical expression that corresponds to a pre-filter surface height representation. Such an expression is achieved using a Fourier series approach, wherein a spatially variant signal can be constructed using a summation of weighted cosine terms, each one of a defined spatial frequency. A general expression for an areal surface defined using this Fourier series approach can be presented in the form

$$z(x,y) = \sum_{n=1}^{N}\sum_{m=1}^{M} A_{n,m}\cos\left(2\pi f_s\left(\frac{m(x+\phi_x)}{N_x} + \frac{n(y+\phi_y)}{N_y}\right)\right), \tag{1}$$

where $N \times M$ is the total number of terms; m and n denote the x and y spatial frequency components of each term, respectively; $A_{n,m}$ defines the amplitude of each term; N_x and N_y represent the size of the surface in the x and y directions as multiples of the scaling length $1/f_s$; and ϕ_x and ϕ_y are the phase shifts of the cosine term in the x and y directions, respectively. N_x/mf_s and N_y/nf_s are equivalent to the x,y wavelength components, respectively.

2.2. Transmission characteristics

In order to obtain the second component of the reference pair, the reference output, a filtration operation must be performed on the input surface. For this work, the filtration operation of interest is the linear Gaussian filter.

In accordance with the ISO 16610-21 specification standard for a linear Gaussian filter for an open profile surface [13], the weighting function is given by

$$s(x) = \frac{1}{\alpha \times \lambda_c} \exp\left[-\pi\left(\frac{x}{\alpha \times \lambda_c}\right)^2\right], \tag{2}$$

where λ_c is the filter cut-off wavelength and $\alpha = \sqrt{\ln 2/\pi}$. From the weighting function, it is possible to obtain the transmission characteristic. The long-wave low-pass transmission characteristic function for the linear Gaussian filter is defined by

$$T(\lambda) = \exp\left[-\pi\left(\frac{\alpha \times \lambda_c}{\lambda}\right)^2\right]. \tag{3}$$

The transmission characteristic is a function that defines the relative magnitude of transmission of a signal through a filter, as a function of frequency. Combining this function with the Fourier series definition of the surface enables simple, traceable application of the filter by adjusting the amplitudes of each cosine according to the frequency of the term and its value in the transmission characteristic function. The high-pass transmission characteristic is simply given by $1 - T(\lambda)$.

The expressions here are given for the profile case. However, as the areal linear Gaussian filter is separable, it is straightforward to apply the same approach to the areal case. For a separable input Fourier series surface expression, wherein each cosine term is only a function of either x or y, the transmission characteristic function can be applied in the same method as for the profile case. This enables both profile and areal filtration algorithms in surface texture analysis software to be assessed using the same technique.

3. Case study

To showcase this new method of software validation for surface texture filtration, a case study has been performed in which reference pairs have been used to assess a commercial surface texture analysis software package. Two reference pair sets have been created; one for profile linear Gaussian filtration and one for areal linear Gaussian filtration.

3.1. Profile filtration

A mathematical profile surface was defined that comprised of three cosine terms, each with amplitude of 1 m, and with wavelengths of $\lambda_1 = 1/10$ mm, $\lambda_2 = 2/10$ mm and $\lambda_3 = 3/10$ mm. Using a cut-off wavelength of $\lambda_c = 2/10$ mm, the transmission characteristic curve was evaluated for each cosine term to obtain the output amplitude for each term, resulting in a new post-filter mathematical profile surface. 1000 datapoint discrete representations of these functions are shown in figure 1.

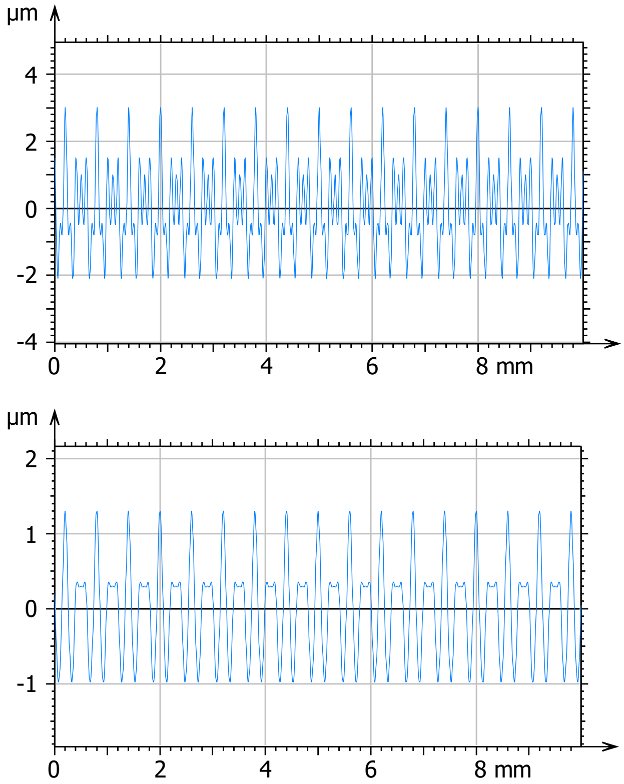

Figure 1. Profile linear Gaussian filter reference pair for $\lambda_c = 2/10$ mm. *Top*: Pre-filter reference. *Bottom*: Post-filter reference

The pre-filter reference profile was input into a commercial surface texture analysis software package and a linear low-pass Gaussian filter operation was performed using a matching filter cut-off wavelength of $\lambda_c = 2/10$ mm. The resulting surface was then aligned and subtracted from the post-filter reference surface to obtain a difference profile, as shown in figure 2. The results show good agreement with the reference surface for the bulk of the profile; however, significant end effects are present. By default, the software was set to cut off the ends of the profile to account of finite filter width end effects using a size of $\lambda_c/2$ for each end. The results show that this is too short, and still leaves significant end effects behind. Adjusting this setting to remove a length of λ_c from each side gives the results shown in figure 3, which shows a much-improved result, with error magnitudes on the order of 10^7 times smaller than the original surface. It should be emphasised that the bulk of the surface shown in figure 2 has the same error magnitudes as those shown in figure 3, however, they are obscured by the significant errors found at the ends of the profile.

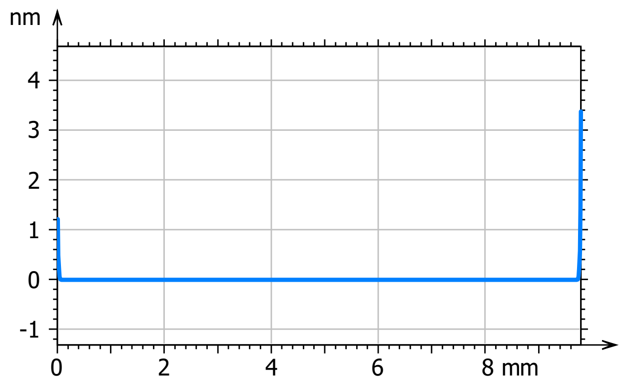

Figure 2. Difference between low-pass post-filter reference and software result with $\lambda_c/2$ width end removal.

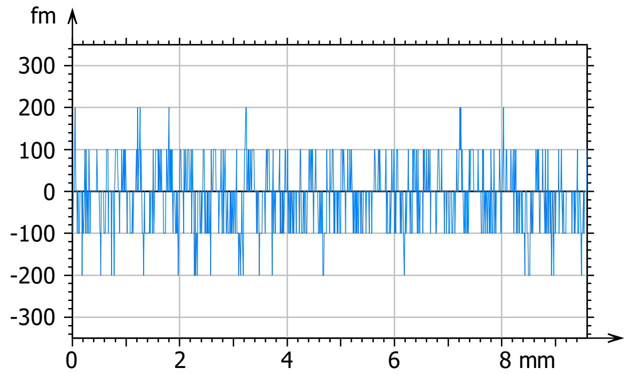

Figure 3. Difference between low-pass post-filter reference and software result with λ_c width end removal.

3.2. Areal filtration

An areal pre-filter mathematical reference surface was created using a total of six separable cosine terms; three with an x component and three with a y component. The x-direction component were given wavelengths of $\lambda_{1,x} = 1$ mm, $\lambda_{2,x} = 2$ mm and $\lambda_{3,x} = 3$ mm, and the y-direction components were given wavelengths of $\lambda_{1,y} = 15/10$ mm, $\lambda_{2,y} = 25/10$ mm and $\lambda_{3,y} = 35/10$ mm. Using a cut-off filter wavelength of $\lambda_c = 2$ mm, the transmission curve was evaluated in the same way as for the profile case for each of the six cosine terms to obtain the post-filter amplitudes. 1000×1000 datapoint discrete representations of these functions are shown in figure 4.

Similar to the profile case, the areal pre-filter reference was input into a commercial surface texture analysis software package and a low-pass areal Gaussian filter was performed with a filter cut-off wavelength of $\lambda_c = 2$ mm. The resulting difference surfaces obtained using the same method as the profile case, for end effect removal of $\lambda_c/2$ and λ_c from each edge, are shown in figures 5 and 6, respectively. The results are similar to those found for the profile case, with a large end effect removal required to fully account for all end effects. In addition, a more structured resulting error in found, as shown in figure 6, with four distinct ‘lobes’ present. The magnitudes of these errors are also larger than those found in the profile case and presented in figure 3.

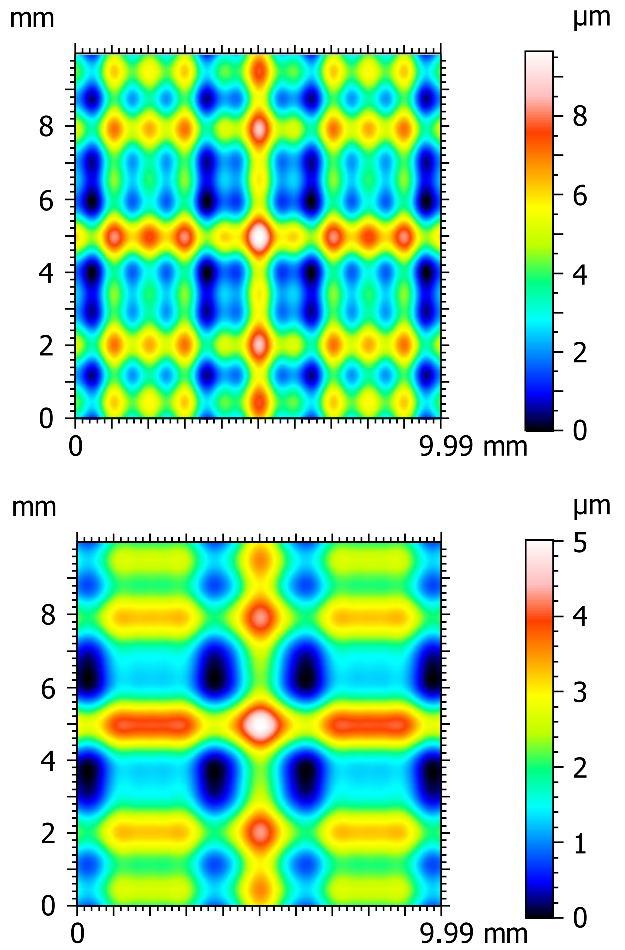

Figure 4. Areal linear Gaussian filter reference pair for $\lambda_c = 2$ mm. *Top*: Pre-filter reference. *Bottom*: Post-filter reference

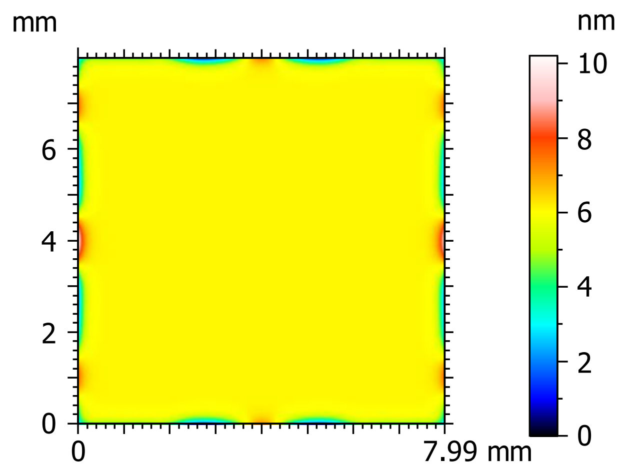

Figure 5. Difference between low-pass areal post-filter reference and software result with $\lambda_c/2$ width end removal.

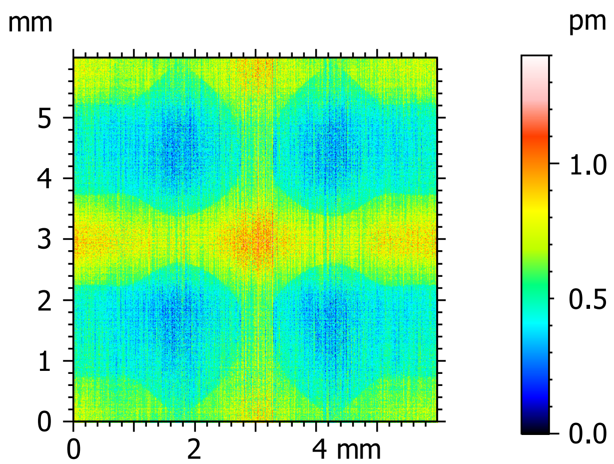

Figure 6. Difference between low-pass areal post-filter reference and software result with λ_c width end removal.

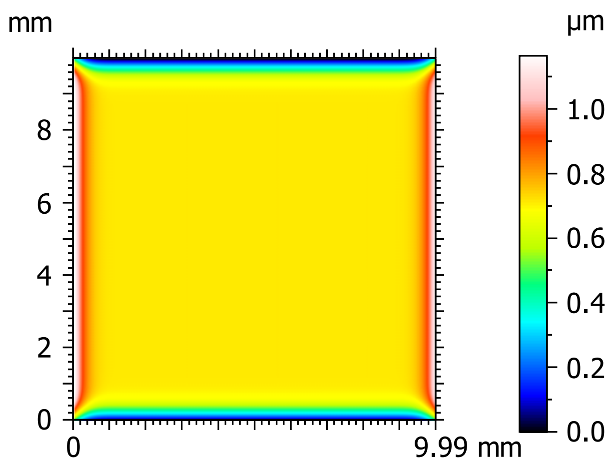

Figure 7. Difference between low-pass areal post-filter reference and software result with end effects managed.

Figure 7 presents the difference results if, instead of removing the edges of the surface to account for end effects, the effects are managed algorithmically. This has the benefit of retaining the same evaluation area as the pre-filter surface, avoiding the need to remove potentially valuable regions of the measured surface. Here, the results show that despite attempts to manage the end effects, significant difference values are still present. The magnitudes of these end effects are enough to dominate the edge regions of the surface and will significantly affect the post-filter surface within these regions, distorting the topography. However, these distortions occur in areas of the surface that would otherwise be removed, and so additional information may still be obtainable by users of the software. By utilising the software validation methods presented here, users can be more informed of the extent of the meaningful information that can be obtained from such regions.

4. Conclusions

The need for accurate surface texture measurement is becoming an increasingly important aspect of precision manufacturing. Surface texture parameters play a key role in the quantitative description of surface texture, and filtration is a crucial prerequisite step to ensure the finite spatial frequency bandwidth of interest is being investigated.

This work presents a novel method for the validation of surface texture filtration software by utilising the mathematical definitions of both surfaces and filtration operations to produce a fully traceable reference pair. This reference pair is then used to assess software performance by comparing the result of the software's operation on the input reference to the output reference.

The work in this paper focusses on the linear Gaussian filter, and has been applied to both profile and areal surfaces. Example reference pairs were used in combination with a commercial surface texture analysis software package to prove to efficacy of the method. In addition, difference software settings that address the end effects introduced when applying a finite width Gaussian filter were investigated in comparison to the reference surfaces.

With the validity of this method established, future work is planned to investigate other standard filtration methods used in both profile and areal surface texture analysis.

References

[1] Leach R K 2014 Fundamental Principles of Engineering Nanometrology (Binghamton: Elsevier Science)
[2] Bruzzone A A G, Cost H L, Lonardo P M and Lucca D A 2008 *Ann. CIRP* **57** 750-769
[3] Menezes P L, Kailas S V and Lovell M R 2011 *Tribology letters* **41** 1-15
[4] Holmberg K and Erdemir A 2017 *Friction* **5** 263-284
[5] ISO 4287 1998 *(GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters* (Geneva: International Organisation for Standardisation)
[6] ISO 25178-2 2012 *(GPS) – Surface texture: Areal Part 2: Terms, definitions and surface texture parameters* (Geneva: International Organisation for Standardisation)
[7] Blunt L, Jiang X, Leach R K, Harris P and Scott P 2008 *Wear* **264** 389-393
[8] Bui S H and Vorburger T V 2007 *Precision Engineering* **31** 218-225
[9] Jung L, Krueger-Sehm R, Spranger B and Koenders L 2004 *XI International Colloquium on Surfaces* (Chemnitz, Germany) 164
[10] Todhunter L D, Leach R K, Lawes S D A and Blateyron F 2017 *Measurement Science and Technology* **28** 065017
[11] Todhunter L D, Leach R K, Lawes S D A, Harris P M and Blateyron F 2019 *Surface Topography: Metrology and Properties* **7** 015020
[12] Todhunter L D, Leach R K, Lawes S D A, Harris P M and Blateyron F 2020 *Surface Topography: Metrology and Properties* In press
[13] ISO 16610-21 2012 *(GPS) – Filtration Part 21: Linear profile filters: Gaussian filters* (Geneva: International Organisation for Standardisation)
[14] ISO 16610-61 2015 *(GPS) – Filtration Part 61: Linear areal filters: Gaussian filters* (Geneva: International Organisation for Standardisation)