Precision Engineering
Journal of the International Societies for Precision Engineering and Nanotechnology
26 (2002) 222–235

PRECISION ENGINEERING

Recent advances in separation of roughness, waviness and form

J. Raja*, B. Muralikrishnan, Shengyu Fu

Center for Precision Metrology, University of North Carolina at Charlotte, 9201 University City Blvd, Charlotte, NC 28223, USA

Received 17 September 2001; accepted 6 December 2001

Abstract

Engineering surfaces are comprised of a range of spatial wavelengths. Filtering techniques are commonly adopted to separate the different wavelength components into well-defined bandwidths. Filtering is done prior to numerical characterization and it is also essential for extracting information needed to provide process feedback and establish functional correlation. This paper reviews commonly used filters in surface metrology like the 2RC, Gaussian and several new ones currently under research such as the spline, morphological, wavelets, regression filters and robust regression filters. The need for these new filters and examples illustrating the features of these filters are also presented. © 2002 Elsevier Science Inc. All rights reserved.

Keywords: Surface metrology; Filters; Roughness; Waviness

1. Introduction

A typical engineering surface consists of a range of spatial frequencies. The high frequency or short wavelength components are referred to as roughness, the medium frequencies as waviness and low frequency components as form. Fig. 1 illustrates this. In many cases the original profile may also contain significant form such as a radius. In the early days, different instruments and measurement techniques were adopted to capture the different wavelength regimes. Visual assessment using microscopy was used to identify any torn material or micro burr. Stylus-based instruments were used to obtain roughness. Other special instruments obtained form information. Today, with the availability of increasingly sophisticated gages, sensors and powerful data processing capabilities using personal computers, there is an overlap of measuring capability. A typical stylus-based instrument can capture roughness, waviness and form. A roundness measuring instrument can also gather straightness data and a CMM can get both dimensional information and form. Fig. 2 shows the current metrology measurement spectrum. As the bandwidth of measurement instruments increases, it becomes essential to separate surface profile data into meaningful wavelength regimes before numerical characterization.

Historically, it has been accepted that different aspects of the manufacturing process generate the different wavelength regimes and these affect the function of the part differently [3]. However, there are no case studies that conclusively prove this relationship. By separating surface profile into various bands, it is possible to map the frequency spectrum of each band to the manufacturing process that generated it. Thus, filtering of surface profiles serves as a useful tool for process control and diagnostics. While engineers commonly trace manufacturing process variations based on surface profile data, mapping the functional performance of a component based on surface profile information has been a challenge. The different wavelength regimes play a key role in critical parts like crankshafts and bearings. Thus, separation of signal into various bandwidths has to be viewed from a functional standpoint as well. Recent trend in outsourcing of manufacturing makes it essential to define surface texture requirements very clearly. This has made it necessary to use filtering techniques to establish the required wavelength regimes before numerical characterization. In addition, meaningful comparison of parameters from different surface texture measuring instruments can only be done if filtering techniques are used to establish identical bandwidths. Hence filters used in surface texture instruments have become critical for commerce, process diagnostics and to establish functional correlation. This paper reviews the evolution of current filters that are defined in the standards and the need for new filters. The features of the new filters are presented through examples.

* Corresponding author.
E-mail address: jraja@uncc.edu (J. Raja).

PII: S0141-6359(02)00103-4

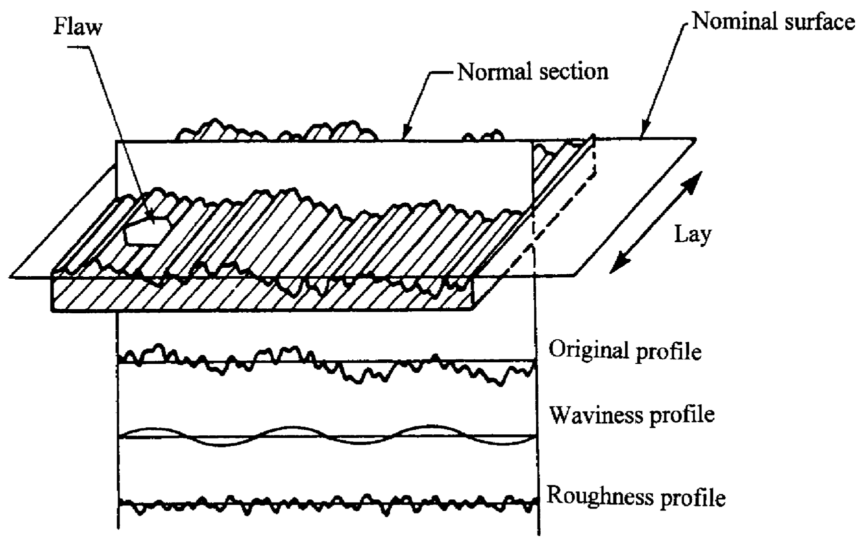

Fig. 1. Roughness and waviness in a surface [1].

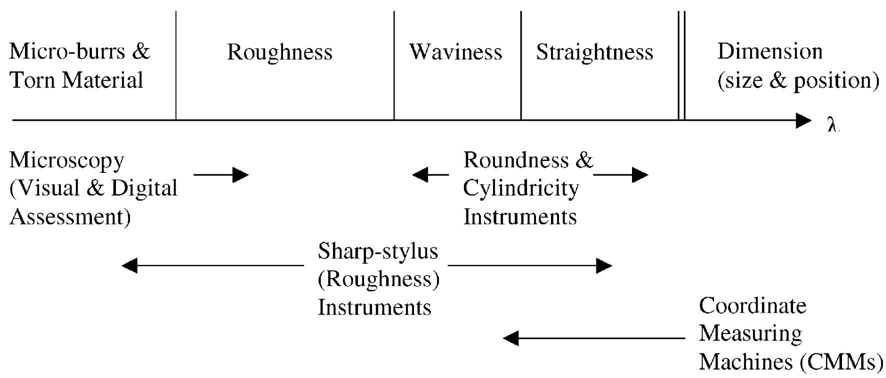

Fig. 2. Metrology measurement spectrum [2].

2. Filters currently used to characterize surface profiles

2.1. 2RC filter

The earliest filter used in surface metrology is the analog 2RC filter. The highpass 2RC filter can be realized digitally using the weighing function given in Eq. (1)

$$S(x) = \frac{A}{\lambda_c}\left(2 - A\frac{|x|}{\lambda_c}\right)\exp\left(-A\frac{|x|}{\lambda_c}\right) \tag{1}$$

where $A = 3.64$ for 75% transmission at the cutoff, x the position from the origin of the weighing function ($-\infty < x < 0$) and λ_c is the long wavelength roughness cutoff. The mean line is obtained by convolving the profile with the weighing function in Eq. (1). The mean line is then subtracted from the original profile to obtain the roughness profile. The transfer function of the 2RC highpass filter is

$$\frac{\text{output}}{\text{input}} = \left(1 - \mathrm{i}k\frac{\lambda}{\lambda_c}\right)^{-2} \tag{2}$$

where $\mathrm{i} = \sqrt{-1}$ and $k = 1/\sqrt{3} = 0.577$. Fig. 3 shows the weighing function and the transmission characteristics of a 2RC highpass filter.

The major disadvantage of the 2RC filter is its nonlinear phase. An example illustrating the phase distortion effect of the 2RC filter is shown in Fig. 4. The mean line (0.8 mm cutoff) and the profile are shown in Fig. 4(a). The roughness profile is shown in Fig. 4(b). From Fig. 4(a), it can be seen that the mean line has a phase offset which causes considerable distortion in the roughness profile. This effect becomes more severe as the cutoff increases.

To overcome the problem of phase distortion, Whitehouse [4] introduced a phase-correct filter. While zero phase is unattainable, a filter with symmetrical weighing function can be designed to yield linear phase. Raja and Radhakrishnan [5] have explored the use of digital filters, particularly finite impulse response filters (FIR) that have linear phase for surface profile filtering.

Another disadvantage of the 2RC filter is that waviness cannot be obtained by simply subtracting the profile from roughness because the transmission at the cutoff is 75%.

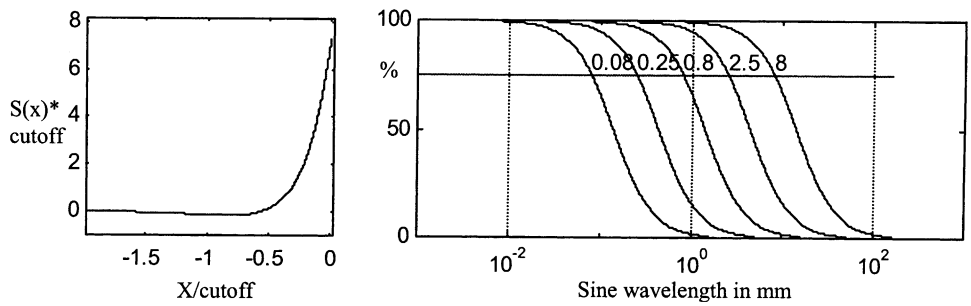

Fig. 3. Weighing function and transmission characteristic of 2RC highpass filter.

Therefore, a complementary waviness filter that transmits 75% at the cutoff is necessary to capture waviness. It is a normal practice to consider the mean line obtained by convolving a profile with the weighing function given in Eq. (1) as the waviness. However, true waviness is obtained by convolving the profile with the weighing function given in Eq. (3)

$$s(x) = \frac{xA^2}{\lambda_c^2}\,\mathrm{e}^{-xA/\lambda_c}, \quad 0 < x < \infty, \quad A = 2\pi\sqrt{3} \tag{3}$$

where x is the position from the origin of the weighing function and λ_c is the long wavelength roughness cutoff.

The definition of a digital filter provides a direct implementation for 2RC filter using convolution [1]. While it is clear, simple and versatile, more storage is needed and the computational speed is low for this method. An alternative recursive technique is discussed by Raja and Radhakrishnan [5] and by Whitehouse [6] to overcome this problem. While the ASME B46.1 [1] still includes the 2RC filter, ISO has eliminated this filter from their standards. A new filter, referred to, as the Gaussian filter was developed to overcome two primary drawbacks of the 2RC filter, nonlinear phase and the need for simpler way to implement both a roughness and a waviness filter. The characteristics of this filter are discussed in Section 2.2.

2.2. Gaussian filter

The most widely used filter today is the Gaussian filter, which is described in ASME B46.1 [1] and ISO 11562 [7]. The weighing function and transmission characteristic of a Gaussian lowpass filter are given by

$$S(x) = \frac{1}{\alpha\lambda_c}\exp\left(-\pi\left(\frac{x}{\alpha\lambda_c}\right)^2\right) \tag{4}$$

$$\frac{A_{\mathrm{output}}}{A_{\mathrm{input}}} = \exp\left(-\pi\left(\alpha\frac{\lambda_c}{\lambda}\right)^2\right), \tag{5}$$

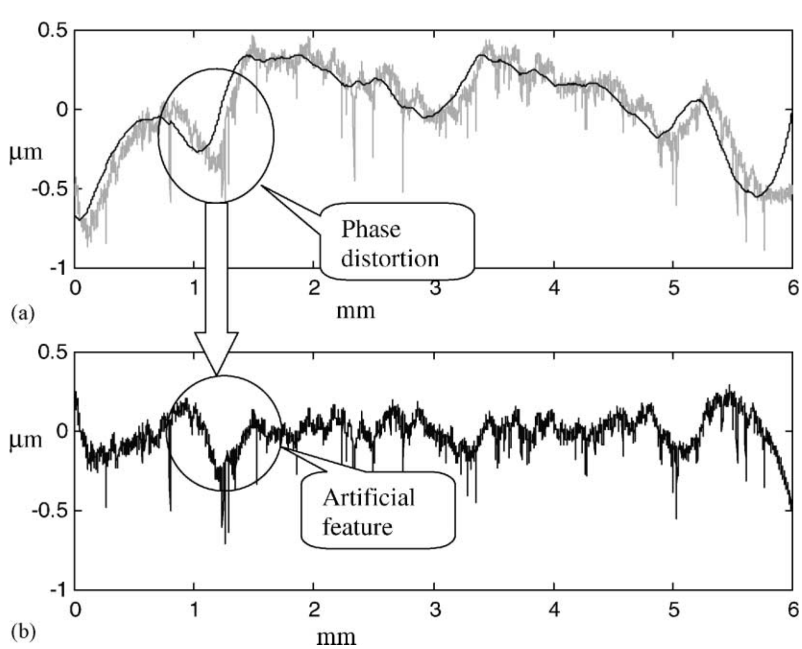

Fig. 4. (a) Profile and 2RC mean line (not waviness profile); (b) roughness profile.

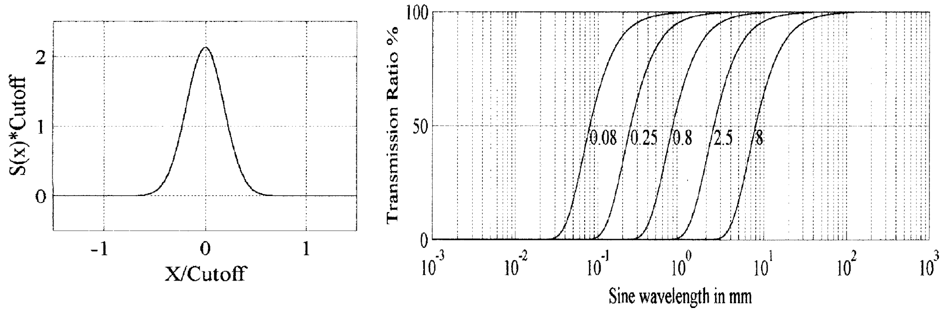

Fig. 5. Weighing function and transmission characteristic of Gaussian filter.

respectively, where $\alpha = \sqrt{\ln 2/\pi} = 0.4697$, x is the position from the origin of the weighing function, λ_c is the long wavelength roughness cutoff and λ is the wavelength of different sinusoidal profiles on the surface. They are shown in Fig. 5.

An important property of Gaussian filter is its linear phase, which is a major advantage over 2RC filter. Also, the filter is designed to have 50% transmission at the cutoff. This allows the calculation of waviness by simply subtracting the roughness from the raw profile, another important improvement over the 2RC filter. An example profile and the Gaussian mean line (0.8 mm cutoff) are shown in Fig. 6. The 2RC mean line is also shown to illustrate the linear phase of the Gaussian filter and the nonlinear phase of the 2RC filter.

The boundary distortion due to the local weighed average is inevitable for both 2RC and Gaussian filters. Therefore, the mean line at the boundary region cannot be used for evaluation purposes. Generally, the first half and the last half cutoff length are discarded to eliminate end effects. Convolution is the most common approach for implementing Gaussian filter [1,6]. For increasing the speed, implementation using FFT was introduced by Raja and Radhakrishnan [8]. Another fast and reliable convolution algorithm for Gaussian filter has been derived by Krystek [9] based on a recurrence relation for the weighing function using the symmetry condition. Other algorithms have also been investigated by many researchers. For instance, a new fast algorithm for constructing a series of Gaussian filters according to the approximation of Gaussian function and central limit theorem was applied by Yuan et al. [10]. The objective of this approach is to reduce the multiplication operations in the procedure to increase calculation efficiency.

While the Gaussian filter is an improvement over the 2RC, there are still several issues with the use of this filter. Edge effects prevent the use of the first and last cutoff. This filter also performs poorly on profiles with deep valleys such as the ones found in plateau honed surfaces. An empirical filtering method referred to as R_k filter was developed to deal specifically with plateau honed surface profiles.

2.3. R_k filter

The Gaussian filter is not robust against outliers. Special applications such as plateau honing require a filter whose mean line is not distorted by the valleys. ISO 13565 [11] recommends a two-step filtering approach using a Gaussian phase correct filter in accordance with ISO 11562. In the first step, the primary profile is filtered using a low pass Gaussian filter. All points in the primary profile that lie below the mean line are replaced by the mean line itself. Thus, all valleys are suppressed for the second step. The modified profile is sent through the same Gaussian low pass filter and the new mean line obtained becomes the final mean line. The primary profile is subtracted from this mean line to

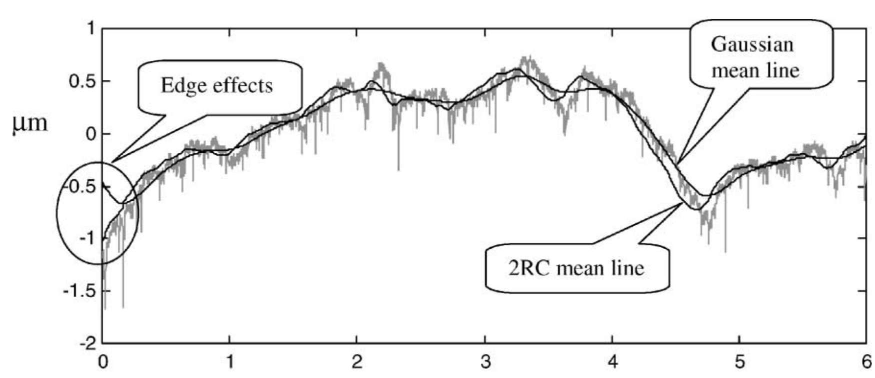

Fig. 6. Gaussian mean line.

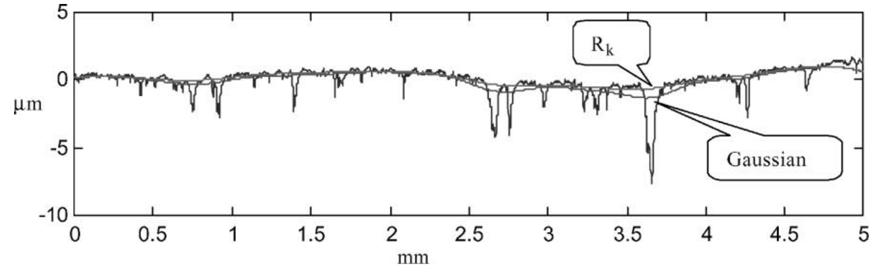

Fig. 7. R_k and Gaussian mean line on a profile with deep valleys.

obtain the roughness profile. A profile with deep valleys is shown in Fig. 7 with the mean line generated by Gaussian and R_k filter with a 0.8 mm cutoff. The Gaussian mean line is pulled down near the valleys while the R_k mean line hugs the texture. The effect of the Gaussian mean line on the roughness profile is shown in Fig. 8. Artificial features are introduced into the roughness profile because the filter is not robust against outliers/valleys.

DIN standards [12] recommend a triangular weighing function as shown in Fig. 9. The roughness amplitude transfer function is given by

$$\frac{A_{\text{output}}}{A_{\text{input}}} = 1 - \left(\frac{\lambda}{\pi\alpha\lambda_c}\right)^2 \sin^2\left(\frac{\pi\alpha\lambda_c}{\lambda}\right) \tag{6}$$

where λ is the wavelength of the sine wave to be filtered, $\alpha = 0.44294647$ and $\alpha\lambda_c = B/2$. The two-step filtering procedure is the same as that described in ISO 13565.

R_k filter suffers from the same edge effect problems mentioned before. Also the two-step iteration process is not always robust against very deep valleys. Splines, robust splines, regression and robust regression filters offer solutions to these problems. Subsequent sections present them in greater detail.

3. Advanced filters for surface profile filtering

3.1. Spline filter

Spline filter was introduced to overcome the unrealistic separation of roughness in surfaces with large form and the end effects of both 2RC and Gaussian filter. There are two kinds of spline filters: non-periodic and periodic. Non-periodic splines are used for filtering open profiles and

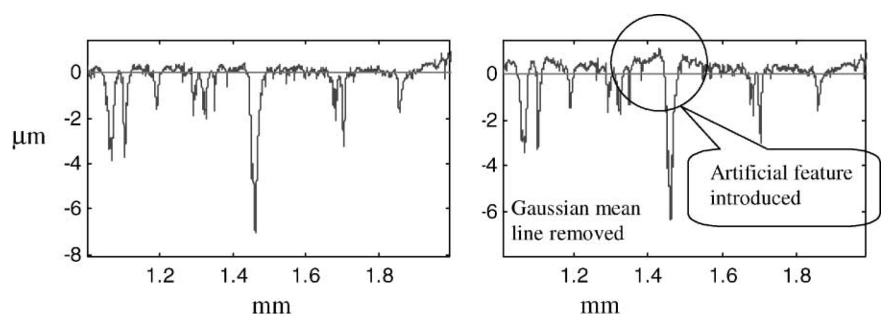

Fig. 8. Roughness profile distortion effect.

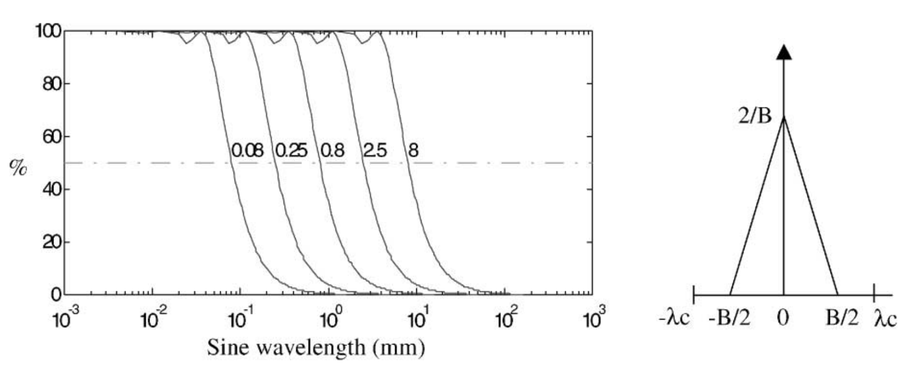

Fig. 9. Transfer characteristics and weighing function.

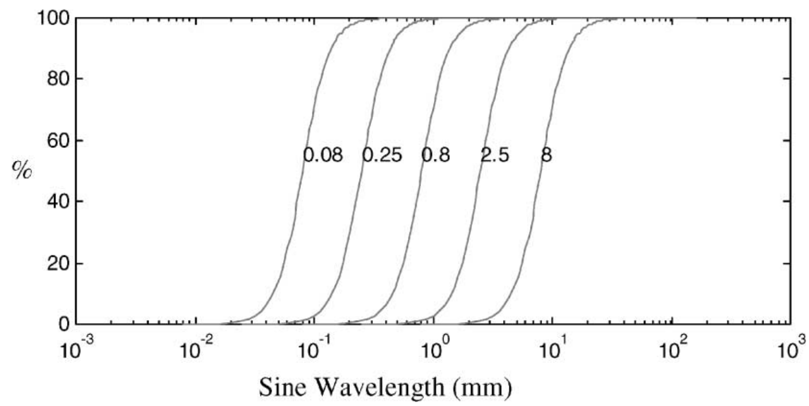

Fig. 10. Lowpass transmission characteristic ($\Delta x = \lambda_c/200$).

periodic splines for closed profiles. The weighing function of a spline filter cannot be given by a simple closed formula. Therefore, filter equations are used instead of weighing functions to describe spline filters. The filter equation for the non-periodic spline filter is given by

$$(1+\alpha^4 Q)\omega = z \tag{7}$$

where

$$Q = \begin{bmatrix} 1 & -2 & 1 & & & & & & \\ -2 & 5 & -4 & 1 & & & & & \\ 1 & -4 & 6 & -4 & 1 & & & & \\ & \cdot & \cdot & \cdot & \cdot & \cdot & & & \\ & & \cdot & \cdot & \cdot & \cdot & \cdot & & \\ & & & \cdot & \cdot & \cdot & \cdot & \cdot & \\ & & & & 1 & -4 & 6 & -4 & 1 \\ & & & & & 1 & -4 & 5 & -2 \\ & & & & & & 1 & -2 & 1 \end{bmatrix}_{n\times n} \tag{8}$$

and α is given by

$$\alpha = \left(2\sin\left(\frac{\pi\,\Delta x}{\lambda_c}\right)\right)^{-1} \tag{9}$$

The lowpass transmission characteristics is given by

$$\frac{a_1}{a_0} = \left(1 + 16\alpha^4 \sin^4\left(\frac{\pi\,\Delta x}{\lambda}\right)\right)^{-1} \tag{10}$$

Fig. 10 shows the transmission characteristics and Fig. 11 shows a mean line obtained from a spline filter applied to a profile with large form. The absence of edge effects in the spline is notable. Spline filters are described in detail by Krystek [13,14]. ISO/TC 213 is currently working on a draft document to include spline filters into their standards.

3.2. Robust spline filter

Robust spline filter is a modification of the spline filter to overcome the problem of large form and end effects while being robust against deep valleys. This filter is currently being discussed in the ISO/TC 213 committee.

The spline filter has taken care of two drawbacks of the Gaussian filter—the problem of large form and end effects. Recent research work has provided another solution to this problem by modifying the implementation of the Gaussian filter, namely Gaussian regression filter. The Gaussian regression filter is discussed in Section 3.3.

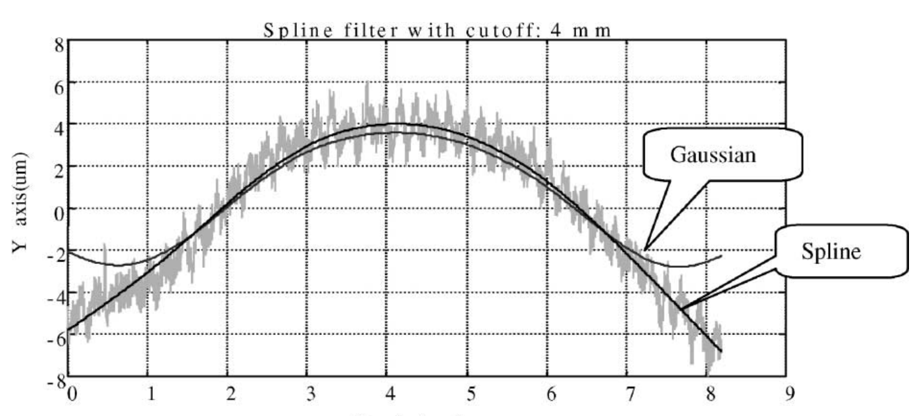

Fig. 11. Comparison between Gaussian and spline filter.

3.3. Gaussian regression filter

The Gaussian regression filter [15,16] is a modification of the Gaussian filter in order to evaluate the entire length of the profile. The Gaussian regression filter is defined by the following general regression arrangement:

$$\sum_{1}^{n}(z_l - w_k)^2 s_{kl}\,\Delta x \to \underset{w_k}{\mathrm{Min}} \qquad (11)$$

where z is the profile ordinate; w the mean line ordinate; n the number of points; k the index for the location of the weighing function; l the index for profile points and s is the weighing function as given by

$$s_{kl} = \frac{1}{\lambda_c\sqrt{\ln(2)}}\exp\left(-\frac{\pi^2}{\ln(2)}\frac{((k-l)\,\Delta x)^2}{\lambda_c^2}\right) \qquad (12)$$

λ_c is the cutoff.

In the regression approach, the weighing function is calculated for every point on the profile and the objective function is minimized to compute the ordinate on the mean line w. A zero-order regression filter minimizes the square of the deviation of the profile ordinate from a horizontal line at each point. Thus, the minimization problem involves computing a constant term at every point of the profile. The second-order regression filter minimizes the square of the deviation of the profile ordinate from a quadratic curve at each point. Here, the minimization involves finding three coefficients of the quadratic curve at every point of the profile.

3.4. Zero-order Gaussian regression

The zero-order regression filter can be mathematically shown to be equivalent to the convolution given in Eq. (13)

$$w(l) = \sum_{i=1}^{n} z(i)s_{\mathrm{reg}}(l-i) \qquad (13)$$

$$s_{\mathrm{reg}}(l-i) = \frac{s(l-i)}{\sum s(l-i)} \qquad (14)$$

From Eq. (14), it can be seen that the weighing function of this filter is modified in the first and last cutoff sections as shown in Fig. 12. However, it remains unchanged in the interior regions of the profile. Fig. 13 shows a profile with a Gaussian and a zero-order Gaussian regression mean line. Notice the absence of end effects in the regression filter. The regression filter is described in detail by Brinkmann et al. [15,16].

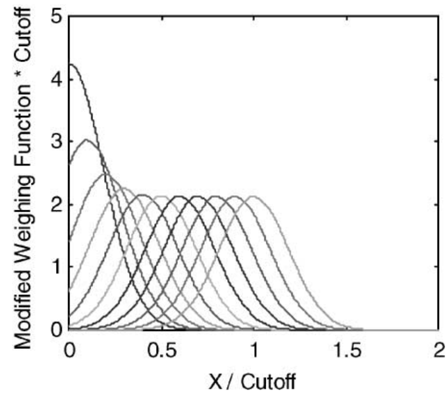

Fig. 12. Progression of weighing function.

3.5. Second-order Gaussian regression

The second-order Gaussian regression filter [16] minimizes the deviations between the input dataset and a quadratic term to obtain the ordinate of the mean line at each point of the profile. The second-order filter, like the spline, can be used for form removal. However, it is computationally expensive, as the regression process requires polynomial fitting for every point. Fig. 14 shows a Gaussian and second-order Gaussian regression mean line on a curved profile.

3.6. Robust Gaussian regression filter

The robust algorithm [15] applies a regression filter iteratively to a dataset until the mean line is satisfactory. A median statistic is used as the index to decide when to stop the iteration. The filter can be applied to datasets with outliers that would distort a simple Gaussian mean line. While the R_k technique applies the Gaussian window twice to the

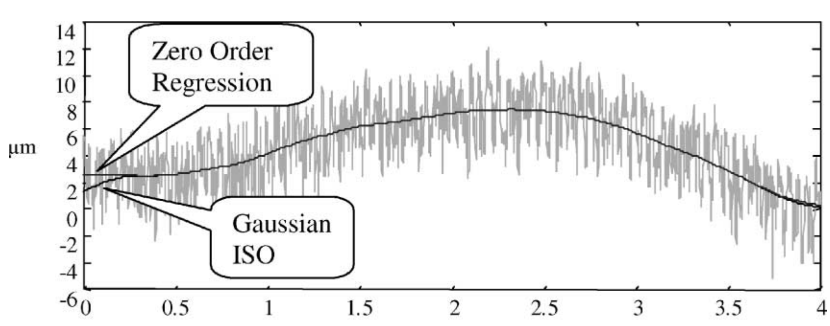

Fig. 13. Gaussian and zero-order Gaussian regression mean line, cutoff = 0.8 mm.

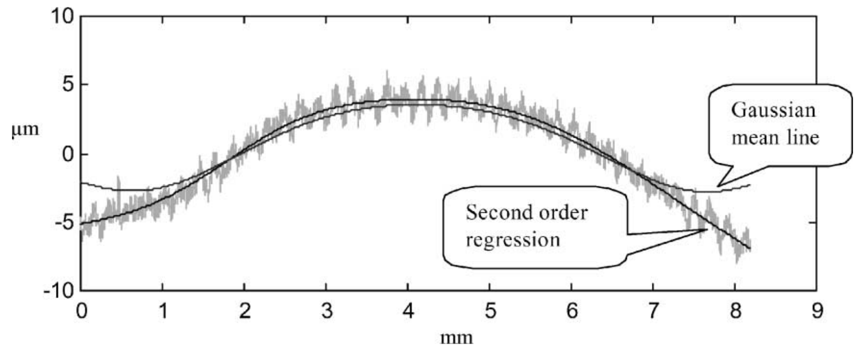

Fig. 14. Gaussian and second-order Gaussian regression mean line, cutoff = 4 mm.

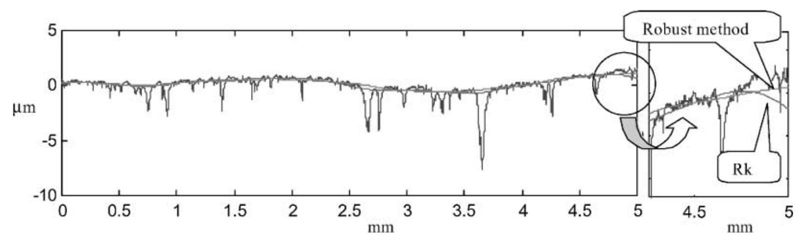

Fig. 15. Robust zero-order Gaussian regression and R_k mean line.

dataset, the robust Gaussian regression algorithm applies a regression filter several times depending on the end condition criteria. The robust algorithm is given by

$$\sum_{1}^{n}(z_l - w_k)^2 s_{kl}\delta_{i,l}\,\Delta x \to \operatorname*{Min}_{w_k} \tag{15}$$

where $\delta_{i,l}$ is an additional vertical weight, i the iteration number and l is the ordinate index of the profile. In the first iteration, $\delta_{i,l}$ is set to unity. In subsequent iterations, $\delta_{i,l}$ is computed as follows:

$$\begin{aligned} \delta_{i+1,l} &= \left(1 - \left(\frac{r_{i,l}}{C_B}\right)^2\right)^2, \quad \text{for } \left|\frac{r_{i,l}}{C_B}\right| < 1 \\ \delta_{i+1,l} &= 0, \qquad\qquad\qquad\qquad \text{otherwise} \end{aligned} \tag{16}$$

where $C_B = 4.4 \times \text{median}(z_l - w_l)$. Fig. 15 shows the mean line generated by the robust algorithm and the R_k procedure. The regression approach has resulted in an improved mean line at the end.

ISO/TC 213 is currently working on a draft document to incorporate regression and robust regression filters into their standards. To summarize, regression filters permit evaluation of the entire length and higher order regression filters perform better than Gaussian filters on profiles with large form. Robust filters provide better mean line for profiles with deep valleys.

Having discussed several filters and their characteristics, it is worthwhile to note that traditionally, a single cutoff value has been used to separate roughness from waviness and another cutoff to separate waviness from form. However, with increasing overlap of measurement capabilities of current instruments and the emerging trend of using surface profiles for process diagnostics, there is a need for the separation of signal into more meaningful bandwidths. This has resulted in the development of multi-band filters and filter banks. One recent development in this regard is the use of wavelets for surface profile analysis. Wavelet analysis is discussed in Section 4.

4. Wavelet analysis and wavelet-based filters

Partitioning a signal into multiple bands for purposes of providing process feedback or functional correlation can become a computationally expensive task. Also, commonly used filters such as the Gaussian filter are not suitable for such applications because of their poor transmission characteristics. Wavelets provide good separation of signal into multiple bands in a computationally efficient manner.

Wavelets are mathematical functions that partition data into different frequency components, enabling us to study each component with a resolution matched to its scale. They have advantages over traditional Fourier methods in analyzing physical situations where the signal contains discontinuities and sharp spikes. The fundamental idea behind wavelet analysis is to analyze signal according to scale. Wavelet analysis provides a flexible time-scale window localized on time-scale plane. Gross features would appear when looking at a signal with a large window. Similarly, small features would appear when the signal is viewed with a small window. Wavelets permit looking at both the small and the large features simultaneously. This makes wavelets interesting and useful.

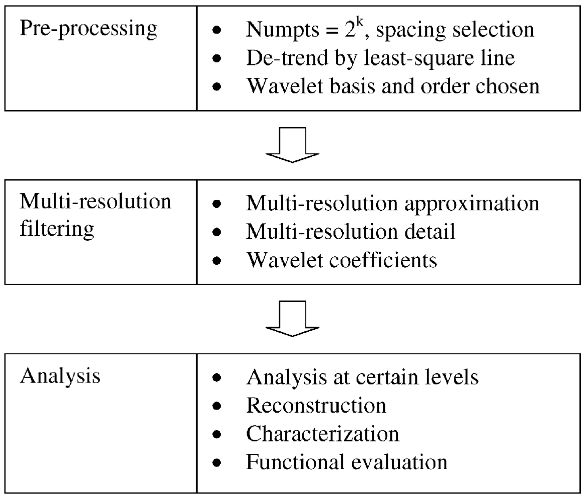

Fig. 16. Multi-resolution analysis for surface profiles [20].

Chen et al. [17] and Liu and Raja [18] presented an early study on the application of multi-resolution analysis (MRA) for analyzing multi-scale engineering surfaces. As octave filter banks, wavelets can be used to decompose signal into different bands with different scales, which is also called multi-resolution analysis of a signal [19]. In MRA, the dyadically dilated wavelets constitute a bank of octave band pass filters and the dilated scaling functions form a low pass filter bank. The efficient implementation of discrete wavelet transform (DWT) is to get successive approximations of a signal by applying the low pass filter bank and successive details of a signal by applying the band pass filter bank. DWT appears to have a great potential for analyzing the multi-scale features in engineering surfaces due to its properties of good time-scale localization and flexible time-scale resolution. In order to analyze engineering surface texture, multi-scale approximations of original texture at different

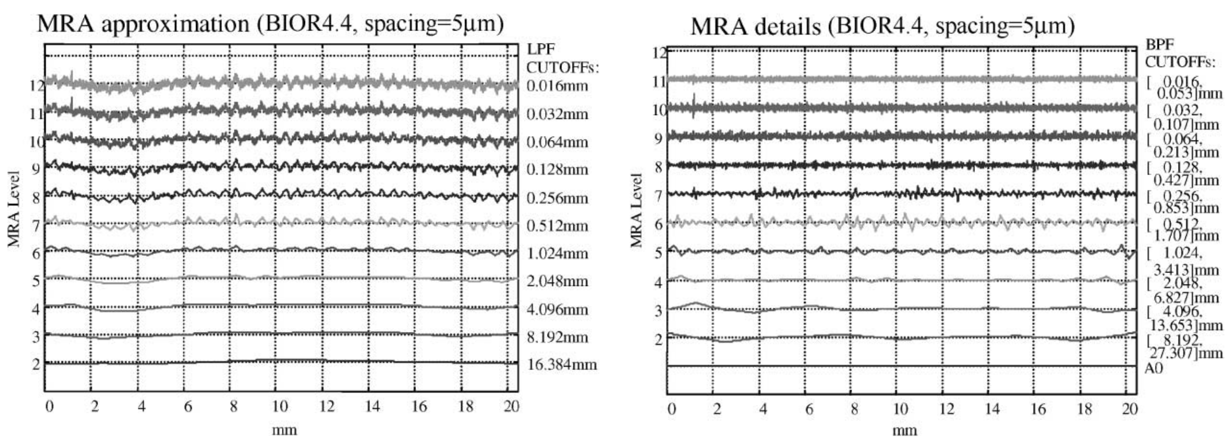

Fig. 17. MRA approximations and details of a piston pin bore surface profile.

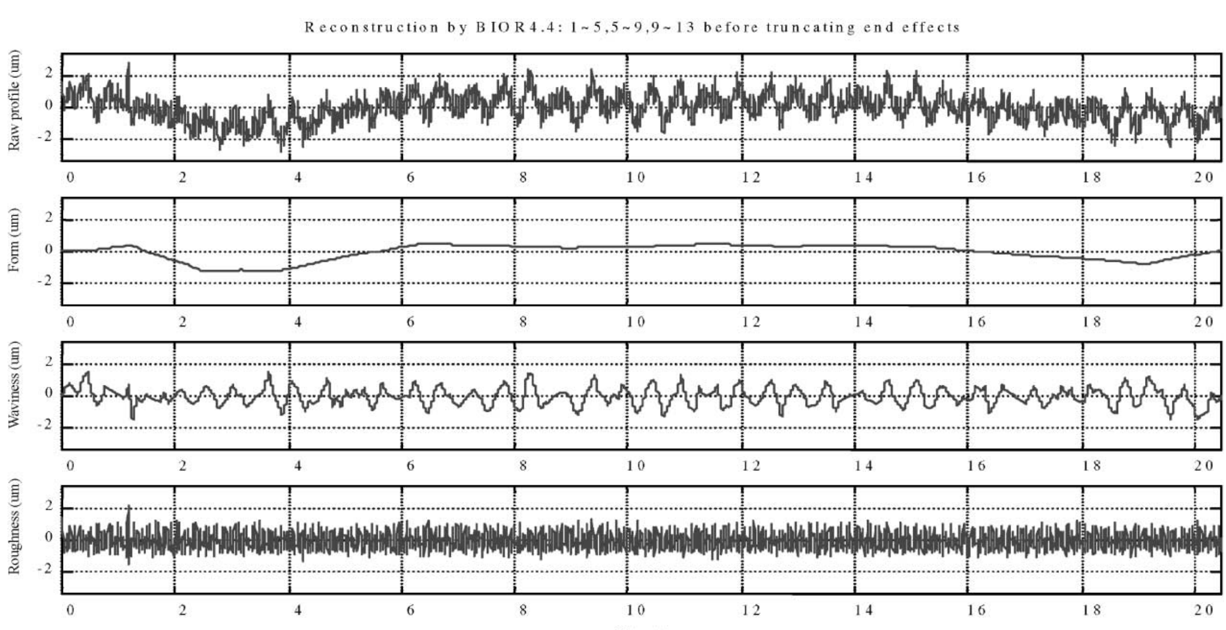

Fig. 18. MRA reconstruction at levels: 1–5, 5–9, 9–13.

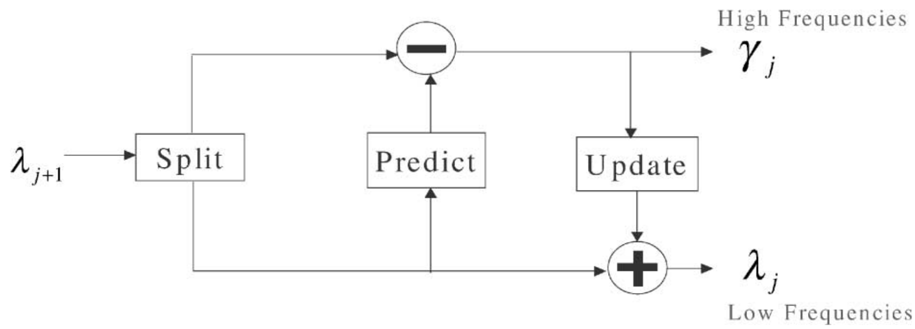

Fig. 19. Lifting stages: split, predict and update.

resolution levels will be extracted by DWT. This will give a clear overview of the multi-scale features of surface texture. Then the separation of multi-scale features based on wavelength can be made according to the information provide by the multi-scale approximations. Fig. 16 shows the general procedure to do MRA for a surface profile.

Due to the linear phase requirement of surface analysis, biorthogonal wavelet family is usually applied for wavelet analysis. Due to the scope of the paper, the mathematical theory of design and implementation of the biorthogonal wavelets is referred to Vetterli and Herley [21]. Figs. 17 and 18 show an MRA analysis using biorthogonal wavelets using the wavelet toolbox in Matlab.

In 1994, the lifting scheme was developed by Sweldens [22], which leads to so-called "Second Generation Wavelets". Lifting leads to algorithms that can easily be generalized to complex geometric situations, which typically occurs in engineering surface analysis. The lifting scheme is a new approach for the construction of biorthogonal wavelets entirely in the spatial domain. This is in contrast to the traditional approach, which relies heavily on the frequency domain. The lifting scheme consists of three stages: split, predict and update, which are shown in Fig. 19. An application of the lifting scheme for surface profile analysis is presented by Jiang et al. [23].

Wavelet analysis is a logical extension of a simple filter. It permits us to analyze signal according to scale. In Section 5, an entirely different class of filters is discussed–Morphological filter, which is a superclass of the envelope filters of the late-1970s. While these filters provide envelope mean lines and are only affected by the peaks or the valleys, they can also be used to build a ladder structure that makes them very similar to wavelets. Morphological filters and scale-space techniques are discussed next.

5. Morphological filters

A discrete morphological filter [24] takes two inputs, the profile z and the structuring element s and produces a filtered profile w. Dilation and erosion are two fundamental operations. Dilation expands the input set by the structuring element. Erosion shrinks the input set by the structuring element. A typical surface profile recorded by any stylus instrument is the result of dilation of the true surface by the stylus tip. Closing and opening are secondary operations. Closing is obtained by dilation followed by erosion. Opening is obtained by erosion followed by dilation. Closing filter produces an envelope mean line that could be useful in applications involving rolling ball/sliding plane contact simulations. Fig. 20 shows a profile and mean lines generated by closing filters, one with a straight-line structuring element of size of 0.1 mm and another with 0.05 mm. It is obvious that the mean line generated using a larger line will ride on

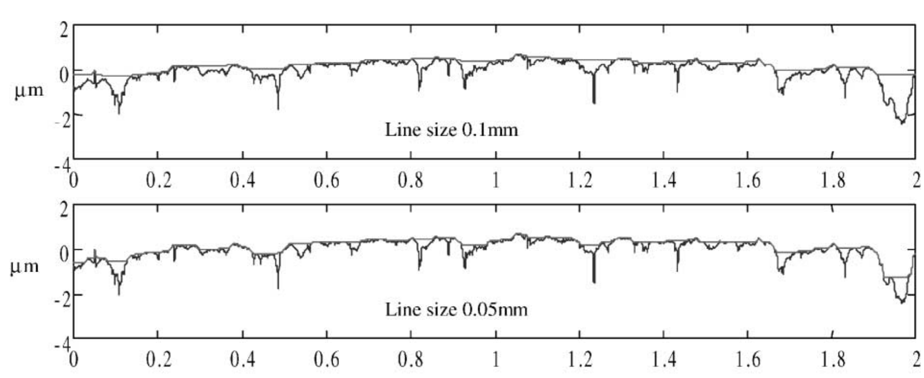

Fig. 20. Morphological closing filter mean lines.

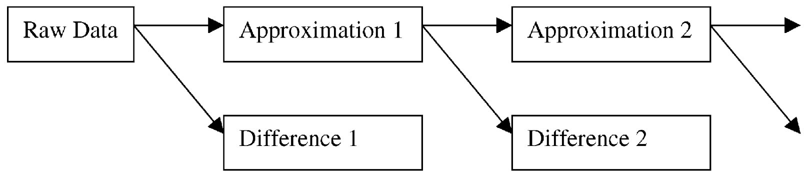

Fig. 21. Alternating symmetrical filter representation.

the larger peaks and is not influenced by valleys whose size is smaller than its length.

Morphological filters lend themselves to outlier analysis. A closing filter of a given scale will remove all valleys whose widths are smaller than this scale. An opening filter will remove all peaks whose widths are smaller than the scale of the filter. An alternating symmetrical filter [25] is a combination of a closing and opening filter and can be used

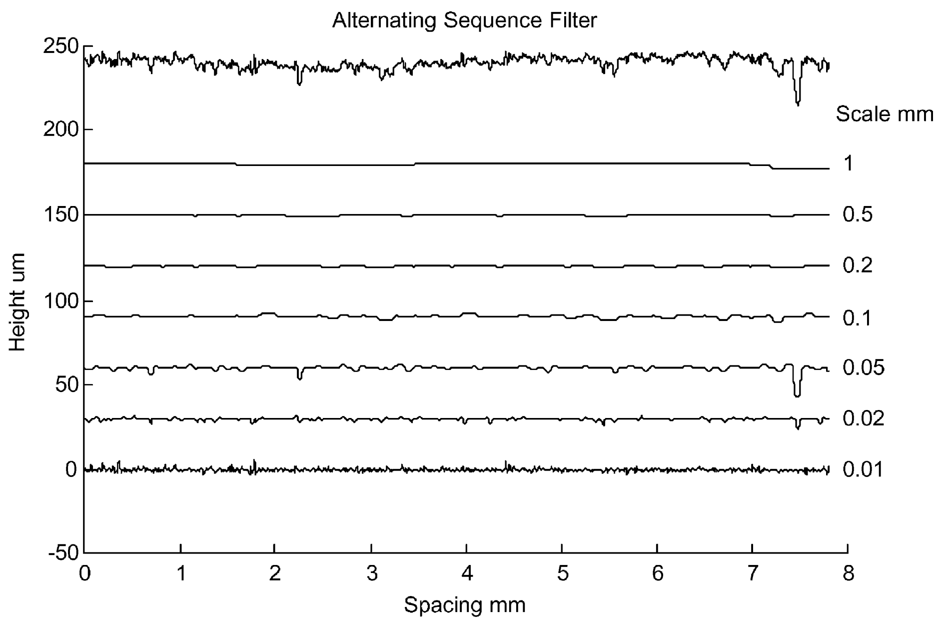

Fig. 22. Difference profiles.

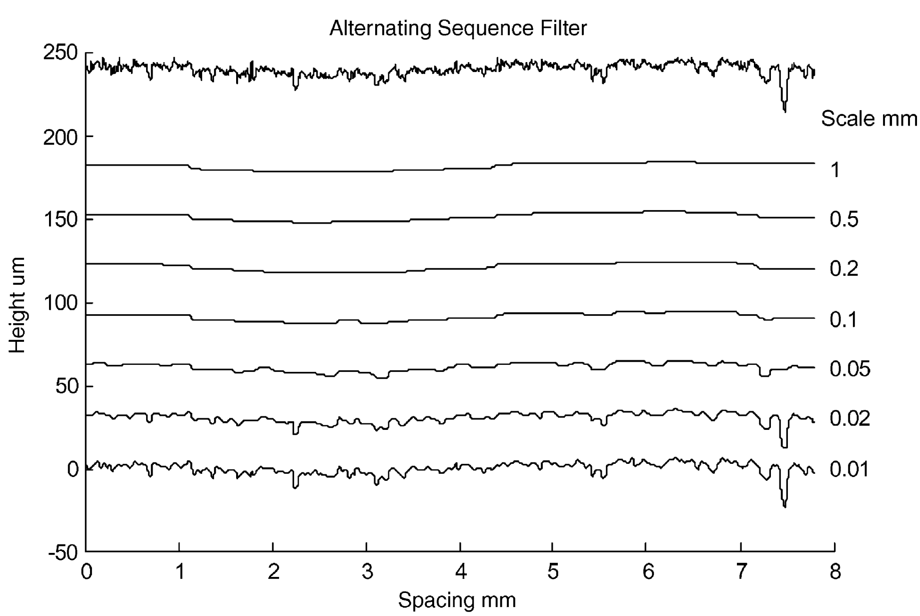

Fig. 23. Approximation profiles.

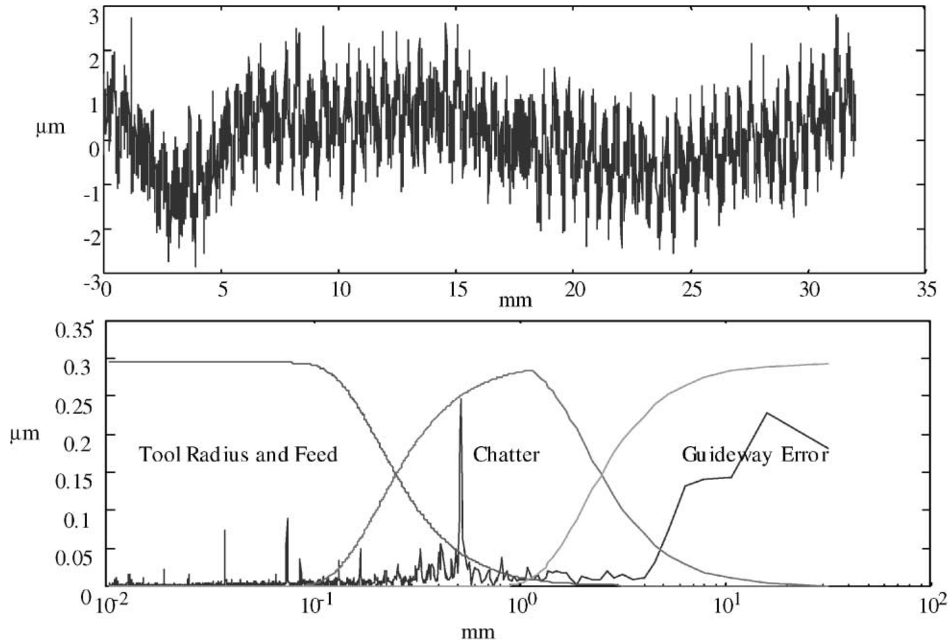

Fig. 24. Process analysis example.

to remove both peaks and valleys that are smaller then the scale of the filter. A series of alternating sequence filters can be applied to a profile, starting with a scale that is slightly larger than the stylus tip. As the scale is graduallyincreased, the successively smoother profiles can be plotted on a ladder structure. This ladder structure is useful in visualizing surface creation and also helps in identifying and removing outliers.

The structure of an alternating symmetrical filter is very similar to multi-resolution analysis in that the profile is successively viewed at different scales. At each level, an approximation and a difference profile is generated.

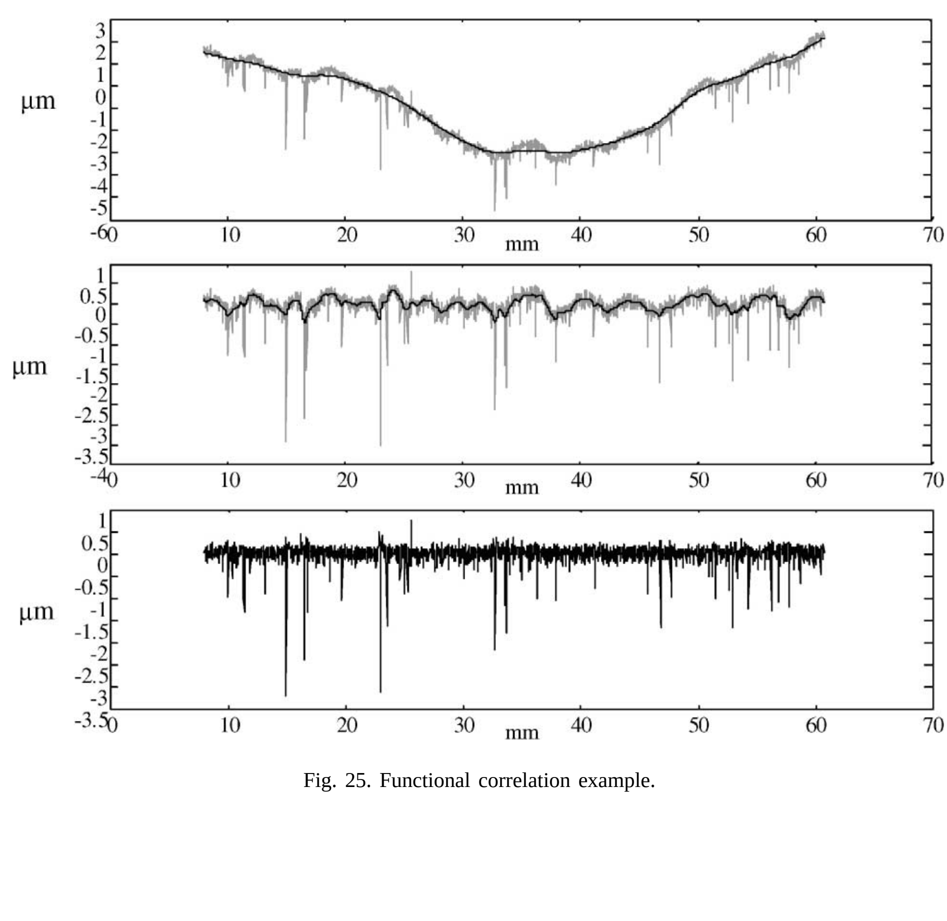

Fig. 25. Functional correlation example.

The approximation is then analyzed at a larger scale. The schematic of an alternating symmetrical filter is shown in Fig. 21. Fig. 22 shows an example profile and the difference profiles generated by using ball structuring elements of different sizes. Fig. 23 shows the approximation profiles at each level. The final profile can be reconstructed by simply adding all the differences and the approximation of the last level. Partitioning of the signal into various scales and reconstruction is very similar to wavelet analysis.

ISO/TC 213 is currently drafting a report on morphological filters and scale-space techniques for their standards.

The preceding sections presented several filters and their characteristics. After having looked at the different filters, one question remains to be answered. Why filter surface profiles? The answer is tied to the fundamental reason for measuring surface profiles—for functional correlation and process diagnostics. The last section presents an example illustrating process diagnostics and functional correlation in surface metrology.

6. Application of filtering in process diagnostics and functional correlation

To analyze surface texture appropriately, the different wavelength components should be separated reasonably by applying filters with different cutoffs. Fig. 24 is a piston pin bore profile and its FFT plot from a study by Malburg [2]. The FFT plot shows the different wavelengths and their sources. The short wavelengths are generated by tool radius and long wavelengths by slideway error. Chatter is clearly visible in the medium wavelength band.

Functional performance of a part is usually determined by different wavelengths on a surface. From a study by Malburg [2], the middle wavelength components are critical to a diesel engine crankshaft pin's performance because they are relative to localized loading and ultimate failure of the bearing. It is necessary to control long wavelength aspects in a reasonable level for proper fit and short wavelength components for tribological requirements. Bandpass filtering is needed to separate those function critical wavelength components. Fig. 25 shows the result from bandpass filtering of a crankshaft pin profile.

7. Conclusions

Advances in filtering techniques enable us today to separate the different wavelength regimes without any distortions. It is easy to specify and implement well-defined bandwidths using digital filters. Current research emphasis is in the area of multi-resolution analysis and more robust filters. The need to establish stable manufacturing process and provide functional correlation for components will require finer bandwidth analysis in the future. The new filters provide a powerful toolbox to move surface texture analysis beyond simple parameter calculation based on one cutoff. Number of groups in the world are using these techniques that could lead to case studies demonstrating manufacturing process control and functional correlation.

References

[1] ASME B46.1. Surface texture (surface roughness, waviness, and lay), 1995.

[2] Malburg MC. A unified methodology for the application of surface metrology. Ph.D. dissertation, University of Warwick, UK, and University of North Carolina at Charlotte, USA, 1996.

[3] Whitehouse DJ. Surfaces—a link between manufacture and function. Proc Inst Mech Eng 1978;192:179–88.

[4] Whitehouse DJ. Improved type of wavefilter for use in surface-finish measurement. Proc Inst Mech Eng 1967–68;182:306–18.

[5] Raja J, Radhakrishnan V. Digital filtering of surface profiles. Wear 1979;57:147–55.

[6] Whitehouse DJ. Handbook of surface metrology. Bristol, UK: Institute of Physics Publishing, 1994.

[7] ISO 11562. Geometrical product specification (GPS)—surface texture: profile method—metrological characteristics of phase correct filters. Geneva: International Organization for Standardization, 1996.

[8] Raja J, Radhakrishnan V. Filtering of surface profiles using fast Fourier transform. Int J Mach Tool Des Res 1979;19:133–41.

[9] Krystek M. A fast Gauss filtering algorithm for roughness measurements. Prec Eng 1996;19:198–200.

[10] Yuan YB, Qiang XF, Song JF, Vorburger TV. A fast algorithm for determining the Gaussian filtered mean line in surface metrology. Prec Eng 2000;24:62–9.

[11] ISO 13565-1. Geometrical product specification (GPS)—surface texture: profile method surfaces having stratified functional properties. Part 1. Filtering and general measurement conditions, 1996(E).

[12] DIN 4776. Measurement of surface roughness—parameters R_k, R_{pk}, R_{vk}, M_{r1}, M_{r2} for describing the material portion in the roughness profile, 1990.

[13] Krystek M. Discrete linear profile filters. In: Proceedings of the Xth International Colloquium on Surfaces. Chemnitz University of Technology, Chemnitz, 2000. p. 145–52.

[14] Krystek M. Form filtering by splines. Measurement 1996;18:9–15.

[15] Brinkmann S, Bodschwinna H, Lemke HW. Development of a robust Gaussian regression filter for three-dimensional surface analysis. In: Proceedings of the Xth International Colloquium on Surfaces. Chemnitz University of Technology, Chemnitz, 2000. p. 122–32.

[16] Brinkmann S, Bodschwinna H, Lemke HW. Accessing roughness in three-dimensions using Gaussian regression filtering. In: Proceedings of the 8th International Conference on Metrology and Properties of Engineering Surfaces, in Association with IMEKO. University of Huddersfield, UK, 2000.

[17] Chen X, Raja J, Simanapalli S. Multi-scale analysis of engineering surface. Int J Mach Tools Manufact 1995;35(2):231–8.

[18] Liu X, Raja J. Analyzing engineering surface using wavelet filter. In: Proceedings of the SPIE. Vol. 2825, 1996.

[19] Mallat S. A theory for multi-resolution signal decomposition: the wavelet representation. IEEE Trans Pattern Anal Mach Intell 1989;11(7):674–93.

[20] Liu X. Advanced techniques for separation of roughness, waviness and form. Ph.D. dissertation, University of North Carolina at Charlotte, 1999.

[21] Vetterli M, Herley C. Wavelets and filter banks: theory and design. IEEE Trans Signal Proc 1992;40(9):2207–32.

[22] Sweldens W. The lifting scheme: a custom-design construction of biorthogonal wavelets. Appl Comput Harmon Anal 1996;3(2):186–200.

[23] Jiang XQ, Blunt L, Stout KJ. Development of a lifting wavelet representation for surface characterization. Proc R Soc Lond A 2000;456:2283–313.

[24] Srinivasan V. Discrete morphological filters for metrology. In: Proceedings of the 6th IMEKO ISMQC Symposium on Metrology for Quality Control in Production. TU Wien, Austria, 1988.

[25] Scott PJ. Scale-space techniques. In: Proceedings of the Xth International Colloquium on Surfaces. Chemintz University of Technology, Chemnitz, 2000. p. 153–61.