ISO Filters in Precision Engineering and Production Measurement

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Abstract. Filters are used in precision engineering and production measurement to suppress unwanted components in measured data, to reconstruct the sampled surface in case of tactile measurements, or to separate portions of different scales. The application of such filters comprises a wide area, in essence, coordinate measurement, form and contour measurement, as well as surface texture measurement. So far, almost exclusively the Gaussian filter, as standardised in ISO 11562, has been used in this area. But for some time past, a new series of ISO documents (ISO/TS 16610) has been available which — besides the Gaussian filter which is still available — specifies additional filters for the field of geometrical product specification and verification. This publication gives an overview of these new ISO filters.

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1. Introduction

The currently used linear mean-line filters historically originate from roughness measurement — the electrical filters still existing in older instruments having been replaced by digital filters in computer-assisted instruments of newer construction. These initially simulated the electrical analogue filters but were later improved in their performance in order to avoid the characteristics of the previous filters. For a lack of suitable alternatives, the filters introduced in roughness measurement were increasingly used in form measurement for the separation of form deviations. But it turned out very quickly that such an undifferentiated application of these filters to a field for which they had not originally been developed led to problems. Finally, using measured data to establish datums makes a rethinking of extraction and filtration methods necessary, since the currently available methods are in conflict with the need for a close-fitting geometrical feature according to ISO 1101:2004 [1].

The Advisory Group ISO/TC 213/AG 9 *GPS extraction techniques* was established at the inaugural meeting of the ISO/TC 213 *Geometrical Product Specification and -verification (GPS)* on 14^{th} of June 1996 in Paris. The task of this group was to develop new techniques for the extraction of surface and profile information. The purpose of these investigations should be to determine the possible field of application, to find enhancements to current filtering techniques, to develop complements to existing sampling methods, and to identify the possibilities of a standardisation of the new procedures. The following methods, among others, should be discussed: splines, wavelets, robust filtration, morphological filters, optimal sampling methods (also non-equidistant, if applicable), as well as detection and, if applicable, removal of outliers. The result of these more than fourteen years of work — that is still being pursued at present — is a series of documents of the series of standards ISO/TS 16610 (see [2] to [13]) which, today, consists of twelve parts (nine of them having already been published), as well as the respective European and national versions. Other parts are currently in progress, so that the full document will continue to grow. This work has been done for several years by the working group ISO/TC 213/WG 15 established some years ago, which is to be regarded as the successor of the advisory group ISO/TC 213/AG 9 and is continuing and expanding its work. This already shows how important data extraction and filtration is today in geometrical product specification and verification.

The aim of the document ISO/TS 16610 is to familiarise the user of the GPS standards with the new methods which are based on modern mathematical methods and algorithms. Over time, instrument manufacturers will integrate these new methods as options in their measurement instrument software in order to give the users the opportunity to utilise the newly created tools to gain experience. Some usable implementations of the new filter methods are already partially available for the user. After a reasonable time it will be decided on whether and, if so, which of the new methods should be transferred to standards in future. Some of the methods dealt with in ISO/TS 16610 have, however, already influenced the newly developed standards in ISO/TC 213, which have already been partly published or will be published within the next few years. Thus, the user is well advised not to close his eyes when confronted with the new techniques, but to look into them as soon as possible. This publication understands itself as a help in this respect.

2. Historical Development

The linear profile filters initially originated in roughness measurement. They were and are still used in this field to decompose the measured profiles into long-wave (low frequency) and short-wave (high frequency) components (see Figure 1). The short-wave profile component (in Figure 1 denoted by $r(x)$) is termed *roughness profile*, whereas the long-wave profile component (in Figure 1 denoted by $w(x)$) is termed *mean line of the profile*. Later, linear profile filters were introduced also in form measurement (e. g. in roundness measurement). Here, the short-wave profile component is the waviness and the long-wave profile component the form.

The profile filters used in roughness measurement were standardised for the first time in the German standard DIN 4768-1 [14], which was issued in August 1974. The

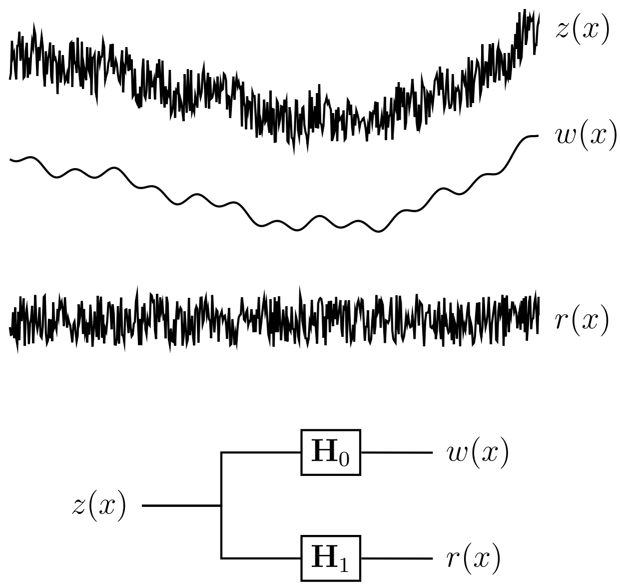

Figure 1. Separation of a primary profile $z(x)$ by a profile filter into a long-wave profile component $w(x)$ and a short-wave profile component $r(x)$. The transfer path of the filter denoted by $\mathbf{H}_0$ is termed low-pass and the transfer path denoted by $\mathbf{H}_1$ is termed high-pass.

wave filters described herein were electrical two-stage RC filters (RC filters are electrical networks composed of resistors (R) and capacitors (C) which include buffer amplifiers, where necessary). Filters of this type cause significant phase shifts in the transmission of the measured profile (see Figure 2), whereby asymmetric profile distortions emerge which also have a significant effect on the characteristics calculated from the profile values.

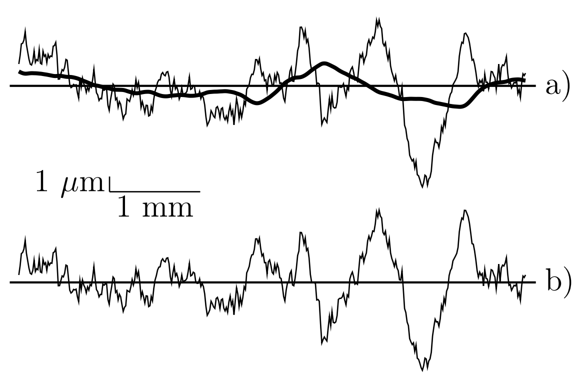

Figure 2. Electrical 2RC-filtering (λ_c = 1,6 mm): a) Phase shift of the mean line (bold line) compared to the unfiltered profile (thin line), b) distortion of the roughness profile.

The influence of these profile distortions was generally negligible for the roughness characteristics R_a, R_z and R_{max}, as long as the cut-off wavelengths (λ_c) recommended in DIN 4768-1 were applied, but for the measurement of other roughness characteristics and waviness measurement, these profile distortions were not acceptable. This caused the electrical RC filter to be replaced by a so-called phase-correct filter which no longer causes phase shifts, so that profile distortions no longer occur during filtration.

The first approach for a phase-correct profile filter was the so-called phase-correct 2RC filter. It was obtained by mirroring the single-sided weighting function of the electrical RC filter at the axis of ordinates, which causes the weighting function to become symmetric. The theory of the FOURIER transformation shows that for symmetric weighting functions, no phase shift can occur. Thus, the new filter had the desired property without deviating too much from the analogue filter function. Figure 3 shows that this modification could rule out the previously occurring profile distortions. The mean line is in phase with the measured profile, and the resulting roughness profile is unaltered.

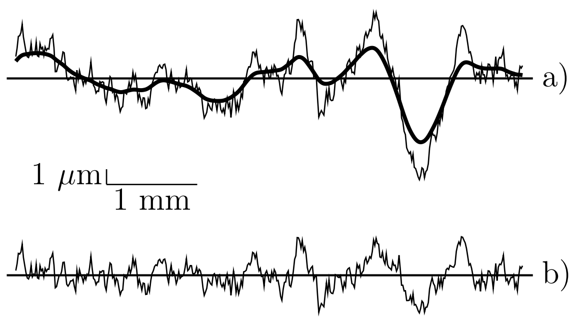

Figure 3. Phase-correct 2RC-filtering (λ_c = 1,6 mm): a) mean line (bold line) and unfiltered profile (thin line), b) roughness profile.

The phase-correct 2RC filter cannot be realised with analogue methods, i. e. by means of electrical networks, because it is not causal. Thus, the implementation of this filter was only possible after the measurement instruments had been equipped with digital processors.

Besides its application in roughness measurement, the phase-correct 2RC filter very quickly made its way into roundness measurement (see ISO 4291:1987 [15] and ISO 6318:1987 [16]). Since the first of these standards is still valid today, the phase-correct 2RC filter is actually still supposed to be used in roundness measurement. Usage in current industrial practice, however has differed from this for some time already and has made use of the Gaussian filter according to ISO 11562:1998 [17] instead. The name of this filter comes from the bell-shaped Gaussian function which was chosen as a weighting function.

The Gaussian filter was standardised for the first time in the German standard DIN 4777 [19] in May 1990. This standard was based on the available consultation results of the competent ISO working group ISO/TC57/SC1 at that time. However, the publication of a corresponding ISO draft standard was delayed for organisational reasons for so long that the interim publication of a DIN standard was decided at the national level. This interim publication aimed to accommodate in standardisation the transition from electrical RC filters to phase-correct Gaussian filters which had already taken place. The corresponding international standard ISO 11562:1996 [17] was eventually released in 1996. This was followed in 1997 by the European version EN ISO 11562:1997, and finally, in April 1998 by the German standard DIN EN ISO 11562:1998, which replaced the national standard DIN 4777. In September 1998, a corrected version [18] was issued to correct a formula.

The contents of the standard ISO 11562:1998 is virtually identical to the contents of the German national standard DIN 4777:1990, except for the newly added appendices. In addition, the clauses 1 to 4 were adjusted to the newest state of ISO standardisation and editorially revised, without, however, changing the technical content of the specification of the phase-correct filter.

The following aspects were considered for the elaboration of the standard ISO 11562:

(i) The phase shifts which occurred when using the former electrical two-stage RC filters led to corruptions of measurement values due to profile distortions, in particular in the case of surfaces produced by means of modern manufacturing methods, such as, e. g., plateau surfaces with grooves for lubrication retention. Therefore, the new filter had to be phase-correct to significantly improve profile reproduction. Since such filters cannot be realised by electrical circuits, it became necessary to move on to computer-aided digital processing of the measurement values.

(ii) The filter characteristics of the low-pass filter (suppression of short wavelengths) and of the high-pass filter (suppression of long wavelengths) are complementary, i. e. they add to unity. It was therefore reasonable to define the cut-off wavelength so that the amplitude of a sine wave of equal wavelength is just transmitted through both filters to 50 % (with the electrical RC filters, the cut-off wavelength was still so defined that a sine wave of equal wavelength was just transmitted to 75 % by the low-pass filter).

(iii) The new filter had to be compatible with the electrical two-stage RC filters specified in former national and international standards insofar as comparable results can be achieved within the natural variation of roughness measurement values (these usually amount to a few percent).

The conditions mentioned are fulfilled by the Gaussian filter specified in the standard. Due to its symmetric weighting function, this filter is also a phase-correct filter. Figure 4 therefore shows, as expected, that with the Gaussian filter, results comparable to those obtained by the application of the phase-correct 2RC filter are achieved.

Doubts about the correctness of the application of the mean-line filters led to the implementation of a different filtering method in the French automotive industry. This method is called the MOTIF method and is based on the work of J. Boulanger (see e. g. [20]). This filter was first nationally standardised only in France, later also internationally. The latest version of this ISO standard, still valid at present, is ISO 12085 [22], [23].

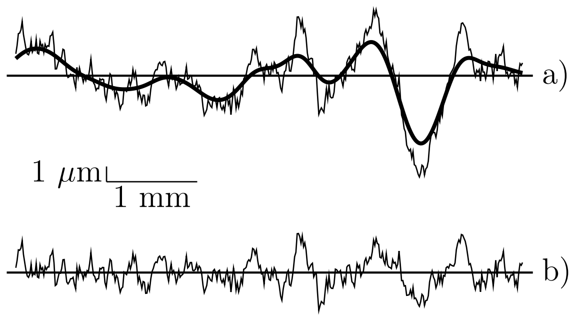

Figure 4. Gaussian filtration (λ_c = 0,8 mm, in comparison to the application of the phase-correct 2RC-filter shown in figure 3 only half the value is chosen): a) mean line (bold line) and unfiltered profile (thin line), b) roughness profile.

From the standpoint of classification, the MOTIF method does not belong to the mean-line filters (so called M system) but to the envelope filters (so called E system) which dates back to the publications of H. v. Weingraber from the years 1956 [24] and 1957 [25], respectively. Presumably the MOTIF method was essentially motivated by the previously existing method for the extraction of form deviations of surfaces on the basis of sections [26] which was also based on the E system. The corresponding standard is no longer valid. E system filters are generally non-linear, i. e. they cannot be dealt with by the methods of Fourier transformation. This immediately results in the fact that there is no transfer function and that no cut-off wavelength can be specified either. They are replaced by certain characteristic lengths. This is accordingly valid also for the MOTIF method. There is a superficial similarity between this method and the morphological filters — which will be discussed later — but without the rigorous mathematical foundations of the latter.

The MOTIF method could not establish itself internationally. The problem lies in its heuristic rules that considerably complicate its correct implementation. This has already led to errors in the corresponding evaluation algorithms in the instruments equipped with the MOTIF method. A study of the problem can be found in T. Hartmann [27]. In addition, it turned out that under certain conditions, the MOTIF method quickly reached its performance limits. In these cases, parts of the algorithm lead to false statements. The consequence is that the roughness and waviness of a surface cannot be described realistically in every conceivable case.

3. Limitations of the Gaussian filter

The Gaussian filter according to ISO 11562:1998 [17] is now practically the only standard mean-line filter. After its introduction in modern computer-aided measurement instruments, it soon became clear that the unconsidered use of this filter may cause new problems. This became particularly obvious in form measurement, where the separation of the form deviation from waviness and roughness is a problem that has not been solved satisfactorily.

But there was also reason to think about improvements with regard to filtering in roughness measurement. For a certain class of surfaces, namely those in which the distribution function of the profile values is highly asymmetric or multi-modal, the Gaussian filter proved inappropriate. This is the case, for example, in highly porous material with relatively deep pores and a smooth surface (ceramics) or with honed surfaces. Figure 5 shows such a profile.

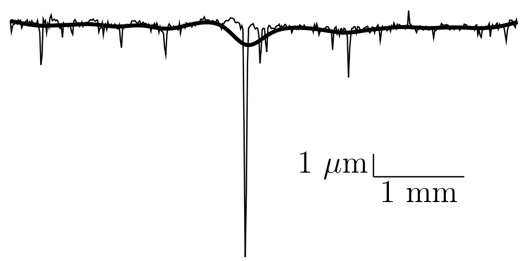

Figure 5. Application of the Gaussian filter according to ISO 11562 ($\lambda_c = 0,8$ mm) to a profile with a porous surface: mean line (bold line), unfiltered profile (thin line).

As can be seen, the mean line is drawn in an undesirable manner to the deep valleys of the profile. Instead of the bold mean line in Figure 5, one would probably rather expect a mean line which is always located above the mean line obtained by the application of the Gaussian filter within the critical regions of the deep valleys. This realisation led to a procedure standardised in ISO 13565-1 [28], [29], which, based on the Gaussian filter, provides a mean line located closer to the surface. The procedure works in two steps: first, the measured profile is filtered as usual by the Gaussian filter, subsequently all parts of the measured profile located below the resulting first mean line are removed. The profile thus obtained is then filtered a second time by the Gaussian filter. The resulting second mean line is then the result of the low-pass filtering. The roughness profile is finally obtained by subtraction of this second mean line from the originally measured profile.

Although the method according to ISO 13565-1 often provides acceptable results, it is recommended to be critical with regard to the modus operandi. First, it is noted that the failure of the Gaussian filter in the above-mentioned cases is causally related to the fact that this filter is not robust. This property is common to all linear mean-line filters. The reason for this is that these filters correspond to a mathematical approximation according to the least squares method which is known to be sensitive to data that are located far away from the majority of the measured points. Methods which are insensitive to this are called robust. It now seems that the method according to ISO 13565-1 is robust, because it appears to give the desired result. However, this is not the case since the resulting mean line belongs to the modified data and not to the original data. This approach is therefore not acceptable. It is ultimately only a heuristic solution of the problem, too, which was already subject to criticism in the case of the MOTIF method.

After the application of the Gaussian filter instead of the phase-correct 2RC filter in roundness measurement (actually not conforming to the standards), it soon turned out that comparable results can only be obtained if the cut-off wavelength of the Gaussian filter — in comparison with that of the phase-correct 2RC filter — is chosen to be only half as large (in roundness measurement correspondingly twice the cut-off wave number). The comparison of Figure 4 with Figure 3 clearly confirms this statement. The reason for this is that with the transition from the phase-correct 2RC filter to the Gaussian filter, the definition of the cut-off wavelength was changed so that, with the old filter, it belongs to an attenuation of 75 % in the transfer function of the low-pass filter and an attenuation of 50 % with the new filter. Thus, this results in a shift of the transfer functions of the two filters relative to each other, as shown in Figure 6. Obviously, the effect is that with the Gaussian filter, short-wave portions of the profile are attenuated more strongly than was the case with the phase-correct 2RC filter. The filtered profile thus contains less short-wave components than was previously the case and, thus, appears relatively smoother. The consequence in roundness measurement is, therefore, in some cases a decrease of the resulting roundness deviations compared with previous results. This means that in critical cases, the previous product specifications are no longer valid and should be changed with respect to consistent quality management although nothing in the manufacturing process — and hence in the product — has changed. This is obviously not a satisfactory situation.

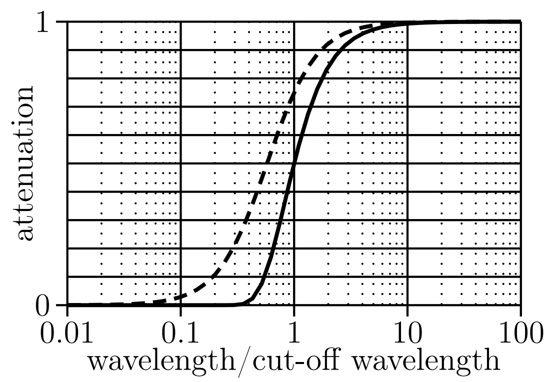

Figure 6. Transfer function of the Gaussian filter (continuous line) and of the 2RC-filter (dashed line).

By shifting the transfer function of the phase-correct 2RC filter with respect to the transfer function of the Gaussian filter, the observed discrepancy can be avoided to a large extent. It can be shown that doubling the cut-off wavelength of the phase-correct 2RC filter compared with that of the Gaussian filter (which is, of course, equivalent to half of the cut-off wavelength of the Gaussian filter, or a doubling of the cut-off wave number in roundness measurement, respectively, relative to the cut-off wavelength of the phase-correct 2RC-filter) yields almost optimal results. The result of such a shift is shown in Figure 7. In this way, the difference between the transfer functions of the two filters can be reduced from almost +40 % to approximately ±10 %, and the deviation curve can be made symmetric as far as possible. This, again, is of course only to find a pragmatic solution to the problem.

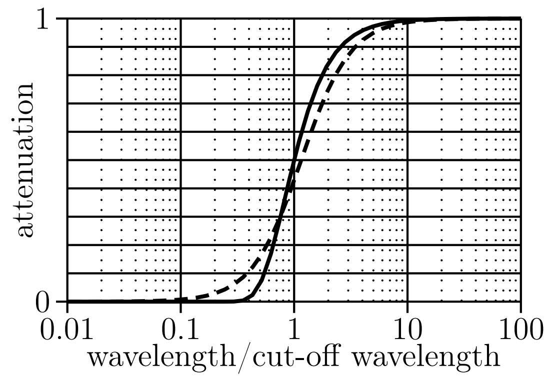

Figure 7. Transfer function of the Gaussian filter (continuous line) and the shifted transfer function of the 2RC-filter (dashed line). The shift was carried out by doubling the cut-off wavelength of the 2RC-filter.

Actually, the Gaussian filter, as standardised in ISO 11562, should not be used in roundness measurement in any case, because the filter is not periodic — as should actually be the case for the closed profiles which always occur in roundness measurement. In practical application, it is made periodical by truncating the weighting function at a position (prescribed or arbitrary, depending on the implementation) at both ends, symmetrically to its maximum. Then, the resulting function is continued periodically, now merely existing on a finite interval. In doing so, it is often not even taken into account that the intended periodicity is only ensured if the existence interval of the truncated weighting function is equal to the circumference of the nominal circle within the sectional plane of the profile measurement or, alternatively, an integral divisor thereof (so-called commensurability requirement). But even if this is ensured, the transfer function can no longer be that of a Gaussian filter (for details, see M. Krystek [36], [37]), as directly follows from the theory of the Fourier transformation. The deviation is not even constant, but depends on the circumference or rather the diameter of the workpiece to be measured and becomes greater, the smaller the workpiece and the larger the cut-off wavelength — or rather the smaller the cut-off wave number — of the filter is. The normalisation condition (the area under the weighting function has always to be equal to 1) — which is also often neglected after the truncation of the weighting function, which, in turn, leads to a change of radii (bias error) — has, in contrast, no effect on the calculation of the roundness deviation, because only differences of radii occur, so that this systematic error, being constant for the entire profile, is cancelled.

The standardised Gaussian filter, like all filters of the convolution type, is strictly speaking not adequate for periodic (i. e. open) profiles of unlimited length, because the existence region of its weighting function is an infinite interval. However, real profiles are always finite in length. From this it follows that during the filtration with the Gaussian filter, inevitable distortions have to occur at the ends of the profiles; they are known as end-effects. Figure 8 shows an example of this.

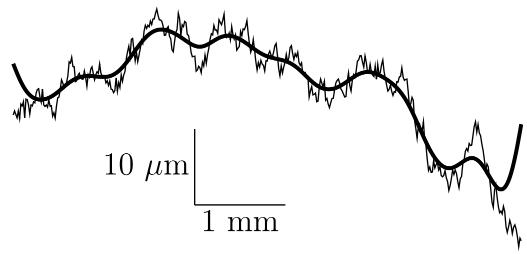

Figure 8. End effects during the filtration of a profile with the Gaussian filter according to ISO 11562 (λ_c=0,8 mm).

As can be seen, the closer it comes to the respective end, the more the mean line deviates from the expected course at both ends of the profile. The region at the ends of the profile, which is thus distorted by the end effect, is about the length of the cut-off wavelength of the filter and is currently truncated after the filtration has taken place. This, however, means that no longer the entire measured data set is available for further evaluation, or that a longer measurement length is needed all in all. This is particularly inconvenient in the case of long cut-off wavelengths.

The problem of end effects with linear filters of the convolution type is dealt with in the document ISO/TS 16610-28 [6]. There, suggestions are made on how to deal reasonably with end effects and which appropriate ways there are to mitigate these effects.

In the past, discussions have been held on using the Gaussian filter according to ISO 11562 also for form measurement in order to separate the portions of the form from roughness and waviness. Thereby, using ten times the value of the cut-off wavelength which is specified for the roughness measurement of the respective profile at a time is suggested. Figure 9 shows the application of the Gaussian filter in such a case.

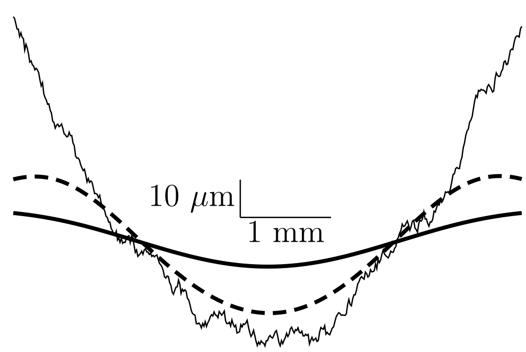

Figure 9. Application of the Gaussian filter according to ISO 11562 as a form filter. The cut-off wavelength used was $\lambda_f = 10\lambda_c = 8$ mm (bold continuous line) and $\lambda_f = 5\lambda_c = 4$ mm (bold dashed line), respectively. The cut-off wavelength specified for the roughness measurement at the present profile is $\lambda_c = 0,8$ mm.

It turns out that the mean line (i. e. the extracted form portion) is no longer within the range of the primary profile, i. e. the filter is useless in this case. Even an occasionally suggested halving of the cut-off wavelength does not bring about the desired improvement, as can be gathered from Figure 9. The effect shown here becomes all the more prominent, the more the form portion deviates from a linear behaviour, i. e. the more the profile is curved. Besides the end effects increasing more and more with the cut-off wavelength of the filter, the behaviour shown in Figure 9 is caused by the fact that the Gaussian filter leaves only linear functions unchanged. Form portions that can be described by a polynomial of second or higher degree are distorted by the filter. But since the majority of form portions is at least locally describable by quadratic functions, a form filter should leave such functions unchanged. The Gaussian filter is therefore not suitable as a filter for the extraction of form portions.

The Gaussian filter according to ISO 11562 is defined by a continuous weighting function. The effect of this filter is therefore mathematically described by a convolution integral. Since the measured profile is only available at discrete equidistant positions, the convolution integral is to be approximated by a convolution sum. Taking into account the above-mentioned fact that the Gaussian filter should only be applied to profiles that do not deviate too much from a linear course, methods for the approximation of the convolution integral can be used which yield exact results for linear functions, such as e. g. SIMPSON's integration method. In practice, however, the simpler rectangular integration method is used almost exclusively; it provides accurate results only for constant functions. The procedural error is proportional to the slope of the sampled function and the sampling interval. In order to keep this error small, the profile should therefore be aligned before filtration (i. e. the fitting straight line to be determined is to be subtracted from the profile), and the sampling interval should be kept small.

Besides the approximation error of the chosen numerical integration method, the maximum permissible sampling interval is still restricted by two other criteria, namely by the sampling theorem applied to the profile to be measured and to the weighting function of the filter. Concerning the discretisation of the weighting function, the opinion is widespread that it is sufficient to sample it at seven equidistant points within an interval symmetric to the maximum and having a length of twice the cut-off wavelength. This, however, leads to an overlap of the transfer function with its periodic aliasing copies in a region in which the amplitude transfer function is still greater than 21 %, as can be easily shown. In order to avoid this aliasing effect, the aforementioned interval must be sampled at least at eleven equidistant points. For this purpose, it can be calculated that the transfer function primarily overlaps with its periodically occurring aliasing copies in a region where the amplitude transfer function is about 1,3 %, so that the error caused by the band overlap becomes negligible compared to the measurement uncertainty of the roughness measurement. Thus, the sampling rule for the weighting function leads to the requirement that the sampling interval may not exceed one fifth of the filter cut-off wavelength used. For the filter stipulated in roughness measurement (see ISO 4287 [32], [33], [34], [35]), the values of $0,5 \ldots 5$ μm as specified in ISO 3274 [30], [31], arise for the maximum sampling interval. Thus, the discretisation of the weighting function becomes the limiting factor. This is unfortunately often ignored and leads to unexpected results. For further details concerning the implementation of the Gaussian filter, see M. Krystek [36], [37]. This publication also includes appropriate algorithms in the C programming language.

4. Spline filters

Spline filters get their name from the fact that the mean line resulting from the filtration is a spline. Very different functions belong to the family of splines. The best known are the third-degree polynomial splines — also called cubic splines. These functions consist of piecewise third-degree polynomials which build seamless transitions and are sufficiently smooth. Such a spline curve is created, for example, as the elastic line of a homogeneous isotropic elastic rod (curve template, spline) that is held by fixed bearings. Detailed information on spline filters is given in M. Krystek [40], [41], [42], [43].

The transfer function of the spline filter based on cubic splines is steeper than that of the Gaussian filter (see Figure 10), i. e. with spline filters, it is possible to achieve a better selectivity than with Gaussian filters. The difference between the transfer functions of these two filters, however, is smaller than the difference between the transfer functions of the Gaussian filter and the phase-correct 2RC filter, so that an application of the spline filter instead of the Gaussian filter implies no significant change of the parameter values. Investigations undertaken by the author about 15 years ago at the Physikalisch-Technische Bundesanstalt (PTB) showed that, for example, the differences in the values of roughness parameters in the application of those two filters are much smaller than the existing uncertainty.

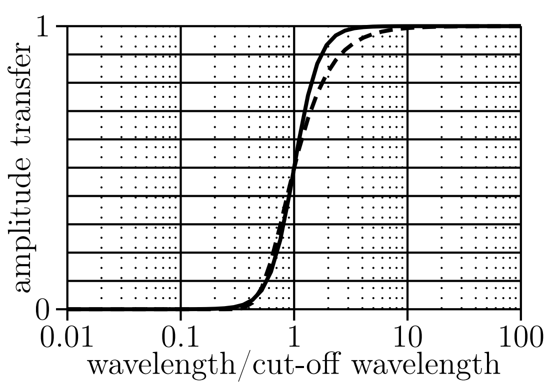

Figure 10. Transfer function of the spline filter (solid line) and of the Gaussian filter according to ISO 11562 (dashed line).

The spline filter was developed to avoid the disadvantages of the Gaussian filter. Unlike the latter, it is a purely digital filter, i. e. there is no need for sampling the weighting function, as was still the case with the Gaussian filter or previously with the phase-correct 2RC filter. Hence, the implementation of the spline filter implies fewer uncertainties, so that the results of filtration for different implementations and platforms are more consistent than is the case with the Gaussian filter. Spline filters are defined by their filter equations and not by a weighting function, as is the case with the Gaussian filter. These filter equations are linear matrix equations with a simple structure. Their algorithmic implementation leads to programs that have a very simple structure and, beyond that, are even much faster than all currently known algorithms used with the Gaussian filter. The computing time for the algorithm of the spline filter is only about half of an FFT-based convolution algorithm for the Gaussian filter and also smaller than that of the fast Gaussian filter algorithm [44] which is said to be currently the best implementation of this filter.

There are two different variants of the spline filter: the non-periodic spline filter which should be applied to open profiles, such as those occurring, e. g., in straightness measurement, and the periodic spline filter which should be applied to closed profiles, such as, e. g., those occurring in roundness measurement.

First, the non-periodic spline filter for open profiles will be considered. This filter is designed in such a way that the end effects occurring with the Gaussian filter are avoided, as can be seen in the example shown in Figure 11. For comparison, the result of a filtration performed with the Gaussian filter is plotted, too (cf. Figure 8). For this example, the cut-off wavelength of both filters was chosen to be equal.

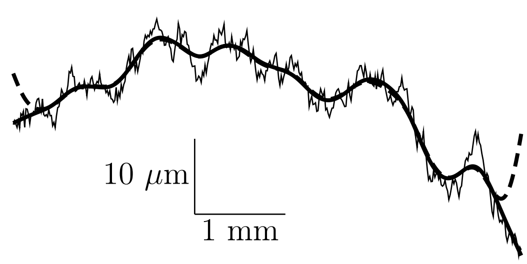

Figure 11. Comparison of the mean lines calculated using the spline filter (solid line) and the Gaussian filter (dashed line) for a roughness profile with equal cut-off wavelength of both filters.

Spline filters which are based on cubic splines — such as the filter defined in ISO/TS 16610-22 [5] — leave cubic polynomials unchanged when filtering, whereas the Gaussian filter only leaves linear functions unchanged. The spline filter is therefore much better suited to follow a profile with a large form portion than is the Gaussian filter. This property can be clearly seen in Figure 12. Also here, the result of the filtration using a Gaussian filter at the same wavelength was plotted for comparison (cf. Figure 9). As can be seen, the spline filter, contrary to the Gaussian filter, is very well suited as a form filter.

We will now consider periodic spline filters for closed profiles. Obviously, the problem of end effects does not occur in the case of closed profiles, since there are no ends. Problems can, however, occur when a non-periodic filter is used for the filtration of closed profiles. Upon filtering, this leads to a discontinuity where the beginning and

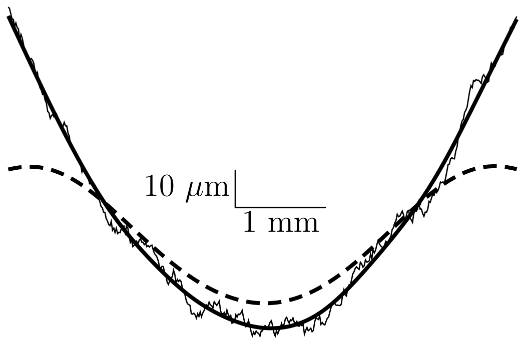

Figure 12. Comparison of the mean lines calculated using the spline filter (solid line) and the Gaussian filter (dashed line) for a profile having a large form portion with equal cut-off wavelength of both filters.

the end of the profile meet, which is characterised by a jump. This can be clearly seen in the right part of Figure 13. When a periodic filter is used, however, the connection is smooth. This is a sufficient demonstration of the necessity of using two different types of filters for open and for closed profiles.

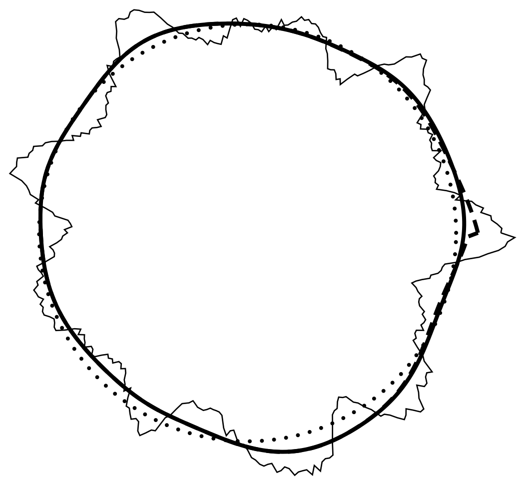

Figure 13. Filtration of a roundness profile (thin solid line) using a periodic spline filter (thick solid line) and a non-periodic spline filter (thick dashed line). The least squares circle is shown as a dotted line.

It must be pointed out that in Figure 13, a very small cut-off wave number (large cut-off wavelength) was chosen for the filter to extract the form which is obviously not a perfect circle, as shown by comparison with the least squares circle. In roundness measurement, one would work with a larger cut-off wave number (smaller cut-off wavelength), so that basically, only the roughness is suppressed, whereas besides the form also the waviness remains in the filtered profile.

A summary of the advantages of the spline filter is given here:

(i) purely digital filter, i. e. no discretisation of the weighting function necessary, contrary to the Gaussian filter, thus, no bias effect;

(ii) faster, memory-saving and roundoff-error-tolerant algorithm (twice as fast as the best algorithm available for the Gaussian filter), i. e. well suited for processing large amounts of data;

(iii) steeper transfer function than the Gaussian filter, i. e. better discrimination;

(iv) no end effects, i. e. the measured information can be used totally or the sampling lengths can be correspondingly shortened;

(v) the profile does not need to be aligned prior to filtering;

(vi) well-suited as a form filter, since third-grade polynomials are not biased;

(vii) can adapt to any boundary conditions, i. e. variants are available for open and closed profiles.

Spline filters can be easily extended to be used as areal filters. This will very soon be necessary, since it has been realised that the appropriate characterisation of technical surfaces is possible not only by measuring and analysing profiles, but also that certain properties can only be assessed by means of areal detection. Spline filters can be developed for space curves or for non-equidistant data, which enables their utilisation in coordinate measuring technology. It is also possible to take into account data which do not have the same degree of accuracy. Such extensions of the spline filter have, however, not yet been dealt with in ISO/TS 16610.

Cubic spline filters have been implemented for approximately 10 years in the evaluation programmes of the measuring instruments of certain German manufacturers, so that users have already been able to gain some experience through practical use.

5. Spline-Wavelets

While the Fourier transformation is a one-parameter transformation only (the parameter is either the wavelength or the frequency), the wavelet transformation is a two-parameter transformation; besides the wavelength or the frequency, it is also possible to localise the place (in the case of a spatial transformation) or the time (in the case of a temporal transformation) at which the wavelength or frequency in question occurs. If one tried to explain this by means of a musical metaphor, it would mean that with the Fourier transformation one would know which tones of a symphony exist but not when they occur and how long they last. With the wavelet transformation, in contrast, one would also obtain these missing pieces of information. Music is not characterised by the spectrum alone.

In precision engineering, matters are similar. To characterise surfaces appropriately, it is not sufficient to know the existing wavelengths, the place in which these occur is also important. Otherwise, it might not be possible to differentiate different textures. Something like a spatially resolved spectrum analysis is therefore necessary. In mathematics, this is generalised as multi-scale analysis. There are several methods for such analyses. One of them is based on the wavelet transformation. More detailed information on this method can be found, e. g., in I. Daubechies [45] or I. Daubechies and W. Sweldens [46].

There are many different wavelet transformations, depending on the wavelet used. This must be chosen in accordance with the requirements placed on the transformation. One can go by the rule that the shape of the wavelet used should be as similar as possible to the shape of the property to be detected (peak, edge, smooth or rough surface, etc.). In ISO/TS 16610-29 [7], only spline wavelets and B-spline wavelets which are compactly supported are dealt with. They are related to the spline filters described in the previous section.

As already mentioned, the wavelet transformation is, in the field of precision engineering, mainly applied to multi-scale analysis. Multi-scale analysis is performed by means of a cascade of appropriate filters (filter bank).

To figure out how the wavelet transformation works, one can imagine that more and more details of a certain scale size (wavelength) are progressively discarded from the measured profile; the finest details are the first to be eliminated. Each of these steps is called a level of transformation. The wavelet transformation can be interrupted at any level, i. e. it is not necessary to go any further than the depth at which the information needed to characterise the surface is available.

At each level, the remaining profile is smoother than that of the previous level. The effect is, thus, comparable to that of a low-pass filter, whereat the cut-off wavelength of the low-pass filter also grows with each level increase. There is, thus, a progression from the roughness to the waviness to the form portion of the profile. The resulting profiles of each level are also called *profile averaging*; the parts which are eliminated from the profiles are therefore called *profile details*. It must be observed that the profile details are only the parts which have been eliminated from the profile from one level to the next, whereas the profile averaging of each level represents the remaining profiles after eliminating all details of the current and all previous levels. Consequently, the original profile can, except for a negligible constant part, be reconstructed from the sum of all its profile details. Obviously, not the usual summation is meant but the corresponding inverse wavelet transformation.

As a first example of a multi-scale analysis, the profile averaging and the corresponding profile details of the wavelet transformation of a profile measured on a turned surface are shown in Figures 14 and 15, respectively. The turning grooves are clearly to be seen at level 1, i. e. they have the scale size of this level. One can also see that they are present over the whole profile and are obviously periodic. These are indeed known properties of turned surfaces. At levels 2 and 3, a periodic waviness appears which is present on the whole surface and is practically periodic. At levels 4 and 5, only the form portion of the profile is visible.

Since it is possible to characterise turned surfaces alone with non-localised periodic parts, i. e. by means of their spectrum, wavelet transformation would not have been necessary. In this case, the Fourier transformation would have sufficed.

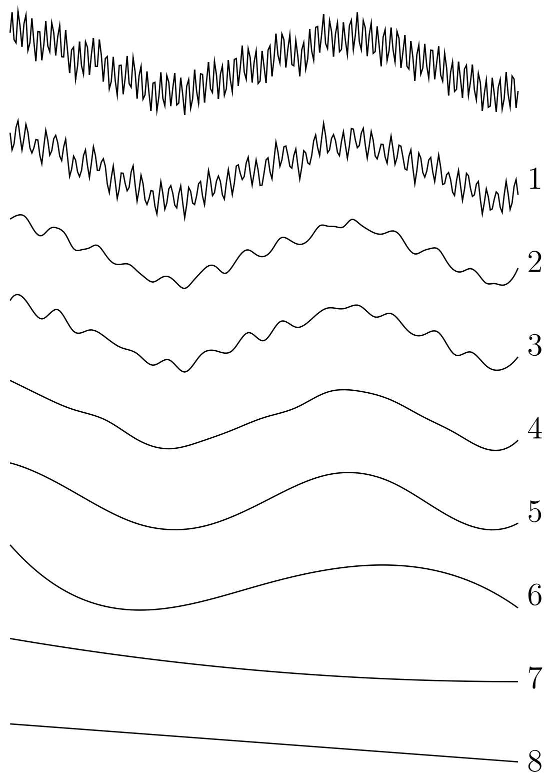

Figure 14. Profile averaging of a turned surface. The original profile is shown at the top. Thereunder the profile averagings for the levels given by the numbers shown at the respective right sides are plotted.

This statement is, however, no longer true for the next example of a multi-scale analysis. In this example, the profile averaging is shown in Figure 16, and the corresponding profile details of the wavelet transformation of a profile measured on a honed surface are shown in Figure 17. At levels 1 to 3, roughness is clearly visible over the whole surface. At levels 4 and 5, the localised deep grooves typical of honed surfaces are clearly to be seen, although one can catch a glimpse of the deepest ridge already at level 2 in the profile details. This ridge is strongly localised, which is recognisable by the fact that it is present at practically all levels apart from level 1. This information on its localisation would be lost in the Fourier spectrum. In this case, the wavelet transformation is therefore indispensable; the Fourier transformation is no longer sufficient.

The only objection one could raise is that the ridge was also clearly visible in the original profile and one could have therefore spared a tedious multi-scale analysis. This is certainly true as long as the characterisation of the surface is possible by merely looking at it, i. e. by means of a subjective assessment. For automated process control and process adjustment, it is necessary to identify desired or undesirable surface characteristics objectively. This, however, presupposes an automatically running separation and classification of the existing original texture details. In this precise case, the wavelet transformation is most certainly an adequate approach.

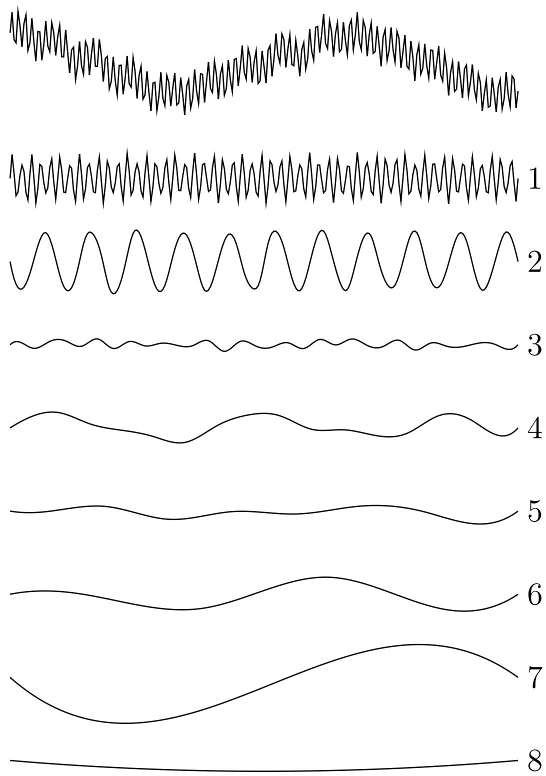

Figure 15. Profile details of a turned surface. The original profile is shown at the top. Thereunder the profile details for the levels given by the numbers shown at the respective right sides are plotted.

The property of the wavelet transformation to detect local disturbances in the surface profile makes it an appropriate method to detect peculiarities (outliers) and discontinuities (jumps) within datasets — whereat it is also very easy to determine their position. The reason for this is that the wavelet coefficients belonging to such deviations tend to be significantly larger than the other coefficients. It means that a simple limit can be used for detection.

A kind of outliers which is particularly easy to detect is caused by disturbing electrical impulses, so-called spikes, in the sets of measured data. These do not actually exist on the surface. They are nearly always characterised by the fact that they strongly differ from the remaining data by one single point. This results in their being already fully visible at level 1 of the profile details.

At level 1 of the profile details, there are, however, very fine structures, such as, e. g., high-frequency roughness parts. Since they have only small amplitudes, the spike, in contrast, seems particularly large and can be easily detected by its exceeding of a certain amplitude and eliminated, as shown in Figures 18 to 20.

Wavelets can also be used to reduce the noise level of a set of profile data. To this end, the wavelet transformation is successfully used as an optimal filter (see Figure 21 as an example).

The wavelet transformation can, of course, be applied not only to profiles but also

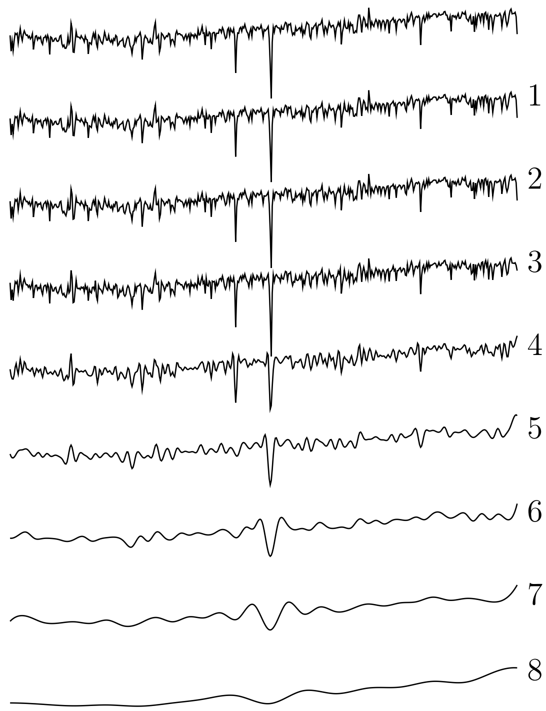

Figure 16. Profile averaging of a honed surface. The original profile is shown at the top. Thereunder the profile averagings for the levels given by the numbers shown at the respective right sides are plotted.

to surfaces.

6. Robust Spline filters

The robust spline filter was developed as a complement to the spline filters previously dealt with in order to serve as a replacement for the special filter according to ISO 13565-1 [28] which was based on the Gaussian filter. Contrary to the latter, this is a purely digital filter — like the usual spline filter. Hence, its implementation implies fewer uncertainties, so that the filtration results for different implementations and platforms are more consistent than is the case with the special filter according to ISO 13565-1.

There are two different variants of the robust spline filter: the non-periodic robust spline filter which should be applied to open profiles, such as those occurring, e. g., in straightness measurement, and the periodic robust spline filter which should be applied to closed profiles, such as, e. g., those occurring in roundness measurement.

Figure 22 shows the application of the non-periodic robust spline filter to the profile of a porous surface. As can be seen, the pores are very well suppressed.

The reason for the good suppression of the pores in this example is that this filter is robust. Filters are called *robust* when they are insensitive with respect to outliers. This is true for the special filter according to ISO 13565-1 as the example shown in Figure 23

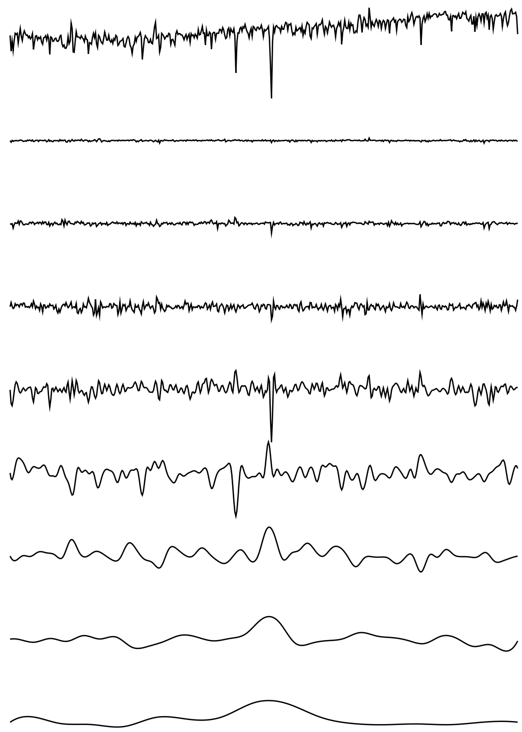

Figure 17. Profile details of a honed surface. The original profile is shown at the top. Thereunder the profile details for the levels given by the numbers shown at the respective right sides are plotted.

demonstrates. The negative (downward-oriented) outliers do not disturb the filtering result; the positive (upward-oriented) outliers, however, lead to an undesirable bias of the mean line. This is not the case with a robust spline filter.

The robustness of filters is often a desirable property when it comes to the acquisition of measured data in a disturbed environment. In such cases, one always has to expect outliers. Since in the case of non-robust linear filters of the convolution type the smoothing of the data is related to the least squares fit which is known to be sensitive to outliers, one must often call upon such non-linear filters. With regard to this, there are different approaches. Many of these presuppose a certain model for the statistical distribution of the outliers. The fundamental conceptions of robust profile filters are summarised in ISO/TS 16610-30 [8].

The first robust splines were discussed by P. J. Huber [56] on the basis of statistical considerations. The spline filter presented here is based on the L_p approximation and was developed by M. Krystek [43] independently. This filter thus belongs to the L_p-norm-based (metric) methods. They are known to be robust for $p = 1 \ldots 1,5$). The filter equation given in ISO/TS 16610-32 [10] belongs to the special choice $p = 1$, i. e. to the L_1 approximation.

It must also be mentioned that the robust variant of the Gaussian filter described in ISO/TS 16610-31 [9] leads to results comparable to those of the robust spline filter.

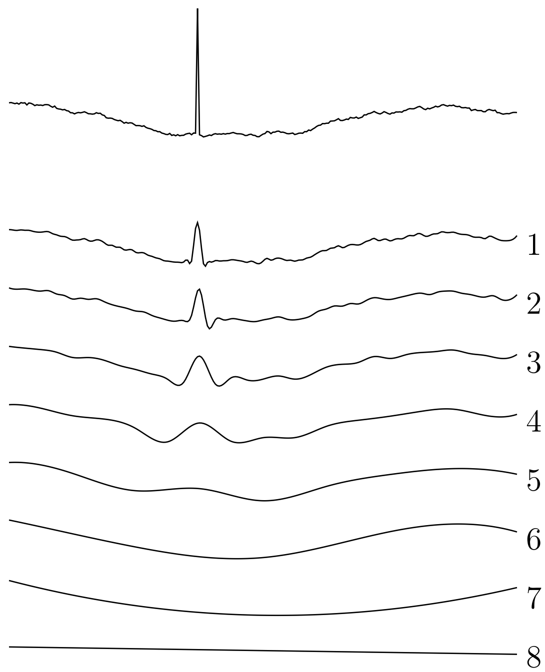

Figure 18. Profile averaging of a profile with an outlier. The original profile is shown at the top. Thereunder the profile averagings for the levels given by the numbers shown at the respective right sides are plotted.

There is, however, in contrast to the robust spline filter, no robust Gaussian filter for closed profiles. The implementation of the Gaussian filter is also much more complex than that of the robust spline filter, since it is based on statistical methods. For more details on the theory and implementation of the robust Gaussian filter, please refer to J. Seewig [57] [58].

7. Morphological filters

Today, morphological filters are often used for image processing; in connection with form filters, they are, however, still largely unknown. They cannot be described by means of the usual methods of the Fourier transformation or convolution, but are based on set-theoretic considerations. Morphological filters do not provide a mean line (M system) as a result, but an envelope (E system).

The use of morphological operations and filters in precision engineering is actually nothing new. Already the tactile extraction of a workpiece surface by means of a stylus, as is usual in, e. g., roughness measurement, represents a morphological operation, even though this is not always perceived as such. The so-called stylus correction, which is included by many instrument manufacturers in their measuring instrument software, is, strictly speaking, also a morphological operation. The thus corrected measurement result gives an image of the workpiece surface which can be considered as the result of a morphological filtering operation when applied to the real surface of the workpiece.

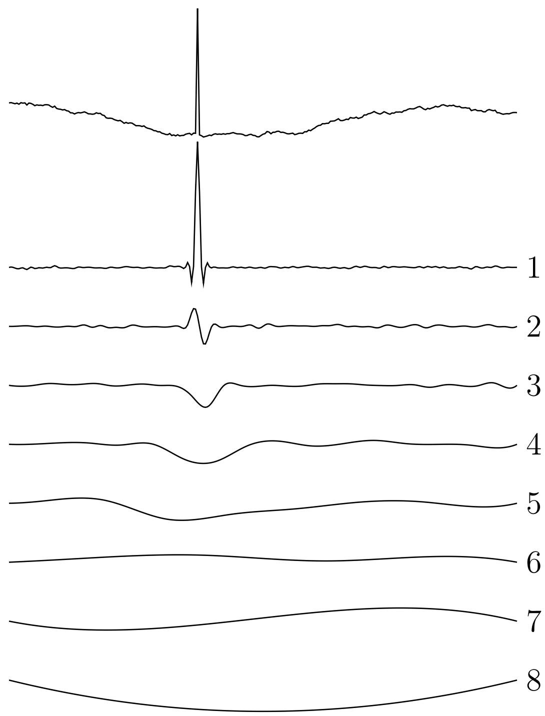

Figure 19. Profile details of a profile with an outlier. The original profile is shown at the top. Thereunder the profile details for the levels given by the numbers shown at the respective right sides are plotted.

Figure 20. Profile shown in Figures 18 and 19 after the outlier has been removed (the arrow points to its previous position).

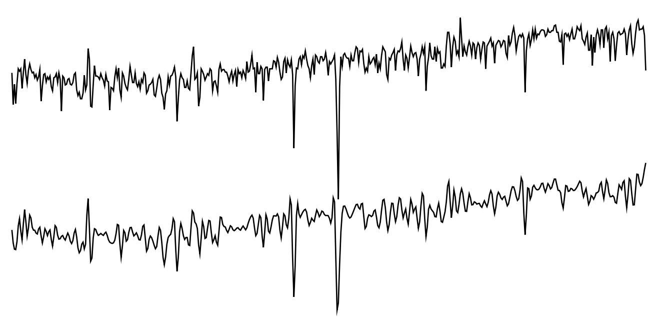

Figure 21. Noise suppression using a low-pass filter based on the wavelet transformation. The measured profile is shown at the top and the filtered profile at the bottom.

Figure 24 shows an example of tactile extraction and stylus correction.

The profile shown in Figure 24 has a length of 0,2 mm and the amplitudes are represented 130 times as high as in reality. The tactile extraction was performed with a sphere of a 2 μm radius. The tactile extraction suppressed the details of the profiles which are smaller than the diameter of the stylus tip and rounded off the peaks by the

Figure 22. Comparison of the mean lines calculated using the non-periodic robust spline filter (solid line) and the Gaussian filter according to ISO 11562 (dashed line) for the profile of a porous surface with the same cut-off wavelength (λ_c =0,8 mm) of both filters.

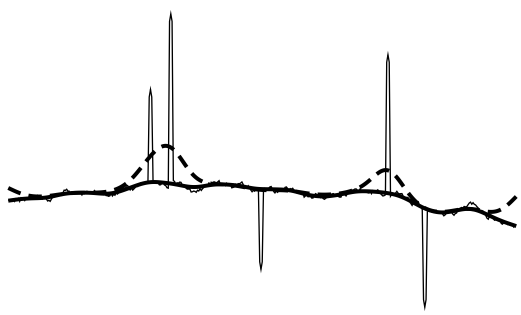

Figure 23. Comparison of the mean lines calculated using the robust spline filter (solid line) and the special filter according to ISO 13565-1 (dashed line) for a profile with outliers with the same cut-off wavelength (λ_c =0,8 mm) of both filters.

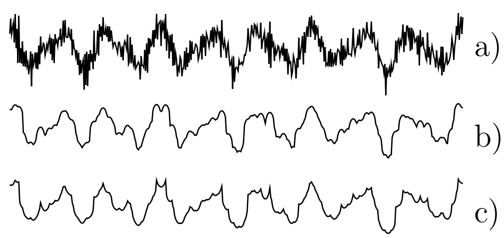

Figure 24. Tactile extraction of a profile: a) original profile, b) extracted profile, c) extracted profile after stylus correction; stylus radius $r = 2$ μm.

radius of the contacting spherical portion of the stylus. The tactile extraction causes an unavoidable smoothing of the profile which is often designated as mechanical filtration. Under certain circumstances, part of the information which is lost due to the tactile extraction can be recovered. As shown in Figure 24, the profile peaks which had been rounded off by the tactile extraction can be reconstructed by a stylus correction.

The tactile extraction of a profile and the subsequent stylus correction are examples of the complementary dual basic operations of morphological filtering, i. e. dilation and erosion. The sphere used for the tactile extraction is an example of a so-called structuring element of the morphological operation. Morphological operations which are dual to each other always have a structuring element of the same form and dimension. Under certain conditions, dual morphological operations are even inverse to each other, i. e. when they are performed one after the other, the changes caused by the first operation are reversed by the second operation. In this case, a perfect reconstruction is obtained. Taking a sphere as the structuring element, the condition for such a perfect reconstruction is that the original profile displays no radii of curvature which are smaller than the radius of the sphere. In addition, the morphological sampling theorem (with regard to this, please see R. M. Haralick [47]) must be taken into consideration; this theorem differs from the usual sampling theorem (for this, see H. Nyquist [48]) for linear signal processing which is based on the Fourier transformation. The first theorem defines that for a sphere as structuring element, the sampling interval must be smaller than the sphere radius. For other structuring elements, other or additional conditions apply to obtain a perfect reconstruction.

The considerations presented here have led to the definition of the mechanical surface of a workpiece as specified in the draft ISO/FDIS 14406 [49]. According to this document, the mechanical surface is defined as the track of the centre point of a sphere having a pre-defined radius which rolls under the surface which was obtained as the track of the centre point of a sphere having the same radius but which rolled on the real surface. This definition is illustrated by Figures 25 and 26. As can be seen, the mechanical surface is obtained in two steps: the tactile extraction step and the reconstruction step. This corresponds to the now usual acquisition of a surface with contact stylus instruments and a subsequent stylus correction.

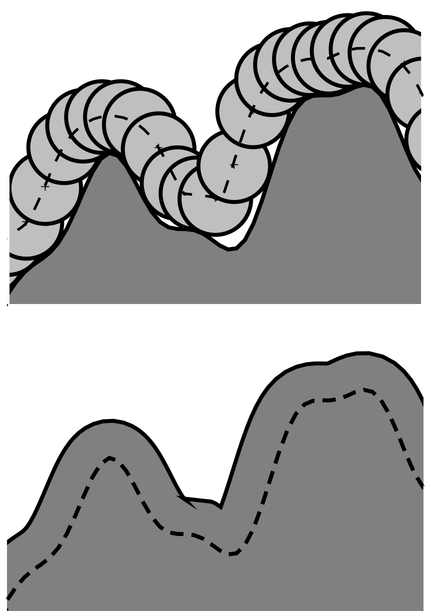

Figure 25. Rolling a sphere on the real surface (tactile extraction step).

Remarks on the definition of the mechanical surface:

(i) The thus defined mechanical surface is always an upper envelope of the real surface.

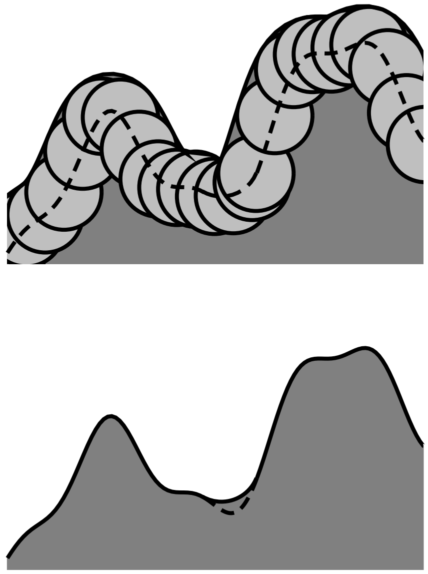

Figure 26. Rolling a sphere under the surface which was obtained as the track of the centre point of the sphere as shown in Figure 25 (reconstruction step).

(ii) The mechanical surface is identical to the real surface when the radius of the contacting sphere is smaller than the local radius of curvature at each point of the real surface.

(iii) The smaller the sphere radius, the better the approximation of the mechanical surface to the actual surface. In the limiting case in which the sphere radius tends towards zero, both surfaces are equal.

The combination considered in the definition of the mechanical surface of the two dual morphological basic operations is called *closing*. Closing is the most simple morphological filter and consists of a dilation, followed by an erosion. From a mathematical point of view, one can, thus, consider the mechanical surface to be the result of the application of a closing filter using a sphere as a structuring element to the real surface. Thereby, dilation takes place when extracting the surface, and erosion must be performed during the subsequent processing of the measured values. Today, this second step is, however, not performed very often, so that existing information remains unexploited, i. e. one pursues work on the basis of a surface profile having been biased by prior dilation, in the belief of being in the possession of an image of the real surface.

The difference caused by this wrong approach is illustrated in Figure 27. If no stylus correction is performed upon profile extraction (dilation) in order to get to the closing, but if one, instead, filters at once using the Gaussian filter according to ISO 11562 (a practice which is quite usual in roughness measurement today), one does not obtain the same result as if one had first performed the stylus correction prior to filtering with the Gaussian filter. When comparing the result of the correct procedure — i. e.

first the stylus correction, then the Gaussian filtration — with the application of the Gaussian filter to the profile of the real surface, one observes good agreement. When comparing it with the result of the wrong procedure — i. e. Gaussian filtration without previous stylus correction — there is no good agreement. As can be seen, the filtered profile resulting from the wrong procedure is significantly larger than the filtered profile resulting from the correct procedure. This effect is caused by dilation in which the maxima of all peaks of the profile are widened and heightened by the radius of the contacting sphere, which can only be reversed by erosion.

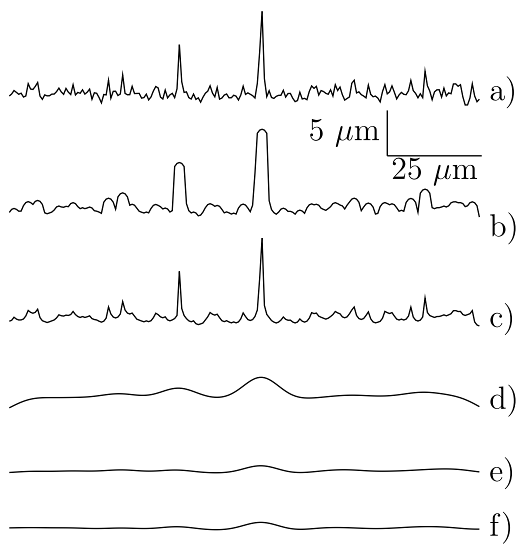

Figure 27. Tactile extraction of a profile ($l_{\mathrm{m}} = 0,125$ mm, $r = 2\mu$m): a) original profile, b) original profile after tactile extraction (dilatation), c) extracted profile after stylus correction (closing), d) profile b after filtration with the Gaussian filter according to ISO 11562, e) profile c after filtration with the Gaussian filter according to ISO 11562, f) original profile after filtration with the Gaussian filter according to ISO 11562. The cut-off wavelength of the Gaussian filter was $\lambda_{\mathrm{c}} = 25$ μm in all cases.

Figure 27 also shows that the result of the closing filter represents a good approximation to the profile of the real surface. All details are, however, suppressed which are smaller than the diameter of the contacting sphere used. This is often a desired effect which can be largely influenced by the radius of the sphere. Some even recommend using morphological filtration alone and fully dispensing with filtration with mean-line filters. Whether this is always possible and even sensible in individual cases still has to be investigated. Thereby, it must be taken into account that morphological filters, due to their structure, are not robust (but in a different way than linear mean-line filters), which is surely not unproblematic in the case of measurements taking place in strongly disturbed environments and requires additional demanding mathematical treatment.

The closing filter is particularly well-suited for suppressing — in the profile measured — deep pores and ridges existing in the surface without, however, eliminating the peaks of the surface. This is clearly shown in Figure 28 for the profile of a ceramic

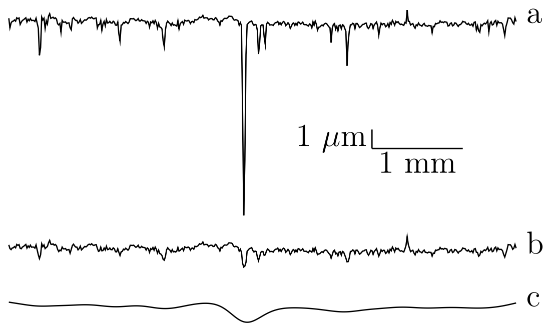

Figure 28. Application of a closing filter using a sphere as structuring element (b) and a Gaussian filter according to ISO 11562 (c) to a profile of a surface with pores (a). Parameters: $l_{\mathrm{m}} = 5,6$ mm, $r = 0,4$ mm, $\lambda_{\mathrm{c}} = 0,8$ mm.

surface with deep pores and in Figure 29 for the profile of a honed surface. In addition, the filtering effect of the Gaussian filter is shown in both cases for comparison purposes. Thereby, the cut-off wavelength of this filter was each time made equal to the diameter of the sphere used as the structuring element in order to obtain comparable results between the two filters (both filters then approximately suppress details of the same size).

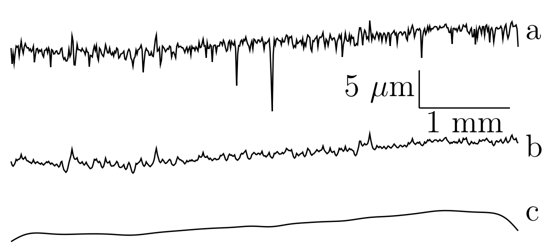

Figure 29. Application of a closing filter using a sphere as structuring element (b) and a Gaussian filter according to ISO 11562 (c) to a profile of a honed surface (a). Parameters: $l_{\mathrm{m}} = 5,6$ mm, $r = 0,4$ mm, $\lambda_{\mathrm{c}} = 0,8$ mm.

Due to the properties shown, it is logical to always use the closing filter instead of the special filter according to ISO 13565-1 for the filtering of the profiles of plateau-type surfaces when it is desired to suppress ridges without, however, suppressing or reducing the amplitude of upward peaks by filtration, as is the case with the Gaussian filter and also with the special filter according to ISO 13565-1. Such a specification may make sense, e. g., to characterise sealing surfaces or to investigate the tribological properties of technical surfaces.

The filter which is dual to the closing filter is the opening filter. It occurs when the two morphological basic operations are carried out consecutively in reverse order to the closing filter, i. e. first erosion, then dilation. The inversion of the order of the two morphological basic operations leads to giving the opening filter properties which are opposed to those of the closing filter. Whereas the closing filter always provides an upper envelope of the profile, the opening filter always provides a lower envelope of the profile. The immediate consequence is that the opening filter, contrary to the closing filter, suppresses not the ridges but the peaks of a surface. This property is clearly visible in Figure 30 where both filters are compared with each other.

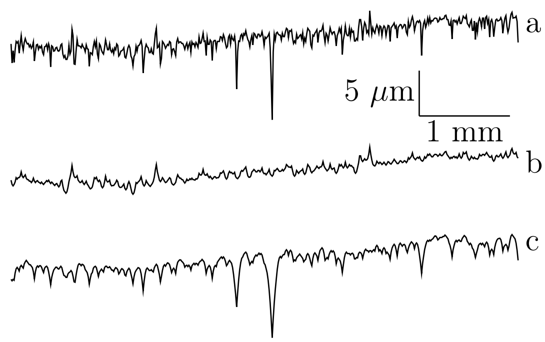

Figure 30. Comparison of the application of a closing filter (b) and an opening filter (c) using a sphere as structuring element to a profile of a honed surface (a). The radius of the sphere is $r = 0,4$ mm for both filters.

Its property of suppressing peaks of the surface without, however, suppressing by filtration downward ridges or pores or reducing their amplitudes, makes the opening filter well-suited for the investigation of certain functional properties of technical surfaces such as, e. g., the lubricating behaviour or the durability of varnishes and other surface coatings.

Opening and closing filters are the most simple morphological filters. By combining these two filters in diverse ways, it is possible to build more complex morphological filters such as, e. g., the so-called alternating sequential filters (with regard to this, please see S. Sternberg [52], for instance), which, in the most simple case, are composed of one opening and one closing filter. These two filters can be used consecutively in exactly two ways: as opening-closing filters and as closing-opening filters. The effect of the two resulting alternating sequential filters is shown in Figure 31.

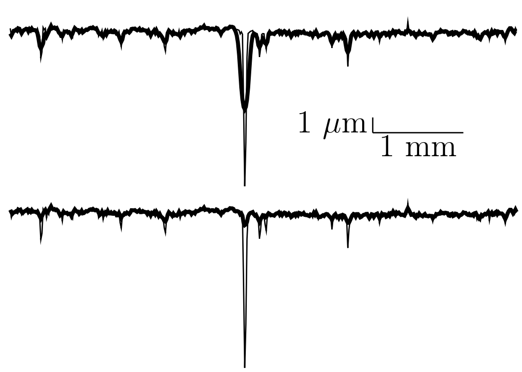

Figure 31. Application of an alternating sequential filter using a sphere ($r = 0,5$ mm) as structuring element to a profile of a ceramic surface with pores (at the top opening-closing filter, at the bottom closing-opening filter). An equal sphere radius of the structuring elements has been chosen for both filters. The unfiltered profile is shown as a thin line, the filtered profile as a thick line, respectively.

As can be seen in the figure, the order of the morphological filters involved is essential to the behaviour of alternating sequential filters. The opening-closing filter has the essential properties of the opening filter, i. e. the filtered profile largely runs at the lower boundary of the unfiltered profile. Due to the closing influence, there is, however, no lower envelope anymore, but the ridges are partly cut off. Correspondingly, the closing-opening filter has the essential properties of the closing filter, i. e. the filtered profile largely runs at the upper boundary of the unfiltered profile. In this case, however, due to the opening influence, there is no upper envelope anymore, but the peaks are partly cut off.

For the example shown in Figure 31, an equal sphere radius of the structuring elements has been chosen for both morphological basic filters which form the alternating sequential filter. They are therefore also called *symmetrical alternating sequential filters*. Such filters play an important role in the scale-space methods which will be dealt with in the next section. It is also possible to choose a different sphere radius of the structuring element for the two morphological basic filters so as to obtain so-called *asymmetrical alternating sequential filters*. This asymmetry enables the adaptation of the filters to certain specifications of the filter characteristics, such as, e. g., a strong suppression of ridges and a weak cut-off of the peaks, or vice versa. It is even possible to choose different structuring elements for the two morphological basic filters so as to increase the flexibility of the alternating sequential filters in order to, e. g., better take into account the different form of ridges and peaks.

As demonstrated, morphological filters open up various potential applications in precision engineering. In future, specification and verification adapted to the function of workpieces will surely no longer be possible without detailed knowledge of the effect of morphological operations or the targeted use of morphological filters (see also M. Dietzsch et. al. [50]). Also for establishing datums, morphological operations and filters have proven advantageous compared to the usual mean-line filters which were standard up to then (see M. Dietzsch et. al. [51]).

It is, of course, unproblematic to extend the use of morphological filters to closed profiles or to surfaces.

8. Morphological scale space methods

The morphological scale-space method dates back to G. Matheron [53]. For morphological filtering, it is the method which is analogous to the multi-scale analysis of the wavelet transformation. This method is figuratively comparable to the sieving of an amount of particles of different grain sizes which fall through a set of sieves with decreasing mesh size and are, thus, separated according to their size. Similarly, the morphological scale-space method separates details of a surface by using the symmetrical alternating sequential filters described in the previous section. These filters consist of a certain succession of successively positioned opening and closing filters; thereby, the size of the structuring element becomes larger with each step. This basically builds a filter bank of morphological filters.

Symmetrical alternating sequential filters eliminate ridges and peaks whose width is smaller than that of the structuring element, i. e., in the case of a sphere as a structuring element, all details of the profile which are smaller than the sphere diameter are eliminated by the filter. Furthermore, they also fulfil the so-called sieving criterion. This states that the successively performed filtering of a profile by means of two filters whose structuring element is of different size, leads to the same result as if the profile had been filtered by means of only the filter whose structuring element is the larger of the two. Also here, the comparison with mechanical sieving works. A wide-meshed and a fine-meshed sieve positioned successively provide as a result of the sieving process within the wide-meshed sieve also the same grain size as the wide-meshed sieve alone, i. e. the fine-meshed sieve does not influence the result in the wide-meshed sieve.

For the morphological scale-space method, it is possible to use four different types of symmetrical alternating sequential filters (for more details, see J. Serra [54] and [55]): the closing-opening filter (M sieve), the opening-closing filter (N sieve), the closing-opening-closing filter (R sieve) and the opening-closing-opening filter (S sieve). In ISO/TS 16610-49 [13], only the M sieve with a constant ratio of the scale interval (sphere radii) is recommended for the application of the morphological scale-space method to geometrical product specification and verification.

M sieves basically have the characteristics of closing filters and are, therefore, compatible with the definition of the mechanical surface when a sphere is chosen as the structuring element. The combination of closing and opening filters causes ridges and peaks to be simultaneously suppressed whose width is smaller than the width of the structuring element (i. e. smaller than the sphere diameter). With such a chain of filters with an increasing sphere radius, it is, thus, possible to separate the details of different widths (scale values) occurring in a profile. The scale value (i. e. here the sphere radius) replaces the cut-off wavelength of linear filters so that the increasing succession of scale intervals (sphere radii) of the scale-space method based on morphological filters corresponds to the increasing succession of levels (cut-off wavelengths) of the multi-scale analysis based on the wavelet transformation. This creates a total correspondence between the two methods.

The cut-off wavelengths of the multi-scale analysis are always in a constant ratio of 2 to each other. This value is yielded by the theory of the wavelet transformation. The experience in dealing with multi-scale analysis has, however, also shown that this ratio is nearly optimal, since this value is, on the one hand, large enough to clearly differentiate the details of different levels; on the other hand, it is not so large that significant details are lost. On the basis of this realisation, it makes sense to also choose a ratio of the scales (sphere radii) of approximately 2 for the morphological scale-space method. To be, at the same time, consistent with the recommended sampling peak radii of roughness measurement according to ISO 3274, the series ..., 1 μm, 2 μm, 5 μm, 10 μm, 20 μm, 50 μm, 100 μm, 200 μm, 500 μm, 1 mm, 2 mm, 5 mm, 10 mm, ... has been chosen in ISO/TS 16610-49. The smallest value of this series is thereby limited by the morphological sampling theorem and can, therefore, not be smaller than the value of the length of the sampling interval. It is sensible to let the series of the scales begin with the value of the stylus tip radius used for the measurement of the profile (the morphological sampling theorem should have been taken into account in the measurement). In principle, there is no upper limit to the values for the scale series.

To enable a direct comparison of the results of the morphological scale-space method with those of the multi-scale analysis, the same profiles were used for the analysis.

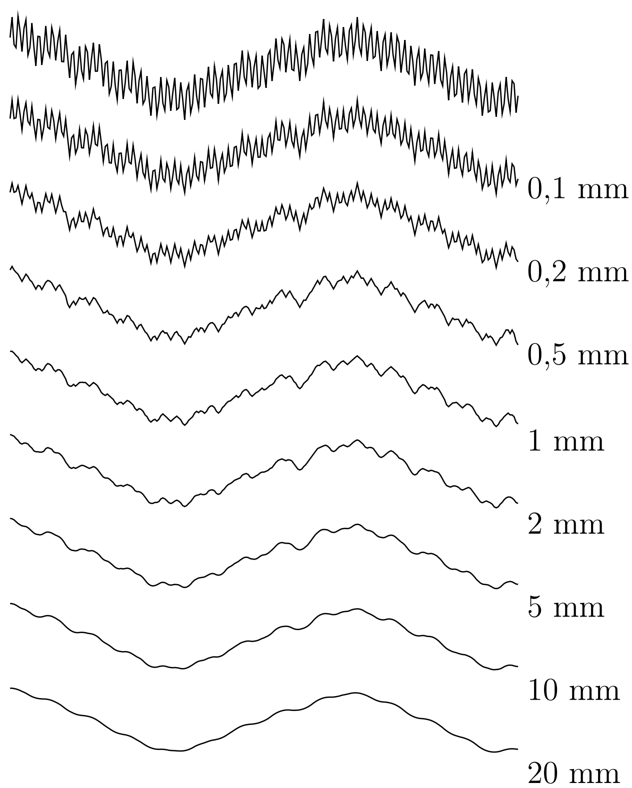

Figure 32. Profile averaging of a turned surface. The original profile is shown at the top. Thereunder the profile averagings for the scale values (sphere radii) given by the numbers shown at the respective right sides are plotted.

Figure 32 shows the profile averaging of a turned surface, Figure 33 the corresponding profile details. Here, the scale series was started with a sphere radius of 0,1 mm to make it comparable to level 1 of the multi-scale analysis of this profile to which a cut-off wavelength of 87,5 μm belongs. As shown in Figure 33, the periodic turning marks are visible in the scale range $100 \ldots 500$ μm when the morphological scale-space method is used, whereas they become visible at levels 1 to 4 (which corresponds to a cut-off wavelength of $87,5 \ldots 700$ μm) in the case of the multi-scale analysis (cf. Figure 15). The results of these two methods are, thus, in good agreement with each other, also with regard to the wavelength spectrum, which was obtained by means of a FOURIER transformation of the profile. Here, a practically continuous spectrum occurs in the wavelength range $0 \ldots 610$ μm. Such a continuous spectrum is typical for the overlapping of the periodic structure of the turning marks with the existing roughness

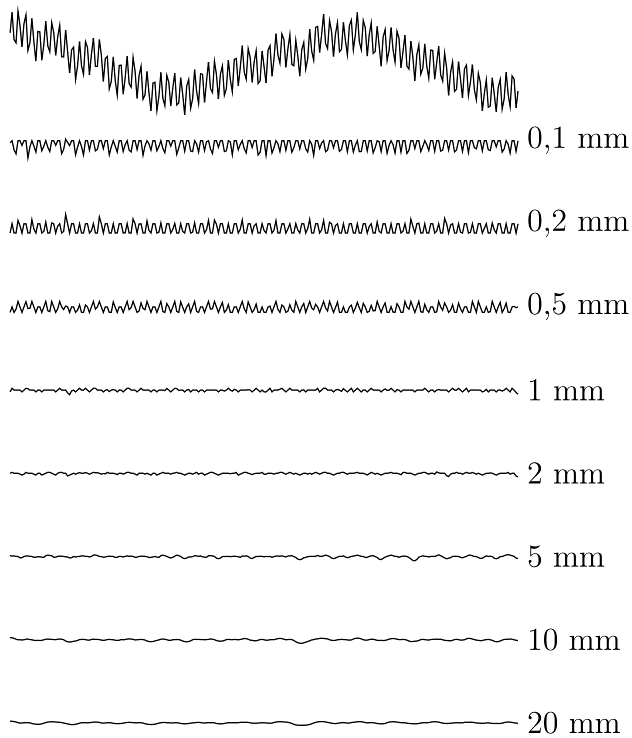

Figure 33. Profile details of a turned surface. The original profile is shown at the top. Thereunder the profile details for the scale values (sphere radii) given by the numbers shown at the respective right sides are plotted.

of the surface. This roughness is no longer resolved by any of the two methods due to the smallest scale interval or the smallest cut-off wavelength chosen, respectively; it, however, shows in the morphological scale-space method through the deviation of the profile details of the scales from the periodicity.

Figure 34 shows the profile averaging of a honed surface, Figure 35 the corresponding profile details. Here, the scale series was started with a sphere radius of 50 μm to make it comparable to level 1 of the multi-scale analysis of this profile to which a cut-off wavelength of 44,8 μm belongs. As shown in Figure 35, the deep ridges are visible almost exclusively at the scale value of 50 μm when the morphological scale-space method is used, whereas they have an influence at levels 2 to 8 (i. e. at nearly all levels) in the case of the multi-scale analysis (cf. Figure 17). The discrimination of the morphological scale-space method is, thus, considerably better in the case of this profile than in that of the multi-scale analysis. The poorer resolution of the multi-scale analysis is due to the use of the cubic spline wavelets which, due to their smooth run, are not very well suited to detect peculiarities such as the small peaks and ridges occurring in this profile. In this case, other, better suited wavelets should be used.

All in all, the morphological scale-space method seems to obtain the better result than the multi-scale analysis in the light of the two examples shown here. It would, however, be wrong to draw hasty conclusions from this, since there has, up to now, been no systematic comparison of the two methods.

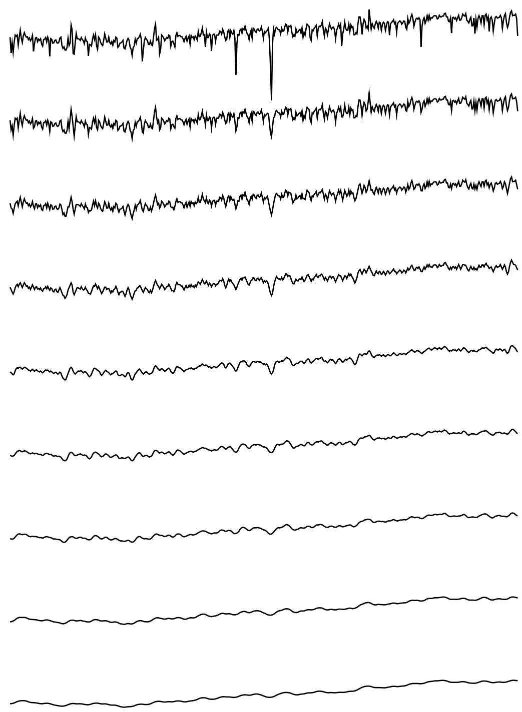

Figure 34. Profile averaging of a honed surface. The original profile is shown at the top. Thereunder the profile averagings for the scale values (sphere radii) given by the numbers shown at the respective right sides are plotted.

The property of the morphological scale-space method of detecting local disturbances in the surface profile makes it — just as the wavelet transformation — an appropriate method to detect peculiarities (outliers) and discontinuities (jumps) within datasets — whereby it is also very easy to determine their position.

Outliers are nearly always characterised by the fact that they strongly differ from the remaining data by individual points. This results in their being already fully visible at very low scale intervals of the profile details. However, only very fine structures, such as, e. g., high-frequency roughness parts are usually located there. Since they have only small amplitudes, the outlier, in contrast, clearly stands out and can be easily detected due to its exceeding of a certain amplitude (see Figure 36, scale value 50 μm).

The profile averaging belonging to the scale value for which the outlier was detected is free of this outlier (see Figure 37, scale value 50 μm). However, it contains no more details which have the same width as the outlier. Now, such details can surely not be attributed to roughness but are a special kind of noise which is known as excess noise. Consequently, the profile averaging which belongs to the scale value at which the outlier was detected already represents the profile which has been freed of the outlier. The morphological scale-space method thus makes it particularly easy to eliminate outliers.

The morphological scale-space method can also be very effectively used to

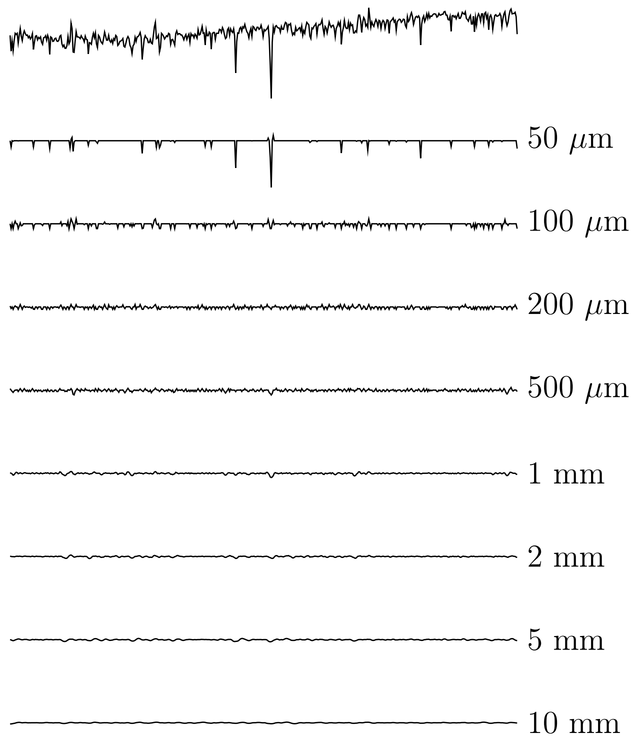

Figure 35. Profile details of a honed surface. The original profile is shown at the top. Thereunder the profile details for the scale values (sphere radii) given by the numbers shown at the respective right sides are plotted.

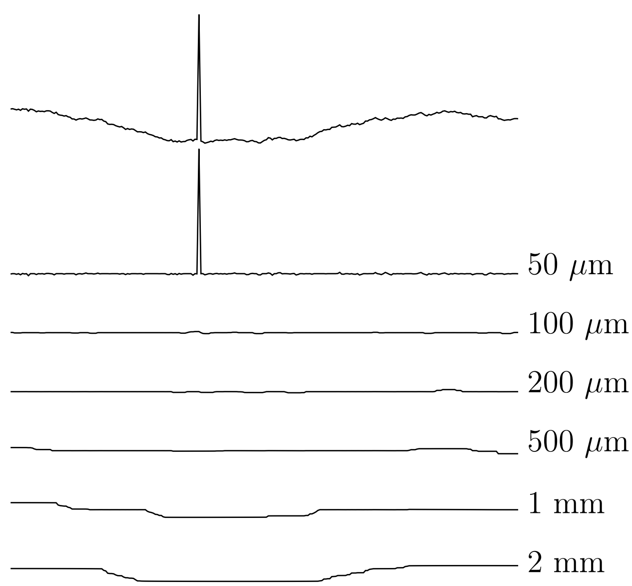

Figure 36. Profile details of a profile with an outlier. The original profile is shown at the top. Thereunder the profile details for the scale values (sphere radii) given by the numbers shown at the respective right sides are plotted.

simultaneously eliminate outliers and suppress noise. Thereby, even the aforementioned excess noise can be suppressed (see Figure 38). This is particularly remarkable, because

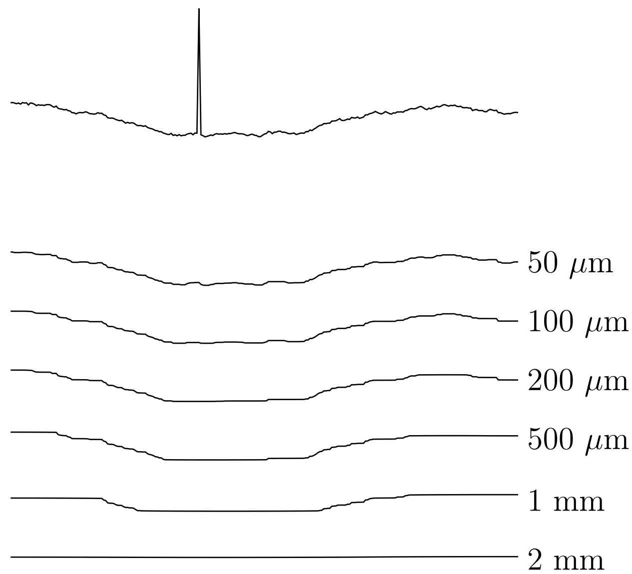

Figure 37. Profile averaging of a profile with an outlier. The original profile is shown at the top. Thereunder the profile averagings for the scale values (sphere radii) given by the numbers shown at the respective right sides are plotted.

linear filters cannot eliminate such noise out of a data set.

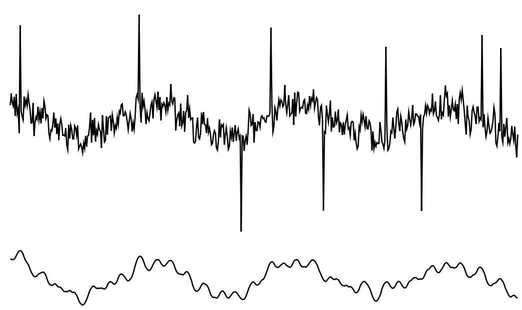

Figure 38. Simultaneous outlier elemination and noise suppression by the morphological scale-space method. The noise is composed of a superposition of excess noise and coloured noise. The measured profile is shown at the top and the filtered profile at the bottom.

Excess noise, unlike normal noise, does not occur along with excessively weak signals but also in the case of very strong signals. It appears in random, relatively strong, impulses which sometimes occur as bursts. In image processing, this phenomenon is known as "salt and pepper noise"; in sound signal transmission, it appears in the form of cracking noises.

9. Summary and Outlook

In this publication, an overview of the filtering methods included in the ISO/TS 16610 series of documents is given and illustrated in the light of examples of their potential application fields. Thereby, only profile filters were addressed. In some places, it has, however, been mentioned that the filters presented here could easily be extended to areal filtering. One of the possibilities of realising this, is for linear filters, for example, the so-called tensor product, which is described in Section 60 of ISO/TS 16610 [59] which is still a draft. This part of ISO/TS 16610 serves to prepare an extension of the documents to linear areal filters. But also for morphological filtering methods, it is envisaged that corresponding areal filters are included in ISO/TS 16610. The ISO/TS 16610 series will, thus, be extended in the near future. The necessity to do so has become obvious from the constantly growing awareness that modern industrial testing processes for the characterisation of technical surfaces can no longer be based solely on profile measurements.

The aim of the ISO/TS 16610 series was and still is to familiarise the user of the GPS standards with the new methods which are based on modern mathematical methods and algorithms. Over time, instrument manufacturers will progressively integrate these new methods as options in their measurement instrument software in order to give users the opportunity to familiarise themselves with the newly created tools and to gain experience. Some implementations of the new filtering methods are even already available in modern measuring instruments. Some of the methods described in ISO/TS 16610 have, however, influenced the newly developed standards in ISO/TC 213, which have already been published or will be published within the next few years. Thus, the user is well advised not to close his eyes when faced with the new techniques, but to look into them at an early stage.

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