Hernla, M.: Inspection of Surface Geometry.
X. International Colloquium on Surfaces, Chemnitz 2000. Proceedings and Poster, Shaker Verlag Aachen 2000, pp. 23-32

Inspection of Surface Geometry

Dr.-Ing. Michael Hernla, Dortmund

1. Introduction

The recent situation in geometrical product specifcation (GPS) measurement is characterized by discussions on the following items:

- Geometric features and symbols on drawings
- Tolerances and tolerance zones
- Deviations of size, distance, location, orientation, form, waviness and roughness
- Conditions of measurements like stylus and stylus radius, probing forces, filters
- Evaluation of uncertainty

The central question is that of geometric features. The standard ISO 14660 defines the terms real, extracted and associated feature [1], [2]. The extracted feature is an approximated representation of the real feature, obtained by extracting a finite number of points from the real feature. This extractation is performed in accordance with specified conventions.

One such convention is the use of standardized Gaussian wavelength filters with stated cut-off wavelength, in form measurements e.g. λ_c=0.8 mm [3]. The extraction of geometric features by filtering causes the following problems:

1. Filters with stated cut-off wavelength λ_c=0.8 mm demand a maximum distance of points of Δx=0.16 mm according to the sampling theorem. Measurements on large objects may obtain in this way some thousands of points.
2. Small dimensions of less than 2 mm are not measureable at all, because the filter cuts off all the errors of measurement as well as the deviations of form.
3. Filtering may cut off information about the surface. In this way local deviations of form may stay undetected, see **figure 1**. Due to the stated cut-off wavelength of the filters, e.g. in waviness measurements of sealing surfaces 95% of spin structures are not recognized [4]. The result of measurement may cause a fatal error, if the unknown error of form does matter the function of the workpiece.
4. The residual errors of the filtered profile are not independent, but correlated, because they contain systematic errors of form. This is a characteristic of a filtered profile being only a poor approximation of the real surface. In this case the dispersion of random errors and the uncertainty may be evaluated too large.

2. Quality of approximation

The existence of systematic errors of form within the residual errors of a filtered profile may be tested quite simply. From mathematical statistics the sign test is known: If there are some longer sections of residual errors with same signs, they contain systematic deviations, see **figure 1**. The amount of the test value ξ_2 shall be smaller than its critical value [5], see **table 1**. For the residual errors z_i of number n=101 in **figure 1**, we get the test value ξ_2=36 and a critical value of 20. The errors are not random, but contain systematic deviations.

Another statistical test is that of the correlation coefficient r. Its amount shall be smaller than its critical value [6], see **table 1**, too. For the residual errors z_i in **figure 1**, we get the correlation coefficient r=0.61 and its critical value 0.19. The conclusion ist the same as before: the residual errors are correlated and not independent.

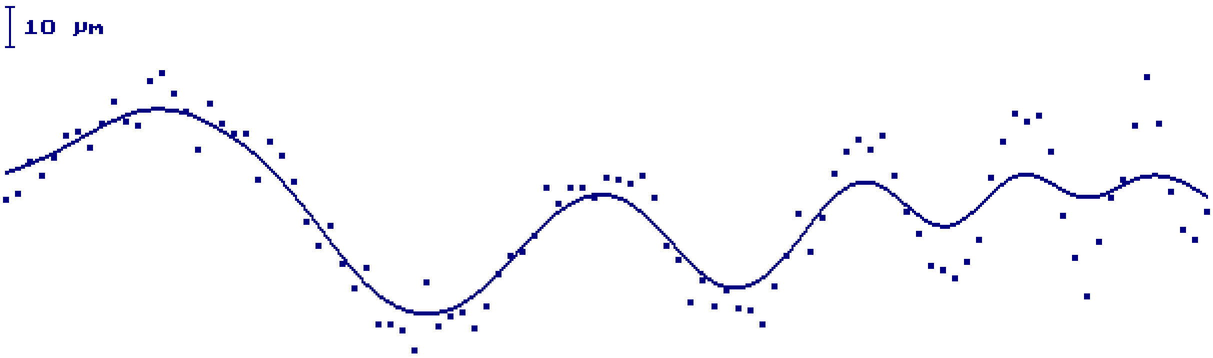

Figure 1: Extracted points of a surface profile (measuring length L=5 mm) and filtered surface profile using a standardized Gaussian wavelength filter (λ_c=0.80 mm); r=0.61>0.19, ξ_2=36>20, s_r=7.8 µm

	Test value	Critical value
Sign test	$\xi_2 = \sum_{i=2}^{n} \operatorname{sgn}(z_{i-1}) \operatorname{sgn}(z_i)$	$\lvert\xi_2\rvert \le 2\sqrt{n-1}$
Correlation coefficient	$r = \dfrac{\sum_{i=2}^{n} z_{i-1} z_i}{\sum_{i=1}^{n} z_i^2}$	$\lvert r\rvert \le \dfrac{t_{1-\alpha/2,n-m}}{\sqrt{n-m+t_{1-\alpha/2,n-m}^2}}$

Table 1: Test of quality of profile approximation; test values and critical values for independent random errors, with quantile $t_{1-\alpha/2,n-m}$ of the Student's distribution for a two-sided level of confidence P=1-α

3. Separation of random errors

The problem is caused by the filter, the solution is to modify the filtering process. By iterative variation of the cut-off wavelength a filter may be found, of which the residual errors are completely uncorrelated und independent. The iteration has to be continued until the correlation coefficient r is zero respective its amount is smaller than the critical value r_{zm}.

In **figure 2** the extracted feature of the extracted points of **figure 1** is shown, using an iterative filtering process with variable wavelengths. The resulting cut-off wave-length λ_c=0.30 is very much shorter than the standardized one. There are no longer sections with same signs of the residual errors, and the test values are close to zero. The residual errors are uncorrelated and independent.

The filtered profile of **figure 2** is a better approximated representation of the real surface than the profile in **figure 1**. As mentioned above, the uncertainty of the extracted feature may be evaluated [7], [8]. Using the standard deviation $u(z)$ of the independent residual errors z_i, we get the expanded uncertainty of the Gaussian filter for a level of confidence of 95%. This standard deviation $u(z)$ is a realistic estimation for the uncertainty contribution of local deviations of form of a surface, measured with a limited number of points, containing the dispersion of the measuring system [9], [10].

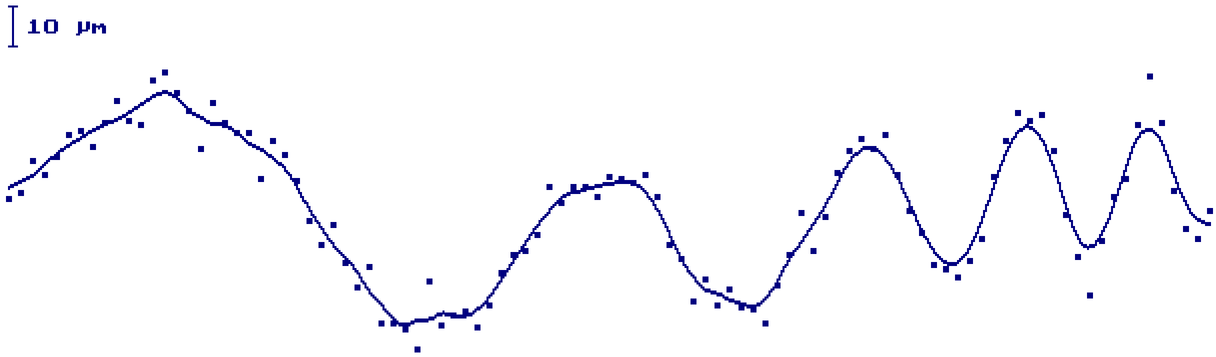

Figure 2: Extracted points of figure 1 with iterative filtered surface profile using a Gaussian wavelength filter (λ_C=0.30 mm); r=0.00<0.19, ξ_2=|2|<20, s_r=4.1 µm

4. Associated features

In addition to the extracted feature, various associated features may be calculated. They are ideally geometric features without deviations of form, according to specified conventions. Very often used is the total least square feature (median feature, Gaussian feature), another the adjacent feature. The equation of the median straight line is known from mathematical statistics as the regression straight line [11].

According to the Guide to Expression of Uncertainty in Measurement [7], we get an expanded uncertainty of the total least square straight line for the level of confidence of 95%. The orientation and location of the total least square straight line is independent from the filtered profile, but their uncertainty depends on the standard deviation of the random residual errors of the filtered profile. The total least square line and their confidence intervals, based on the extracted points from **figure 1**, are shown in **figure 3**.

In **figure 3** also the adjacent straight line to the filtered profile is shown. The contact condition is almost the same like in ISO 1101 [12]. The deviation of form has to become a minimum. In this case it is the maximum distance of the extracted to the associated feature. Based on the known uncertainty of the contact points (i.e. the uncertainty of the filtered profile at these points), the uncertainty of the adjacent straight line may be calculated according to the Guide [7], [11]. Supplementary, the uncertainty contributions of other components like environment or geometric errors of the measuring system have to be taken into account for complete uncertainty evaluations.

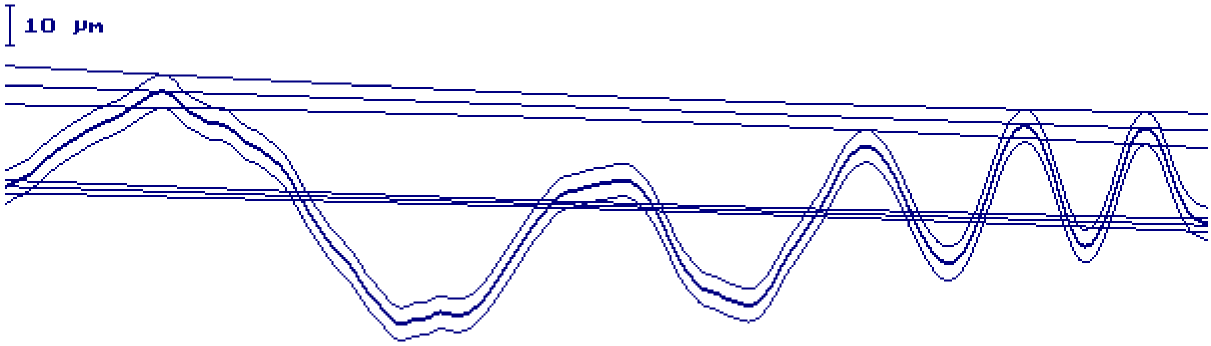

Figure 3: Total least square line and adjacent straight line to the filtered profile of figure 2, and confidence intervals

5. Spline filters

Alternatively to the Gaussian filter used in the figures above, a discrete polynomial spline filter may be used [11], [13], [16]. For the example of **figure 1**, within the limits of the confidence intervals we get the same filtered profiles and standard deviations of the independent residual errors, see **figure 4**.

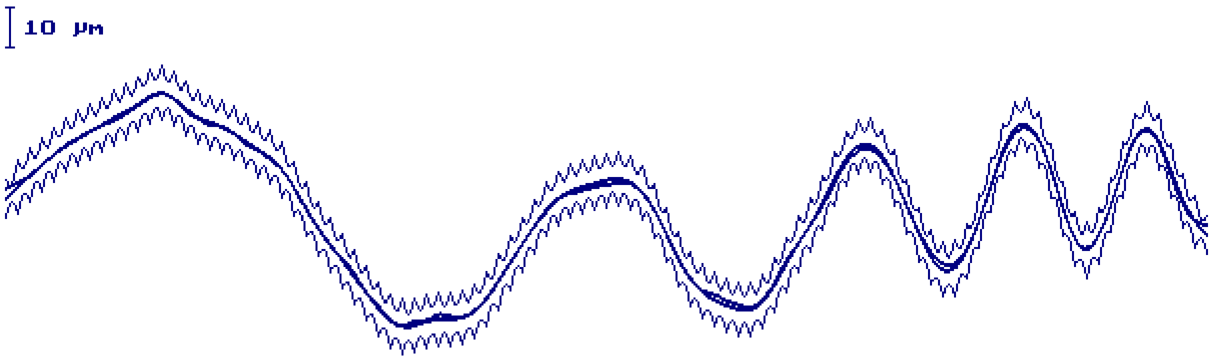

Figure 4: Iterative filtered surface profile of the extracted points of figure 1 using a spline filter (λ_C=0.39 mm, r=0.00<0.20, ξ_2=|-8|<20, s_r=4.0 µm), in comparison with the profile of figures 2 and 3, and confidence interval of the spline function

6. Roughness

A special problem is the definition of the mean line for roughness measurements. Based on the extracted feature, there is to associate a mean line. Some authors already discussed the disadvantage of standardized Gaussian filters with negative efforts of outliers and surfaces with one-sided deviations [13], [14].
The solution seems to be a special robust filter, e.g. a modified Gaussian or spline filter. Its mean line is used for the separation of long wave profile components according to specified conventions. One of them is the cut-off wavelength λ_C, another the cut-off wavelength λ_S for cutting the random errors. For the λ_S-filter the above conclusion is valid, too. It does not take into account the real deviations of the surface and the errors of the measurement itself [11], [15].

7. Applications

As the above discussions made it quite clear, the current way of filtering is no useful method in surface measurements. This conclusion is valid for all measurements of geometrical properties. Filters of any kind with stated cut-off wavelength are not in accordance with the regards of the technical reality, but only a poor makeshift.

The powerful possibilities using extracted features with known uncertainty shall be discussed at the example of form, orientation and distance measurement of two profiles. Two data sets of extracted points are shown in **figure 5**, the results of measurements are given in **table 2**. According to ISO 1101, all points of the surface shall be within the tolerance zone. Usually, the extracted points are taken for the surface, but we don not know, how good they represent the unknown real surface. Therefore it is not possible to evaluate the uncertainties of measurement.

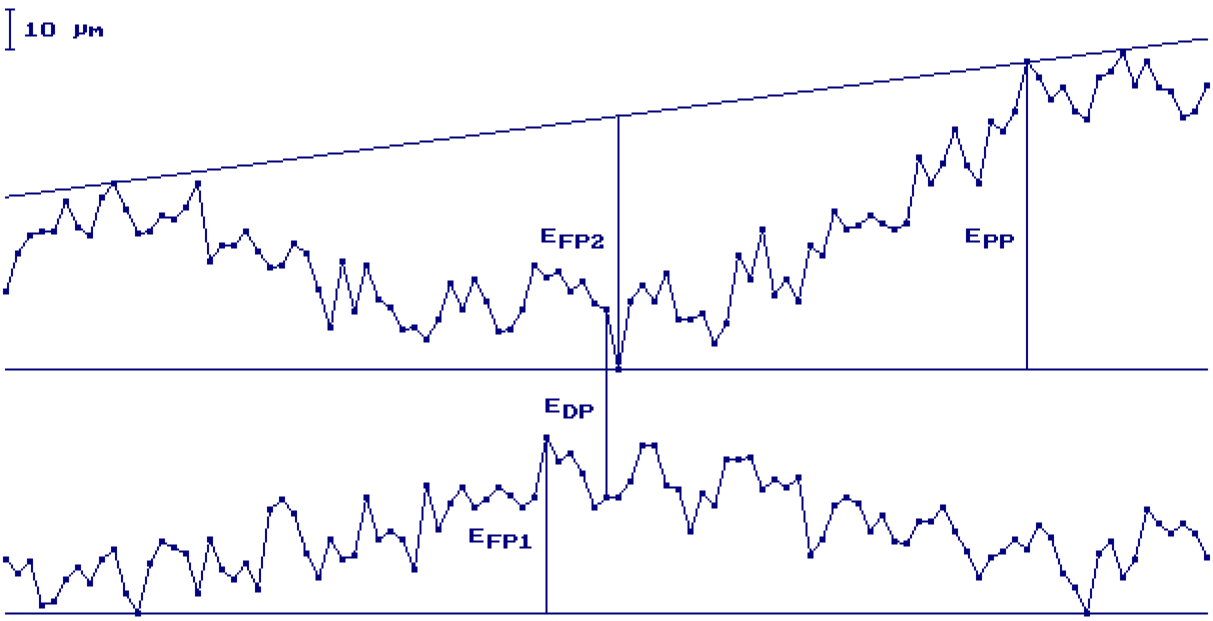

Figure 5: Two data sets of extracted points with their extracted features, iterative filtered with spline filters, deviations of form E_{FP} and of parallelism E_{PP} according to ISO 1101, and distance E_{DP} in the centre of the profiles according to ISO 14660-2

The deviations of form und orientation of the iterative filtered profile with discrete polynomial spline filters are shown in **figure 6**. Only the extracted features (the filtered profiles) are known with their confidence intervals. Instead of the extracted points, the filtered profiles have to be taken into account to calculate the deviations of form and orientation, and their uncertainties, see **table 2**.

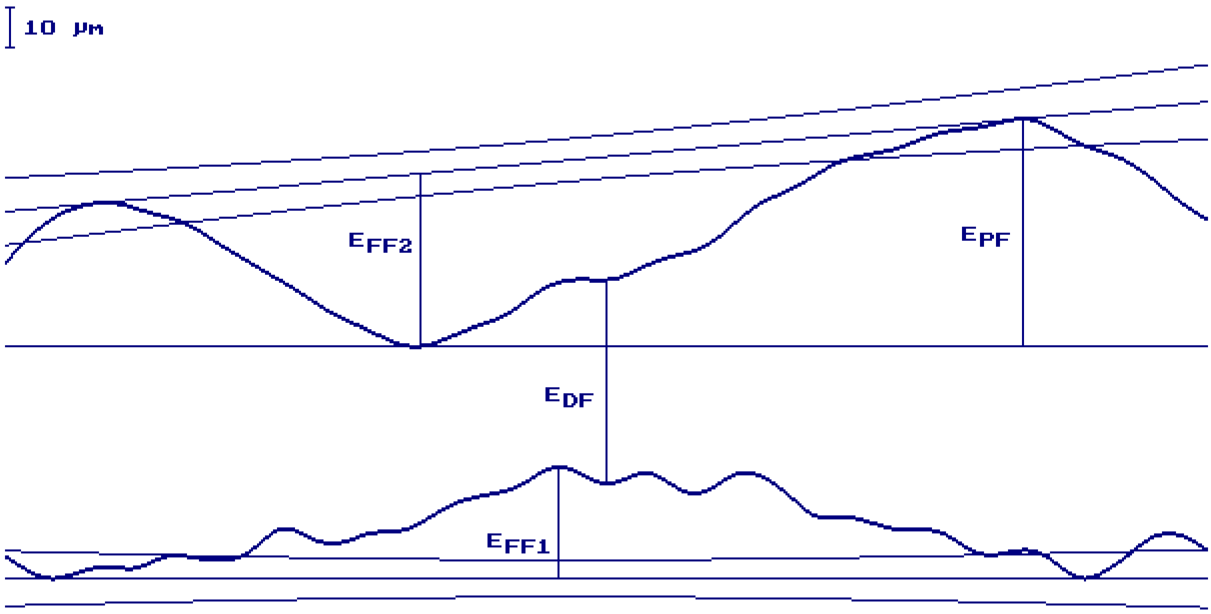

Figure 6: Filtered profiles from figure 5, deviations of form E_{FF} and of parallelism E_{PF} according to ISO 1101, distance E_{DF} in the centre of the profiles, and confidence intervals

Geometrical property of the surface	Figure 5: Extracted points	Figure 6: Filtered profile	Figure 7: Adjacent straight line	Figure 8: Total least square line
Deviation of form, below	E_{FP1}=0.044	E_{FF1}=0.028 U_{FF1}=0.010	E_{FA1}=0.028 U_{FA1}=0.010	E_{FL1}=0.030 U_{FL1}=0.011
Deviation of form, above	E_{FP2}=0.056	E_{FF2}=0.043 U_{FF2}=0.008	E_{FA2}=0.043 U_{FA2}=0.008	E_{FL2}=0.045 U_{FL2}=0.009
Deviation of parallelism	E_{PP}=0.074	E_{PF}=0.057 U_{PF}=0.014	E_{PA}=0.027 U_{PA}=0.018	E_{PL}=0.030 U_{PL}=0.005
Distance in the centre of the profiles	E_{DP}=9.978	E_{DF}=9.976 U_{DF}=0.013	E_{DA}=10.046 U_{DA}= 0.007	E_{DL}=10.015 U_{DL}= 0.001

Table 2: Results E of measurements and expanded uncertainties U (k=2 for a level of confidence of 95%) of the profiles in figures 5, 6, 7 and 8, in mm

The definition of the tolerance of orientation in ISO 1101 causes a problem: as to be seen in **figures 5 and 6**, the result is no direction. The result of an orientation measurement gives no information on the direction like "from left to right falling or rising" as it needs e.g. the worker at the machine or the constructor. The deviation of orientation in every case contains the full deviation of form, and according to the recent edition of ISO 1101 there is no other possible interpretation [17].

In the case of immediate contact of surfaces the deviation of orientation should be calculated for the adjacent features, according to the function. In other cases it could be total least square features, also indicating the tendency. To both profiles the adjacent straight lines (**figure 7**) and the total least square lines (**figure 8**) may be associated. The deviation of orientation is calculated multiplicating the deviation of angle with the measuring length. The sign of the result indicates the tendency within the defined datum system, e.g. "from left to right falling or rising". The results of measurements and the uncertainties are also given in **table 2**.

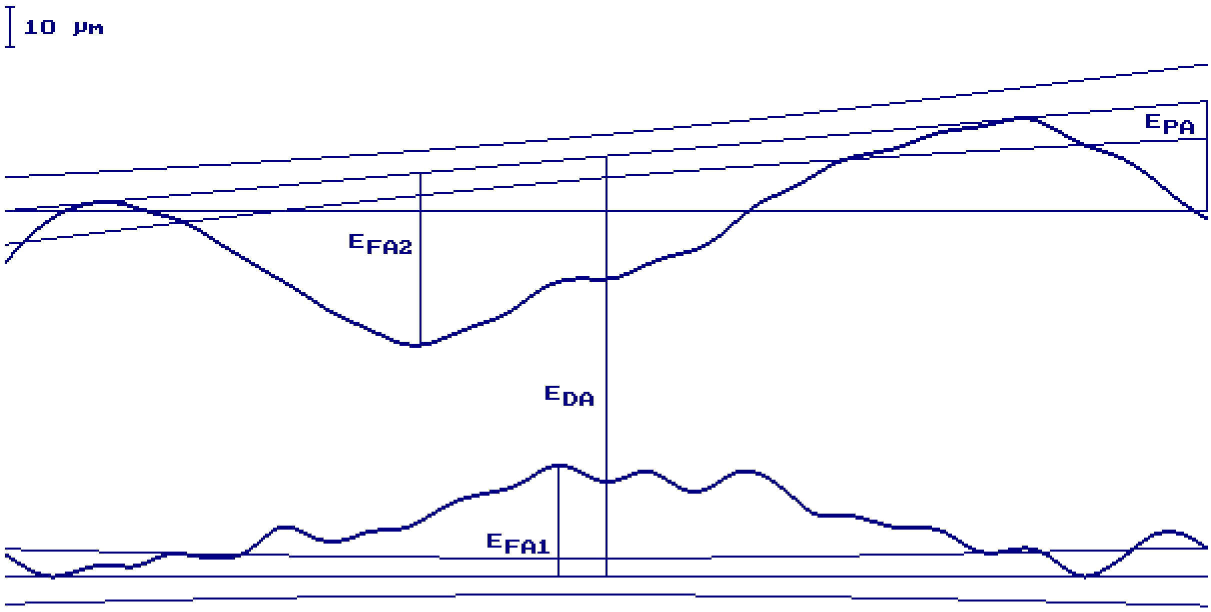

Figure 7: Filtered profiles from figure 5 with adjacent straight lines and confidence intervals, deviations of form E_{FA} and of parallelism E_{PA}, and distance E_{DA} in the centre of the profiles

The deviations of form in **figure 7** are the same like in **figure 6**. In **figure 8** we get other deviations, because another associated feature ist used. For surfaces having no contact function, the use of total least square features has two considerable advantages: they are easy to handle and cause very small uncertainties of measurement. Therefore the standard ISO 1101 should take into account also various associated features.

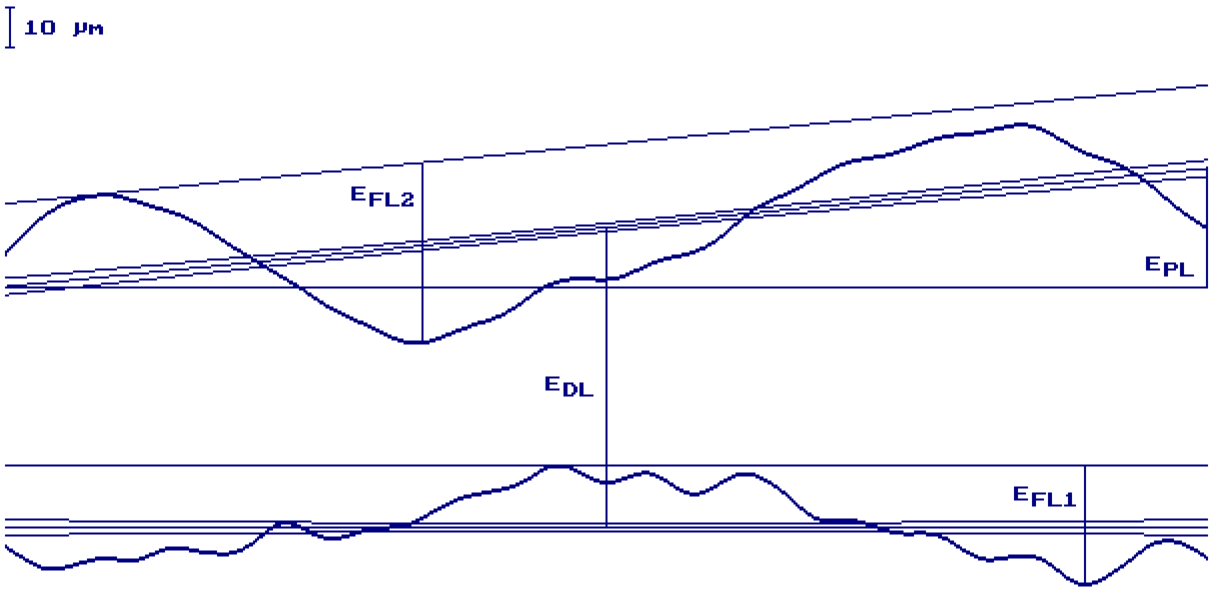

Figure 8: Filtered profiles from figure 5 with total least square straight lines and confidence intervals, deviations of form E_{FL} and of parallelism E_{PL}, and distance E_{DL} in the centre of the profiles

The deviation of orientation may have a positive or negative sign and its amount has to be smaller than or equal to the maximum permissible error given in the technical drawing according to ISO 1101. The tolerance of orientation in the case of associated features has double the value of the maximum permissible error, see **figure 9** [17] The standard should allow the user to choose the associated features according to the function of the surface. In the case of immediate contact of surfaces it should be adjacent features, in other cases it could be total least square features.

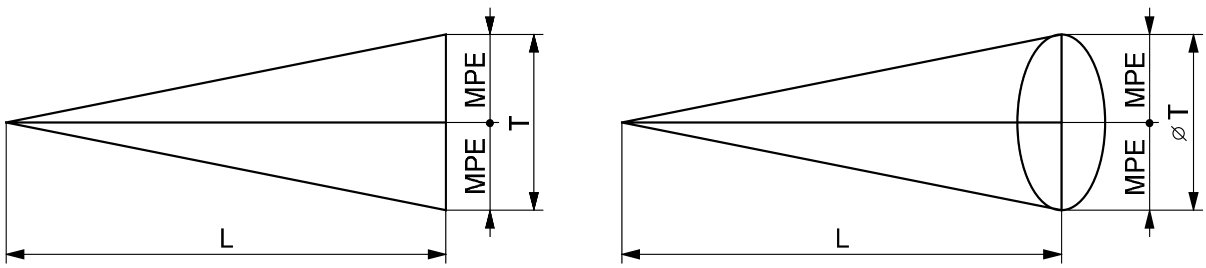

Figure 9: Tolerance zone of orientation of an associated feature in a plane (left) and in the space (right); the tolerance T has double the value of the maximum permissible error MPE

The extracted local size of the two profiles is given in **table 2**, too, at the centre of the profiles. Here, it is possible not only to calculate the distance between the extracted features, but also for the associated features, with measuring uncertainty. In addition to ISO 14660-2 it should be possible to choose the associated features according to the function of the surface, at any place of it. Ideally, the associated feature should be the same for all measurements of form, orientation, location, distance and size. Also, in the standard ISO 5459 [18] datums should be defined and marked in drawings as associated features. In the same way all other geometrical properties of surfaces may be handled, too, e.g. roughness and waviness.

8. Conclusions

Measuring the extracted features of surfaces, we have to separate the independent random errors from the local deviations of form of the surface. This is not possible using filters with stated cut-off wavelength, but using an iterative filtering process with variable wavelength. The condition of independency may be verified by statistical tests, e.g. for the sign of the residual errors or the correlation coefficient.

The definitions of geometrical properties have to take into account the various geometric features. The standard ISO 14660-2 only defines the extracted local size of two (nominally) parallel surfaces. But, distances may be calculated for the extracted features as well as the associated features, at any point of the surfaces. Indications of tolerances in drawings have to specify the geometric features, the points of the surface and the direction of evaluation, corresponding to the demands on the functional properties of the surfaces.

The standards should establish a collection of tools for all possible cases, and the applier should have the choice of his appropriate tool. Until today there are existing a few half-done solutions, suitable only for some special cases. The international standardization is just at the very first beginning.

9. References

[1] ISO/DIS 14660-1 (1996): Geometrical Product Specifications (GPS) – Geometric Features – Part 1: General terms and definitions
[2] ISO/DIS 14660-2: (1996): Geometrical Product Specifications (GPS) – Geometric Features – Part 2: Definitions of extracted axis of a cylinder and a cone, extracted median surface, extracted local size and diameter
[3] ISO 11562 (1996): Geometrical Product Specifications (GPS) – Surface texture: Profile method – Metrological characteristics of phase correct filters
[4] Rau, N.; Hercke, T.; Seibold, M.: Welligkeit nicht länger Stiefkind. Werkstatt und Betrieb, München 131 (1998) 11, pp. 1022-1025
[5] DIN 1319-4 (1999): Grundlagen der Meßtechnik; Teil 4: Auswertung von Messungen; Meßunsicherheit
[6] Rasch, D.: Einführung in die mathematische Statistik, Band II. Deutscher Verlag der Wissenschaften, Berlin 1976
[7] Guide to the Expression of Uncertainty in Measurement. International Standardization Organization, Geneva 1993
[8] Krystek, M.: Einfluß des Wellenfilters auf die Unsicherheit eines Meßergebnisses bei Rauheitsmessungen. DIN-Tagung Geometrische Produktspezifikation und -prüfung (GPS) in Mainz, Beuth Verlag Berlin 1999

[9] Hernla, M.: Abschätzung der Meßunsicherheit bei Koordinatenmessungen unter den Bedingungen der industriellen Fertigung. VDI-Fortschrittberichte Reihe 2 Nr. 274, VDI-Verlag Düsseldorf 1992
[10] Hernla, M.: Aufgabenspezifische Meßunsicherheit bei Koordinatenmessungen. Technisches Messen, München, 64 (1997) 7/8, pp. 286-293
[11] Hernla, M.: Anwendung von Filtern bei der Auswertung gemessener Oberflächenprofile. Technisches Messen, München 67 (2000) 3, S. 128-135
[12] ISO 1101 (1983): Technical drawings, geometrical tolerancing; tolerances of form, orientation, location and runout; generalities, definitions, symbols on drawings
[13] Krystek, M.: Verschiedene, in Diskussion befindliche Filterverfahren zur Formmessung. DIN-Tagung Geometrische Produktspezifikation und -prüfung (GPS) in Erlangen, Beuth Verlag Berlin 1997
[14] Bodschwinna, H.; Seewig, J.: Verbesserung des phasenkorrekten Filters nach E DIN ISO 11562 zur Trennung von Rauheit, Welligkeit und langwelligen Formabweichungen. DIN-Tagung Geometrische Produktspezifikation und -prüfung (GPS) in Erlangen, Beuth Verlag Berlin 1997
[15] Hernla, M.: Auswertung gemessener Oberflächenprofile. IX. Internationales Oberflächenkolloquium Chemnitz 1996, Vortragsband pp. 57-66
[16] Krystek, M.: Formfilterung durch Splines. IX. Internationales Oberflächenkolloquium Chemnitz 1996, Vortragsband pp. 67-78
[17] Hernla, M.: Form- und Lageabweichungen - die Definitionen reichen nicht. Qualität und Zuverlässigkeit, München, 39 (1994) 10, pp. 1116-1122
[18] ISO 5459 (1981): Technical drawings, geometrical tolerancing; Datums and datum-systems for geometrical tolerances