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Correlating motif analysis and morphological filters for surface texture analysis

Correlating Motif Analysis and Morphological Filters for Surface Texture Analysis

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Abstract

In contrast to the mean-line based evaluation system, motif analysis and morphological filters are two techniques oriented to the characterization of functional properties of surfaces. The motif combination procedure is consistent with the functionality of the morphological closing filter that insignificant peaks on the profile are suppressed. By linking the functionality of the structuring elements with motif combination criterions, morphological envelopes are computed efficiently. Reversely the morphological closing filter coupled with horizontal line-segment structuring elements with lengths equivalent to the motif limits for roughness and waviness provides an alternative for motif analysis. The proposed morphological method has a sound mathematical basis and is stable. An example of applying the empirical motif method (ISO 12085) and the morphological method is demonstrated. The motif parameters resulted from two methods reveal that they coincide with each other. Thus two distinct function oriented methods for surface texture evaluation are technically correlated by mutual exploitation.

Keywords: Motif analysis; morphological filters; surface texture analysis

1. Introduction

Surface texture is one of the most critical factors and important functionality indicators in the performance of high precision and nanoscale devices and components [1]. They are requested by design intents to meet the requirements of geometrical specification in order to achieve expected functions. These engineering surfaces are comprised of diverse features which form surface texture. The size and type of these features have fundamental impacts on functional properties of surfaces. Surface metrology, as a bridge between the manufacture of components and their function, takes one of critical tasks to connect surface texture with the function. Filtration techniques in surface metrology are the means to separate different components in the measured data, such as roughness and waviness. The Gaussian filter as a typical mean-line based filter, although a good general filter, is not applicable for all functional aspects of a surface. In contrast motif analysis and morphological filters are two techniques more oriented to the characterization of functional properties of surfaces [2].

The motif method is a pragmatic approach, evolved from the purely graphic method originally developed by French automotive industry, with the aim of solving functional problems [3]. This work could date back to the 1970's. A huge amount of work was produced to build up a "roughness data bank" with more than 27000 profiles from a range of workpieces. An empirical method based on the profile bank was developed to describe roughness and waviness, including the creation of motifs, the construction of the upper envelope and the calculation of dedicated parameters, called R&W [4]. The empirical method first became a French industry standard CNOMO (comite de Normalisation des MOyens de production) [5] and later its main concepts and most of parameters were adopted by ISO 12085 [6]. However even though the set of rules for motif combination was standardized, the tweaking of the rules has continued because the method is not stable [7]. Scott proposed a formal mathematical theory to stabilize motif combination rules and found a couple of properties that motif combination rules must satisfy in order to archive certain desirable metrological properties [8]. As a result the concept of motif analysis was generalized and the combination rules were laid on a stable mathematical basis. With the advancement of surface measurement instruments, the profile motif method was extended to three-dimension based on image segmentation techniques, e.g. the watershed transform [9; 10]. The wolf pruning technique was further employed as the discrimination criterion in the combination of areal motifs, which guarantees the uniqueness and stability of the solution [11; 12]. Areal motif methods provide useful tools for the evaluation of surface geometry, on the basis of which novel feature parameters are employed to characterize surface texture [13; 14].

Morphological filters are other functional methods for surface texture assessment. They were derived from the traditional envelope filtration system proposed by Von Weingraber [15], which is obtained by rolling a ball with the selected radius over the surface. With the introduction of mathematical morphology, morphological filters offer more tools and capabilities than its predecessor [16; 17]. They are conducted by performing morphological operations on the input surface with circular or flat structuring elements. Regarded as the complement to the mean-line based filters, morphological filters are relevant to geometrical properties of surfaces and hence give better results to the functional prediction of surfaces [18]. Over the last decade, morphological filters have found many practical applications and were accepted by ISO 16610 [19-21] as a useful part of the filtration toolbox. The morphological closing filter was utilized to approximate the conformable interface of two mating surfaces [22]. The surface topography of an internal combustion engine cylinder was decomposed by morphological alternating symmetrical operations so that different surface components were analyzed separately [23]. ISO 16610-49 illustrated an example of detecting the defective processing mark from a milled surface using morphological scale-space techniques [21].

A comparison was conducted by Shunmugam to compare the characterization results from the mean-line system, the envelope system and the motif method [24]. However there are few studies focusing on the similarities of motif analysis and morphological filters. Although they are different in origins and work mechanisms, the motif method and morphological filters have certain links between them. A pure mathematical link between motif analysis and morphological filters was presented by Scott [11]. However more practical and technical links should be identified for the benefit of metrologists. This paper seeks to correlate profile motif analysis and morphological profile filters in a technical point of view so that the similarities of two distinct methods can be identified. It will be presented that morphological envelopes could be computed by applying the generalized motif combination and on the contrary morphological method could provide an alternative approach for motif analysis of roughness and waviness. Section 2 gives a brief introduction to the empirical motif method (ISO 12085) and morphological filters. In Section 3, an approach is presented to calculate morphological profile filters based on motif combination. Section 4 employs the morphological closing profile filter coupled with the horizontal line-segment structuring element to conduct motif analysis. Finally Section 5 gives the conclusion.

2. Function oriented methods for surface texture analysis

2.1. The empirical motif method

ISO 12085 presents a profile motif method for the evaluation of surface texture. A motif is defined as a portion of the primary profile between the highest points of two local peaks which are not necessary adjacent. As presented in Fig. 1, a motif is characterized by its length, two depths, and the T characteristic (the smaller one between the two depths). The initial motifs are the identified portions between adjacent local peaks. The four rules, i.e. the envelope condition, the length condition, the enlargement condition and the similar condition, are applied on the initial motifs to remove insignificant ones and generate significant ones. Two conventional limits A for separating roughness and B for waviness, with default values 0.5 mm and 2.5 mm, are used in the combination process to produce roughness motifs and waviness motifs, respectively. The upper envelope line (waviness profile) is established by joining the highest point of peaks of the primary profile after the discrimination of peaks. The waviness motifs are derived on the basis of the upper envelope line. The motif combination is an iterative procedure. Existing motifs are combined as long as they are unable to be combined any more. The final resultant motifs are then used for further quantitative characterisation.

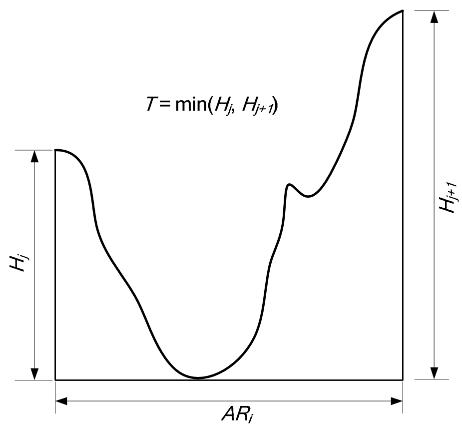

Fig. 1. Roughness motif.

Compared to 27 amplitude parameters, 3 spacing parameters and 12 hybrid parameters for the mean-line based evaluation system [25], the motif method presented by ISO 12085 only gives 7 parameters to evaluate functional behaviours. These parameters are efficient, easy to compute, well suited for functional analysis [26]. As listed in Table 1, they include 2 amplitude parameters and 1 spacing parameter for roughness motifs and 3 amplitude parameters and 1 spacing parameter for waviness motifs. ISO 12085 also attempts to link these motif parameters with the function of surfaces by specifying the most important ones for different kinds of functional surfaces.

Table 1. Motif parameters.

	Roughness motifs	Waviness motifs
Mean spacing	AR	AW
Mean depth	R	W
Maximum depth	Rx	Wx
Total depth		Wte

The motif method is a peak oriented means to assess surface profiles, complementing the filtering methods and best suited for dealing with multi-process surfaces where no standard characteristics occur [2]. Fig. 2 and Fig. 3 illustrate an example of applying the motif method to an engineering surface profile. Fig. 2 presents the roughness motifs with A 0.5 mm marked by the segment frames. Fig. 3 illustrates the waviness motifs with B 2.5 mm based on the upper envelope. The MountainsMap software from DigitalSurf [27] was employed to conduct motif analysis in the context of this paper.

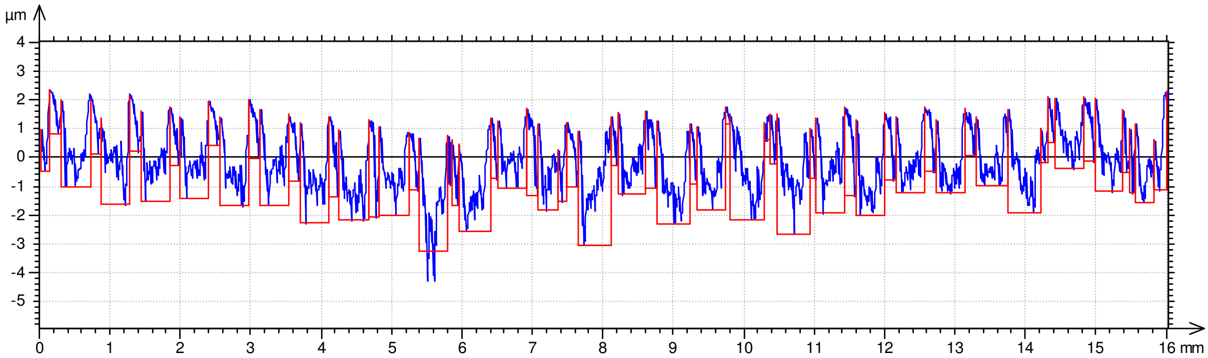

Fig. 2. Roughness motifs of a mill surface profile with A 0.5 mm.

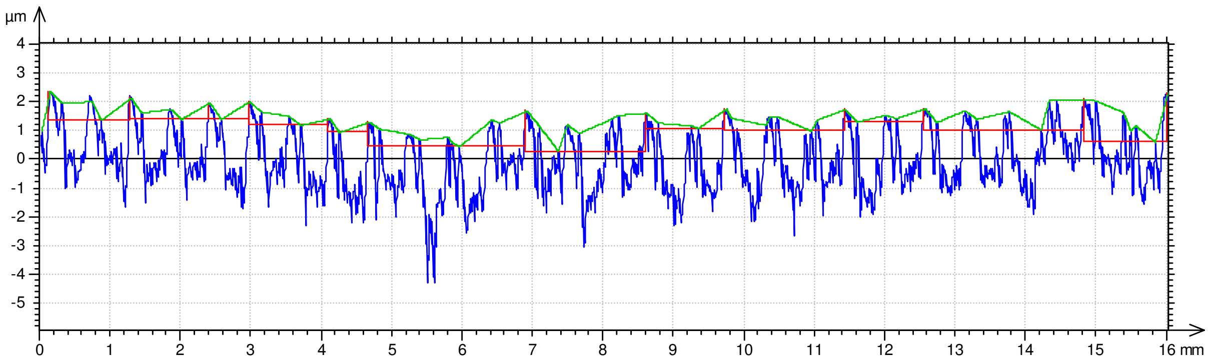

Fig. 3. Waviness motifs and the upper envelope of a mill surface profile with B 2.5 mm.

2.2. Morphological filters

Morphological filters laid their basis on mathematical morphology which is a discipline for the analysis of spatial structure of images [28]. In mathematical morphology, the input set is probed by another set, called the structuring element, at various locations. By varying the size and shape of the structuring element, the geometrical structure of the input set could be extracted [29]. There are four basic morphological operations, namely dilation, erosion, opening and closing, which form the foundation of mathematical morphology. These morphological operations are introduced into the traditional envelope system, leading to the generation of morphological filters. Essentially the early envelope filter is a dilation operation of the surface with the rolling ball acting as the structuring element, followed by an offset of ball radius.

Two standard structuring elements are recommended by ISO 16610-41: the circular disk structuring element and the horizontal line-segment structuring element. Using the circular disk structuring element, the dilation of the profile is the locus of the centre of the disk as it rolls over the surface profile from the above. See Fig. 4. Dual to dilation, erosion is obtained by rolling the disk over the surface profile from the below. Closing and opening are dilation and erosion combined pairs in sequence. Applying the dilation followed by the erosion yields the closing, whereas a reverse combination generates the opening. As regard to the horizontal line-segment structuring element, the dilation envelope is the locus of the centre of the line-segment as it slides over the profile. See Fig. 5. Likewise other operations are archived in a similar manner.

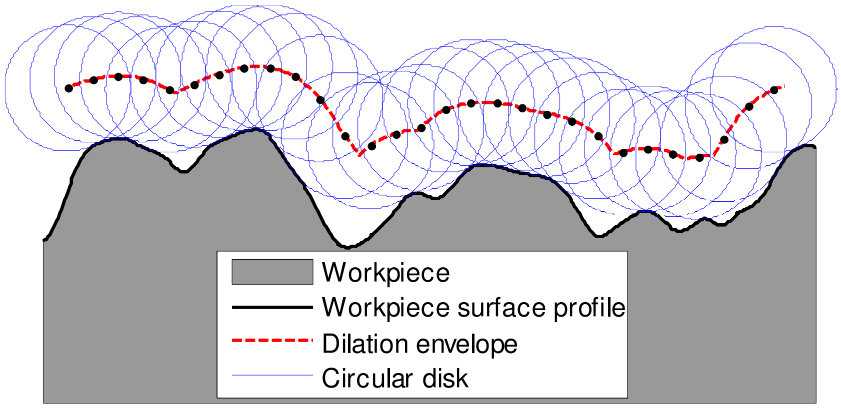

Fig. 4. The dilation envelope of an open profile using the circular disk structuring element.

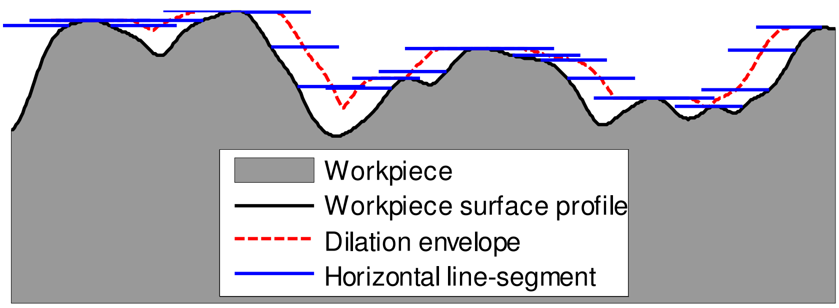

Fig. 5. The dilation envelope of an open profile using the horizontal line-segment structuring element.

Morphological filters are geometrically methods. The closing filter suppresses the peaks on the surface which are smaller than the structuring element in size, while the opening filter removes the valleys accordingly. The alternating symmetrical filter is the combined operation of the closing filter and the opening filter with the same structuring element. Therefore both the peaks and the valleys are suppressed.

Morphological operations are nothing new in the field of surface metrology. The scanning process of the tactile stylus over the workpiece surface, as a common practice in roughness measurement, is a morphological dilation operation [30]. The mechanical surface could be reconstructed by carrying out on the measurement data the erosion operation with a sphere of the same radius to the stylus tip [31].

3. Morphological filters based on motif combination

By convention, morphological filters are implemented in a manner similar to image processing whereby the measured data are treated as image pixels. Fig. 6 presents a basic method to compute the dilation operation of profile data with the disk structuring element [32]. The coordinates are sampled from the disk centre to the two ends with the same sampling interval to that of the profile. These disk ordinates are placed to overlap the profile ordinates with the disk centre locating at the target profile point. The ordinate where the mapping pair of the profile ordinate and the disk ordinate gives the maximum value determines the height of the disk centre. This procedure is repeated for all the profile ordinates to obtain the whole dilation envelope. The erosion envelope can be easily obtained by first flipping the original profile followed by flipping its dilation envelope. Combining dilation and erosion operations in sequence will yield closing and opening envelopes. Although this direct implementation conforms to the definitions of morphological operations, it is not efficient in terms of performance [33].

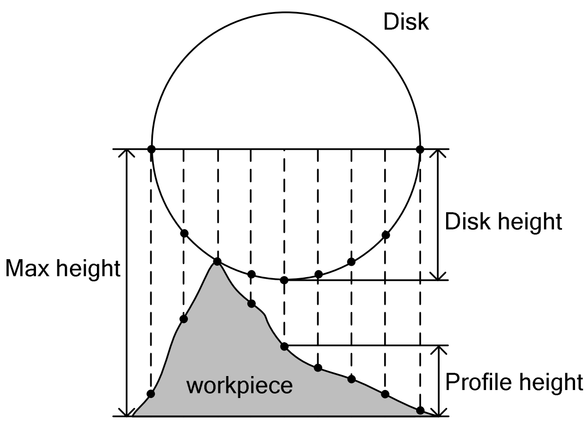

Fig. 6. Computation of the dilation operation with the disk structuring element.

An alternative way to compute morphological filters is to use motif combination. The motif combination procedure eliminates insignificant motifs and generates significant ones. It is similar to the functionality of morphological filters that those features on the profile smaller than the structuring element in size are suppressed by the filters. In this sense, two different methods lead to the same goal. If comparing the motif combination in motif analysis and the feature suppression in morphological filtration, it indicates an access to compute morphological filters by means of motif combination. An efficient algorithm to compute motif combination was developed [8]. A couple of definitions were given as the data type used in the motif combination algorithm.

Events: an event split the profile into a number of discrete sections. The events might be the highest points on all the local peaks or all the upcrossing of the profile through a reference line or even every sample point of the profile. They are numbered in order along the profile. The initial set of events is all the sample points on the profile.

Motif: a motif (i, j), where $i < j$, consists of that section of the profile between the i th and j th events.

Motif Combination Test: it is performed on two adjacent motifs (say, two motifs (i, j) and (j, k)) with the common event (say, j) to determine whether the common event is significant or not. If the event is not significant, two adjacent motifs to that event are combined (say, motifs (i, j) and (j, k) are combined to form a new motif (i, k) and thus the event is eliminated.

The basic motif combination procedure starts with the set of all events, namely all the measured data on the profile, and then it eliminates the insignificant events by repeatedly applying the motif combination test on adjacent motifs until all the motifs could pass the test. The outline of the motif combination algorithm is presented in Fig. 7.

```
Algorithm MotifCombination(X)
{Given a measured profile X with n points, compute
the final motifs motifs }

Chain list motifs= {(p1, p2), (p2, p3), …, (pn-1, pn)};
while true
      if CombineMotifs(motifs)
            break;
      end if;
end while;
return motifs;

Procedure CombineMotifs(motifs)
flag = false;
motif1 = motifs(1);
for i = 2 to motifs.length
      motif2 = motifs(i);
      if CombineTest(motif1, motif2)
            motif1 = {motif1.Start, motif2.End};
            motifs.Remove(motif2);
            flag = true;
      end if;
end for;
return flag;
```

Fig. 7. The algorithm for motif combination.

The motif combination procedure however could be employed to compute morphological filters. The key is to link the functionality of the structuring element to the combination criterion. As illustrated in Fig. 8, for the circular disk structuring element, the motif combination test is to place the disk on the far boundary events of two adjacent motifs (say, i and k) and check whether the disk is able to touch the common event (say, j). As to the horizontal line-segment structuring element, the motif combination test is to position the horizontal line-segment to the highest motif event (say, k) and examine whether the line-segment could touch the common event (say, j), see Fig. 9. If the common event does not intervene, which means the adjacent motifs are not significant, then the two adjacent motifs are merged into a single one (say, the motifs (i, j) and (j,k) are merged to yield the new motif (i,k)). In the final round, the events that comprise the significant motifs are in essence the points on the profile which are in contact with the structuring element during the rolling or sliding process.

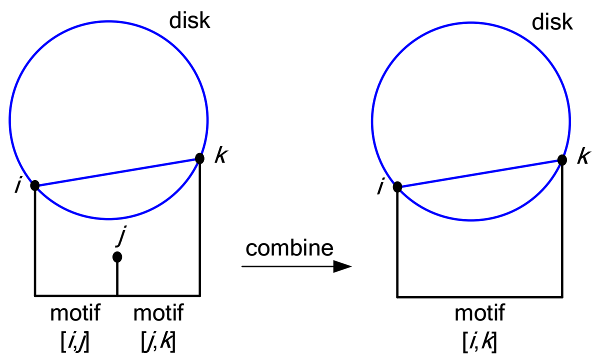

Fig. 8. Motif combination by rolling a disk.

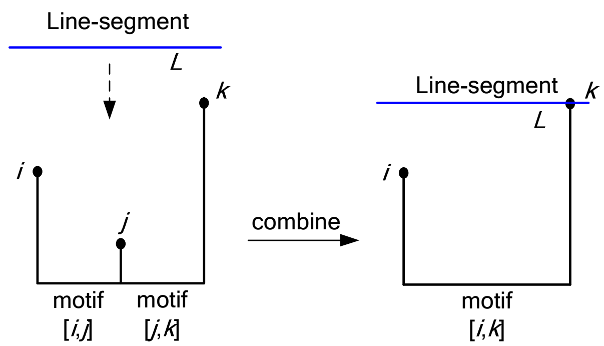

Fig. 9. Motif combination by sliding a horizontal line-segment.

With the final motifs, the closing envelope ordinates for the disk structuring element are computed by interpolating points on the arcs determined by these motifs at each sampling position. And for the horizontal line-segment structuring element, the closing envelope ordinates are identified by taking the lower height of two boundary events on the motif. Fig. 10 and Fig. 11 illustrate two examples of applying the morphological closing filter to an open profile using the motif combination method. The experimental profile consists of 250 sampled points with sampling interval 5 μm. In Fig. 10, the profile is filtered by a 0.5 mm disk. The figure presents the closing envelope on the top of the measured profile along with the motif events marked by the dots. Fig. 11 presents the resulting envelope and motif events obtained by applying the morphological closing filter with line-segment length 0.1 mm.

In comparison to the traditional computation method of morphological filters, the adoption of motif combination is more efficient, especially in the case of large data set and large structuring elements. Even though motif combination was original developed for motif analysis, in a generalized form it finds its use in the computation of morphological filters.

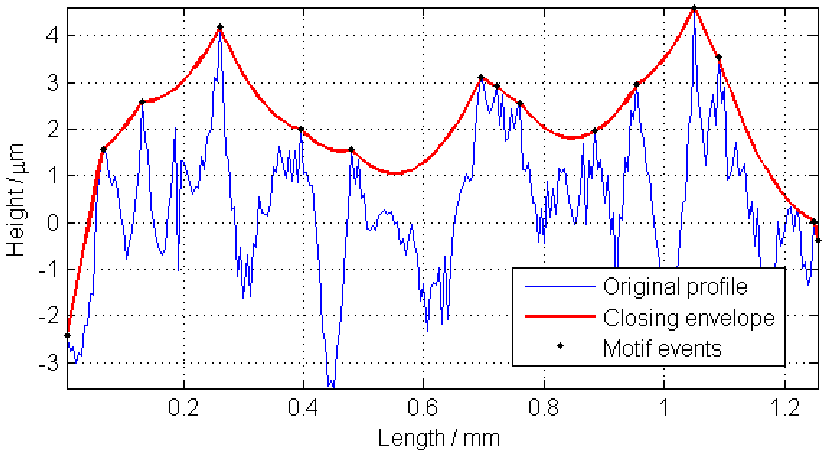

Fig. 10. The closing envelope with disk radius 0.5 mm and final motif events.

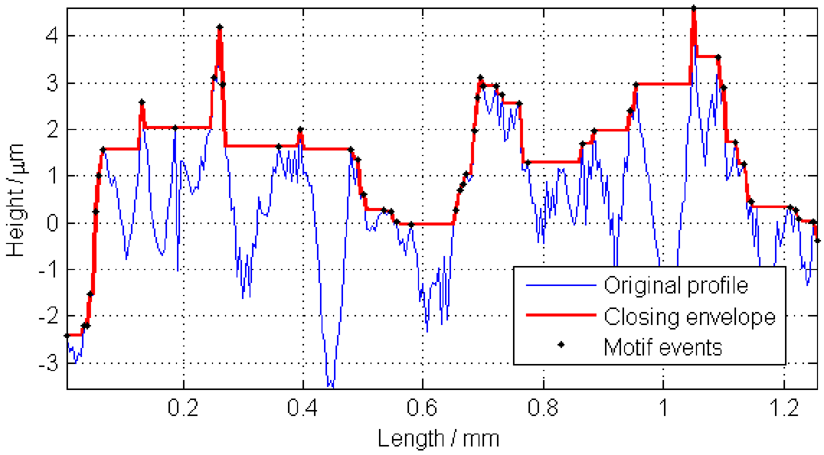

Fig. 11. The closing envelope with line-segment length 0.1 mm and final motif events.

4. Motif analysis based on morphological filters

The motif method presented in ISO 12085 is a pragmatic ad hoc approach to identify and characterize surface texture. The combination rules are derived on the basis of the experiences of huge amount of practical evaluation. This empirical approach, however, has several drawbacks. Firstly, the motif combination rules are not robust. Once any problem with the approach arises, the combination rules are tweaked to overcome them. Even though one set of rules were standardized in ISO 12085, the tweaking of the rules has continued. Secondly, the motif combination rules are so ambiguous and complex to implement that it leads to variations of results across different measurement softwares. More seriously the worse problem is its instability: small changes to the input profile may cause a significant change in the analysis results with ‘relevant’ feature appearing or disappearing, almost randomly [11].

To overcome the limitation of the empirical motif method, other methods were attempted. The watershed segmentation was proposed as a more reliable method [34]. This method was initially developed for areal surface segmentation. Nevertheless it could be easily transposed to the profile counterpart. The catchment basin defined by a pit, a saddle point and a ridge line was degenerated to a motif with a pit and two adjacent peaks. The four conditions used in motif combination rules were replaced by pruning conditions in the change tree.

Another option would be morphological methods. As stated in the preceding section, owning to the relationship between motif analysis and morphological filters, morphological envelopes can be calculated by combining motifs and specifying combination criterions in accordance with the functionality of structuring elements. Considering in a reverse order, it is of interests to apply morphological operations in motif analysis. According to Scott’s theory, the morphological closing filter is a special motif analysis method in that it conforms to the motif conditions [8]. This suggests that the closing filter could be a valid candidate for motif analysis. For convenience of comparison, the morphological closing filter with the horizontal line-segment structuring element is employed to conduct motif analysis in this paper. The length of the line-segment used for roughness and waviness evaluation are set to 0.5 mm and 2.5 mm in order to match the conventional roughness and waviness motif limits used in the empirical motif method. The circular disk structuring element may serve as another valid option. However the appropriate disk radius has to be chosen to achieve comparable results.

Fig. 12 presents a milled surface profile. Using the empirical motif method, this profile is first operated by the roughness motif combination with the motif limit A 0.5 mm. Afterward the upper envelope is constructed by joining the roughness motifs. Finally the waviness motifs are archived based on the upper envelope with the motif limit B 2.5 mm. See Fig. 13.

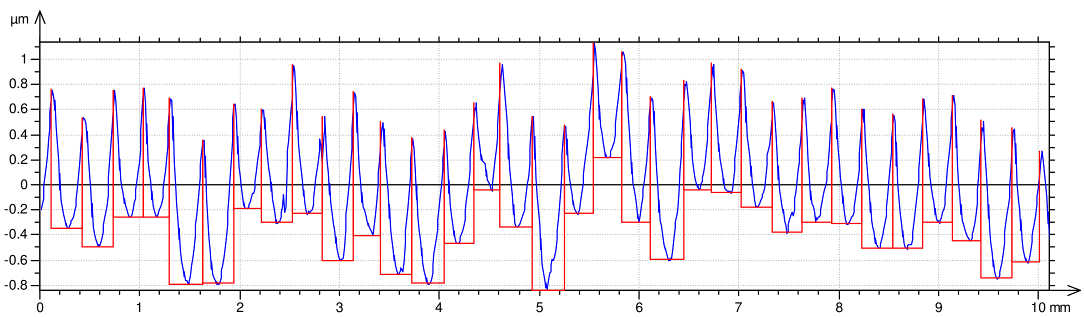

Fig. 12. Roughness motifs of the profile with A 0.5 mm.

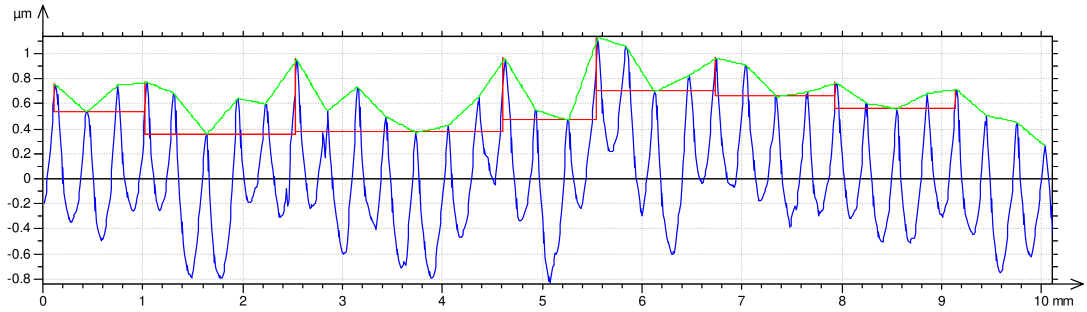

Fig. 13. Waviness motifs of the profile with B 2.5 mm.

Alternatively this experimental profile is again analyzed by the morphological closing filter. It is first processed by the closing filter with the horizontal line-segment structuring element (0.5 mm in length). The motif combination algorithm presented in Section 3 is employed in computation. As Fig. 14 illustrates, the closing operation generates an envelope passing through the final motif events. The roughness motifs are obtained by taking the profile portions between the adjacent motif events.

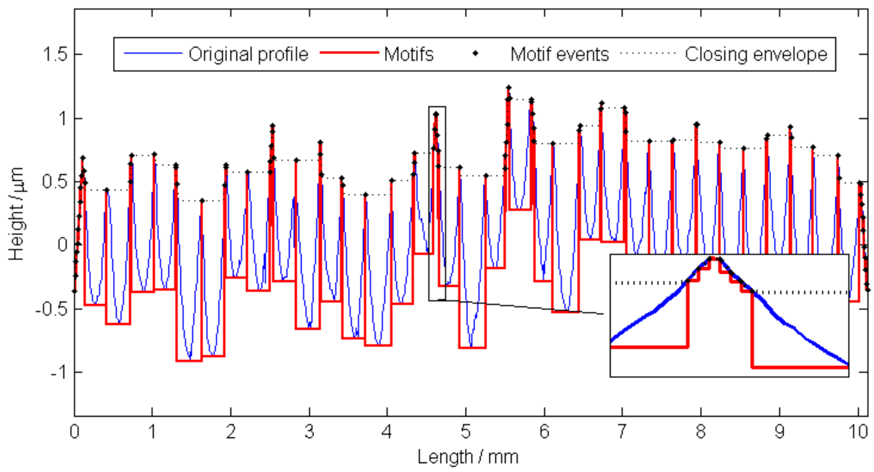

Fig. 14. The roughness motifs of the profile obtained by the morphological closing filter with line-segment length 0.5 mm.

However it could be noticed in the magnified part of Fig. 14 that the roughness motifs generated by the morphological closing filter contain some tiny ones. These tiny motifs should be eliminated because they are not consistent with the nature of significant motifs. They are easy to detect due to the fact that they appear on the ridge of peaks and are short in length compared to the adjacent significant motifs. An algorithm is presented in Fig. 15 aiming to combine these tiny motifs. Given a set of significant motifs and tiny motifs between them, the highest motif event is hunted in the portion of profile between two inconsecutive significant motifs. Then the part of the portion on the left of the highest motif event is combined to the left significant neighbour motif and similarly the right part of the portion is merged into the right significant neighbour motif. This process is repeated over all the motifs and the result is the refined significant motifs.

See Fig. 16. It is obvious that the tiny motifs presented in the magnified part are merged into their adjacent significant ones. These motifs are treated as the solution to roughness motifs.

```
Algorithm EliminateTinyMotif (motifs)
{Given a  set of significant motifs motifs,}
{eliminate tiny motifs between them}

for i = 1 to motifs.length - 1
    motif1 = motifs(i);
    motif2 = motifs(i + 1);
    if motif1.End != motif2.Start
        event = max(Events| motif1.End: motif2.Start);
        motif1.End = event;
        motif2.Start = event;
    end
end
end for;
```

Fig. 15. The algorithm for tiny motifs elimination.

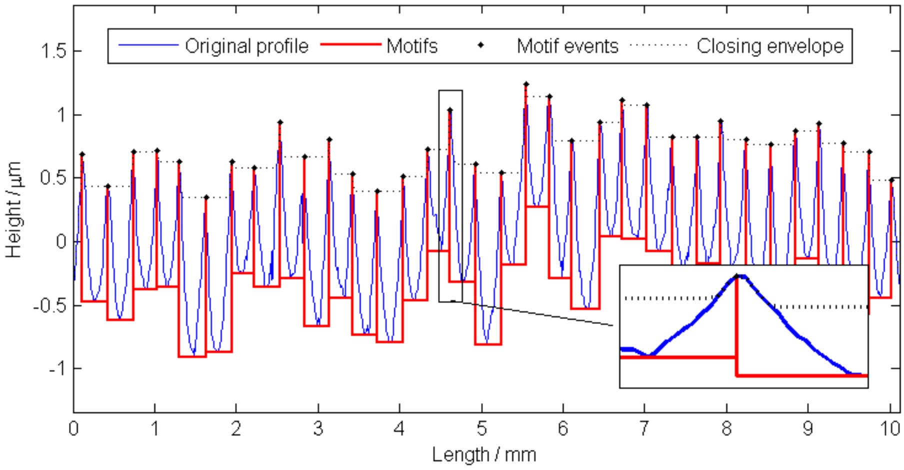

Fig. 16. The roughness motifs of the profile with tiny motifs combined.

To further assess the waviness motifs, the upper envelope is constructed by joining the roughness motifs generated in the last step. The same morphological method is applied on the upper envelope with line-segment length 2.5 mm. Fig. 17 presents the waviness motifs of the profile and the closing envelope.

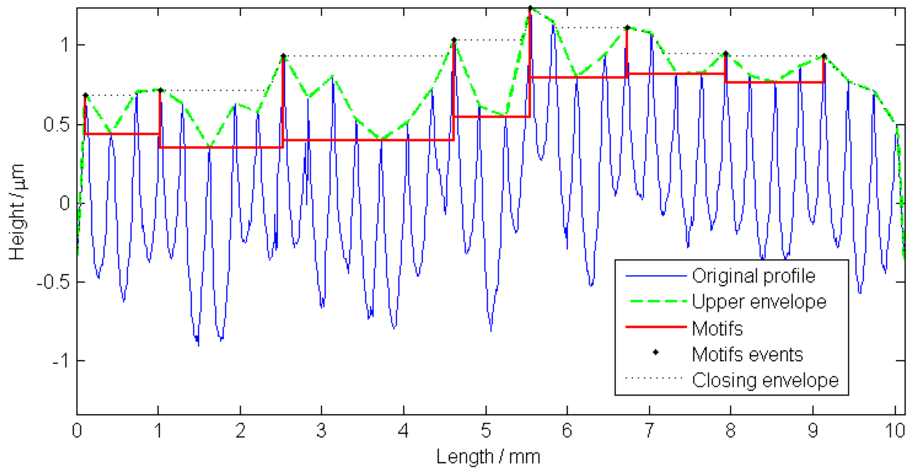

Fig. 17. Waviness motifs of the profile obtained by the morphological closing filter with line-segment length 2.5 mm.

With the final roughness and waviness motifs resulted from the empirical motif method and the proposed morphological method, 7 motif parameters are calculated and listed in Table 2 and Table 3 respectively for comparison. It is clearly shown in the tables that the results of the two distinct methods are very close to each other, which indicates that the two methods are consistent with each other.

Table 2. Roughness motif parameters calculated by the motif method of ISO 12085 and the proposed morphological method.

Parameters	*AR*	*R*	*Rx*
Motif method of ISO 12085	0.293 mm	1.08 µm	1.49 µm
Morphological method	0.299 mm	1.13 µm	1.44 µm

Table 3. Waviness motif parameters calculated by the motif method of ISO 12085 and the proposed morphological method.

Parameters	*AW*	*W*	*Wx*	*Wte*
Motif method of ISO 12085	1.29 mm	0.379 µm	0.664 µm	0.869 µm
Morphological method	1.29 mm	0.385 µm	0.687 µm	0.896 µm

Morphological filters have a sound mathematic basis and they are stable. The motif analysis based on the morphological closing filter overcomes the shortcomings of the empirical motif method, such as instable and complex to implement. In principle motif analysis is a generic method. The motif combination criterion could be arbitrary. They could be modified to suit any given function. The empirical motif method and the proposed morphological method are two special cases of the generic motif analysis. Although they are different in their origins, both of them are effective methods to evaluate functional properties of surfaces.

5. Conclusion

Regarded as the complement to the mean-line based evaluation system, motif analysis and morphological filters are two function oriented approaches, more relevant to functional properties of surfaces. Although they have different origins, there exist certain links between them.

The motif combination procedure to eliminate insignificant motifs is consistent with the functionality of the morphological closing filter that the profile peaks smaller than the structuring element in size are suppressed. Therefore by linking the functionality of the structuring element with motif combination, morphological envelopes are computed efficiently compared to the traditional method. Moreover by specifying the motif combination criterion, i.e. how two adjacent motifs could be combined, various types of structuring elements are available, for instance, the circular disk and the horizontal line-segment.

In a reverse order, the morphological closing filter can be unitized to conduct motif analysis. For convenience of comparison, the horizontal line-segment structuring element is employed with lengths equivalent to the conventional roughness and waviness motif limits. The proposed morphological method has a sound mathematical basis and overcomes the drawbacks of the empirical motif method. An example is given to demonstrate the comparison of the empirical motif method and the morphological method. The resulting roughness and waviness motifs and the motif parameters reveal that the two methods coincide with each other.

To sum up, different in their origins and work mechanism, two distinct function oriented methods for surface texture evaluation, i.e. motif analysis and morphological filters, are technically correlated by mutual exploitation.

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Figure List

Table List