AN INTRODUCTION TO MORPHOLOGICAL FILTERS IN SURFACE METROLOGY

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ABSTRACT

Acting as the complementary tool to the mean-line based filtration techniques, e.g. the Gaussian filter, morphological filters are function oriented and relevant to geometrical features of surfaces. This paper aims to present an introduction to morphological filters in surface metrology. By introducing mathematical morphology, morphological filters offer more capabilities than the early envelope system. The variation of morphological filters includes: the closing filter, the opening filter, the alternating symmetrical filter and multi-scale space techniques. The existing algorithms concerning with the implementation of morphological filters are presented. A couple of typical applications of morphological filters are illustrated as well.

Keywords morphological filters; morphological operations; surface metrology

1 INTRODUCTION

Surface metrology is the study of surface topography — measurement of small scale geometrical features on surfaces. It has profound influences on manufacture quality as it plays two important roles. On one hand, it helps to control the manufacture process: monitor changes in the surface texture and indicate changes in the manufacturing process such as machine tool vibration and tool wear (Jiang, 2007b). On the other hand, it helps functional prediction: characterize geometrical features that will directly impact on tribological and physical properties of the whole system (Bhushan 1996), for instance, the friction of two contact surfaces and the optical fatigue of one reflecting surface. Controlling the manufacture helps repeatability and hence the quality of conformance. Functional prediction helps function and assists in performance optimization (Whitehouse 1994).

For engineering surfaces, their topography consists of versatile geometrical features, such as peaks/ pits, ridges/valleys. In surface texture analysis, the extraction and separation of various scales of features are mainly conducted by filtering. Among various filtration techniques, morphological filters are most suitable for the functional prediction of components since their logic is more related with geometrical properties of engineering surfaces.

2 HISTORICAL DEVELOPMENT

Filtration has always been important in surface metrology. It is the means by which the surface features of interest are extracted from the measured data for further analysis (Jiang 2007a). There are two competing filtering systems: the M-system (the mean-line filtering system) and the E-system (the envelope filtering system).

In history, the mean line based filters have been the dominant choices for the separation of roughness, waviness and form error. In contrast to the M-System, Von Weingraber (1956) proposed an alternative method to separate the fine texture from overall form. In many engineering applications, surface texture plays an important role during the contact between mating surfaces. Therefore on a measured profile he simulated this contact by rolling a ball (disk) over a surface (profile), see Figure 1. The locus of the center of the rolling ball followed by a compensation of ball radius yields the envelope and it was then considered as the reference line. The deviation from the envelope was fine texture or roughness. This method is known as the E-System. The envelope filter is quite different from the mean-line based filtering techniques in that the envelope is mainly determined by geometrically prominent peaks in the profile/surface, whereas the mean-line based filters generate the reference line by averaging processes.

In the late 1990's, mathematical morphology were introduced into the envelope filtering system and morphological filters emerged (Srinviasan 1998). Morphological filters are essentially the superset of early envelope filters but offering more tools and capabilities. They are carried out by performing morphological operations on the input set (profile/surface) with circular or horizontal flat structuring elements (in most cases circular). Morphological operations can be combined together to achieve a superimposed effect, which is referred as alternating symmetrical filters. Scott (2000) presented scale-space techniques that further developed morphological filters. Scale-space techniques could provide multi-resolution analysis to surface texture by which various scales of geometrical features can be extracted from original surface and subsequently analyzed separately.

3 MORPHOLOGICAL OPERATIONS

There are four primary morphological operations, namely dilation, erosion, closing and opening. They form the foundation of the discipline of mathematical morphology. Dilation combines two sets using the vector addition of set elements. The dilation of A by B is

$$D(A,B) = A \oplus \check{B} \,. \tag{1}$$

where $\check{B}$ is the reflection of B through the origin of B.
It is defined on the basis of vector addition, also known as the Minkowski addition, which was first introduced by Minkowski (1903). The Minkowski addition of two input sets A and B is the set:

$$A \oplus B = \{c \mid c = a + b, a \subseteq A \ \& \ b \subseteq B\} \,. \tag{2}$$

Erosion is the morphological dual to dilation. It combines two sets using the vector subtraction of set elements. The erosion of A by B is

$$E(A,B) = A \ominus \check{B} \,, \tag{3}$$

where

$$A \ominus B = \overline{\overline{A} + B} \,. \tag{4}$$

Opening and closing are dilation and erosion combined pairs in sequence. The opening of A by B is obtained by applying the erosion followed by the dilation,

$$O(A,B) = D(E(A,B), \check{B}) \,. \tag{5}$$

Closing is the morphological dual to opening. The closing of A by B is given by applying the dilation followed by the erosion,

$$C(A,B) = E(D(A,B), \check{B}) \,. \tag{6}$$

4 MORPHOLOGICAL FILTERS

Closing and opening filters are two envelope filters, whose outputs envelope the input surface. They differ from the obsolete envelope filter in that the early envelope filter is essentially equivalent to the dilation operation, usually offset by ball radius.
Figure 2 and Figure 3 illustrate two examples of applying the closing operation and the opening operation on an open profile with the disk structuring element respectively. The closing filter is obtained by placing an infinite number of identical disks in contact with the profile from above along all the profile and taking the lower boundary of the disks (Scott 2002). On the contrary the opening filter is archived by placing an infinite number of identical disks in contact with the profile from below along all the profile and taking the upper boundary of the disks.
It is obviously revealed in the figures that the closing filter suppresses the valleys on the profile which are smaller than the disk radius in size, meanwhile it remains the peaks unchanged. Conversely, the opening filter suppresses the peaks on the profile which are smaller than the disk radius in size, while it retains the valleys. The selection of the disk radius depends on the size of physical features on surfaces.
Alternating sequential filters are the combination of openings and closings with various structuring element sizes, which will suppress both the peaks and valleys smaller than the size of the structuring element. If the size of structuring element of the closing filter is equivalent to that of the opening filter and the structuring element in use is symmetrical about its origin, then the alternating sequential filter is called as the alternating symmetrical filter (ISO 16610 2010). Scale space techniques are to use a series of alternating sequential filters with the structuring elements increasing in size to extract different scales of information of the surface.

5 ALGORITHMS

The traditional implementation of morphological filters was original developed for the early covering envelope filter, which in essence is a dilation envelope offset by the ball/disk radius. Figure 4 presents a basic method to compute the dilation operation with the disk structuring element for profile data (Shunmugam and Radhakrishnan 1974). The disk ordinates are computed from the disk centre to the two ends with the same sampling interval to the measured profile. These 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 obtained by first flipping the original profile followed by flipped its dilation envelope. Combining the dilation and erosion in sequence will lead to the closing and opening envelopes. In the case of areal data, the disk is extended to the ball, on which the ball ordinates are calculated on the hemisphere.

Although this algorithm follows the definition of dilation and erosion, it is time-consuming in performance. Scott (1992) proposed an alternative way to calculate the profile envelope using motif combination. The motif combination procedure eliminates insignificant motifs and obtains significant ones. It is consistent with the functionality of morphological filters that the features on the profile smaller than the structuring element in size are removed by the filters. This consistency provides an access to computing morphological filter by means of motif combination. For rolling a disk on the profile, the functional motif combination test is to check if the disk is possible to contact the common event by placing the disk on two adjacent motifs, as illustrated by Figure 5. With the final motifs, the envelope ordinates are computed by interpolating points on the arcs determined by the solution motifs.

A recent algorithm for morphological filters is based on the link between the alpha hull and morphological operations that the hull obtained by rolling the alpha ball is equivalent to the morphological opening/closing in theory (Lou et. al. 2011; Jiang et. al. 2011). The alpha shape method depends on the Delaunay triangulation of the sample point set from which the alpha shape facets could be extracted (see Figure 6). The morphological envelope is computed by interpolating points on the arcs determined by the alpha shape facet.

6 APPLICATIONS

Morphological operations are nothing new in the field of surface metrology. The scanning of the tactile stylus over the workpiece surface, as a common practice in roughness measurement, is a hardware implementation of morphological dilation operation (Krystek 2004). The workpiece surface as the input set is dilated by the structuring element, the probe tip to generate the morphological output, the measured surface. In order to obtain the real surface, although it is not entirely possible, an approximate surface, namely the real mechanical surface, could be reconstructed by carrying out on the measurement data the erosion operation with a sphere of the same radius as the stylus tip (Roger et. al. 2005).

The morphological closing filter could be utilized to approximate the form of the functional surface for conformable interface of two mating surfaces (Malburg 2003), for instance a soft gasket in contact with a solid block in order to provide the sealing function. The morphological closing envelope generated by the circular structuring element is used to approximate the conformable gasket surface such that the void area between the conformable surface and the rigid surface can be derived to further characterize the sealing or load distribution.

Morphological scale-space techniques could provide multi-resolution analysis to surface. ISO 16610 PART 49 (2010) illustrates an example of detecting the defective processing mark from a milled surface. Figure 7 shows a profile which is from a milled surface and was measured with a 5µm tip stylus. The series of scale values (0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 5) was used starting with the first value larger than the stylus tip radius. Figure 8 shows the differences between successively smoothings. The deflective milling mark can easily be identified at scales 2 and 5mm and milling marks at scales 0.5 and 0.2mm.

7 CONCLUSIONS

Morphological filters are function oriented techniques. Compared with the mean-line based filters (e.g. the Gaussian filter) which are averaging processes, morphological filters, depending on geometrical properties of surfaces could offer better results to the functional prediction of components.

Morphological filters evolved from the early envelope filter provide more capabilities with variation of useful techniques, including the closing filter, the opening filter, the alternating sequential filter and the scale-space techniques. They have found many practice applications, such as the reconstruction of the real mechanical surface, the approximation of conformable interface and the detection of the deflective marks. Three algorithms for morphological filters, i.e. the direct algorithm, the motif combination and the alpha shape are available.

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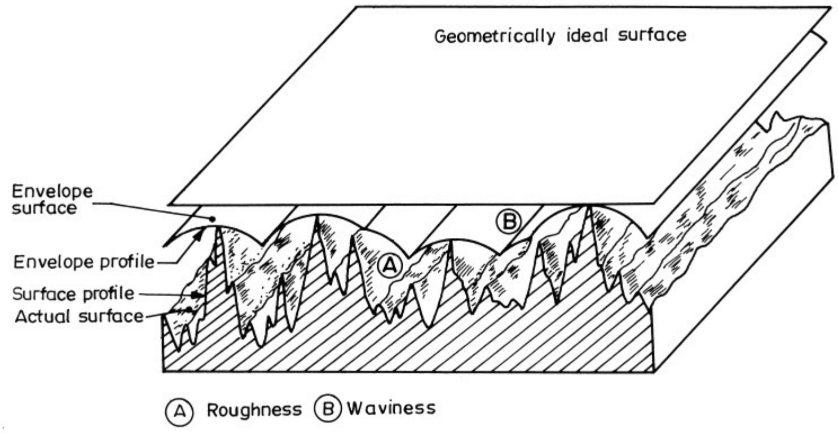

Figure 1: Profile and surface envelope (Haesing 1964).

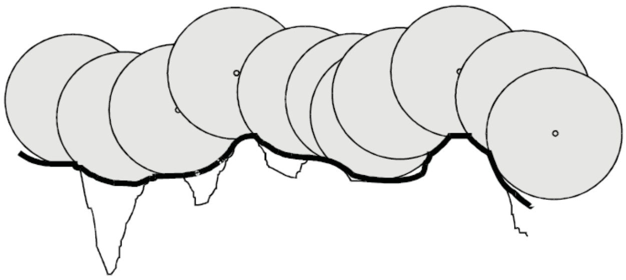

Figure 2: The closing envelope of an open profile by a disk (Scott 2000).

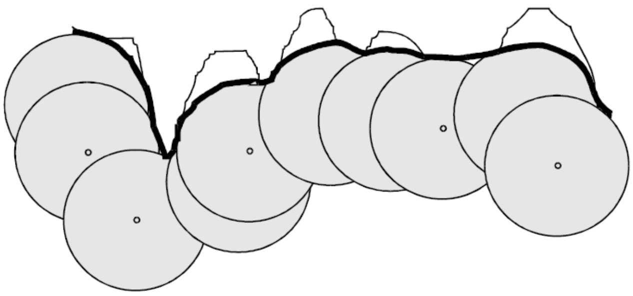

Figure 3: The opening envelope of an open profile by a disk (Scott 2000).

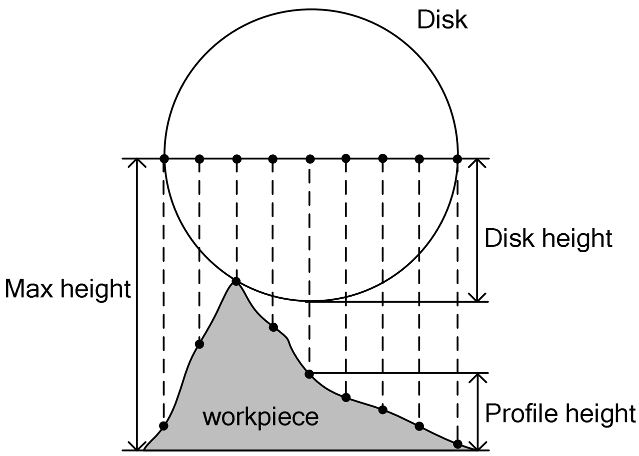

Figure 4: Computation of the dilation operation with the disk structuring element.

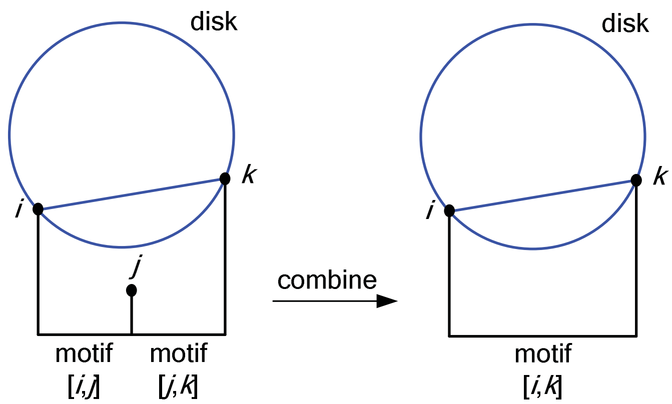

Figure 5: Motif combination by rolling a disk.

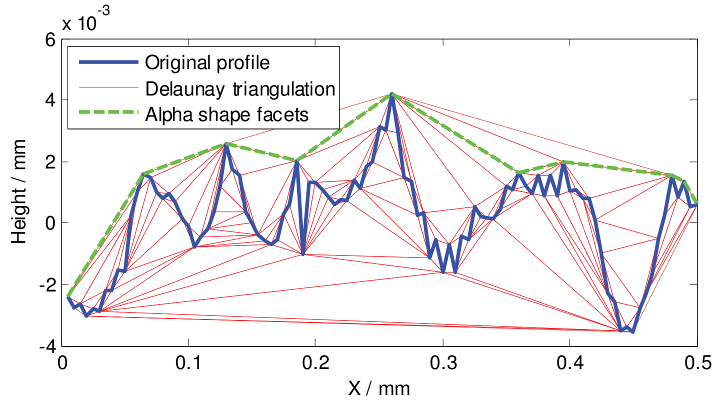

Figure 6: Alpha shape facets extracted from the Delaunay triangulation of the profile data.

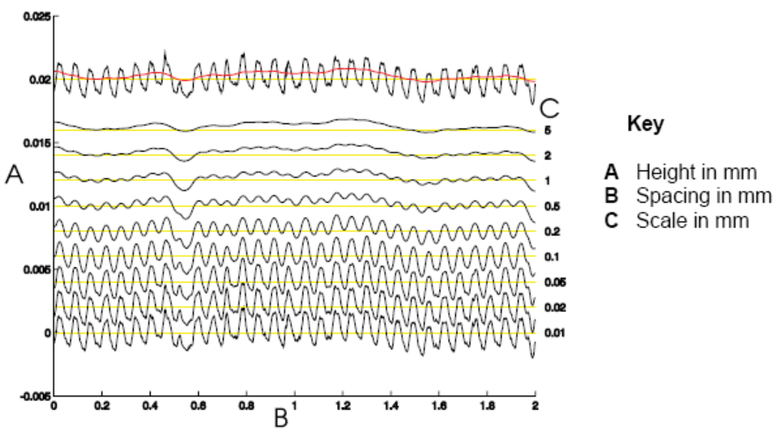

Figure 7: Successively smoothed profiles from a milled surface using a circular disk (ISO 16610 Part 49 2010).

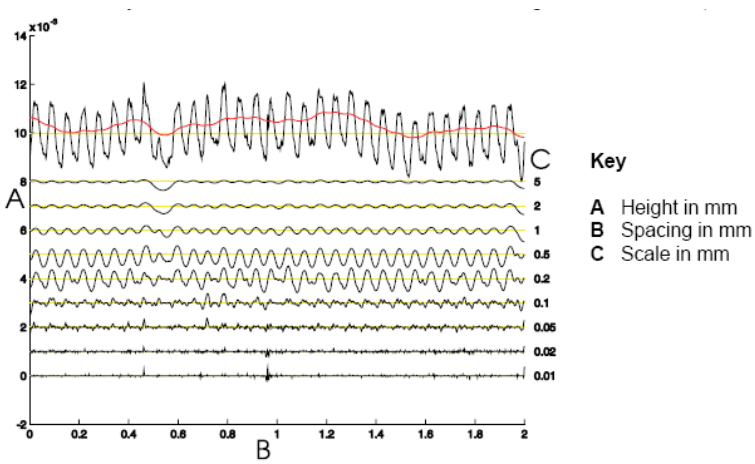

Figure 8: Differences on a profile from a milled surface using a circular disk (ISO 16610 Part 49 2010).