TOPOGRAPHY CHARACTERIZATION OF ENGINEERING SURFACES USING MATHEMATICAL MORPHOLOGY

Application to the characterization of wear in internal combustion engine cylinder liners

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Abstract.

A state of the art of 3D surface characterization techniques in the automotive and steel industries is presented, and links with mathematical morphology are highlighted.

A surface topography decomposition method is described. It decomposes a surface into three elements: reference surface (waviness and form), superficial roughness (related to friction and wear) and valleys (related to lubricant circulation and reservoirs). It is applied to cylinder liners from an internal combustion V6 engine in order to remove form and waviness components. The study of the resulting superficial roughness component allows a precise wear characterization.

Key words: surface topography characterization, wear, internal combustion engine bore, cylinder liner, surface decomposition, roughness

1. Introduction

Most users of mathematical morphology are acquainted with the analogy between a grey level image and a topographic surface. Following this analogy, image features are conveniently described using terms borrowed from topography, like valleys, crest lines and watersheds. This is probably the reason why the authors were surprised when, doing bibliographic work in the framework of a French project aiming at reducing friction in car engines, they found that extremely few authors established any relations between surface characterization and image processing and, no need to say, even fewer evoked mathematical morphology. This, in spite of the fact that new surface metrology tools allow to obtain precise 3D data (a matrix of heights, i.e. the equivalent of a 2D image), which give considerably more information than classical 2D metrology tools (profilometers), and that active research in this field tries to propose characterization parameters for 3D surfaces [20, 7, 8, 9, 10] .

In the first part of this paper, a state of the art of 3D surface characterization in the automotive and steel industry is presented, and links with mathematical morphology are highlighted. Only characterizations computed directly on the set of 3D data are presented, even if other characterization methods for the same type of surfaces exist, to which mathematical morphology can also be applied, like the study of the optical behaviour of reflected light [1]. The simulation of these surfaces by means of Boolean models, initially developed for roughness purposes [11], will not be presented here. The links to mathematical morphology show that often existing characterization tools can be described in terms of mathematical operators, providing therefore a solid formal background as well as efficient algorithms to implement them. New perspectives for the application of mathematical morphology to this domain are stressed.

In the second part, a particular application is developed. A surface topography decomposition methodology is presented. It decomposes a surface into three elements: reference surface, superficial roughness (related to friction and wear) and valleys (related to lubricant circulation and reservoirs). The study of the resulting superficial roughness component has allowed a precise wear characterization.

2. Surface characterization in the automotive and steel industries

The geometric characteristics of a surface are directly related to important macroscopic properties, like lubrication, friction, wear and adhesion, characteristics that are essential for forming, painting or mechanical performance.

The first surface characterization methods were based on profiles, which were mainly characterized by means of statistics computed on the heights histogram (though the motifs method, described below, constitutes an exception).

Today, 3D data become easily available, motivating the development of 3D surface characterization parameters [7, 8, 9, 10, 14, 15, 17, 20]. The first step has been the generalization of statistical parameters obtained from the histogram. However, this measures clearly do not take advantage of the 3D data. The use of the covariance or of frequential analysis is more interesting. Another trend is composed by researchers who try to characterize the topological properties of the surface, which are supposed to play an important role in the definition of lubrication performance. However, several publications show a lack of a strong theoretical framework when coming to the characterization of spatial relations.

In the following sections two domains of engineering surface characterization are further described : the computation of a reference surface, and topological characterization. They have been chosen because, in the authors opinion, the application of mathematical morphology to them should prove very useful.

2.1. REFERENCE SURFACE

The computation of a reference surface is interesting for two reasons. Firstly, it allows to remove low frequency surface components, called *form* (for the very low ones) and *waviness*, which are often considered either as an acquisition artifact, or as an unimportant component for the definition of some macroscopic characteristics. Secondly, the reference surface can be used to classify the points of the original surface into two classes: valleys or plateaux, which supposedly play different roles in the definition of macroscopic characteristics.

The most commonly used reference surface is the plane minimizing the mean square distance to the original surface [6]. This solution works correctly if form and waviness can be modelled by a plane, and if the surface heights follow a gaussian distribution. These hypothesis are often wrong. Other techniques have been proposed (for a review, refer to [6]) ; among these, one is considered to give a good reference surface, but is also considered as too computationally intensive: the *rolling ball* or *envelope surface* technique. This method was initially proposed for profiles [21] and afterwards generalized to surfaces [19]. The resulting reference surface is the locus of the ball center as it rolls over the profile or the surface. This operation can simply be described as a dilation of the equivalent image by the ball.

If the dilation by a ball is considered too computationally intensive, then the use of simpler structuring elements, as squares, hexagons or cones could be studied. However, if the use of the sphere is still preferred, then a good approximation, as long as the radius of the sphere is not too small with respect to the surface roughness, would be the parabola. Efficient algorithms exist for the computation of erosions and dilations with this class of structuring elements [3]. Another natural extension of this reference surface computation method would be the use of a closing instead of a dilation in its computation.

In section 3, a reference surface computation method based on the morphological alternate sequential filter is presented and applied to the characterization of wear in combustion engine cylinder liners.

Once that the reference surface is computed, it can be removed from the original one in order to obtain a globally flat surface, which is easier to characterize.

2.2. TOPOLOGICAL CHARACTERIZATION

Topological characterization of a surface is considered important for applications such as lubrication, sealing and painting.

The *motifs method* [4], empirically defined by the automotive industry several years ago, and wich became an international standard only recently (ISO 12085), could be considered as a forerunner of this kind of characterization. It aims at characterizing the size of important catchment basins. It begins by considering the consecutive catchment basins of the profile, and then fusions them iteratively using some empirical rules. When the basins cannot grow further (their width cannot exceed a given constant) some statistical measures are computed (means, standard deviations of the widths and depths of the basins) [4].

Researchers have recently tried to generalize this method to 3D surfaces. Scott [17] has proposed a generalization based on the work of Kweon and Kanade [12], who extract terrain features from elevation maps and describe them using a *topographic change tree.* This kind of approach would greatly benefit from analogous work in image processing. For instance, the *max-tree* defined by Salembier et al. [16] is very similar to the topographic change tree. The work of Soille and Gratin on drainage network extraction [18] could also be interesting in this domain.

The use of the watershed springs to the mind of the mathematical morphology expert when trying to characterize surface topology. To the extent of the authors knowledge, the only research work which has applied applied the morphological watershed to the characterization of industrial surfaces is the PhD thesis of Barré [2]. She used the watershed as basic tool to propose a generalization of the motif method to 3D surfaces.

Other researchers in industrial surface characterization have developed tools which could be described in terms of flooding and watershed [14, 15]. Hence, they could take benefit from all the theoretical and algorithmical results concerning the morphological watershed.

3. Wear characterization in cylinder liners

Friction between the piston rings and the cylinder liners in internal combustion engines is one of the main causes of energy loss in a car. As part of the study of the contact between the rings and the liner, a methodology to measure wear in the cylinders is proposed.

3.1. Topography acquisition and filtering

The cylinder liners considered in this work come from the V6 engine from Peugeot-Citroën and Renault. The liners are plateau-honed with a crosshatch angle of about 50 degrees (see the first image of Fig. 1). Topography maps were measured for each cylinder at top-dead-center [1] and mid-stroke [2] using a mechanical stylus of $1,25 \mu m$ radius. A 3D raster scan of 512×512 points, with a spatial sampling step of $3 \mu m$, was chosen. After quantization and filtering out the cylinder form, the data were converted into a 16 bits image. A light morphological filter (opening by reconstruction followed by closing by reconstruction with a square structuring element of size $6 \times 6 \mu m$) was applied in order to remove some outlier values.

Fig. 1 shows an example of a resulting image. The surface is composed of rough plateaux separated by valleys. These elements play different roles with respect to friction, hence it is interesting to analyze them separately. To achieve this aim, a decomposition methodology is needed.

3.2. Reference surface using an alternate sequential filter

An alternate sequential filter of size n with structuring element B is applied to the surface I. The output surface is considered as a reference surface R. The initial surface elements that lie above the resulting reference surface R are then considered as plateaux roughness, denoted by P, and the surface elements that lie below the reference surface are considered as valleys or holes, denoted by V. If M is a sampling point then:

$P(M) = sup(I(M) - R(M), 0)$ and $V(M) = inf(I(M) - R(M), 0)$,
hence:
$I(M) = R(M) + V(M) + P(M)$.

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[1] The level of the liner corresponding to the top of the piston trajectory

[2] The level of the liner corresponding to the middle of the piston trajectory

It is then possible to compute separately the characteristics of the plateaux roughness and of the valleys.

The decomposition procedure only requires two parameters: the elementary structuring element B and the maximum filtering size n. For practical reasons, B is a 3×3 pixels square. The choice of n depends on the size of the elements that have to be filtered : nB has to be larger than the largest topography elements to be filtered. Thus the choice is based on simple physical observations. Moveover, this parameter will be the same for all the images of the same sort. In the framework of the current application this choice has been easy, and the same parameters have been kept for the full set of data (around 40 images coming from 20 cylinders). The sampling step is $3\mu m$ and the largest valleys are around $50\mu m$ wide. The value of n has been set equal to 20. Therefore the largest topography elements that have been erased are $2 \times 20 \times 3 = 120\mu m$ wide. A wide margin has been left with respect to $50\mu m$. A more detailed description of this decomposition method can be found in [5].

Fig. 1 shows an example of real topography decomposition. Note that the shape of the structuring element is clearly visible in the reference surface. They could be reduced by using a more isotropic structuring element, like a disk, at the expense of more computing time.

3.3. RESULTS

In order to evaluate wear in cylinder liners at top-dead-center and mid-stroke, topography maps were acquired on different cylinders at these two regions before and after running the tests. For practical reasons, the measures before and after the tests were not taken at exactly the same position, thus the results must be interpreted from a statistical viewpoint.

The tests were made on a SPC[3] machine from PSA, which simulates a V6 engine[13]. The 3D topography parameter chosen to characterize wear was Sa (the mean of the absolute differences with respect to the mean height). Wear normally causes a reduction of Sa. The resulting global Sa measures before and after the tests, at top-dead-center and mid-stroke, are summarised in table I. As the reader can see, these measures do not clearly show wear, for two main reasons:

- The contribution of the valleys to Sa is very important, and overshadows the contribution of plateaux roughness. This interference is even more severe if it is considered that the sampling area, from a statistical point of view, is too small with respect to the largest valleys, which do not always appear in all the images. Such a valley can accentuate the global Sa significantly.
- Some images, like the one presented in Fig. 1, show low frequency components, which can interfere with the Sa measurement.

Consequently, the decomposition operator described above was applied in order to separate the plateaux roughness from the other surface components and the Sa of this component was measured. The results appear in Table II.

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[3] The acronym SPC comes from the French "*Segment-Piston-Chemise*", which stands in English for "Piston-Ring-Liner".

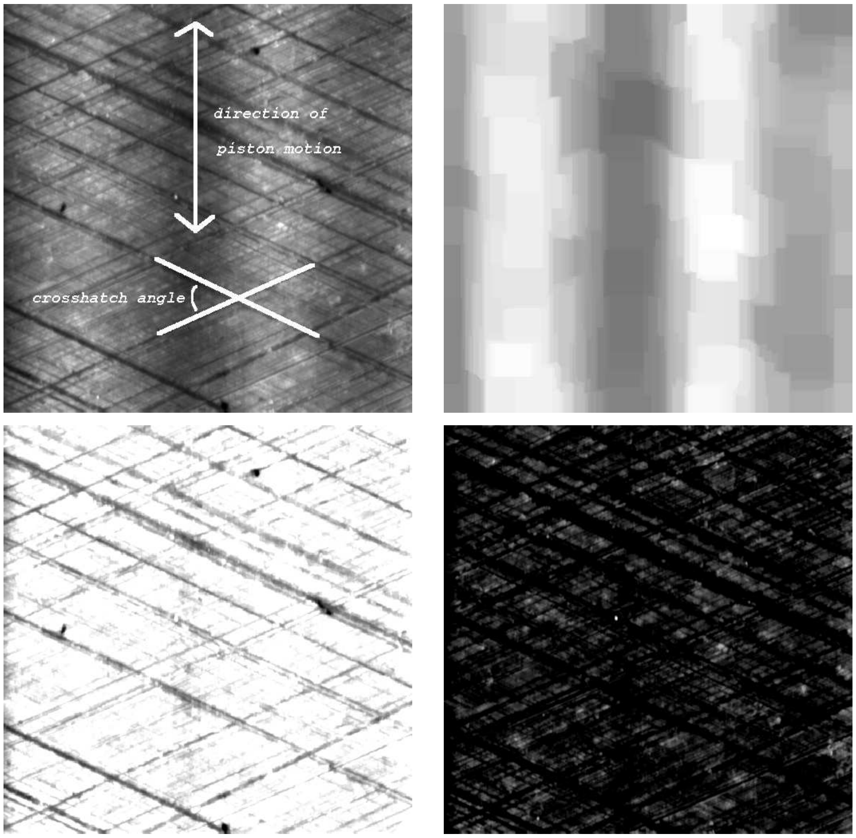

Fig. 1. Decomposition example of the surface topography of a cylinder liner. Top left: original image. Top right: reference image resulting from the alternate sequential filtering; waviness has been extracted. Bottom left: valleys. Bottom right: plateaux roughness. Note that grey levels have been adapted in order to allow accurate visualization, therefore the grey level scale changes from one image to the other.

	Sa at top-dead-center		Sa at mid-stroke	
Cylinder	Before test	After test	Before test	After test
12	0.28	0.38	0.30	0.34
17	0.68	0.78	0.49	0.39
18	0.53	0.33	0.30	0.28
19	0.70	0.66	0.48	0.45
20	0.63	0.66	0.38	0.42
21	0.46	0.43	0.38	0.46

TABLE I

Global Sa parameter for cylinder liners at top-dead-center and mid-stroke before and after the tests. Measures are given in μm.

	Plateaux Sa at top-dead-center		Plateaux Sa at mid-stroke	
Cylinder	Before test	After test	Before test	After test
12	0.082	0.108	0.075	0.104
17	0.223	0.201	0.187	0.112
18	0.138	0.090	0.086	0.088
19	0.174	0.131	0.119	0.084
20	0.174	0.117	0.093	0.078
21	0.163	0.130	0.115	0.129

TABLE II

Plateaux Sa parameter for cylinder liners at top-dead-center and mid-stroke before and after the tests. Measures are given in μm.

Firstly, note that wear is clearly apparent at top-dead-centre. All cylinders, except one, show a significant decrease in Sa after the tests. Secondly, wear is not clearly discerned at mid-stroke. This difference between top-dead-centre and mid-stroke is normal, given that the piston functions in hydrodynamic regime at mid-stroke, and in mixed regime at top-dead-centre.

4. Conclusion

A short state of the art of engineering surface characterization has been presented. It shows a lack of a strong theoretical framework when dealing with topological parameters. The authors believe that mathematical morphology could constitute such a framework for many applications. Moreover researchers in this field could take advantage of the existing morphological operators and algorithms. Efforts in this direction are just beginning.

A decomposition method that allows decomposition of a topographic surface into three components: plateaux roughness, reference surface and valleys, has been presented. The method has been applied to the surface of combustion engine cylinder liners. It has enabled characterization of wear in the cylinders, not possible with standard 3D measurement and analysis techniques.

This decomposition method can be also used as filtering tool, in order to remove low frequency surface components. It has been used for example as pre-filtering of an analysis process that computes the parameters to be fed into a boolean random function model. Finally, studies have been undertaken on the valley images produced by the method in order to characterize lubricant retention properties of the surface.

The study of the correlation of the measures obtained from these images, and the performance of the corresponding liner, should help us to detect the important features of the surface with respect to friction, and eventually optimize the surfaces and reduce friction.

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