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Bi-Gaussian surface identification and reconstruction with revised autocorrelation functions

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ABSTRACT

The newly proposed continuous separation method for bi-Gaussian stratified surfaces, as the improvement of the existing ISO segmented one, is investigated. The continuous method provides an accurate surface-separation solution but is much more efficient. It has great stability to resist the fluctuations of the probability material ratio curves that are universally observed on real engineering surfaces. In contrast to the ISO segmented method, the continuous one is roughness-scale independent. When using a bi-Gaussian approach, it is difficult to identify component correlation lengths because of missing points in each individual component. An iterative process is used to overcome the defect in determining autocorrelation function (ACF). The ACF quality of the revised bi-Gaussian approach is better than that of the Johnson approach.

1. Introduction

Surface can be regarded as the fingerprint of a component [1,2]. Its analysis enables 1) manufacture-process quality to be evaluated [3,4], 2) tribological behavior to be rendered [5,6], 3) functional performance to be altered [7,8], 4) contact or wear mechanisms to be revealed [9,10]. Therefore, it is imperative to search for an appropriate method to analyze surfaces accurately and efficiently, although these two antagonistic demands must always be balanced. Rough surface analysis is a subject of current interest and hence the objective of the present study.

To achieve the target surface-analysis method, an understanding of existing methods is of primary importance. The arithmetical mean deviation Ra and the central moment parameter set (Rq, Rsk and Rku) are widely used. Ra is broadly applied as roughness in industry, but it is not sensitive to small deviations from the mean value. Root mean square deviation Rq is commonly used in research and is more sensitive to deviations. Skewness Rsk embodies the surface asymmetry: a skewness of zero reflects a symmetric shape, a negative skewness describes a surface with peaks under the mean plane, a positive skewness relates to a surface with high peaks but shallow valleys. Kurtosis Rku is the most sensitive to extreme data: a centrally distributed surface corresponds to a kurtosis greater than 3; a well spread distribution has a kurtosis smaller than 3. Note that Sa, Sq, Ssk and Sku are the corresponding 3D extensions defined in ISO 25178-2 [11]. In addition to amplitude parameters, spatial parameters such as ACF, texture aspect ratio, fastest decay autocorrelation length, and summit density are also used.

Although researchers have realized that rough surfaces will be altered by wear, and thus have diverted attention from Gaussian to non-Gaussian distribution, a vital reality is still often ignored. Wear causes the remaining surface not only to exhibit a non-Gaussian property, but also to have a stratified character, i.e., a worn surface is an original Gaussian surface superimposed with a truncating surface up to a certain height [12]. In fact, the wear-generated, truncating surface is not a perfectly smooth plane but a Gaussian distributed rough surface [13], thus yielding a bi-Gaussian surface as termed in Refs. [2,5,6,14]. The concept of bi-Gaussian surfaces was introduced in studies on a two-process (e.g., plateau honing operation) cylinder liner that consists of smooth wear-resistant and load-bearing plateaus with intersecting deep valleys working as oil reservoirs and debris traps [15–17]. It was then extended to the field of worn surfaces [2,5,6,14,18–21]. Up to now, the probability material ratio curve method [22], which is based on the material ratio curve, has been used as an effective surface characterization method. Williamson [23] found that the material ratio curve of a Gaussian distributed surface exhibits a straight line when plotted on a Gaussian standard deviation scale. The intercept of the straight line is the mean value, and the corresponding slope is Rq. In line with the previous works [2,5,6], σ is used in the present study. Thus, a bi-Gaussian stratified surface should exhibit two linear regions, as shown in Fig. 1. Rpq (=σ_u) corresponds to the upper surface, and Rvq (=σ_l) corresponds to the lower surface.

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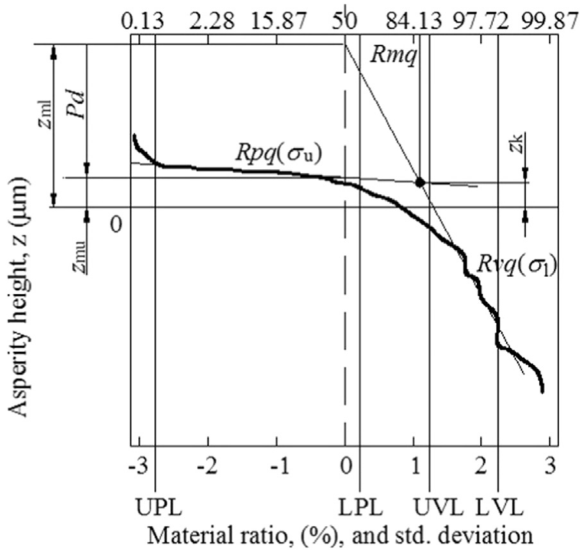

Fig. 1. Probability material ratio curve method [5].

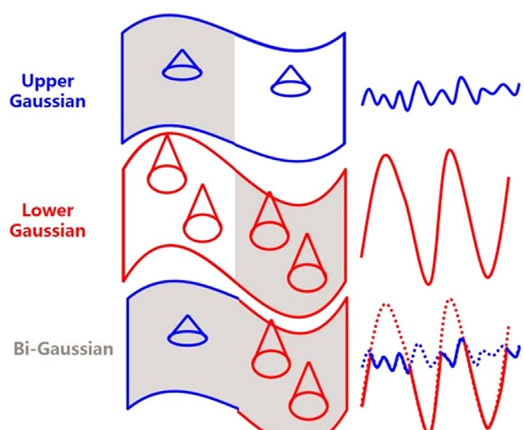

Fig. 2. Generation of bi-Gaussian surface based on superposition principle.

Table 1
Surface parameters of the measured worn surfaces.

Parameter	Value					
	SiCG	RiCG	SiCF	TCF	RiCF	MiCF
σ (μm)	0.0292	0.0596	0.0922	0.0339	0.0641	0.200
Ssk	−2.51	−1.80	−1.56	−10.0	−4.00	−6.50
Sku	15.9	14.6	7.46	146	34.3	59.9
λ_x (μm)	3.61	11.2	4.25	4.25	15.6	12.4
λ_y (μm)	3.28	7.88	3.90	4.25	9.22	11.0
Ratio of unmeasured points (%)	0.000286	0.0228	0.133	0.0309	0.245	1.03

Further, (Rmq, z_k) defines the transition from the upper component to the lower, whilst Pd is the distance between the mean planes of the two components z_{mu} and z_{ml}.

The probability material ratio curve method has been used to analyze bi-Gaussian surfaces [14–21]. In addition to surface characterization, the bi-Gaussian viewpoint has been used to simulate rough surfaces based on the superposition principle [10,24,25]. It totally differs from existing Gaussian or non-Gaussian surface generation [26]. Recently, Hu et al. [2] proposed a continuous separation method to develop the segmented linear fit used in the above works [14–22]. The continuous separation method was demonstrated to perfectly respect the unity-area demand on the probability density function and to greatly capture the small roughness-scale component. They then used the continuous form of the probability density function to improve the segmented stratified asperity contact model of Leefe [14]. However, when first proposing the continuous separation method in Ref [2], Hu et al. simply compared their results to a reduced segmented method [17] rather than the procedure in ISO 13565-3 [22]. Although they have reselected the ISO segmented method when extending the continuous method to the fields of lubrication and asperity contact [5], a detailed comparison between the continuous and the ISO segmented separation methods is still missing.

Another interesting issue is the ACF. From the common single-stratum point of view: 1) the ACF of a rough surface can be calculated; 2) then, the correlation lengths of the rough surface can be obtained after specifying the truncation coefficient (usually 0.1 or 0.2); 3) based on the resulting correlation lengths, the rough surface can be reproduced with the use of autoregressive model [27–29], moving average model [30–32] or function series [33–35]. However, with respect to the bi-Gaussian viewpoint, a surface is divided into upper and lower parts at the transition point. The component ACFs (or correlation lengths) are then calculated within the scope of an individual component. Hence, for each component, there is a large proportion of missing points that leads to errors in the solution. Moreover, the anamorphic component correlation lengths induces a sequent error for surface reconstruction. In Ref. [2,5], Hu et al. mentioned this defect of bi-Gaussian approach. During the bi-Gaussian surface reconstruction, they arbitrarily set the input component correlation lengths to those of the whole target surface.

The first aim of the present study is to provide a detailed comparison between the continuous and the ISO segmented separation methods in terms of accuracy, efficiency, stability, and roughness-scale dependence. The second aim is to propose a feasible means of overcoming the defect of bi-Gaussian approach in determining the ACFs of the two components.

2. Surface analysis and reconstruction

2.1. Single-stratum surface

To analyze a single-stratum rough surface, bi-Gaussian surface parameters are not required. The fundamental surface parameters can be calculated as [26].

$$\sigma = \sqrt{\frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M} z_{i,j}^2}, \tag{1a}$$

$$Rsk = \frac{1}{\sigma^3}\frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M} z_{i,j}^3, \tag{1b}$$

$$Rku = \frac{1}{\sigma^4}\frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M} z_{i,j}^4, \tag{1c}$$

$$ACF(p, q) = \frac{1}{\sigma^2}\frac{1}{NM}\sum_{i=1}^{N-p}\sum_{j=1}^{M-q} z_{i,j} z_{i+p,j+q}, \tag{2}$$

$$ACF(\frac{\lambda_x}{\Delta_x}, 0) = 0.2, \tag{3a}$$

$$ACF(\frac{\lambda_y}{\Delta_y}, 0) = 0.2. \tag{3b}$$

z is the surface height relative to the mean plane; M and N are the numbers of points in the x and y directions, respectively; λ_x and λ_y are the 80% x- and y-direction correlation lengths, respectively; Δ_x and Δ_y are the x- and y-direction sampling intervals, respectively. In a surface reconstruction, if the surface height of the target surface follows a Gaussian distribution, σ, λ_x and λ_y are sufficient. The moving average