Tribology International 104 (2016) 328–341

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

# Stratified effect of continuous bi-Gaussian rough surface on lubrication and asperity contact

Songtao Hu[a], Weifeng Huang[a], Noel Brunetiere[b], Zhixiang Song[a], Xiangfeng Liu[a,*], Yuming Wang[a]

[a] State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China
[b] Institut Pprime, CNRS-Universite de Poitiers-ENSMA, 86962 Futuroscope Chasseneuil Cedex, France

ARTICLE INFO

*Keywords:*
Surface simulation
Worn surface
Lubrication
Asperity contact

ABSTRACT

Continuous bi-Gaussian reconstruction approach is applied to two simulated pure bi-Gaussian and four real worn surfaces. It is compared with segmented bi-Gaussian, ISO 13565-3 bi-Gaussian and Johnson reconstruction approaches in terms of surface property, lubrication and asperity contact. The results show that the continuous approach reproduces a surface in good agreement with the original in terms of maximum fluid pressure, cavitation ratio and lift load, because it serves as a concise way to achieve the high resemblance of surface property with the original surface as similar to the ISO approach. The segmented approach sometimes loses efficiency, and the Johnson approach generates a single-stratum surface with steep valleys, inducing large pressure spikes, large cavitation zone and large lift load. The superiority of the continuous approach can be drawn from the contact mechanics study on contact pressure and real contact area.

## 1. Introduction

Surface texture acts as the initial input of tribological behavior analysis such as lubrication, asperity contact, wear and friction. The input data can be obtained from experimental measurements. It, however, requires considerable financial resources and numerous tests to carry out a parametric study. An alternative way of achieving the desired goal is the numerical surface simulation. Broadly speaking, the numerical surface simulation, i.e., surface reconstruction, consists of two main aspects: characterization and generation.

In terms of characterizing rough surfaces, the central moment parameter set *Rq* (=$\sigma$), *Rsk* and *Rku* is widely used and seems to work well for the vast majority of rough surfaces. However, it fails in describing two-process surfaces. The cylinder liner of an internal combustion engine manufactured by plateau honing operation, for instance, is a representative two-process surface consisting of smooth wear-resistant and load-bearing plateaus with intersecting deep valleys working as oil reservoirs and debris traps. Besides two-process surfaces, any prepared surface texture is often rapidly altered by wear, leading to a surface with a large-scale roughness in the valleys and a small-scale roughness in the plateaus left by a truncation of the peaks of the initial large-scale roughness. The two-process and the worn surfaces can be generalized into bi-Gaussian stratified surfaces. Broadly speaking, two main characterizing methods have been developed based on the material ratio curve (Abbott curve) [1]. The first one is the *Rk* parameter set in Fig. 1a according to ISO 13565-2 [2]. Its kernel is based on the use of a minimum slope line, spanning a 40% material ratio, to obtain the core roughness depth *Rk* defined as the width of core band of roughness. The roughness above and below this core band are respectively captured by the reduced peak height *Rpk* and reduced valley depth *Rvk*, where *Rpk* embodies the running-in capacity and *Rvk* embodies the lubricant storage capacity. Another two key parameters, i.e., material ratios *Mr*1 and *Mr*2, are the transition points of ‘peak’, ‘core’ and ‘valley’ regions. Since the *Rk* method implies a three-stratum concept for the surface that conflicts with a two-stage manufacturing process, the probability material ratio curve is provided as another choice referring to ISO 13565-3 [3]. If the material ratio curve of a Gaussian distributed surface is plotted on a Gaussian standard deviation scale, it exhibits as a straight line [4] (the detailed transformation from material ratio curve to probability material ratio curve can be seen in Ref. [5]). By this, the intercept is the mean value of asperity height and the slope is *Rq*. For a bi-Gaussian surface, it should exhibit two linear regions (seen in Fig. 1b) where *Rpq* (=$\sigma_u$) corresponds to the mean square root of the plateau, upper region and *Rvq* (=$\sigma_l$) corresponds to the mean square root of the valley, lower region. The knee-point (*Rmq*, $z_k$) defines the separation of the upper and lower components whilst *Pd* provides the distance between their mean planes ($z_{mu}$, $z_{ml}$). Note that quantities $\sigma_u$, $\sigma_l$, $z_k$, *Pd*, $z_{mu}$ and $z_{ml}$ used in the present study are not included in ISO 13565-3. By using this probability material ratio curve method, Whitehouse [6], Malburg

* Corresponding author.

http://dx.doi.org/10.1016/j.triboint.2016.09.009
Received 29 June 2016; Received in revised form 21 August 2016; Accepted 6 September 2016
Available online 07 September 2016

**Nomenclature**

| | |
|---|---|
| $\bar{A}_c$ | contact area of a summit |
| $A_n$ | nominal contact area |
| $A_r$ | real contact area |
| ACF | autocorrelation function |
| $E$ | equivalent Hertz elastic modulus |
| *erf*, *inverf* | error function, and its inverse function |
| $\bar{F}_c$ | contact load of a summit |
| GSD | Gaussian standard deviation |
| $h$ | local film thickness |
| $h_0$ | distance between smooth plane and mean plane of rough surface |
| *Rku* | kurtosis |
| *M*, *N* | numbers of points in the $x$ and $y$ directions |
| *Mr* | material ratio curve |
| $Mr_1$, $Mr_2$ | material ratios differentiate 'peak', 'core' and 'valley' regions |
| PSD | power spectral density |
| $p_c$ | average contact pressure |
| *Pd* | distance between mean planes of two components |
| $R_s$ | summit curvature radius |
| *Rk* | core roughness depth |
| *Rmq* | material ratio at transition |
| *Rpk* | reduced peak height |
| *Rq* | root mean square, i.e., $\sigma$ |
| *Rvk* | reduced valley depth |
| *Rsk* | skewness |
| *UPL*, *VPL*, *UVL*, *LVL* | limit in ISO 13565-3 |
| $z$ | asperity height |
| $z_k$ | height-coordinate of transition |
| $\Delta$ | sampling interval |
| $\lambda$ | correlation length |
| $\sigma$ | root mean square |

*Subscripts*

| | |
|---|---|
| i, j | counts in $y$ and $x$ directions |
| m | mean value |
| u, l | upper and lower parts |
| x, y | $x$ and $y$ directions |

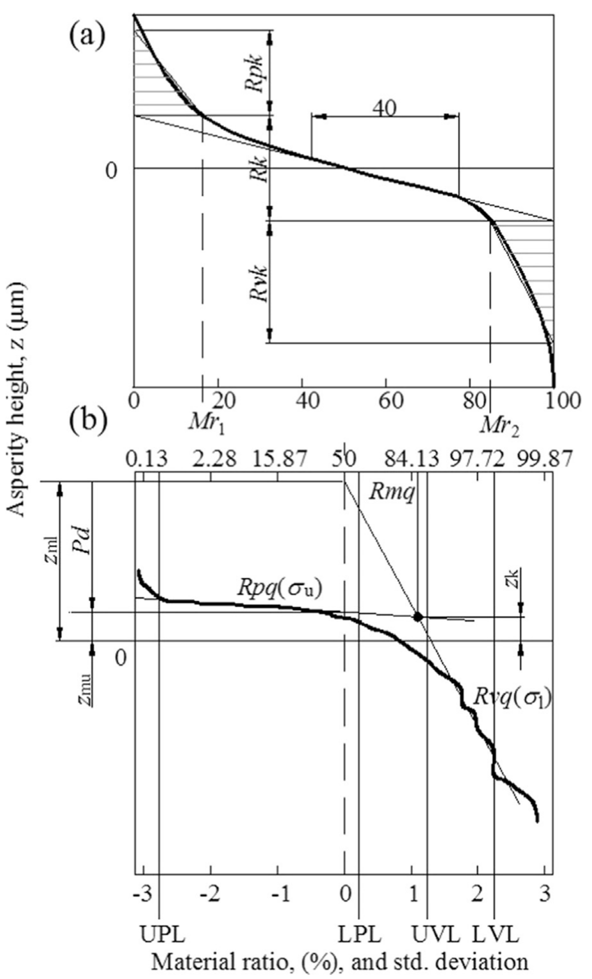


**Fig. 1.** Characterization of a two-process or worn surface.

et al. [7], Sannareddy et al. [8], Leefe [9] and Pawlus and Grabon [10] have characterized bi-Gaussian surfaces.

Recently, Hu et al. [5] pointed that the segmented regression, which was utilized in Ref. [8] to differentiate between the component strata contained within the stratified surface, had two drawbacks. The first one is that the segmented separation method arbitrarily assumes the probability material ratio curve consisting of two straight lines with a knee-point. In fact, the probability material ratio curve should have a smooth transition region, which is a result of the gaps induced in the original plateau profile by the deep valleys in the rough profile [8] and the unity-area demand of the probability density function (PDF). As we known, the cumulative distribution function (CDF) is the integral of the PDF from a certain value to another. From geometrical point of view, the CDF is the area bounded by the PDF, the axis of integral and the interval of integration. If the integral limits tend to be positive and negative infinite, the area, i.e, CDF, should be 1. The arbitrary assumption of the probability material ratio curve arises from the arbitrary assumption of the PDF that the PDF of a bi-Gaussian surface is simply structured by splicing two component PDFs with a knee-point. Since each component satisfies the unity-area demand on its own PDF, there is no reason that the simply spliced PDF respects the unity-area demand. The second drawback is that the segmented separation method prefers to focus on the large-scale roughness (higher slope) and induces a large error for analyzing the surface with the small-scale roughness (lower slope). The drawback is due to the selection of the minimum cumulative error as the principle of searching the optimized knee-point [8]. To solve the first drawback, Hu et al. [5] proposed a surface combination theory and developed a continuous separation method instead of the segmented one. The continuous method has been demonstrated to perfectly overcome the first drawback on measured worn surfaces and numerically generated pure bi-Gaussian surfaces. Furthermore, the second drawback has also been solved as a consequence of the reasonable revision of the PDF in their surface combination theory. However, Hu et al. [5] simply applied their continuous method and the segmented method simply within [−3$\sigma$, 3$\sigma$], and they haven't compared their continuous method with the method in ISO 13565-3.

In terms of generating rough surfaces, three main models have been proposed [11]: autoregressive model [12–14], moving average model [15–17] and function series [18–20]. Direct or fast Fourier transform (FFT) technology can be used in these models to generate a Gaussian or non-Gaussian surface, where the latter is more efficient and needs a smaller storage space. When generating a non-Gaussian surface with prescribed skewness and kurtosis, the Johnson translation system [21] with auxiliary algorithms [22,23] is used. Minet et al. [11] have used the Johnson reconstruction approach [21–23] to reproduce simulated surfaces for three worn seal surfaces. Even if the simulated non-