Wear 316 (2014) 6–18

Contents lists available at ScienceDirect

Wear

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

Estimation of statistical parameters of rough surfaces suitable for developing micro-asperity friction models

Bhargava Sista, Kumar Vemaganti *

Department of Mechanical and Materials Engineering, University of Cincinnati, Cincinnati, OH 45221-0072, United States

ARTICLE INFO

Article history:
Received 21 January 2014
Received in revised form
10 April 2014
Accepted 16 April 2014
Available online 26 April 2014

Keywords:
Random process model
Rough surface
Friction
Sampling interval

ABSTRACT

Numerical models of surface micro-topography find applications in the development of multiscale models for friction and wear between two interacting surfaces. Although much work has been dedicated to developing such multiscale models, they have been hampered by the strong dependence of surface statistics on the resolution of surface topography measurements. The objective of this study is to develop a systematic approach to reduce this dependence so that the resulting statistical parameters are suitable for developing micro-asperity based continuum friction models. The approach significantly reduces but does not eliminate the dependence of surface statistics on the measurement resolution. It is based on fitting a Gaussian function to numerically calculated autocorrelation functions for randomly selected profiles from a surface. The use of a Gaussian function filters out very small scale asperities that affect the statistical parameters but are not tribologically significant. The distributions of the resulting parameters allow us to calculate the spectral moments using Monte Carlo simulations. The approach is applied to numerically generated surfaces as well as micro-topography measurements of a high density polyethylene (HDPE) surface. Results show that the proposed approach is considerably less sensitive to the measurement resolution, especially in comparison to standard statistical sampling methods. We argue that the Gaussian autocorrelation function used in our work is a better choice compared to other forms for continuum-level applications.

1. Introduction

The statistical properties of rough surfaces – standard deviations of heights, slopes and curvatures – are essential to the development of multiscale models of nominally flat surfaces. These statistical properties are usually calculated from two important properties of the surface: the distribution function of surface heights and the autocorrelation function of surface heights. The distribution function describes how the surface heights vary perpendicular to the surface whereas the autocorrelation function describes the manner in which the surface heights vary along the surface. The distance at which this correlation reduces to e^{-1} is called the correlation length.

Contact models of rough surfaces are used in micro-asperity based friction models to determine various quantities such as mean surface separation, real area of contact and normal pressure. The model proposed by Greenwood and Williamson (GW model) [1] is perhaps the earliest and most commonly used contact model for nominally flat surfaces. This model assumes that the micro-asperities are spherical in nature. The surface heights are assumed to be distributed normally, while the radii of curvature of all the asperities are the same. Bush et al. [2] replaced the spherical asperity caps by paraboloids, also with a Gaussian surface height distribution. The principal curvatures of an asperity are the same as those at the summit of the asperity. McCool [3] conducted a thorough comparison of the two models and concluded that the GW model provides good order-of-magnitude estimates of the number of contacts, real area of contact fraction and normal pressure. While the previous works focused on elastic materials, extensions to viscoplastic materials have been studied by Tworzydlo et al. [4].

Reliably estimating the statistical properties of surfaces, however, is often difficult because of the revelation of smaller asperities on the surface at finer resolutions. The issues regarding resolution dependence are well recognized and have been addressed in many studies in the literature. Bhushan et al. [5], for instance, reported that the standard deviation of surface slopes doubles with the resolution, while the standard deviation of surface curvatures quadruples. Whitehouse and Archard [6] pointed out that the statistical properties of a surface are not its intrinsic properties but vary with the sampling interval of measurement. This means the measurements need to be carried out at a length scale appropriate to the phenomenon of interest.

Pawlus et al. [7] applied various micro-contact models to both simulated and measured isotropic, Gaussian surfaces to determine mean surface separation and the real area of contact as functions

* Corresponding author.
E-mail addresses: sistasa@email.uc.edu (B. Sista), Kumar.Vemaganti@uc.edu (K. Vemaganti).

http://dx.doi.org/10.1016/j.wear.2014.04.012
0043-1648/

of normal load. They reported that these quantities are very sensitive to the sampling interval and suggested that this dependency can be reduced by measuring the surface micro-topography at a sampling interval less than 0.85 times the correlation length. But, this would not necessarily ensure that the calculated surface statistics are reliable and represent the actual topographical properties of the surface since new asperities can become visible at lower resolutions.

Zavarise et al. [8,9] presented a detailed analysis of the dependence of the topography properties on the sampling interval for surfaces modeled using both fractal theory and stochastic theory. They reported that the macroscopic quantities (e.g., expected area of contact, normal load) determined using the GW model follow a power law dependence on the sampling interval. Pawar et al. [10] compared the topography parameters including asperity density, mean summit radius, and standard deviation of asperity heights of a rough surface calculated using both the eight-nearest neighbor summit identification (SID) method and by calculating the spectral moments of profiles along a random cross-section. They concluded that using the GW model based on topography parameters obtained from a summit identification scheme is the most reliable approach. But, the SID method is itself dependent on the sampling interval as smaller summits emerge with a reduced sampling interval. All these studies emphasize the importance of accurate and reliable estimation of topographical properties.

Several attempts have been made to determine an optimum sampling interval for measuring the surface profile for a given application. Thomas and Rosén [11] used fractal theory of roughness characterization to determine an optimum sampling interval. They assumed that all the micro-asperities deform in an elastic manner, which corresponds to only a minority of asperities even under moderate normal pressure. Chang [12] determined an optimum sampling interval based on the assumption that the micro-scale asperities undergo superficial plastic deformations and do not significantly impact the elastic–plastic contact problems. This analysis ignores the asperities that have any degree of plastic deformation. Another way of reducing the scale effects is to use digital high pass filters on the measured profile to filter the smaller asperities [13]. The critical cutoff frequency for the high pass filter is chosen as the highest frequency beyond which there is a sudden change in the root mean square (RMS) roughness of the surface. But a sudden change in the RMS roughness may not correspond to any changes in the RMS slope or RMS curvature, and the RMS roughness alone is not sufficient to completely describe the surface.

In this study, we present a systematic methodology for estimating the statistical properties of isotropic, Gaussian random surfaces. The approach reduces but does not eliminate the dependence of the surface parameters on the measurement resolution. For a given profile from a surface's micro-topography, we determine the numerical autocorrelation function (ACF) and fit a Gaussian function to it in order to obtain the ACF parameters. This process is repeated for multiple profiles from the surface in order to obtain distributions of the ACF parameters. The statistical properties of the surface are then computed from these distributions using Monte Carlo simulations. We apply this approach to determine the statistical properties of isotropic Gaussian surfaces generated using the rough surface generation (RSG) toolbox [14] as well as a high density polyethylene (HDPE) surface, whose micro-topography is obtained using optical profilometry.

Any approach that is based on analyzing surface measurements is bound to depend on the resolution at which the surface is characterized. While this dependence cannot be eliminated, the question is how to reduce it so that the resulting surface parameters are useful in constructing models that utilize the surface parameters. In this work, we are specifically interested in estimating surface parameters that are suitable for micro-asperity based friction models. In such models, the smaller asperities do not generally contribute to the overall frictional response, but can significantly skew the surface parameters – see [15, Chapter 3] for further discussion. We seek to filter out such asperities by numerically fitting a Gaussian function to the ACF of a given cross-section. Other applications that call for including the smallest of asperities may use different forms of the ACF. In that sense, the overall approach proposed here is not tied to any specific ACF form.

With the proposed approach, the accuracy of the surface statistical properties is still a function of the sampling interval, but considerably less so than with statistical sampling. The Gaussian ACF used in this work has the property that the resulting spectral moments are independent of the sampling interval, unlike the exponential and fractal ACF forms. This issue is discussed in more detail later in the paper. The use of Monte Carlo sampling to calculate the spectral moments allows us to obtain reliable estimates of macroscopic quantities (such as contact forces and area of contact) using micro-asperity based continuum models.

The rest of this paper is arranged as follows. In Section 2, we discuss the description of rough surfaces using random process modeling. Section 3 addresses the question of estimating the spectral moments of surfaces using statistical sampling and autocorrelation functions. We then propose a Monte Carlo sampling-based approach to obtain the spectral moments in Section 4. Results are described in Section 5, followed by a discussion of their significance and some concluding remarks.

2. Numerical modeling of rough surfaces

There are many ways of developing statistical models of rough surfaces. The three most popularly used methods are the following:

1. Fractal surface models [16,17].
2. Summit identification models [18].
3. Stochastic models [19–21].

Fractal models are developed to represent the multiscale and possibly self-affine nature of rough surfaces. As a result, surface statistics are affected by the fractal dimension and the sampling interval. This will be discussed in more detail in Section 6.2.

In summit identification models, the summits are identified in a discrete surface profile by using several methods such as identifying the highest point among neighboring points and inspecting the change in sign of the slopes and curvatures at different points. These methods are also affected by resolution dependencies as smaller asperities emerge with reduced sampling intervals.

Stochastic models are developed based on the idea that random surfaces are fully characterized by their surface height distribution and autocorrelation function. Motivated by the previous work in this area [19–21], we use the stochastic model approach to characterize surfaces in this paper.

2.1. Random process modeling

Rough surfaces are modeled as random processes with the surface height as the random variable. The Cartesian coordinates in a reference surface are the independent variables. This approach was first used by Longuet–Higgins [22–24] to study ocean surfaces. Nayak [19] used these studies to develop a random process model of rough surfaces. He modeled rough surfaces as two-dimensional, isotropic, Gaussian random processes. In this study, we use the findings of Nayak as the basis for calculating statistical properties of random surfaces.