SURFACE TOPOGRAPHY PARAMETERS IMPORTANT IN CONTACT MECHANICS

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Abstract:

The random surface models are important to many statistical peak-based contact models of rough surfaces. Statistics of 3D surface topographies and 2D profiles are compared and their interrelationship examined for generated and measured common random engineering surfaces. The applicability of the spectral moments approach to random surface specification is checked. Parameters important in contact mechanics, like summit density, summit curvature and summit height obtained by their definitions and predicted by the spectral moment approach, as well as calculated directly from profiles are compared. Also, the values of plasticity index are computed using various methods. Good agreement is found between theory and measurement.

Keywords: *surface topography, contact mechanics, spectral moments.*

1. Introduction

All engineering surfaces are rough and their description is important to the study of many interfacial phenomena, such as friction, wear, electric al and thermal contact resistance, etc. Surface topography is recognized as being an important factor in determining the nature and extent of contact. Because surfaces are rough, the true area of contact, which is much smaller than the nominal area of contact must support very large pressure. Two types of parameters were advocated for contact and wear prediction: parameters based on peak (summits) and parameters based on plots of material ratio.

The pioneering contribution to this field was made by Greenwood and Williamson [1], who developed a basic contact model (GW model) of isotropic surface. Chang *et al.* [2] put forward an elastic-plastic contact model for rough surfaces on the basis of volume conservation of plastically deformed asperities. These models have been extended by many researchers. Parameters connected with peak as peak radius, peak height and peak curvature were used. These parameters are based on a 2D profile. However the statistic of the areal (3D) surface and the statistics of a 2D profile of the surface are not the same. It is necessary to distinguish a peak on a profile from a summit on the surface. A detailed comparison was made by statistical approach. Rough surfaces were modeled as two dimensional, isotropic, Gaussian random surface by Nayak [3]. Dependencies between profile spectral moments and parameters important in contact mechanics were also developed by Bush *et al.* [4]. They were presented by McCool [5]. Surface and profile measurement and their resultant statistics were compared and their interrelationship examined for several common engineering surfaces [6]. Good agreement was found between theory and measurements over a large range of sampling intervals. Yu and Polycarpou [7] compared the summit density and summit radius obtained from numerically generated isotropic Gaussian surfaces.

2. Connections between summit parameters and spectral moments

Spectral moments m_0, m_2 and m_4 can be obtained from profiles. They are equivalent to the mean square height, rms. slope square and second derivative of profile.

The areal (3D) surface summit density is given by [5]:

$$Spd = \frac{1}{6\pi\sqrt{3}}\left(\frac{m_4}{m_2}\right) \cdot \tag{1}$$

The mean summit curvature averaged over all summit heights is [5]:

$$Spc = \frac{8\sqrt{m_4}}{3\sqrt{\pi}} \,. \tag{2}$$

The variance of the summit height is [5]:

$$\sigma_s^2 = \left(1 - \frac{0.8968}{\alpha}\right) m_0 \,. \tag{3}$$

The distance between the mean of the summit height distribution and the surface mean plane is [5]:

$$y_s = \frac{4\sqrt{m_0}}{\sqrt{\pi\,\alpha}} \,, \tag{4}$$

where:

$$\alpha = \frac{m_0\, m_4}{m_2^{\,2}} \,. \tag{5}$$

3. Calculation procedure

Isotropic surfaces of Gaussian ordinate distribution were generated, using the procedure developed by Wu [8]. Each surface of this type is characterized by correlation distance (in which the autocorrelation function decays to 0.1 value) and standard deviation of height. In addition, some measured isotropic Gaussian surface topographies were analyzed. The values of their texture parameter ***Str*** were higher than 0.8. These surfaces were measured by stylus 3D Talyscan 150 equipment with nominal radius of tip 2 μm. The initial numbers of the measured points

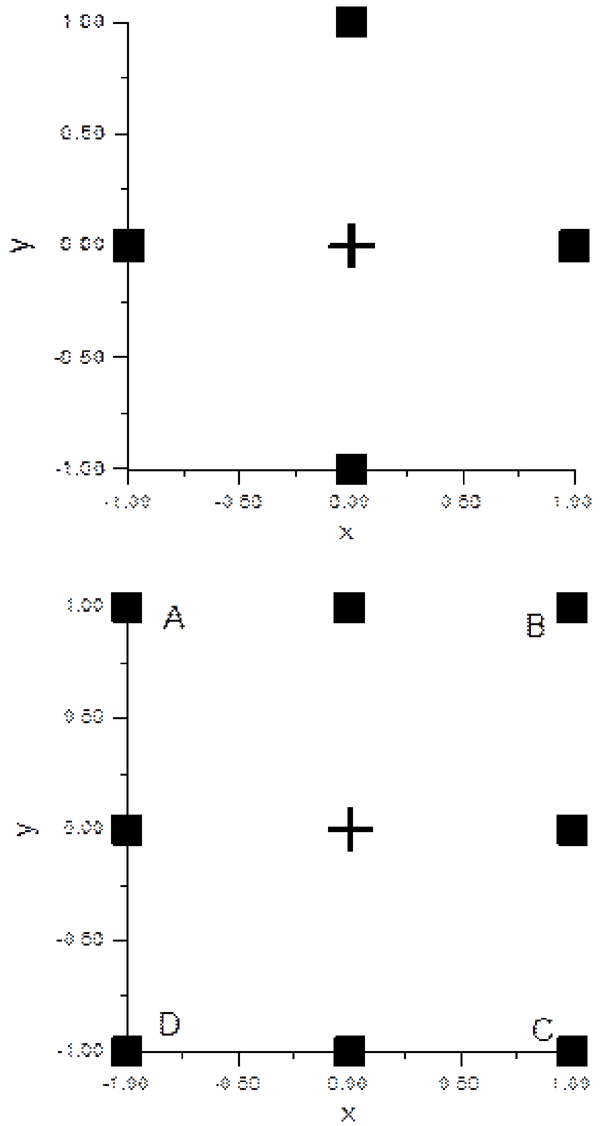


Fig. 1. Various summit identifications

were between 401 x 401 to 601 x 601. The sampling intervals were 5 and 10 micrometers. However in order to decrease correlation length sampling interval sometimes increased and the number of points was reduced. For each of measured surfaces, the form was eliminated by a polynomial of the 2nd degree. Digital filters were not used. For each surface, parameter connected with summits were calculated. For areal measurements, the mean radius of each summit ***R*** was computed as reciprocal of mean arithmetic average curvature in orthogonal directions. Summit curvature was calculated on the basis of three-point formula [9]. The summit identification is a real problem. Usually surface point is a summit if its ordinate was higher than ordinates of four or eight nearest neighbors (see Figure 1). The second possibility was accepted by the present authors. This criterion was based on works of Greenwood [10] and Sayles and Thomas [6] as well as our previous research.

Areal density of asperities ***Spd***, standard deviation of summits heights σ_s and distance between the mean of asperity heights and that of surface ordinates $\boldsymbol{y_s}$ (see Figure 2) were obtained from their definitions directly from areal surfaces. The parameters characterized summits were also determined on the basis of 2D profiles. Sets of parallel profiles were obtained from measured surfaces and average profile spectral moments $\boldsymbol{m_0}$, $\boldsymbol{m_2}$ and $\boldsymbol{m_4}$ were calculated according to procedure presented in paper [11]. Parameters characterized summits were obtained using equations (1)–(5).

It is also possible to estimate parameters characterizing summits from profile peaks analysis (summits are local maxima on the surface, as distinct from peaks, which are local maxima on a profile). Therefore peak density, average peak curvature, standard deviation of peak heights and distance between the mean of line of peak heights and mean profile line were calculated for set of parallel profiles and mean values were taken into consideration.

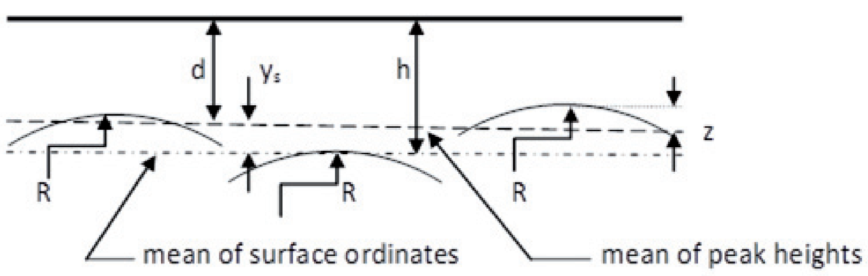


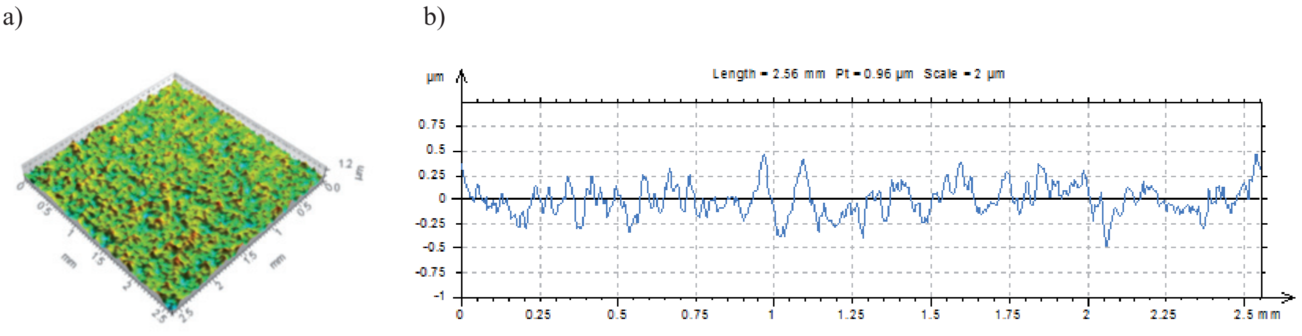
Fig. 2. Scheme of contact of two rough surfaces

As recommended by Nayak [3] summit density was computed as square of peak density multiplied by 1.2.

The well-known plasticity index postulated by Greenwood and Williamson (GW) Ψ [1] in 1966 is widely applied in studying the contact of rough surfaces. The basic assumptions were adopted in GW model:

– asperities are spherical near their peaks (summits),

– there is no interaction between asperities,


a)

b)

Fig. 3. Modeled isotropic surface topography (a), profile from this surface (b)

– only the asperities deform during contact,
– all peaks (summits) have the same radius ***R***.

The contact between two rough surfaces is modeled by contact of single rough surface with a smooth plane. Figure 2 shows the geometry model of contacting rough surfaces, ***z*** denotes the height of asperity, ***d*** separation of the surfaces measured from the summits mean plane, but ***h*** is the separation of the surfaces based on surface heights (ordinates). The plasticity index postulated by Greenwood and Williamson was defined as:

$$\psi = \frac{E^{'}}{H}(\frac{\sigma_s}{R})^{0.5}, \tag{6}$$

where ***H*** is the hardness of the softer contacting materials, and

$$E^{'} = (\frac{1-\nu_1^{2}}{E_1} + \frac{1-\nu_2^{2}}{E_2})^{-1} \tag{7}$$

E_i and ν_i (i = 1, 2) are Young's moduli and Poisson's ratios for the two contacting elements.

In this work the plasticity index was calculated for various methods of computing contact parameters. The following material properties were selected (contact of steel-on-steel elements) $E_1 = E_2 = 2.07 \times 10^5$ MPa, Brinell hardness $H = 200$ (1960 MPa), $\nu_1 = \nu_2 = 0.29$. These properties were also used in paper [2].

Figure 3 shows example modeled surface M1 of correlation ρ = 0.85 between neighboring points and profile from this surface.

4. Results and discussion

The results of calculations of selected surface topographies are listed in Table 1. Index ***s*** means calculation of contact parameters from the areal (3D) surface, ***m*** – using profile spectral moment and ***p*** – basing on the profile peaks analysis. Surfaces 1-5 were modeled, 6-10 measured. ρ means average value of correlation between neighboring points (ordinates) obtained from 6 profiles.

It is evident from the analysis of the simulated and measured surfaces that high values of the ρ parameter (not smaller than 0.85) correspond to large errors of summit density ***Spd*** prediction using spectral moment approach. The errors were bigger than 100%; summit density was overestimated. So the error in obtaining summit density on the basis of profile measurement can be large. For ρ values between 0.25 and 0.77 the deviations of summit density was smaller than 10%; for non-correlated neighboring points (ρ between 0.1 and 0.12) application of spectral moments method caused underestimation of summit density – errors were between 15 and 18%. For high correlation between neighboring ordinates the errors of summit density was also high based on profile peaks analysis. For the other cases application of this method led to overestimation of density; however it was found that summit density should be equal to square of peak density on profile, in this case the error of summit density was smaller than 6% for the ρ coefficient not higher than 0.77.

Mean radius of summit curvature was accurately predicted by spectral moments approach, independently on the ρ value. The errors were smaller than 10%, only for highly correlated points case (ρ = 0.99) deviation was 24%. Estimated value was usually smaller than that obtained by definition. However the analysis of profile peaks led to overestimation of mean summit radius; the errors were in the range: 16–35%.

Relative difference between standard deviation of summit height was usually smaller than 5% but not higher than 10% when spectral moments approach was used. Higher errors occurred for measured surface topog-

Table 1. Surface topography parameters and plasticity indices calculated using different methods

Surface	ρ	σ, µm	σ_s, µm	Spd, 1/µm²	R, µm	y_s, µm	Ψ
$M1_s$	0.85	0.176	0.158	0.00104	157.6	0.17	1.85
$M1_m$		0.174	0.164	0.00211	161.5	0.15	1.84
$M1_p$		0.174	0.169	0.00231	208.3	0.07	1.64
$M2_s$	0.4	0.176	0.132	0.000191	1024.5	0.25	0.65
$M2_m$		0.174	0.137	0.000187	976.6	0.25	0.68
$M2_p$		0.174	0.152	0.000235	1351.4	0.12	0.61
$M3_s$	0.12	0.176	0.123	0.000061	3076.5	0.254	0.36
$M3_m$		0.174	0.13	0.000052	2816.9	0.269	0.39
$M3_p$		0.174	0.142	0.000077	4000.1	0.14	0.34
$M4_s$	0.91	0.93	0.82	0.000232	177.3	0.70	3.92
$M4_m$		0.91	0.87	0.00047	176.8	0.56	4.04
$M4_p$		0.91	0.91	0.000531	232.5	0.28	3.61
$M5_s$	0.65	0.93	0.81	0.000063	714.2	0.95	1.94
$M5_m$		0.91	0.83	0.000061	713.9	1.06	1.92
$M5_p$		0.91	0.87	0.000074	952.4	0.48	1.74
$M6_s$	0.5	0.66	0.46	0.000046	1383.1	0.79	0.99
$M6_m$		0.64	0.5	0.000042	1220.2	0.89	1.18
$M6_p$		0.64	0.51	0.000052	1724.0	0.45	0.99
$M7_s$	0.25	0.82	0.49	0.000026	1666.7	1.1	0.99
$M7_m$		0.8	0.56	0.000024	1538.4	1.24	1.13
$M7_p$		0.8	0.61	0.000029	2173.9	0.64	0.97
$M8_s$	0.99	0.57	0.56	0.00038	436.7	0.134	2.07
$M8_m$		0.56	0.56	0.00081	333.5	0.15	2.44
$M8_p$		0.56	0.56	0.0007	512.8	0.061	1.91
$M9_s$	0.77	2.28	1.78	0.000019	714.2	3.17	2.88
$M9_m$		2.23	1.81	0.0000199	746.3	3.07	2.84
$M9_p$		2.23	1.99	0.000022	833.3	1.75	2.82
$M10_s$	0.1	1.07	0.64	0.000017	1897.5	1.45	1.03
$M10_m$		1.05	0.69	0.000014	1724.13	1.72	1.15
$M10_p$		1.05	0.79	0.000019	2380.9	0.83	1.05

raphies. When the σ_s parameter was calculated directly from profile based on its peaks, the deviations were usually higher (up to 24%). Estimation of summit standard deviation height on the basis of profile analysis using 2 applied methods led usually to overestimation of σ_s. For highly correlated points ($\rho = 0.99$) no difference was found after application of three analysed methods. In this case standards deviation of summit height was equal or very close to standard deviation of ordinates.

When spectral moments method was used, the predicted $\boldsymbol{y_s}$ distance was higher than value obtained from the analysis of simulated and measured surfaces for correlation ρ smaller than 0.77, however for larger ρ values it was usually smaller (except for M8 surface) but differences were not higher than 20%. Calculation of the $\boldsymbol{y_s}$ parameter directly from the profile peaks caused its underestimation (1.7-2.5 times).

Generally when spectral moments were used, good agreement was found between the theory and the results of the areal (3D) surface topography analysis except for summit density which could be overestimated by theory for comparatively high ρ values. However these parameters cannot be calculated on the basis of profile peaks analysis; the errors were higher, particularly for the $\boldsymbol{y_s}$ parameter. Only summit density can be calculated without large errors as the square of peaks density on the profile when correlation between neighboring points was not too high. Therefore when summit contact parameters are estimated from profile spectral moments, ρ values higher than 0.85 should be avoided.

Application of spectral moments method led to correct estimation of plasticity index for modeled surfaces; the errors were not higher than 8%. Differences were larger for measured surfaces (up to 20%). However plasticity index can be determined on the basis of profile peak analysis – the errors were not larger than 10% and for measured surfaces they were smaller than those obtained after using spectral moments approach. The reason of such low deviations is that as a result of application of profile peak analysis both σ_s and $\boldsymbol{R}$ values were overestimated.

Decrease of correlation length ρ causes increase in the distance between the mean of asperity heights and that of surface ordinates $\boldsymbol{y_s}$ and decrease in standard deviation of summit height σ_s. Mean value of standard deviation of ordinates is a little smaller than standard deviation of height of areal surface; differences were a few percents.

5. Conclusion

Applicability of the profile spectral moment approach to areal random surface specification was checked. Good agreement between the analysis of modeled and measured surfaces and theory was generally found. The errors of calculation of parameter important for contact mechanics after the analysis of profile peaks, particularly for the distance between the mean of asperity heights and that of surface ordinates $\boldsymbol{y_s}$, were higher than those after using profile spectral moments. However the errors of computing the plasticity index on the basis of profile peaks analysis was small, especially for small correlation between ordinates. Summit density can be overestimated by the profile analysis (using both applied methods) for comparatively high correlation between neighboring points ρ. Therefore when summit contact parameters are estimated from 2D profiles, ρ values higher than 0.85 should be avoided. Summit density can be calculated as the square of peaks density on the profile when summit was identified based on its eight neighbors for not too high correlation between ordinates. Decrease in the ρ parameter by increase in the sampling interval caused increase in the distance between the mean of asperity heights and that of surface ordinates $\boldsymbol{y_s}$ and decrease in standard deviation of summit height σ_s.

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