Procedures for Calculation of 3D Nanometric Surface Texture Parameters

Juris Krizbergs, *Riga Technical University, Institute of Mechanical Engineering*

***Abstract* - In this article the method and algorithms for three dimensional digital evaluation of surface nanometric texture is proposed. Description of machined surfaces is based on the model containing a certain number of single asperities. For calculation of texture parameters the array of surface point elevations is used. Such array of point heights may be obtained by parallel scanning of surface along a specific number of surface profiles. Any kind of measuring equipment may be used for scanning.**

***Keywords* - roughness, measuring system, texture parameters.**

I. INTRODUCTION

Functioning of the system for areal evaluation of the surface texture is based on the following assumptions:

1. Recording of separate surface point heights – discretization of the surface as presented in Fig.1, using specified number of parallel surface profiles.
2. Calculation of surface texture parameters and the graphic presentation of the measured surface.

Initially the following measuring conditions should be set to provide the best performance of the system:

1. Profile length in the direction of x axis - l_x;
2. Discretization step in the direction of x axis or point spacing along this axis - Δx;
3. The width of the investigated surface area – size in the direction of y axis - l_y;
4. Discretization step in the direction of y axis or profile spacing along this axis -Δy.

Actual measurement conditions, i.e., sampling intervals Δx and Δy, are set according to standard ISO 3274:1996 [1]. Although the surface texture is widely measured by contact stylus instruments, one of the peculiar problems of these instruments is that the stylus tip radius induces distortions in the profiles, leading to a mechanical filtering effect [2]. Consequently, the stylus tip radius r_{tip} induces the limitation of 3D measurement accuracy.

The lengths of probe tracing *lx* and *ly* should be 5 times as long as the widely-used sampling length 0.8 mm (cut-off length according to ISO4288: 1996 [3].

Some recommendations are given also in [4].

According to the specified measuring conditions the system records heights $h_1(i,j)$ of *N1* points along *N2* profiles,

Where

$$N1=\frac{l_x}{\Delta x}+1;\quad N2=\frac{l_y}{\Delta y}+1;$$

i,j – point numbers and profile numbers for points of height $h_1(i,j)$ in directions *x* и *y* respectively: $1\le i\le N1$; $1\le j\le N2$.

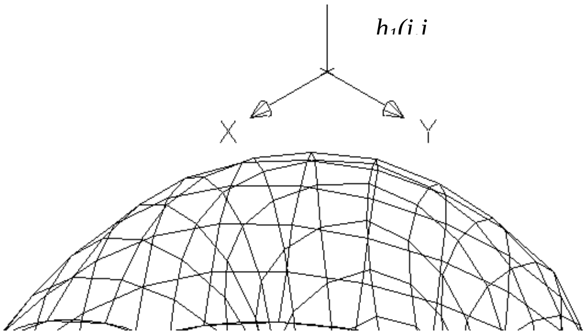

Fig.1. Surface asperity discretization

Thus we obtain the matrix of numbers of size $N1\times N2$ containing values $h_1(i,j)$ that will be used for calculation of surface texture parameters.

II. DATA ANALYSIS

As the datum for calculation of texture parameters the mean plane of rough surface layer should be used. Such plane is determined by equation:

$$f(x,y)=a+bx+cy. \tag{1}$$

The calculation of coefficients of this equation is based on least squares method that gives the following equations:

$$b=\frac{\sum_{i=1}^{N1}\sum_{j=1}^{N2}(h_1(i,j)-\bar{h}_1)x_i}{\sum_{i=1}^{N1}\sum_{j=1}^{N2}x_i(x_i-\bar{x})};$$

$$c=\frac{\sum_{i=1}^{N1}\sum_{j=1}^{N2}(h_1(i,j)-\bar{h}_1)y_j}{\sum_{i=1}^{N1}\sum_{j=1}^{N2}y_j(y_j-\bar{y})}; \tag{2}$$

$$\bar{h}_1=\frac{\sum_{i=1}^{N1}\sum_{j=1}^{N2}h_1(i,j)}{N1N2};$$

$$\bar{x}=\frac{1}{N1}\sum_{i=1}^{N1}x_i;\ \bar{y}=\frac{1}{N2}\sum_{j=1}^{N2}y_j;\ a=\bar{h}_1-b\bar{x}-c\bar{y}. \tag{3}$$

If the discretization steps in both directions are constant, then the calculation of the mentioned above coefficients gets simplified and surface point coordinates are obtained as
$x_i=(i-1)\,\Delta x;\ y_j=(j-1)\,\Delta y$,
and coefficients are calculated as:

$$a=\frac{(7N1\cdot N2+N1+N2-5)\omega-6(N1+1)u-6(N2+1)v}{N1\cdot N2(N1+1)(N2+1)};$$
$$b=\frac{6(2u-(N1-1)\omega)}{\Delta x\cdot N1\cdot N2(N1-1)(N1+1)};\qquad(4)$$
$$c=\frac{6(2v-(N2-1)\omega}{\Delta y\cdot N1\cdot N2(N2-1)(N2+1)},$$

where

$$u=\sum_{i=1}^{N1}\sum_{j=1}^{N2}(i-1)h_1(x_i,y_j);$$
$$v=\sum_{i=1}^{N1}\sum_{j=1}^{N2}(j-1)h_1(x_i,y_j);\qquad(5)$$
$$\omega=\sum_{i=1}^{N1}\sum_{j=1}^{N2}h_1(x_i,y_j).$$

III. PARAMETER CALCULATIONS

For calculation of surface texture parameters the new matrix of point heights is produced. Here the point heights h(i,j) are calculated by subtraction of mean plane points height from the initial matrix: $h(i,j)=h_1(i,j)-f(x_i,y_j)$.

Areal texture parameters to be calculated can be divided into three groups:
1. Asperities quantity parameters;
2. Asperities height parameters;
3. Asperities shape and volume parameters.

Complete list of possible parameters to be calculated is specified by international standards [5].

For application of texture features in different engineering solutions most significant are parameters of asperity peaks. Therefore we relate texture parameters to asperity apex, considering the current point being asperity apex if four closest to it – before and after the current point in two directions - have lower height.

A. Peak number.

According to the mentioned above algorithm the peak number over the surface area (peak density) is calculated as:

$$n_v=\frac{1}{N1\cdot N2\cdot\Delta x\cdot\Delta y}\sum_{i=1}^{N1}\sum_{j=1}^{N2}\eta(i,j),\qquad(6)$$

Where $\eta(i,j)=1,$ if
$z1=h(i,j)-h(i+1,j)\geq 0;\ z2=h(i,j)-h(i-1,j)\geq 0;$
$z3=h(i,j)-h(i,j+1)\geq 0;\ z4=h(i,j)-h(i,j-1)\geq 0;$
$\eta(i,j)=0$ for other values of *z1, z2, z3, z4*.

For calculation of asperity peaks located within specific height over some level *u* we use additional condition:

$$\eta(i,j)=1\ \text{ if }\ h(i,j)\geq u;\ \eta(i,j)=0,\ \text{ if }\ h(i,j)<u.$$

Similarly, we can set the surface layer at height from *u1* to *u2*, where the number of peaks should be calculated:

$$\eta(i,j)=1,\text{ if }\ u1\leq h(i,j)<u2;\ \eta(i,j)=0\ \text{ for other values of } h(i,j).\qquad(7)$$

B. Average asperity peak height.

We calculate this parameter as division of sum of all detected peak heights by the number of these peaks in the investigated nominal area. Then average asperity peak height equals to:

$$h_v=\frac{\sum\limits_{i=1}^{N1}\sum\limits_{j=1}^{N2}\varsigma(i,j)}{\sum\limits_{i=1}^{N1}\sum\limits_{j=1}^{N2}\eta(i,j)},\qquad(8)$$

Where $\varsigma(i,j)=h(i,j)\ \text{ if }\ (z1,z2,z3,z4)\geq 0;$
$\varsigma(i,j)=0$ for other values of *z1, z2, z3, z4*.

Additional conditions for calculation of average peak height for peaks over the level *u* or within specific layer from *u1* to *u2* are the same as for calculation of peak number.

C. Extreme peak height (highest point of surface texture).

This parameter can be found as highest value of matrix *N1×N2* elements:

$$h_{max}=h(i,j)_{max}.\qquad(9)$$

D. Asperity peak curvature.

Evaluation procedure of such parameter needs knowledge about surface profile curve at peak point. As we do not have initial information about this curve, we have to use some kind of approximation of such curve. Large number of tests and measurements of ground and similarly processed surfaces show the possibility to use elliptical parabolloid as the model of surface asperity peak.

Let us determine principal curvatures (within directions of *x, y* axis).

For our approximation the peak curvature may be calculated as

$$k(h)=\frac{4\cdot h_1}{l_1^2},\qquad(10)$$

where h_1- maximum surface profile curve points height difference for curve near the peak; l_1- curve length near the peak.

Using the measured rough surface point heights principal curvatures can be calculated:

In the direction of x axis:

$$k1 = \frac{2 \cdot h(i,j) - h(i-1,j) - h(i+1,j)}{2(\Delta x)^2}. \qquad (11)$$

Accordingly in the direction of y axis:

$$k2 = \frac{2 \cdot h(i,j) - h(i,j-1) - h(i,j+1)}{2(\Delta y)^2}. \qquad (12)$$

Average principal curvature of all peaks on the investigated area in direction of *x* axis will be calculated:

$$k1_v = \frac{\sum_{i=1}^{N1} \sum_{j=1}^{N2} c(i,j)}{\sum_{i=1}^{N1} \sum_{j=1}^{N2} \eta(i,j)}, \qquad (13)$$

where *c(i,j)=k1*, if $(z1, z2, z3, z4) \geq 0$;

c(i,j)=0 for other values of *z1,z2,z3,z4*.

η(i,j) as determined above;

And in the direction of *y* axis :

$$k2_v = \frac{\sum_{i=1}^{N1} \sum_{j=1}^{N2} c(i,j)}{\sum_{i=1}^{N1} \sum_{j=1}^{N2} \eta(i,j}, \qquad (14)$$

where *c(i,j)=k2*, if $(z1, z2, z3, z4) \geq 0$;

c(i,j)=0 for other values of *z1,z2,z3,z4*. Value *η(i,j)* is determined above.

Mean curvature of peaks equal to half the sum of the principal curvatures:

$$k_v = \frac{k1_v + k2_v}{2}. \qquad (15)$$

E. Areal material ratio.

Similar to rough surface profile analysis as the datum we consider the plane that is drawn parallel mean plane through the surface extreme peak point. Let us determine the areal material ratio as relation between the sum of elementary areas created by section of surface with plane parallel to mean plane at level *u* and the nominal investigated area:

$$t_u = \frac{\sum_{i=1}^{N1} \sum_{j=1}^{N2} \mu(i,j)}{lx \cdot ly}, \qquad (16)$$

Where $\mu(i,j) = \Delta x \cdot \Delta y$, if *Hmax-u≤h(i,j)<Hmax*;

μ(i,j)=0 for other values of *h(i,j)*.

F. Surface gradient.

For evaluation of surface behaviour in contact it is very important to know the slope parameters of asperities in both *x* and *y* directions. We use the gradient as the measure of asperity slope. Let us determine the average gradient of asperities within surface layer between levels *u1* and *u2*. Most important is the part of asperities close to peak. According to the accepted surface discretization we calculate the gradient in two directions – *x* and *y* axis.

Then in *x* direction

$$\nabla_x = \sum_{i=1}^{N1} \sum_{j=1}^{N2} |\nabla(i)|, \qquad (17)$$

where $\nabla(i) = \dfrac{h(i,j) - h(i-1,j)}{\Delta x}$ if $u1 \leq h(i,j) \leq u2$;

$\nabla(i,j) = 0$ for other values of *h(i,j)*.

Gradient in the direction of *y* axis

$$\nabla_y = \sum_{i=1}^{N1} \sum_{j=1}^{N2} |\nabla(j)|, \qquad (18)$$

where $\nabla(j) = \dfrac{h(i,j) - h(i,j-1)}{\Delta y}$ if $u1 \leq h(i,j) \geq u2$;

$\nabla(i,j) = 0$ for other values of *h(i,j)*.

For evaluation of surface gradient on ascent or descent in positive direction of coordinate axis (which is important in the analysis of hydrodynamics of lubricated surface friction) we use additional conditions:

$\nabla(i) = \dfrac{h(i,j) - h(i-1,j)}{\Delta x}$; if $\nabla(i) > 0$;

$\nabla(j) = \dfrac{h(i,j) - h(i,j-1)}{\Delta y}$; if $\nabla(j) > 0$;

$\nabla(i) = 0$; $\nabla(j) = 0$ for ascent and vice versa for descent.

G. Surface asperities volume.

This parameter is useful for investigations of surface wear rate, when the mass loss of machine part can be evaluated by means of some method (weighing, radioactive isotopes, etc.). The asperity volume then can be used for determination whether only rough layer has been destroyed and removed or the solid material is removed by wear. For evaluation of this parameter let us calculate the asperities material volume above the specified level *u*:

$$V_u \frac{\sum_{i=1}^{N1} \sum_{j=1}^{N2} V(i,j)}{lx \cdot ly \cdot h_{\max}}, \qquad (19)$$

Where $V(i,j) = \Delta x \cdot \Delta y \cdot (h(i,j) - h_{\max} + u)$,if $h(i,j) - h_{\max} + u) > 0$;

V(i,j)=0, if $h(i,j) - h_{\max} + u) \leq 0$.

$lx \bullet ly \bullet h_{max}$ – the volume of full rough layer on the investigated area.

H. Surface asperities area.

This parameter is used for analysis of corrosion intensity of rough surfaces, evaluation of electrical capacity of the surface, analysis of oil film thickness, etc. For calculation of such parameter we separate the surface to elementary rectangles of size:

$$S_{i,j} = \sqrt{(h(i+1,j)-h(i,j))^2+(\Delta x)^2)\cdot(h(i,j+1)-h(i,j))^2+(\Delta y)^2)}.$$

Then total surface area is calculated by equation:

$$S = \sum_{i=1}^{N1}\ \sum_{j=1}^{N2} S_{i,j}. \qquad (20)$$

IV. CONCLUSIONS

Equations for calculation of parameters do not cover all possible surface texture parameters. Nevertheless, they may be useful for different applications, such as surface performance analysis, prediction of parameter values in machining, etc.

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Juris Krizbergs is a graduate of Riga Polytechnic Institute (RPI) 1961-1970, Mechanical Engineer with Honours, majoring in Industrial Automation. Completed postgraduate studies at Riga Polytechnic Institute (1973-1976), defended Doctoral Thesis, having obtained the degree of Dr. sc. ing. at the Institute for Metrology, Moscow (1986) and was awarded the degree of Dr.sc.ing. by Riga Technical University (1992).

His fields of scientific interest include manufacturing technologies, dimensional metrology.

He is a professor at Riga Technical University; past employment: junior lecturer, senior lecturer, assistant professor, associate professor.

Juris Krizbergs. Virsmas nanometriskās tekstūras 3D parametru skaitļošanas procedūras.

Šis raksts ir veltīts virsmas nanometriskās tekstūras trīsdimensionālas novērtēšanas metodei un algoritmiem digitālā formā. Jaunākie virsmas tekstūras standarti paredz telpisko tās novērtēšanu, izmantojot specifiskus parametrus atšķirībā no agrāk lietotajiem virsmas profila parametriem. Tiek izmantoti integrāli paņēmieni, piemēram, dažādi optiski mērinstrumenti, kur informācija par virsmu tiek iegūta no noteikta laukuma, bet ne no atsevišķiem virsmas punktiem. Ar šādiem paņēmieniem iegūta informācija galvenokārt ir kvalitatīva, bez iespējām iegūt skaitliskas atsevišķu parametru vērtības. Tomēr šādas ģeometrisku parametru vērtības ir ļoti nepieciešamas dažādu virsmas funkciju precīzai skaitliskai novērtēšanai, tādēļ svarīgi iegūt informāciju par konkrētiem virsmas elementiem jeb punktiem.

Šajā rakstā apstrādātu virsmu apraksts balstās uz modeli, kas satur noteiktu atsevišķu izciļņu skaitu. Tekstūras parametru aprēķinam tiek lietots virsmas punktu augstuma vērtību masīvs. Šādu punktu augstumu masīvu var iegūt, skenējot virsmu pa paralēlām trasēm gar noteikta skaita virsmas profiliem. Skenēšanai var izmantot jebkura tipa raupjuma mērīšanas instrumentu, kas darbojas uz paralēlu trašu punktu nolasīšanas principa.

Юрис Кризбергс. Процедуры вычисления 3Д параметров нанометрической текстуры поверхности.

Данная статья посвящена методу и алгоритмам трехдимесионной оценки нанометрической текстуры обработанных поверхностей в цифровой форме. Современные стандарты поверхностной текстуры предусматрывают ее обьемную оценку при помощи специфических параметров в отличии от ранее примененных профильных параметров. Используются интегральные способы, например, разные оптические приборы, информация снимается с определенной площади, но не с отдельных точек. Такая информация по сути является только качественной, без возможности получения численных значений конкретных параметров. Однако такие значения геометрических параметров крайне необходимы для точной оценки разных функций поверхности, поэтому необходима информация об отдельных элементах или точках поверхности.

В данной статье описание обработанных поверхностей основано на модели, содержащей определенное число отдельных выступов. Для расчета параметров текстуры используется массив значений высот точек поверхности, получаемый параллельным сканированием поверхности вдоль определенного числа профилей поверхности. Сканирование может быть выполнено любым прибором измерения текстуры поверхности, основанном на считывании ординат точек, расположенных на параллельных трассах.