THE ANNALS "DUNĂREA DE JOS" OF GALAŢI
FASCICLE V, TECHOLOLOGIES IN MACHINE BUILDING, ISSN 1221-4566
2010

Profiling of Revolution Surfaces Tool for Generation of Helical Surfaces Expressed in Polyhedral Form

Virgil Teodor, Marian Cucu, Nicolae Oancea
"Dunărea de Jos" University of Galaţi, Faculty of Mechanics

ABSTRACT

The profiling of tool's bounded by revolution surfaces – disc tool, end mill tool and ring tool – is based on fundamental theorems of the surfaces enwrapping.

There are situations when the surfaces are known by sampled points, often determined by measuring on coordinate measuring machines.

There are algorithms known for approximation of these discreet points, on helical surface, using Bezier polynomials or B-spline curves.

Relying on an algorithm and a polyhedral representation of the surface measured, a software in Java programing language is approached in the present paper. There are presented numerical applications for profiling the disc tool or end milling tool, reciprocally enwrapping with these surfaces represented by sampled points.

KEYWORDS: tool's profiling, helical surfaces, polyhedral form

1. Introduction

The issue of tools profiling for helical surfaces generation by enwrapping is well known, the solving of this problem calling the fundamental theorems of surfaces enwrapping, for the case when these are represented in analytical forms, 1st Olivier theorem, [1], [2], [3].

Also, complementary methods are presented as: the "minimum distance" method [3], the method of "substitutive circles" [3], the in-plane generation trajectories [4].

More, the development of the capabilities of the graphical software, create the real possibility to solve fast and rigorous this problem [5], [6], [7], [8].

Often, the issue emerges of a non-analytical representation of surfaces, linking with the application of reverse engineering, when the real surfaces of pieces are known by direct measuring on 3D measuring machines.

In this way, the problem of surface approximation appear as well as the problem of replacing these surfaces with an analytical surface as the best approximation of the measured points cloud, in order to allow the using of the analytical methods known.

There are more solutions for this surface form expression, the identification of this [9], [10], and the following approximation, assuming that the surface's type is known, [14], [15], with specific applications in the generating tool's profiling.

Specific solutions are presented for the construction of the generating tool's primary peripheral surfaces [9], [10], [12], [13].

It is also possible to imagine models based on the "minimum distance" method for enough points known as sampled points on a helical surface, to approximate in a discrete form the characteristical curve of the helical surface in contact with a revolution surface reciprocally enveloping [17], [18].

In this paper, an approximation method is proposed for a surface measured by an assembly of in-plane surfaces and a specialized software, made in Java language, in order to produce a profile of the revolution surfaces bounded tools (disc tool, end mill tool, ring tool) reciprocally enveloping with the real surface replaced by this surfaces assembly – the polyhedral method.

2. The Method of Surfaces Polyhedral Representation

The surfaces as they results from measuring with a device which determines the successive coordinates of points, figure 1, may be regarded as being composed of a distinct point grid along the measuring lines.

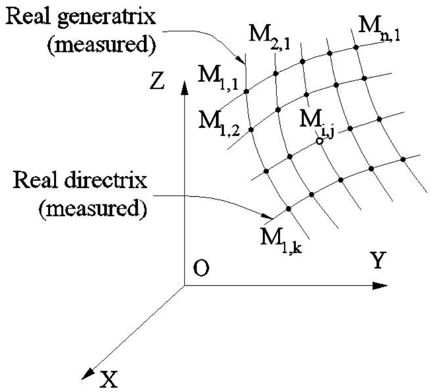


Fig. 1. *Real surface (surfaces represented by sampled points)*

We have to notice that, the measured points distribution along the real generatrix have to be dense enough to describe the surface between the limits of a certain measuring precision, accepted as rigorous from the technical point of view.

Although, the point grid measured on the surface isn't a uniform grid, the algorithm for the determination of surface normal isn't affected, if the point number is big enough.

In the previously presented sense, a real generatrix "j" of surface may be represented by a matrix in the form:

$$G = \begin{Vmatrix} X_{1,j} & X_{2,j} & X_{3,j} & \dots & X_{k,j} \\ Y_{1,j} & Y_{2,j} & Y_{3,j} & \dots & Y_{k,j} \\ Z_{1,j} & Z_{2,j} & Z_{3,j} & \dots & Z_{k,j} \end{Vmatrix}^T . \quad (1)$$

Regarding (1), for the points mesh representing a zone of the surface the following the expression is accepted:

$$\Sigma_{efective} = \left\{ \begin{Vmatrix} X_{1,j} & X_{2,j} & \dots & X_{k,j} \\ Y_{1,j} & Y_{2,j} & \dots & Y_{k,j} \\ Z_{1,j} & Z_{2,j} & \dots & Z_{k,j} \end{Vmatrix}^T \right\}_i ; \quad (2)$$

$$i = 1, 2, \dots, j, \dots m.$$

The normal in a certain point of the real surface (2), be $M_{i,j}$ this point, is defined as normal at one of the polyhedron faces determined by points $M_{i,j}$; $M_{i,j-1}$; $M_{i+1,j}$; etc, see figure 2.

Obviously, in the $M_{i,j}$, four normals may be defined as the points considered, one for each of the polyhedron faces, with the point considered at the top.

For example, starting from the neighboring coordinates on the point $M_{i,j}$:

$$M_{i,j-1} = \begin{Vmatrix} X_{i,(j-1)} \\ Y_{i,(j-1)} \\ Z_{i,(j-1)} \end{Vmatrix} ; \quad (3)$$

$$M_{i,j} = \begin{Vmatrix} X_{i,j} \\ Y_{i,j} \\ Z_{i,j} \end{Vmatrix} ; \quad (4)$$

$$M_{(i+1),j} = \begin{Vmatrix} X_{(i+1),j} \\ Y_{(i+1),j} \\ Z_{(i+1),j} \end{Vmatrix} . \quad (5)$$

The following vectors may be defined:

$$\overrightarrow{M_{i,j}M_{i,j-1}} = (X_{i,j} - X_{i,j-1}) \cdot \vec{i} + \\ +(Y_{i,j} - Y_{i,j-1}) \cdot \vec{j} + (Z_{i,j} - Z_{i,j-1}) \cdot \vec{k} \quad (6)$$

as so as,

$$\overrightarrow{M_{i,j}M_{(i+1),j}} = (X_{i,j} - X_{i+1,j}) \cdot \vec{i} + \\ +(Y_{i,j} - Y_{i+1,j}) \cdot \vec{j} + (Z_{i,j} - Z_{i+1,j}) \cdot \vec{k} . \quad (7)$$

In this way, the normal at the in-plane surface determined by these points is

$$\vec{N}_{i,j}^{(i+1),(j-1)} = \overrightarrow{M_{i,(j-1)}M_{i,j}} \times \overrightarrow{M_{i,j}M_{(i+1),j}} . \quad (8)$$

Similarly, the normals drawn to the others polyhedron surfaces, having the $M_{i,j}$ point at the top, are defined.

An algorithm to scroll the successive generatrix of the measured zone, see (2), will allow to determine the normal vector at the in-plane surfaces formed in this way on the real measured surface.

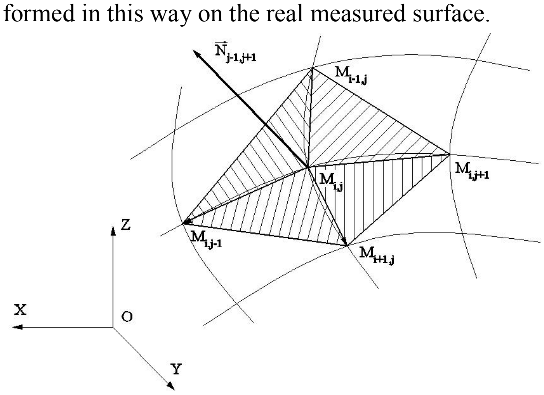


Fig. 2. *Normal at the polyhedral surface*

This mode to represent the measured surface, allows, the determination of the characteristic curve of the surface in its global motion, rotation or translation, linked with the generating tool's type: revolution surfaces bounded tools (disc tool, end mill tool or ring tool); cylindrical tool (planning tool).

3. Measured Surface's Form Fitting

Is is possible, when the number of points measured on the surface isn't too big, and when we suspect that the polyhedron form for surface measured is very different from the real form of the measured surface, to make an adjustment of the measured surface's form (fitting), in order not to appear discontinuities in the description of this surface.

This may be realized based on specialized software, starting from the measured points cloud and obtaining a new cloud, belonging, this time, to the fitted surface. Not all of the points of the new points cloud will represent the measured points on the surface.

After this new cloud is obtained by fitting, the matrix (2) is modified, defining a new approximation grid for the surface and new approximation forms of the vectors starting from point $M_{i,j}$, see (6) and (7) and figure 3, or similarly, from point $m_{i,j}$, for the fitted grid.

In figure 3, with $M_{i,j}$, $M_{i,j-1}$, $M_{i,j+1}$ were noted the initial grid nodes (measured points) and with $m_{i,j}$, $m_{i,j-1}$, $m_{i,j+1}$ the nodes of the fitted grid.

Also, were noted with $\overrightarrow{N}_{M_{i,j}}$ and $\overrightarrow{N}_{m_{i,j}}$ the vectors of normals to the polyhedral surfaces with top in the current point $M_{i,j}$ ($m_{i,j}$), for the two forms of the initial and fitted grid.

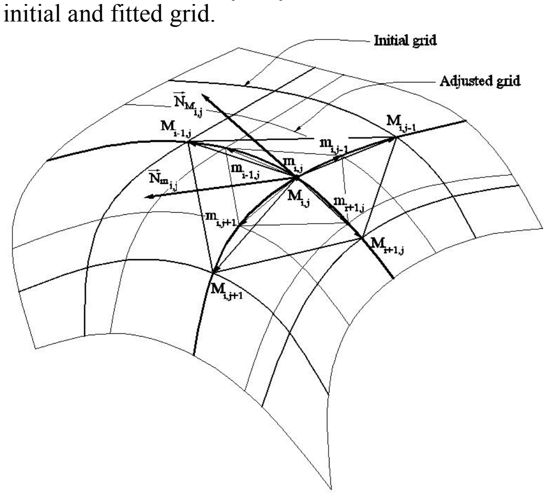


Fig. 3. *Polihedral surfaces: initial grid ($M_{i,j}$; $M_{i+1,j}$; ...);fitted grid ($m_{i,j}$; $m_{i+1,j}$ ...)*

4. The Curve Characteristic of the Helical Surface Expressed by Sampled Points

The goal is to express the curve characteristic in the rotation of the surface to be generated around a fixed axis, defined as position, representing the axis of the future tool bounded by a revolution primary peripheral surface – disc tool or end mill tool.

In figure 4, the reference system and the position of the disc tool axis are presented.

According to the Nikolaev theorem [1], [3], the condition that the $M_{i,j}$ point belongs to the Σ surface also belongs to the characteristic curve is determined by the intersection between the normal drawn at Σ, in this point, and the disc tool's axis.

The systems are defined as follows:

XYZ is the reference system where the measured surface is defined;

$X_1Y_1Z_1$ – reference system joined with the disc tool's axis;

$$\vec{A} = \cos\alpha \cdot \vec{j} + \sin\alpha \cdot \vec{k}\,, \qquad (9)$$

represent the direction of the disc tool's axis regarding the XYZ reference system,

a – distance between the axis $\vec{V}$ (axis of Σ surface) and axis of disc tool.

The angular parameter α, for a helical flute belonging to a cylindrical helical surface with constant pitch — surfaces known in terms of the sampled points — is determined by the condition that the $\vec{A}$ axis should be perpendicular to one of the characteristically-shaped helix surfaces, ussualy on the helix corresponding to the maximum diameter of the surface.

The value "a" - the distance between the two axes of surfaces, $\vec{A}$ and $\vec{V}$, is defined from technological reasons: crossing dimension of the surface to be generated and the external diameter of the disc tool.

The condition that the $M_{i,j}$ current point, of the grid on the Σ surface, to belong to the contact curve with the revolving surface with the axis $\vec{A}$ is that the normal to one of the polyhedron faces, with top in the point $M_{i,j}$, should intersect the axis $\vec{A}$.

In others words, if is defined the $\vec{r}_1$ position vector, see figure 4, as vector which link the O_1 origin with $M_{i,j}$ point,

$$\vec{r}_1 = X_{i,j} \cdot \vec{i} + \left(Y_{i,j} + a\right) \cdot \vec{j} + Z_{i,j} \cdot \vec{k}\,, \qquad (10)$$

where $X_{i,j}$, $Y_{i,j}$, $Z_{i,j}$ are given by (2), the intersection condition with the axis $\vec{A}$ of the normal, may be written in the form of:

$$\left|\left(\vec{A}, \vec{r}_1 \vec{N}_{M_{i,j}}\right)\right| \le \varepsilon\,, \qquad (11)$$

where ε is a positive value, small enough, $\left(\varepsilon = 1 \cdot 10^{-3}\right)$.

In this way, establishing the polyhedron face which corresponding to the (11) enveloping condition, the advance of the following check point in the defining of the characteristic curve is decided.

The assembly of the $M_{i,j}$ points which satisfy the condition (11) represent the helical surface's characteristic curve and, hence, the characteristic curve of the revolution surface which constitute the primary peripheral surface of the disc tool.

In principle, the C_S characteristic curve may have a representation of the following form

$$C_S = \left\{ \begin{pmatrix} X_{i,j} \\ Y_{i,j} \\ Z_{i,j} \end{pmatrix}^T \right\}, \ (i = 1,...,n, \ j = 1,...,m). \quad (12)$$

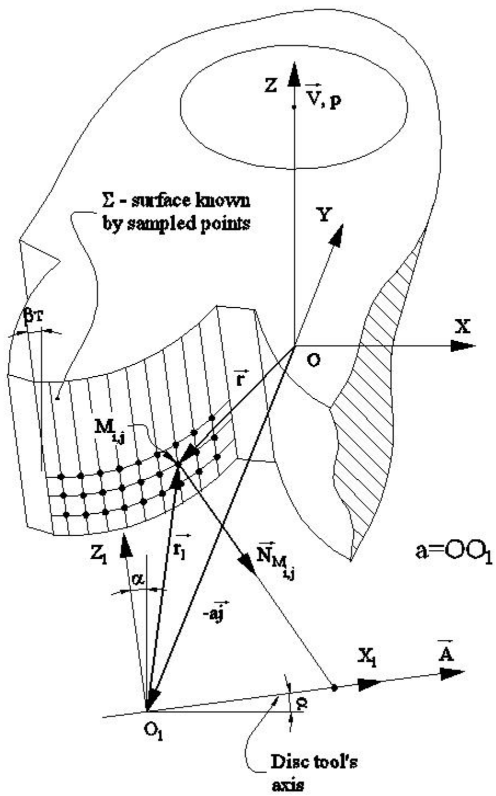


Fig. 4. *Disc tool – reference system*

The disc tool's primary peripheral surface is obtained by revolving the (12) characteristic curve around the axis $\vec{A}$ (disc type tool's axis).

It is possible to define the (12) characteristic curve in the disc tool reference system, see figure 4, by transformation

$$X_1 = A_\alpha \cdot (X - a), \quad (13)$$

where:

$$A_\alpha = \begin{Vmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{Vmatrix}, \quad (14)$$

$\alpha = \beta_T$, $\beta_T = \arctan\dfrac{D_{ext}}{2p}$ is the angle of the external helix of the measured surface and A_α is the matrix of the orthogonal transformation between the versors of the $X_1Y_1Z_1$ reference system, regarding the XYZ reference system (D_{ex} is the external diameter of workpiece and p is the helical parameter);

$$a = \begin{Vmatrix} 0 \\ -a \\ 0 \end{Vmatrix}, \quad (15)$$

"a" is the matrix formed by the O_1 origin coordinates, in reference system XYZ.

Regarding (12), it is possible this way to define the characteristic curve, in a discrete form, in reference system $X_1Y_1Z_1$:

$$C_{1S} = \left\{ \begin{pmatrix} X_{1_{i,j}} \\ Y_{1_{i,j}} \\ Z_{1_{i,j}} \end{pmatrix}^T \right\}, \ (i = 1...n), (j = 1...m). \quad (16)$$

By revolving the characteristic curve (16) around $\vec{A}$ axis (X_1 axis), with θ variable parameter,

$$\begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} X_{1_{i,j}} \\ Y_{1_{i,j}} \\ Z_{1_{i,j}} \end{pmatrix}, \quad (17)$$

the disc tool's primary peripheral surface is obtained expressed as a circle family.

The axial section of the disc tool is obtained from (17), in the form of (see figure 5, too):

$$S_A = \begin{vmatrix} H = X_{1_{i,j}}; \\ R = \sqrt{Y^2_{1_{i,j}} + Z^2_{1_{i,j}}}. \end{vmatrix} \quad (18)$$

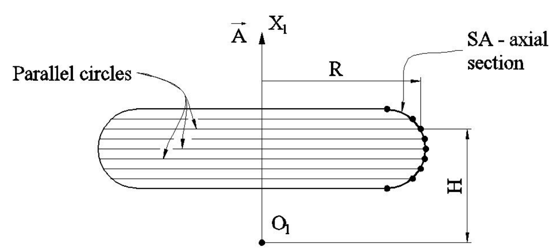


Fig. 5. *Axial section of the disc tool*

5. Fitting of Points Cloud of the Measured Surface

The measured surface of the flank of a cylindrical helical surface – the involute flank of a toothed wheel- is regarded in figure 6.

By direct measuring, the coordinates of the points on the succesive generatrix of a flank, are determined on the 3D measuring machine 3D-MicroHite (see figure 7).

Fig. 6. *Measurement of the teethed wheel*

In the table 1, the coordinates of points belonging to the successive generatrix are presented (Z=const.) measured on the surface.

Table 1. *Sampled points on successive generatrix*

Line *i*	Crt. no.	X [mm]	Y [mm]	Z [mm]
	1	-4.530	-65.313	-0.004
	2	-4.620	-65.727	-0.004
1	⋮	⋮	⋮	⋮
	19	-8.948	-73.000	-0.004
	20	-9.307	-73.436	-0.004
	1	-4.127	-65.196	-1.341
	2	-4.170	-65.548	-1.341
2	⋮	⋮	⋮	⋮
	19	-8.457	-73.350	-1.341
	20	-8.778	-73.766	-1.341
⋮	⋮	⋮	⋮	⋮
	1	-4.100	-65.370	-1.590
	2	-4.294	-66.134	-1.590
10	⋮	⋮	⋮	⋮
	19	-8.558	-73.565	-1.591
	20	-9.063	-74.185	-1.591

The assembly of the successive generatrix form the discrete surface of the flank to be generated, see figure 7, where the coordinates were processed by MatLab software.

Is obvious that the measured surface isn’t a smooth surface and their fitting is necessary in order to make a rigorous interpretation of the measured data.

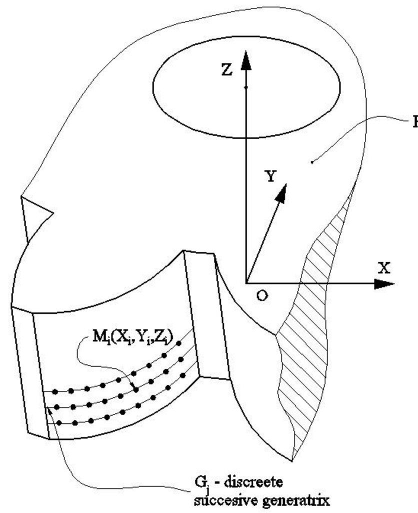


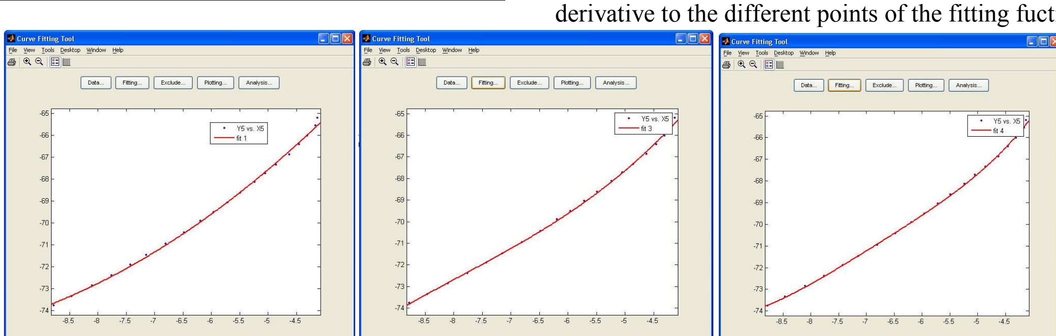
Fig. 7. *Measured points on flank*

It is proposed that each generatrix should fit a polynomial form meeting the following conditions:

- the index R^2 (adjusted R-square) should be closest to 1;

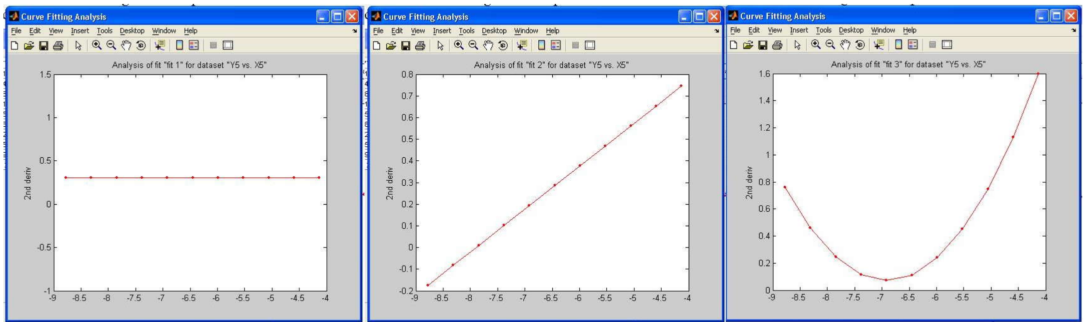
- the second derivative of the substitutive polynomial equation to be straight lined (to be avoid the points on the generatrix where the curvature have important variations);

In figures 8 and 9, the polynomial forms to fit the data are presented so as the first and second derivative to the different points of the fitting fuction



2^{nd} *degree:* $R^2=0.9984$; 3^{rd} *degree:* $R^2=0.9992$; 4^{th} *degree:* $R^2=0.9995$;

Fig. 8. *Substitutive polynomial form*



2^{nd} degree; *3^{rd} degree;* *4^{th} degree;*

Fig. 9. *Second order derivative*

From the analysis of the presented forms, we may conclude that the adjusted R-square index have the value closest to 1 for a second degree approximate polynomial and, at the same time, the second derivative is linear, being eliminated the existence of the points on the fitted generatrix where the curvature have important variations.

Note: Obviously, for other forms of the measured surface, the substitutive polynomial will have other forms.

In the substitutive polynomial evaluation were used the MatLab software.

In this way, all the generatrix may be fitted in the polynomial form. Regarding the coordinates of the measured points, we can notice that the substitutive polynomials may not be of the same degree.

The form of the substitutive surface of the point cloud may be processed with MatLab software, making a denser grid of points which are nodes of the surface substitutive polyhedrons. In figure 10, a screen capture of the surface’s mesh is presented.

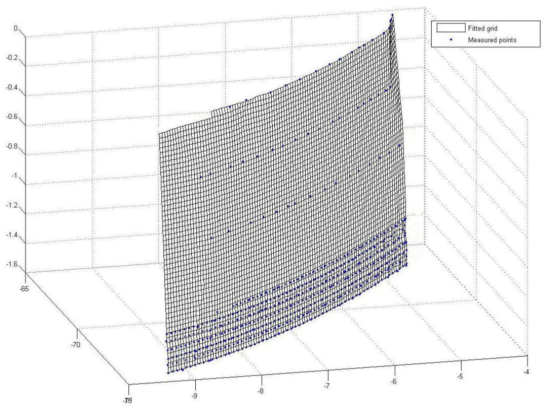


Fig. 10. *The substitutive surface form*

Table 2 also are presents the coordinates on the substitutive surfaces (fitted surface) of the point’s cloud measured on the surface.

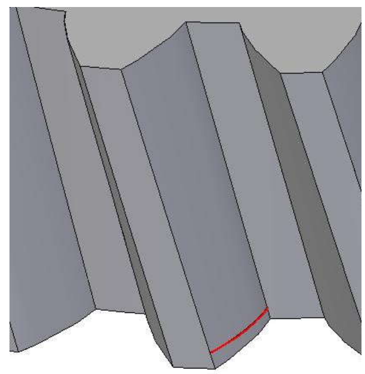


Fig. 11. *The model of helical surface and the characteristic curve represented by sampled points, upon disc tool generation*

Table 2. *Coordinates on the successive generatrix of the substitutive surface*

Line *i*	Crt. no.	X [mm]	Y [mm]	Z [mm]
1	1	-8.4040	-72.4760	-0.0050
	2	-8.3678	-72.4360	-0.0050
	⋮	⋮	⋮	⋮
	100	-4.8182	-66.5860	-0.0050
	101	-4.7820	-66.4900	-0.0050
2	1	-8.4040	-72.4790	-0.00817
	2	-8.3678	-72.4390	-0.00817
	⋮	⋮	⋮	⋮
	100	-4.8182	-66.5880	-0.00817
	101	-4.7820	-66.4920	-0.00817
⋮	⋮	⋮	⋮	⋮
51	1	-8.4040	-73.3590	-1.590
	2	-8.3678	-73.3110	-1.590
	⋮	⋮	⋮	⋮
	100	-4.8182	-67.3660	-1.590
	101	-4.7820	-67.2920	-1.590

The input data for software, made in Java programming language, as numerical development of the previous proposed algorithm are: p=322.80 mm; D_{ex}=150 mm; z= 26 teeth.

6. Dedicated Software

It was elaborated, based on the presented algorithm, in Java programming language, a software which allow the determination of the characteristic curve at contact between the helical surface and the disc tool.

In figure 12, a screen capture of the applet made for this software is presented.

It is possible to import the text file which represents the measured coordinates along the surface's generatrix (or coordinates representing the fitted surface).

Also, it is possible to define the constructive dimensions of the peripheral primary surface of the disc tool reciprocally enveloping with the helical surface.

The α angle of the disc tool's axis is calculated relying on the dimensions measured on the surface, D_{ext} and the helical parameter of the surface to be generated.

The software gives the form and coordinates of the characteristic curve, on the surface, in the polyhedral expression, measured on the fitted surface. The graphical representation is also made for the characteristic curve measured on the involute teeth flank, figure 11 and 12.

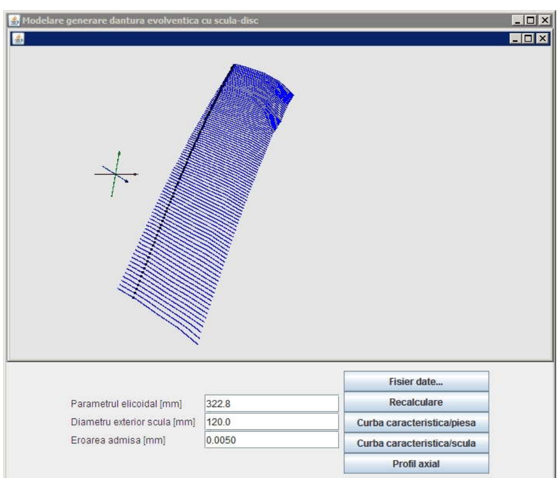


Fig. 12. *Applet for tool profiling*

Note: The applet allows to visualize the characteristic curve for various zoom levels.

The number of points on the characteristic curve is defined according to the mesh for the surface and, also, according to the error level for the enveloping condition (see (11)).

Table 3 presents the coordinates of the characteristically curve upon disc tool generation (D_{es}=120 mm).

The determination of the axial section of the disc tool presumes the coordinate transformation, see figure 4:

$$X_1 = X_{1_{i,j}} \cdot \cos\alpha + Z_{1_{i,j}} \cdot \sin\alpha;$$
$$Y_1 = Y_{1_{i,j}} + a; \qquad (19)$$
$$Z_1 = -X_{1_{i,j}} \cdot \sin\alpha + Z_{1_{i,j}} \cdot \cos\alpha,$$

so, we can determine the coordinates of the axial section of the disc tool, see table 4 and figure 13 and 5.

Table 3. *Coordinates on the characteristic curve*

Crt. no.	X [mm]	Y [mm]	Z [mm]
0	-8.505	-54.150	0.452
1	-8.470	-54.200	0.446
2	-8.434	-54.249	0.441
⋮	⋮	⋮	⋮
97	-5.020	-60.149	-0.087
98	-4.984	-60.225	-0.093
99	-4.948	-60.300	-0.099

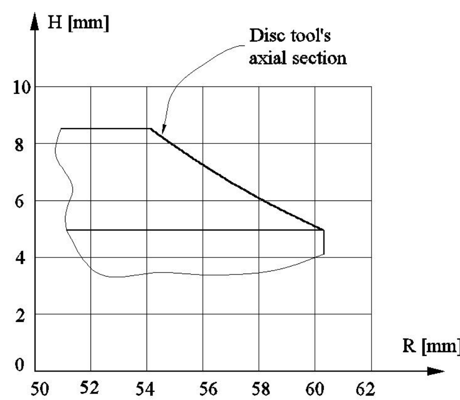


Fig. 13. *Disc tool's axial section*

Table 4. *Coordinates of the axial section of the disc tool*

Crt. no.	$H = X_1$ [mm]	$R = \sqrt{Y_1^2 + Z_1^2}$ [mm]
0	8.505	54.152
1	8.470	54.201
2	8.434	54.250
⋮	⋮	⋮
97	5.020	60.149
98	4.984	60.225
99	4.948	60.300

7. Conclusions

The representation of the cylindrical helical surface with constant pitch, measured point by point on 3D measuring machines - polyhedral representation – allows elaborating software leading to the determination of the characteristic curve for the generation of the helical surface using the disc tool.

The software allows the visualization of the characteristic curve form, determined in this way, in a graphical form.

The unevenness of the measured points, along the surfaces generatrix may be improved using software which allows the fitting of the generatrix.

The form in which is given the axial section of the disc tool, allow the using of data on CNC machines, in order to profile the secondary order tool (the cutter for disc tool relieving).

Acknowledgement

The authors gratefully acknowledge the financial support of the Romanian Ministry of Education, Research and Innovation through grant PN_II_ID_656/2007.

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Profilarea sculelor de revoluție pentru generarea suprafețelor elicoidale exprimate în formă poliedrală

Rezumat

Profilarea sculelor mărginite de suprafețe de revoluție —scula disc, scula cilindro-frontală şi scula inelară— se bazează pe teoremele fundamentale ale înfăşurării suprafețelor.
Există situații în care suprafețele de generat sunt cunoscute în mod discret, prin puncte, deseori aceste puncte fiind măsurate pe mașini de măsurat în coordonate.
Sunt cunoscuți algoritmii pentru aproximarea acestor puncte discrete de pe suprafețele elicoidale, utilizând polinoame de aproximare Bezier sau curbe B-spline.
În această lucrare este prezentat un algoritm bazat pe reprezentarea poliedrală a suprafețelor măsurate şi, în baza acestuia, un produs soft realizat în limbajul de programare Java. Sunt prezentate aplicații numerice pentru profilarea sculelor disc şi cilindro-frontală, reciproc înfăşurătoare cu suprafețele reprezentate prin puncte discrete.

Profilage de l'outil pour la génération de surfaces hélicoïdales exprimée sous forme polyédrique

Résumé

Le profilage de l'outil de bornée être surfaces de révolution - outil de disque, outils de fraisage et un outil anneau - est basée sur des théorèmes fondamentaux de l'enveloppant surfaces.
Ce sont des situations où les surfaces sont connues par les points de l'échantillon, souvent déterminée par la mesure sur les machines à mesurer tridimensionnelles.
Ils sont connus des algorithmes de rapprochement de ces points discrets, sur une surface hélicoïdale, en utilisant les polynômes de Bézier ou des courbes B-spline.
Dans cet article, est présenté un algorithme et, sur cette base, le logiciel réalisé en langage de programmation Java, basé sur la représentation polyédrique de la surface mesurée. Ils sont présentés des applications numériques pour le profilage de l'outil de disque ou d'un outil de fraisage fin, réciproquement enveloppant avec ces surfaces représentées par des points échantillonnés.