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

Teodor Virgil[1], Francisco Javier Santos Martin[2], Cucu Marian[1], Oancea Nicolae[1]
[1]"Dunărea de Jos" University of Galați, Romania
[2]Faculty of Industrial Engineering, University of Valladolid

ABSTRACT

The profiling of tools 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 known algorithms for the approximation of these discreet points, on the helical surface, using Bezier polynomials or B-spline curves.

Such an algorithm is presented in this paper and relying on that algorithm and on the polyhedral representation of the surface measured software programming in Java language was realized. Certain numerical applications for profiling the disc tool or end-milling tool, reciprocally enwrapping with these surfaces represented by sampled points are also presented.

KEYWORDS: helical surfaces known by sampled points, end mill tool's profiling, polyhedral form, enveloping surfaces.

1. Introduction

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

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

Moreoverly, the development of the capabilities of the graphical software, create the real possibility to solve fast and rigorously this problem [5], [6], [7], [8], [16].

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

In this way, a problem appears of surface approximation and the problem of replacing these surfaces with an analytical surface as the best approximation of the measured points cloud, in order to allow the use of the known analytical methods.

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

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

Also, it is 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 characteristic curve of the helical surface in contact with a revolution surface reciprocally enveloping with these [17], [18].

In this paper, is proposed an approximation method for a measured surface by an assembly of in-plane surfaces and a specialized software, made in Java language, in order to profile 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 result from measuring using a device which determines the successive coordinates of the points, figure 1, may be regarded as being composed of a distinct grid of points along the measuring lines.

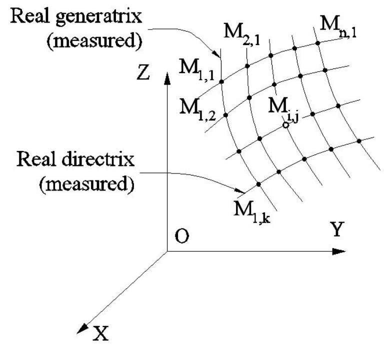


Fig. 1. *Real surface (surfaces represented by sampled points)*

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

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

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

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

$$\Sigma_{efective} = \left\{ \left\{ \begin{pmatrix} X_{i,j} \\ Y_{i,j} \\ Z_{i,j} \end{pmatrix}^T_{i=1\dots n} \right\} \right\}_{j=1\dots m} ; \quad (2)$$

The normal in a certain point of the real surface (2), be $M_{i,j}$ this point, is defined as the normal to 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 $M_{i,j}$ considered points may be defined four normals, one for each of the polyhedron faces, with the point considered as the top.

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

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

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

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

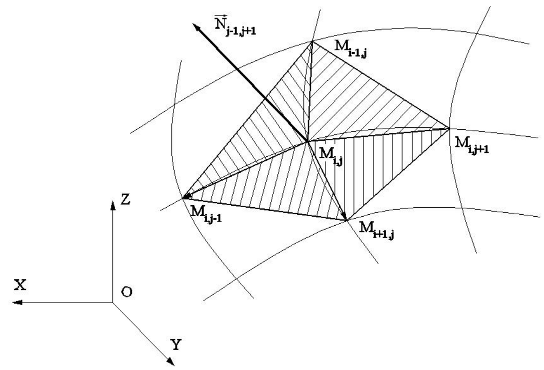


Fig. 2. *Normal to the polyhedral surface*

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, are defined the normals draw to the others polyhedron surfaces with the top point $M_{i,j}$.

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.

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

3. Measured Surface's Form Fitting

It is possible when the number of points measured on the surface may not be too big, and when we suspect that the polyhedron form for measured surface is different to 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 points cloud, belonging, this time, to the fitted surface. Not all of the points of the new points cloud will represent 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.

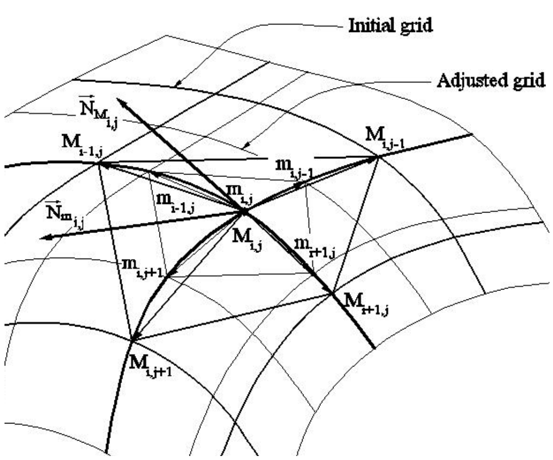


Fig. 3. *Polihedral surfaces: initial grid ($M_{i,j}$; $M_{i+1,j}$; ...); fitted grid ($m_{i,j}$; $m_{i+1,j}$ ...)*

In figure 3, with $M_{i,j}$, $M_{i,j-1}$, $M_{i,j+1}$ points 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.

$\vec{N}_{M_{i,j}}$ and $\vec{N}_{m_{i,j}}$ were also marked as the vectors of the normals to the polyhedral surfaces with the top in the current $M_{i,j}$ ($m_{i,j}$) points, for the two forms of the initial and fitted grid, as they might be different.

4. End Mill Tool

Frequently, the generating tool of the helical surface described in the polyhedral form, may be realized as end mill tool, tool with the incident axis and perpendicular to the axis of surface to be generated, see figure 4.

In the main, it is possible to consider that the end mill tool is overlapped to the $\vec{A}$ axis, if *Y* is the symmetrical axis of gap,

$$\vec{A} = -\vec{j}\,. \tag{9}$$

The position vector of the point $M_{i,j}$, from the substitutive polyhedral surface, has the form of,

$$\vec{r} = X_{i,j}\cdot\vec{i} + Y_{i,j}\cdot\vec{j} + Z_{i,j}\cdot\vec{k}\,, \tag{10}$$

with coordinates $X_{i,j}$, $Y_{i,j}$, $Z_{i,j}$ give by (2).

Consequently, the enwrapping condition becomes

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

with $\varepsilon = \left(1\cdot 10^{-3}\dots 1\cdot 10^{-2}\right)$, so, it is possible to determine, together with (2), an assembly of discrete points on Σ, representing the characteristically curve form.

The advance for the check of the following point in the process of defining the characteristic curve is to be decided by establishing the polyhedron face corresponding to the (11) enveloping condition.

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 end mill tool.

As a principle, the C_S characteristically curve, may have a representation in the form of

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

By revolving of the characteristically curve (12) around $\vec{A}$ axis (Y axis), with θ variable parameter,

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix}\cdot\begin{pmatrix} X_{i,j} \\ Y_{i,j} \\ Z_{i,j} \end{pmatrix}, \tag{13}$$

the end mill tool's primary peripheral surface is obtained, expressed as a circle's family.

The right choice for $\vec{A}$ axis position for a curl of helical surfaces (the case of the teethed wheel with inclined teeth) allows the simultaneous generation of the gap between the two successive teeth ranges.

In this case, the problem finality is the determination of the axial section of the end mill tool, see figure 4,

$$S_A \begin{vmatrix} H = -Y_{i,j}; \\ R = \sqrt{X_{i,j}^2 + Z_{i,j}^2}. \end{vmatrix} \qquad (14)$$

In the equations (14), by $X_{i,j}$, $Y_{i,j}$, $Z_{i,j}$, are denoted the coordinates of the characteristically curve, coordinates which on the helical surface (10), accomplish the condition (11).

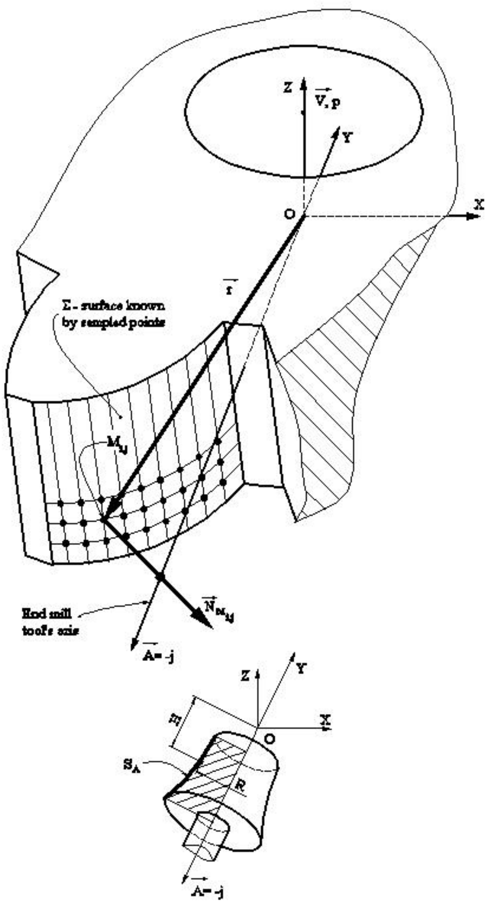


Fig. 4. *End mill tool, tool's axis position*

5. Fitting the Points Cloud of the Surface Measured

The involute flank of a toothed-wheel is regarded as the measured surface of the flank of a cylindrical helical surface, as seen in figure 5.

On the 3D measuring machine, 3D-Micro Hite, the coordinates of the points are determined, by direct measuring, on the succesive generatrix of a flank, as seen in figure 6.

In the table 1, are presented the coordinates of points belonging to the successive generatrix (Z_M=const.) measured on the surface, in the machine reference system ($X_M Y_M Z_M$).

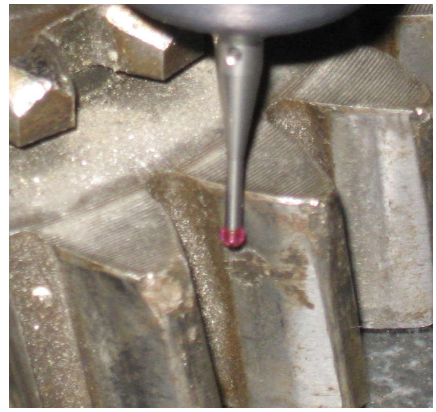


Fig. 5. *Measurement of the teethed wheel*

Table 1. *Sampled points on the successive generatrix*

Line *j*	Crt. no.	X_M [mm]	Y_M [mm]	Z_M [mm]
1	1	222.332	148.352	-450.206
	2	224.289	150.942	-450.207
	3	225.450	152.822	-450.207
	4	226.086	154.019	-450.206
	5	227.149	156.324	-450.207
⋮	⋮	⋮	⋮	⋮
5	1	221.968	147.720	-452.001
	2	223.809	149.664	-452.001
	3	225.382	152.003	-452.001
	4	226.496	154.047	-452.000
	5	227.328	155.798	-452.000

The assembly of the successive generatrix form the discrete surface of the flank to be generated, see figure 6, where the coordinates were processed by MatLab software's Curve Fitting Toolbox.

It is obvious that the measured surface isn't a smooth surface and that the fitting of these is necessary in order to make a rigorous interpretation of the measured data.

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

- the index R^2 (adjusted R-square) to be closest to 1;
- the second derivative of the substitutive polynomial equation to be straight lined (to be avoid the points on generatrix where the curvature have important variations);

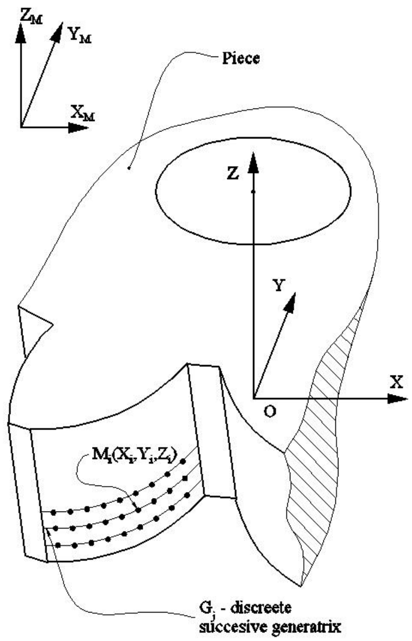
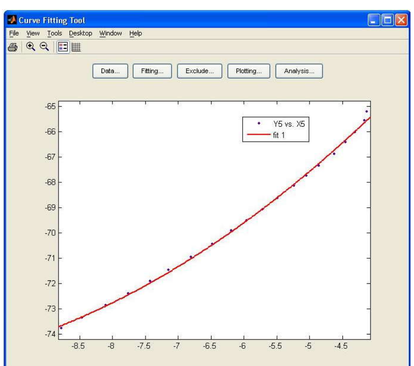
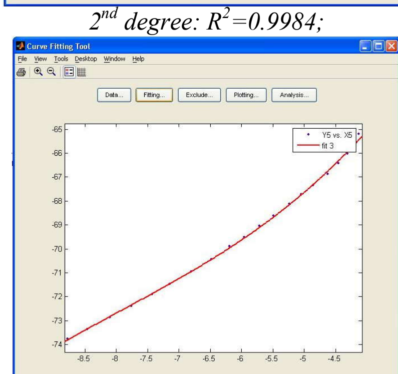


Fig. 6. *Measured points on flank*

In figures 7 and 8, are presented the forms of the polynomials for data fitting so as the first and second derivative, in different points of the fitting function, are calculated using MatLab Curve Fitting Toolbox.



2nd degree: R^2=0.9984;



3rd degree: R^2=0.9992;

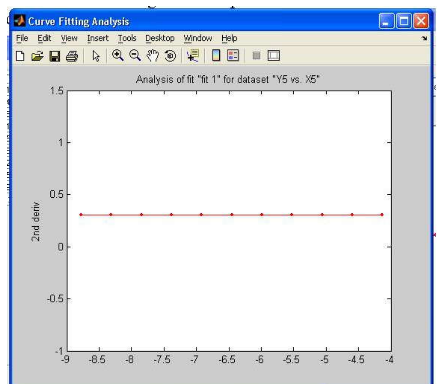
Fig. 7. *Substitutive polynomial form*

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 polynomial approximation and, at the same time, the second derivative being linear, being eliminate the existence of points on the fitted generatrix where the curvature have important variations.

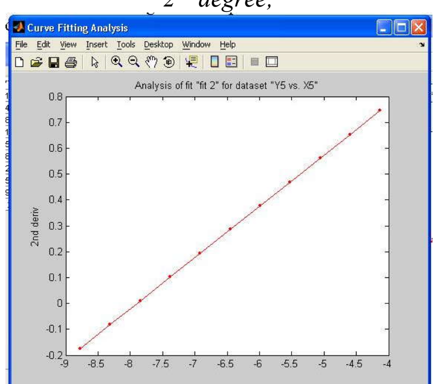
Note: Obviously, for other forms of measured surface, the substitutive polynomial will have other forms.

In the substitutive polynomial evaluation were used the MatLab software.

In this way, all the generatrix may be fitted in a polynomial form. We make the notice that, regarding the coordinates of the measured points, the substitutive polynomials may not be of the same degree.



2nd degree;



3rd degree;

Fig. 8. *Second order derivative*

The form of the substitutive surface of the point's cloud may be processed with MatLab software, making a denser grid of points which are nodes of the surface substitutive polyhedrons. In figure 9, is presented a screen capture of the surface's mesh.

The end mill tool for the generation of the gap between two teeth, assumed, see figure 10, establishing the tool's axis position — axis $\vec{A}$, as symmetry axis of the gap.

It is necessary for that to know the two generatrix on each of the anti-homologous flanks, in the same plane parallel to the front plane, see figure 11.

In the same plane $Z = const.$, the two flanks measured, for the measured points, are substituted for by profiles, known in the range of the superior degree polynomial curves as the intersection between the latter and a circle's arc with an arbitrary radius determining the *S* points, and respectively *D*, on the chord of $\widehat{SD}$ arc.

The straight line which links the points *O* and *M* (the midpoint of the $\overline{SD}$ segment) is the symmetry axis of the gap between two teeth and may be selected as end mill tool's axis — $\vec{A}$.

In table 2, are presented the coordinates measured on the anti-homologous flanks of the teethed wheel.

Table 2. *Coordinates measured on the anti-homologous flanks of the teethed wheel (in the toothed wheel reference system)*

Crt. no.	Right flank			Left flank		
	X [mm]	Y [mm]	Z [mm]	X [mm]	Y [mm]	Z [mm]
1	-7.7711	-75.012	0	2.7116	-67.047	0
2	-6.3317	-73.465	0	3.8437	-69.557	0
3	-4.818	-71.139	0	5.0703	-71.786	0
4	-3.9539	-69.559	0	6.0886	-73.352	0
5	-2.8767	-67.222	0	6.9605	-74.512	0

For one of the profiles, the flank is substituted by a superior degree polyonomial, see figure 9.

A new coordinate system, is admited, on whose basis the toot's gap, $X_1Y_1Z_1$ is reported, the Y_1 axis being the symetry axis of the gap between the two teeth,

$$\begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (15)$$

where β is determined by the relation

$$\tan\beta = \frac{|X_M|}{|Y_M|} \quad (16)$$

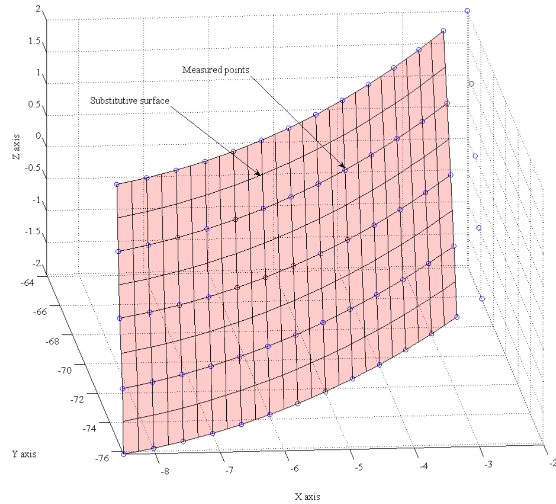


Fig. 9. *Measurd points and mesh grid*

In table 3, are presented the coordinates of the teeth flanks surfaces profiles coordinates, reported for the new reference system and fitted based on the Curve Fitting toolbox from the MatLab.

Also, in figure 10, are presented the substituting forms for the teeth flanks, regarding the $X_1Y_1Z_1$ reference system, with *O* origin of the reference system $X_1Y_1Z_1$ (on the teethed wheel axis).

The end mill tool for generation of gap between two teeth, presume, see figure 11, to establish of the tool's axis — $\vec{A}$ axis, as symmetry axis of the gap. That presume knowing the two generatrix, on the anti-homologous flanks, in the same plane, parallel with the front plane, as seen in figure 11.

Table 3. *Coordinates of the teeth flanks surfaces profiles coordinates*

Line *j*	Crt. no.	X_1 [mm]	Y_1 [mm]	Z_1 [mm]
1	1	-8.407	-75.045	-2.000
	2	-6.501	-73.030	-2.000
	3	-5.082	-70.822	-2.000
	4	-3.963	-68.659	-2.000
	5	-2.955	-66.306	-2.000
⋮	⋮	⋮	⋮	⋮
5	1	-6.884	-74.789	2.000
	2	-5.357	-72.750	2.000
	3	-4.154	-70.796	2.000
	4	-3.332	-69.196	2.000
	5	-2.353	-67.000	2.000

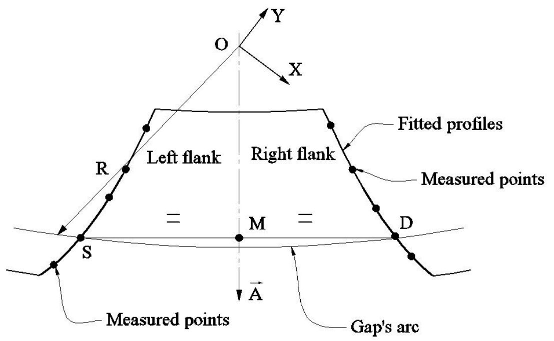


Fig. 10. *The substitutive surface form*

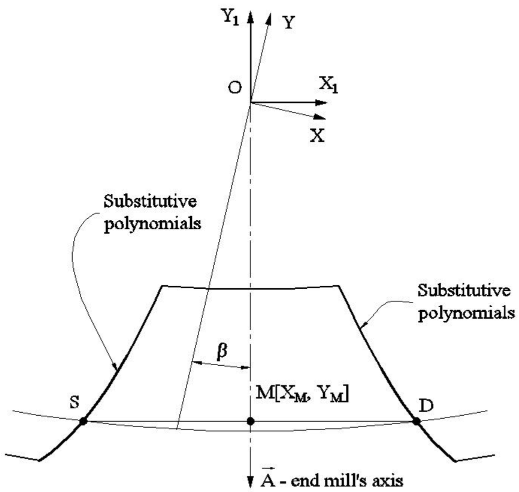


Fig. 11. *Determination of generatrix on anti-homologous flanks*

Table 4. *Coordinates on the successive generatrix of the substitutive surface*

Line *j*	Crt. no	X_1 [mm]	Y_1 [mm]	Z_1 [mm]
	1	-8.500	-76.179	-2.000
	2	-8.400	-76.165	-2.000
1	⋮	⋮	⋮	⋮
	60	-2.600	-75.131	-2.000
	61	-2.500	-75.107	-2.000
	1	-8.500	-76.107	-1.900
	2	-8.400	-76.089	-1.900
2		⋮	⋮	⋮
	60	-2.600	-75.051	-1.900
	61	-2.500	-75.027	-1.900
⋮	⋮	⋮	⋮	⋮
	1	-8.500	-67.358	2.000
	2	-8.400	-67.308	2.000
41	⋮	⋮	⋮	⋮
	60	-2.600	-65.236	2.000
	61	-2.500	-65.175	2.000

For the points measured in the same plane, $Z = const.$, the two measured flanks are substituted with profiles known by polynomial the curves of a superior degree as the intersection of these with a circle’s arc with arbitrary radius, determining the points *S* and *D* on the arc of the circle chord for the arc $\widehat{SD}$.

The straight line which links the points *O* and *M* (the midpoint of the $\overline{SD}$ segment) is the symmetry axis of the gap between the two teeth and may be selected as end mill tool’s axis.

Also, in table 4, are presented the coordinates on the substitutive surfaces (fitted surface) of the point’s cloud measured on the surface.

The input data for software, made in Java programming language, as numerical development of the previous proposed algorithm are: *p*=322.8 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 allows the determination of the characteristic curve upon the contact between the helical surface and the end mill tool.

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 end mill tool reciprocally enveloping with the helical surface.

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

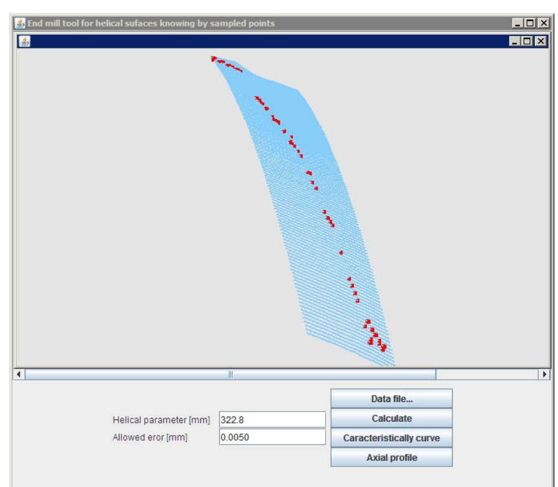


Fig. 12. *Applet for end mill tool’s profiling (characteristic curve)*

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)).

The software allow to calculate the axial section of the end mill tool by the command “*Axial Profile*” (see figure 13).

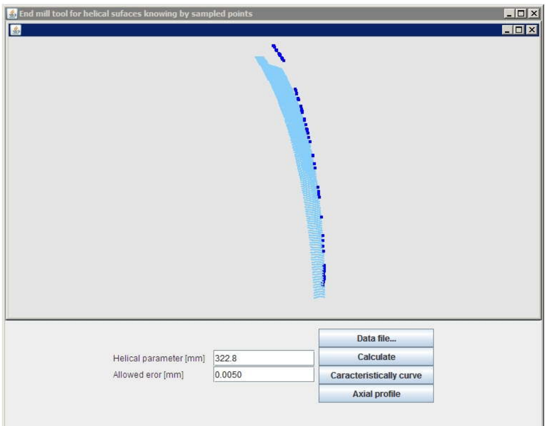


Fig. 13. *Applet for end mill tool’s profiling (axial section)*

In table 5, are presented the coordinates of the axial section at generation using an end mill tool.

Table 5. *Coordinates on axial section*

Crt. no.	R [mm]	H [mm]
0	76.036	9.0078
1	76.098	9.0809
2	76.089	9.062
3	75.937	8.8579
4	75.964	8.8855
5	75.955	8.8671
6	75.946	8.8489
7	75.973	8.8776
8	75.964	8.86
⋮	⋮	⋮
66	66.597	2.9108
67	66.569	2.9069
68	66.542	2.9039
69	66.263	2.8018
70	66.36	2.8504
71	66.081	2.75
72	66.054	2.7505
73	66.151	2.8018
74	66.124	2.804

Coordinates showed in table 5, are determined by applying the presented algorithm and the software previously proposed. The unevenss of this point’s assembly representing the axial section need to fit these coordinates relying on a 4th degree polynomial, which will assure a smooth form of curve.

In this way, the axial section has the coordinates presented in table 6 and figure 14.

Table 6. *Coordinates on axial section after fitting*

Crt. no.	R [mm]	H [mm]
0	66.124	2.7719
1	66.256	2.8066
2	66.388	2.8438
3	66.521	2.8834
4	66.653	2.9253
5	66.785	2.9692
6	66.917	3.0152
7	67.049	3.0631
8	67.182	3.1127
⋮	⋮	⋮
67	74.849	7.6373
68	74.981	7.7648
69	75.114	7.8963
70	75.246	8.0318
71	75.378	8.1717
72	75.51	8.316
73	75.642	8.465
74	75.775	8.619
75	75.907	8.778

The fitting errors determined using the MatLab Curve Fitting Toolbox are: R-square=0.9993; Adjusted R-square=0.9991.

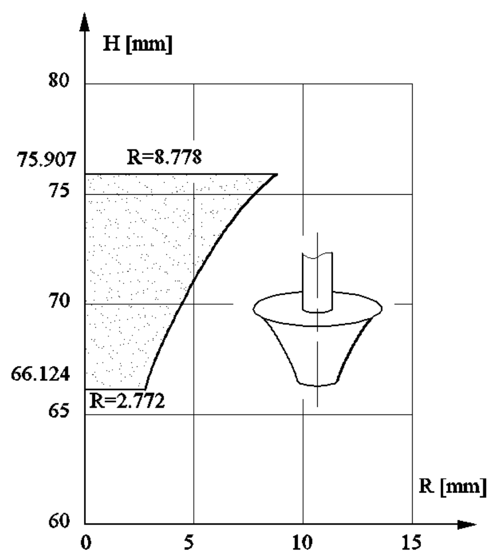


Fig. 14. *End mill tool’s axial section*

7. Conclusions

The representation of the cylindrical helical surface with constant pitch, measured point by point on 3D measuring machines - polyhedral representation – allows to elaborate a software which leads to the determination of the characteristic curve upon the generation of the helical surface using the end-mill tool.

The software allows the visualization of the characteristic curve form, determined in this way, in the 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 end mill tool, allows the using of data on CNC machines, in order to profile the secondary order tool (the cutter for disc tool relieving).

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Profilarea sculelor suprafețe de revoluție pentru generarea suprafețelor elicoidale exprimate în formă poliedrală
—Scula cilindro-frontală—

Rezumat

Profilarea sculelor mărginite de suprafețe de revoluție – scula-disc, scula cilindro-frontală, sculele inelare – se bazează pe teoremele fundamentale ale înfăşurării suprafețelor.
Sunt multiple situații în care cunoaşterea suprafețelor pentru care este necesară profilarea unei astfel de scule generatoare, este în formă discretă, prin puncte, cel mai adesea determinate prin măsurarea pe maşini de măsurat în coordonate.
Sunt cunoscuți algoritmi pentru aproximarea acestor puncte discrete, pe suprafață, cu polinoame Bezier sau prin curbe B-spline.
În lucrare, se prezintă un algoritm şi, în baza acestuia, un produs soft realizat în limbaj Java, bazat pe o reprezentare poliedrală a suprafeței măsurate. Se prezintă aplicații numerice, pentru profilarea sculelor de tip disc sau cilindro frontale, reciproc înfăşurătoare acestor suprafețe reprezentate în formă discretă.

Profilage de la Révolution surfaces 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 disque, outils fraisage et outil anneau - est basée sur des théorèmes fondamentaux des surfaces enveloppants.
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.