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Algorithm for Corrective Profiling of the Gear Shaped Tool

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ABSTRACT

In this paper, is presented an algorithm for corrective profiling of the gear shaped tool which generate by the surfaces enwrapping method, correction realized by modification of the active back surfaces form or of the chip bearing surface.

The paper present a numerical example for the corrective profiling of a gear shape tool for the generation of a rectilinear profiles in-plane curl (hexagonal shaft).

Keywords*: corrective profiling, gear shaped tool, in-plane curl profiles.*

1. Introduction

In present, the technological development in the cutting process presume, more and more, together with the decreasing of the absolute generating errors specifically for the machining processes, the elaboration of new methods and techniques for errors prediction and compensation. Are known and applied analytical models [4], [6], models based on genetic algorithms [3] as so as those based on polynomial neural network [1].

Also, are known and much used methods for error compensation using software, which leads to alternative path for tool's movement [4].

All these things are possible in the frame of integrated CAD, CAM, CAI systems.

In this paper, is presented a model for rolling generating tools, based on an algorithm which presume that, in the goal to generate a target surface (a virtual surface) different from the initial surface to be generated, for which was designed the tool's profile, is possible to found a solution consisting on the actual tool's cutting edge form correction, see figure 1.

This is proposed to be realized by changing the tool's bearing surface form, as the easiest technologically solution.

The tool's bearing surface modification may be made by tool's re-sharpening, for a relief angle different from the initial one, for which was designed the tool, leading to a new actual cutting edge — the approximated profile.

In this way, is possible to determine the situation when the new actual cutting edge is closed enough to the tool's profile, re-designed for the generation of the new target surface and, in consequence, may be approximated with this.

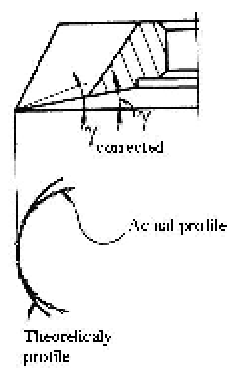

Fig. 1. *Actual gear shape tool's cutting edge*

Obviously, not in every situation this solution is possible. Still, this solution seems to be the most economically method for corrective re-profiling of this tool's type.

This way to think at correction problem have sense for a repeatable production, when the generating condition are similarly for all the blanks machined with the same tool (technological system, mode of operation, working conditions etc. constant in time).

2. Algorithm for gear shaped corrective profiling modeling

The actual surfaces, machined in the generating process, who's the in-plane crossing profile may be measured, may be represented by a

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matrix whose elements are the coordinates of the points belongs to these profiles, see figure 2 and (1). In the most situations, the actual profile doesn't coincident with the nominal profile due of indefinite causes.

$$\Sigma = \begin{Vmatrix} X_1 & Y_1 \\ X_2 & Y_2 \\ \vdots & \vdots \\ X_m & Y_m \end{Vmatrix}. \qquad (1)$$

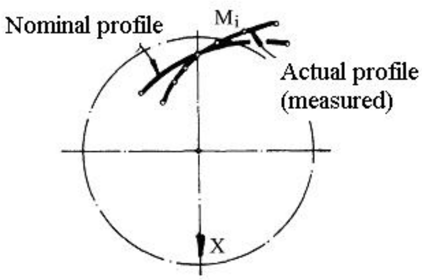

Fig. 2. *Actual and nominal profile*

In order to increase the generation precision, is proposed the modification of tool's profiles, regarding the actual profile of the generated profile, different against the geometrical profile (theoretically), figure 2, presuming that the technological system, reacting in the same way, will lead to an actual surface closest to the nominal one (the theoretical surface).

2.1. Virtual profile

Presuming that the process will be the same, for any generation re-run, in the same way, in the sense that the generating errors will take the same values, is proposed the notion of *virtual profile* obtained as mirror image of points belongs to the actual profile regarding the theoretically profile, figure 3.

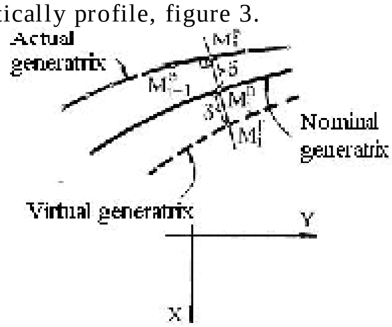

Fig. 3. *Virtual profile*

The virtual profile modeling is made in the following way:

- is construct the normal to actual profile in the M_i point, being known two successive points along this,

$$M_i^e = \begin{Bmatrix} X_i^e \\ Y_i^e \end{Bmatrix} \qquad (2)$$

and:

$$M_{i+1}^e = \begin{Bmatrix} X_{i+1}^e \\ Y_{i+1}^e \end{Bmatrix}, \qquad (3)$$

with equation

$$\left(X - X_i^e\right)N_x + \left(Y - Y_i^e\right)N_y = 0, \qquad (4)$$

where: N_x and N_y are the directrix parameters of the normal, with

$$tg a_i = \frac{\left|Y_{i+1}^e - Y_i^e\right|}{\left|X_{i+1}^e - X_i^e\right|}, \text{ and} \qquad (5)$$

$$N_x = \cos a_i,\ N_y = \sin a_i;$$

- is intersect the normal (4) – the normal at actual profile in the point M_i with the nominal profile (theoretical profile), analytical known from equations:

$$X = X(u), Y = Y(u), \text{ u—variable}, \qquad (6)$$

obtaining the coordinates of M_i^n on this nominal profile,

$$M_i^n = \left\{X_i^n \quad Y_i^n\right\}; \qquad (7)$$

- is calculated the δ distance between M_i^e and M_i^n,

$$d = \left|\sqrt{\left(X_i^n - X_i^e\right)^2 + \left(Y_i^n - Y_i^e\right)}\right|; \qquad (8)$$

- is determinate the current point's coordinates on the virtual profile,

$$M_i^F : \begin{cases} X_i^F = X_i^n + d\cos a_i; \\ Y_i^F = Y_i^n + d\sin a_i. \end{cases} \qquad (9)$$

The M_i^F points assembly determine the *virtual profile*, based on which will be determinate the corrected profile of gear shaped tool.

2.2. Corrected profile

The corrective profile modeling for gear shaped tool using the tangents method

If we accept the profile expressed of the gear shaped tool in form

$$G_F = \begin{Vmatrix} X_1^F & X_2^F & \cdots & X_m^F \\ Y_1^F & Y_2^F & \cdots & Y_m^F \end{Vmatrix}, \qquad (10)$$

based on the *tangents method* [2], [7], is defined the profiles family expressed in the discreetly form, in the gear shaped cutter reference system:

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$$\begin{Vmatrix} x \\ h \end{Vmatrix} = \begin{Vmatrix} \cos j_2 & -\sin j_2 \\ \sin j_2 & \cos j_2 \end{Vmatrix} \cdot \left[\begin{Vmatrix} \cos j_1 & -\sin j_1 \\ \sin j_1 & \cos j_1 \end{Vmatrix} \cdot \begin{Vmatrix} X_i^F \\ Y_i^F \end{Vmatrix} + \begin{Vmatrix} -A_{12} \\ 0 \end{Vmatrix} \right], \quad (11)$$

for i=1, 2, 3, …, n.

After developing, result:

$$\begin{vmatrix} x = X_i^F \cos(j_1 + j_2) - \\ -Y_i^F \sin(j_1 + j_2) + A_{12} \cos j_2; \\ h = X_i^F \sin(j_1 + j_2) + \\ +Y_i^F \cos(j_1 + j_2) + A_{12} \sin j_2. \end{vmatrix} \quad (12)$$

The enwrapping condition specifically for the tangents method [7] is:

$$\left[(I+1)Y_i^F - IA_{12} \sin j_1\right] \sin b_i^F + \\ +\left[(I+1)X_i^F + IA \cos j_1\right] \cos b_i^F = 0, \quad (13)$$

with definition:

$$b_i^F = arctg\left(\frac{Y_{i+1}^F - Y_i^F}{X_{i+1}^F - X_i^F}\right) \quad (14)$$

where: $X_i^F, Y_i^F, X_{i+1}^F, Y_{i+1}^F$ are coordinates of the virtual generatrix matrix G^F and I is the gear ratio, $I = R_{rp}/R_{rs}$, see figure 4.

Gear shaped tool’s profiling modeling using the “minimum distance” method [7]

The gear shaped tool’s profiling is made accepting that the virtual generatrix is described by a matrix on form (10).

Based on the minimum distance method theorems, see figure 4, is determine the virtual generatrix family, in the tool’s reference system, starting from the relative movement:

$$x = w_3(-j_2)\left[w_3^T(kj_1)X - a\right]; \quad (15)$$

where:

$$a = \begin{Vmatrix} -A_{12} \\ 0 \\ 0 \end{Vmatrix} \text{ and } j_2 = \frac{R_{rp}}{R_{rs}} kj_1; \quad (16)$$

— *X* is the matrix formed with the virtual generatrix coordinates (10);

— j_1 — the angular increment of the rotation movement.

The virtual profiles family is expressed by a matrix on form

$$(G)_{kj_1} = \begin{Bmatrix} x_1 & x_2 & \mathbf{L} & x_m \\ h_1 & h_2 & \mathbf{L} & h_m \end{Bmatrix}_{kj_1}, \quad (17)$$

$(k = 1, 2, \mathbf{K}, n)$.

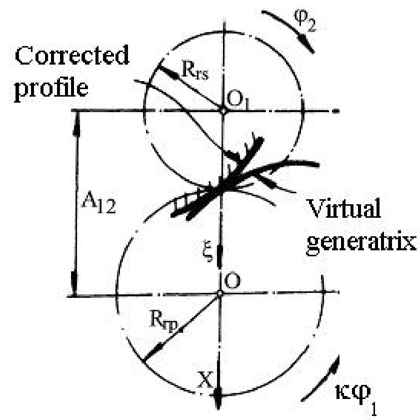

Fig. 4. *Reference systems: C_1—piece’s centrode, C_2—tool’s centrode*

The enwrapping condition associated with the $(G)_{kj_1}$ family is:

$$d_{min} = \left\{ \left\| \left\{ \left[x_{i,kj_1} - R_{rs}\cos(kj_1)\right]^2 + \left[h_{i,kj_1} - R_{rs}\sin(kj_1)\right]^2 \right\}^{\frac{1}{2}} \right\| \right\}_{min} \quad (18)$$

where: $k = 1, \mathbf{K}, m$ and $i = 1, \mathbf{K}, n.$

The (x_{i,kj_1}, h_{i,kj_1}) points are took from the array (17), on the gear shaped tool’s corrected profile.

The totality of points belongs to the array (17) which verify the minimum distance condition (18) represent, finally, in form:

$$P_C = \begin{Vmatrix} x_1^C & x_2^C & \mathbf{L} & x_n^C \\ h_1^C & h_2^C & \mathbf{L} & h_n^C \end{Vmatrix} \quad (19)$$

the corrected profile.

2.3. Approximated profile

We make the remark that, in proposed conditions, this corrected profile is an ideal profile (see 2.2).

The constructive form of this gear shaped cutter tool’s type and the re-sharpening possibilities don’t make possible the realization of a generating profile identically with the corrected profile, previously determined.

We accept that the most economically modality to correct the tool’s profile is the changing of the rake angle of this, figure 5.

In this way, by modification of the back angle γ, the actual profile after re-sharpening is modified, being able, in certain conditions (values of γ angle), to be closest to the tool’s corrected profile (12), (13) or (17), (18).

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Obviously, we should accept an error margin for the approximated profile (actual, after re-sharpening) regarding the corrected profile.

The actual profile after sharpening (re-sharpening) of gear shaped tool result as intersection between the tool's back face and the conical surface which represent the bearing surface of this, figure 5.

Is presumed known the theoretically profile (correspondent to the geometrical generatrix of surface to be machined), P_T, determined by one of known methods [7].

The back surface is considered as a ruled surface determined by the line *Da*, which stay with a point on the P_T tool's theoretical profile curve, figure 5.

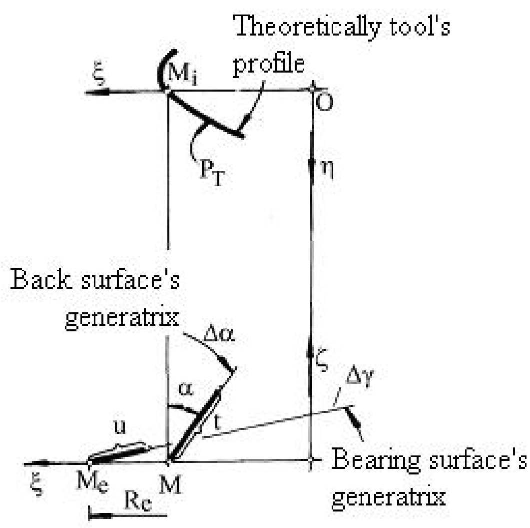

Fig. 5. *Back surface*

Is accepted, for the theoretically profile P_T, an expression, on form

$$P_T = \begin{Vmatrix} x_1^T & x_2^T & \mathbf{L} & x_n^T \\ h_1^T & h_2^T & \mathbf{L} & h_n^T \end{Vmatrix}^T . \qquad (20)$$

The back surface, with (Δa), have the parametrical equations,

$$(\Sigma a): \begin{cases} x = x_i t \sin a; \\ h = h_i; \\ z = t \sin a, \end{cases} \qquad (21)$$

points x_i, h_i belongs to the P_T directrix, see (20), and *t* continuously variable.

The bearing face is a revolution surface, generated by the rectilinear generatrix, *Dγ*, corresponding to the M_e point, found on R_e radius on profile (the maximum radius of the P_T profile regarding the gear shaped cutter's axis of revolution).

The bearing surface's generatrix equations are:

$$\Delta g: \begin{cases} x = R_e - u\cos g; \\ h = 0; \\ z = u \sin g. \end{cases} \qquad (22)$$

By rotation of the *Dγ* generatrix around the *ζ* axis:

$$\begin{Vmatrix} x \\ h \\ z \end{Vmatrix} = \begin{Vmatrix} \cos j & -\sin j & 0 \\ \sin j & \cos j & 0 \\ 0 & 0 & 1 \end{Vmatrix} \begin{Vmatrix} R_e - u\cos g \\ 0 \\ u \sin g \end{Vmatrix}, \qquad (23)$$

is generated a conical surface, with equations:

$$S_g: \begin{cases} x = (R_e - u\cos g)\cos j; \\ h = (R_e - u\cos g)\sin j; \\ z = u\sin g, \end{cases} \qquad (24)$$

representing the bearing surface of gear shaped cutter.

The intersection between the (21) and (24) surfaces represent the approximated profile of gear shaped cutter, P_A, see figure 6:

$$P_A: \begin{cases} (R_e - u\cos g)^2 = (x_i + t\sin a)^2 + h^2; \\ t = \dfrac{u \sin g}{\cos a}; \\ j = \arcsin\left(\dfrac{R_e - u\cos g}{h_i}\right). \end{cases} \qquad (25)$$

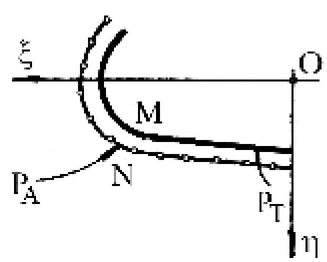

Fig. 6. *Tool's corrected profile (P_C) and approximated profile (P_A)*

For different values of *γ* parameter, may be obtained different forms of the approximated profile after tool's re-sharpening. Is accepted that profile which is closest to the corrected tool's profile (12), (13) or (17), (18).

For a point's number big enough to describe the two profiles, the corrected one, P_C, and the approximated one, P_A, may be defined a relative position between these.

For point *M* belongs to the corrected profile (19), $M = \{x_i^C \quad h_i^C\}$, are calculated

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the distances to the P_A profile’s points, $N=\left\{x_j^A \quad \eta_j^A\right\}$, with relation (see figure 6):

$$d=\left|\sqrt{\left(x_i^C-x_j^A\right)^2+\left(\eta_i^C-\eta_j^A\right)^2}\right|, \qquad (26)$$

$$\left(i=1,2,\ldots,n\right),\left(j=1,2,\ldots,n\right).$$

The minimum value of (26) distance represent or points M and N a value comparative with the distance measured on normal at one of the curves, between P_C and P_A.

The δ values are limited, by γ angle variation, at an accepted value, small enough to consider the two curves, P_C and P_A, very closed (identical from technical point of view).

3. Numerical application

Is proposed the methodology application for a corrective model application of gear shaped tool for generation of a hexagonal crossing section shaft.

Is determined, in conformity with the complementary theorems of surfaces enwrapping [7], profile family of hexagonal shaft flank:

$$\begin{vmatrix} x=-a\cos\left(1+i\right)\varphi_1-t\sin\left(1+i\right)\varphi_1+ \\ +A_{12}\cos\left(i\varphi_1\right); \\ \eta=-a\sin\left(1+i\right)\varphi_1+t\cos\left(1+i\right)\varphi_1+ \\ +A_{12}\sin\left(i\varphi_1\right), \end{matrix} \qquad (27)$$

t is variable with $0\le t\le a$;

i — gear ratio, $i=\dfrac{R_{rp}}{R_{rs}}$

and the enwrapping condition:

$$\left|\frac{\dot{x}_t}{\dot{x}_\varphi}-\frac{\dot{\eta}_t}{\dot{\eta}_\varphi}\right|<\varepsilon,\ \left(\varepsilon=1\cdot10^{-2}\ldots1\cdot10^{-3}\right). \qquad (28)$$

In principle, the (27) and (28) equations assembly determine the theoretical cutting edge form as a coordinates matrix:

$$P_T=\begin{Vmatrix} x_1 & x_2 & \ldots & x_i & \ldots & x_n \\ \eta_1 & \eta_2 & \ldots & \eta_i & \ldots & \eta_n \end{Vmatrix}. \qquad (29)$$

Based on this profile, is determined the tool’s flank, as cylindrical surface having as directrix the profile, known in numerical form, P_T:

$$\Sigma_\alpha\begin{vmatrix} x=x_i-\left(l\cdot j\right)\sin\alpha; \\ \eta=\eta_i; \\ z=\left(l\cdot j\right)\cos\alpha, \end{vmatrix} \qquad (30)$$

with: $i=1\ldots n$; $\text{j}=1\ldots\text{m}$, and l — variable along the cylindrical surface’s generatrix.

By re-sharpening of the gear shaped cutter on the bearing face, after a conical surface, coaxial with the tool’s axis, is obtained the actual tool’s generatrix.

The equations of face generatrix are:

$$\begin{aligned} &x=R_e-u\cos\gamma; \\ &\eta=0; \\ &z=u\sin\gamma, \end{aligned} \qquad (31)$$

with:

$$R_e=\sqrt{x_V^2+\eta_V^2}, \qquad (32)$$

where:

$V\left(x_V,\eta_V\right)$ is the point on the actual profile, the far off point to the gear shaped cutter axis.

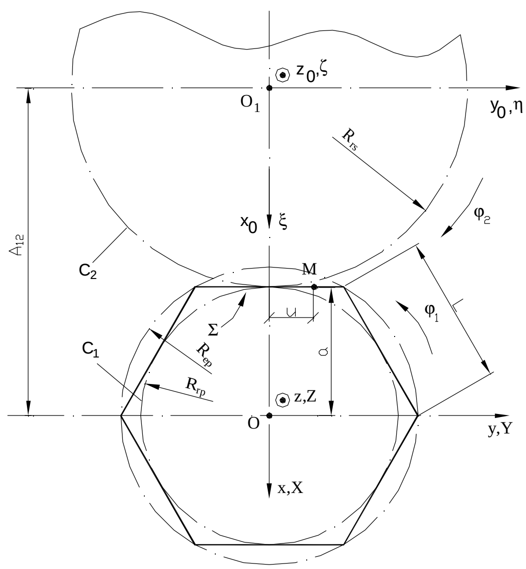

Fig. 7. *Hexagonal shaft profile*

Result the theoretically bearing surface (initial):

$$S_\gamma\begin{vmatrix} x=\left(R_e-u\cos\gamma\right)\cos\psi; \\ \eta=\left(R_e-u\cos\gamma\right)\sin\psi; \\ z=u\sin\gamma, \end{vmatrix} \qquad (33)$$

with:

$\psi=\psi_k\cdot j$,

ψ_k — angular increment;

$k=1\ldots n$;

$j=1\ldots m$;

γ —initial rake angle.

The intersection between Σ_α and S_γ surfaces represent the approximated gear shaped cutter profile.

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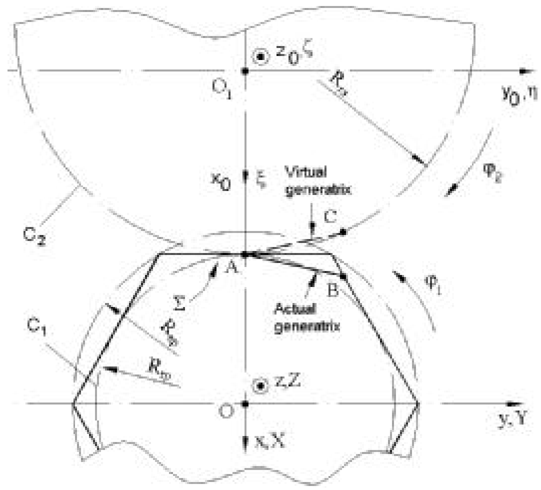

Fig. 8. *Virtual and actual generatrix*

Obviously, exist a dependency of approximated profile regarding the geometrical parameters, *a* — the back angle and *γ* rake angle of gear shaped tool.

Is proposed an actual profile model (segment *AB* from figure 8) for which result a virtual profile model (the zone *AC* in figure 8) in form:

$$G_F \begin{vmatrix} X = -a + l \sin a; \\ Y = l \cos a, \end{vmatrix} \quad (34)$$

with: l variable parameter;

q — geometrical characteristic of virtual profile model of shaft (the inclination angle of the virtual profile regarding the theoretically profile).

Is accepted that the virtual generatrix G_F, lead, in the gear shaped tool's reference system, at profile family:

$$\left(G_F\right)_{j_1} \begin{vmatrix} x = -\left(a - l \sin q\right)\cos\left[\left(i+1\right)j_1\right] - \\ -l \cos q \sin\left[\left(i+1\right)j_1\right] + \\ +A_{12}\cos\left(ij_1\right); \\ h = -\left(a - l \sin q\right)\sin\left[\left(i+1\right)j_1\right] + \\ +l \cos q \cos\left[\left(i+1\right)j_1\right] + \\ +A_{12}\sin\left(ij_1\right). \end{vmatrix}$$

(35)

The equations assembly determined by the model's family —G_F— of the virtual profile and the enwrapping condition

$$\left| \frac{\dot{x}_l}{\dot{x}_{j1}} - \frac{\dot{h}_l}{\dot{h}_{j1}} \right| < e, \quad (36)$$

determine the corrected gear shaped tool's profile, in form

$$P_C = P_C^{\Sigma} \begin{Vmatrix} x_1 & x_2 & \mathbf{L} & x_C \\ h_1 & h_2 & \mathbf{L} & h_C \end{Vmatrix}. \quad (37)$$

For the most far off point regarding the gear shaped cutter's axis (the sharpening conical surface axis):

$$M_V \begin{vmatrix} x_V = R_{rp} - a + R_{rs}; \\ h_V = 0, \end{vmatrix} \quad (38)$$

and, so, $R_e = A_{12} - a$, is determined, based on the (33) equations, the analytical model of the corrected face, in form:

$$S_g \begin{vmatrix} x = \left(R_e - u\cos g_C\right)\cos y; \\ h = \left(R_e - u\cos g_C\right)\sin y; \\ z = u \sin g_C. \end{vmatrix} \quad (39)$$

In the (39) equations, g_C is the corrected rake angle's value, by whom is realized the correction of the bearing surface's form, in order to make a new cutting edge — the gear shaped tool's approximated profile.

Are presented examples of algorithm applications based on original software, realized in java programming language and presented as applet.

The software realize the numerical modeling of the gear shaped tool's profile for generating a hexagonal shaft, the corrected profile, the variation limits of this profile as so as the approximated profile's coordinates.

As example, in figures 9, 10 and 11, are the graphical representations of the corrected profile, the limit profile and the approximated profile, distinct and over posed, and in table 1 are presented the coordinates of these profiles, for a rake angle $g_C = 10^{\circ}$, a back angle $a = 6^{\circ}$ and the generating model error $q = -0.3^{\circ}$.

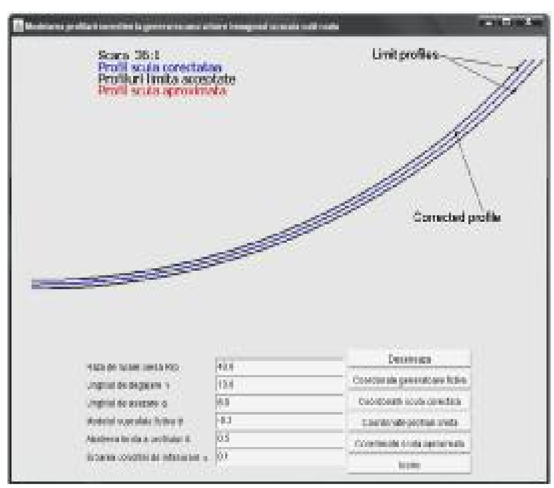

Fig. 9. *Corrected profile and limit profiles*

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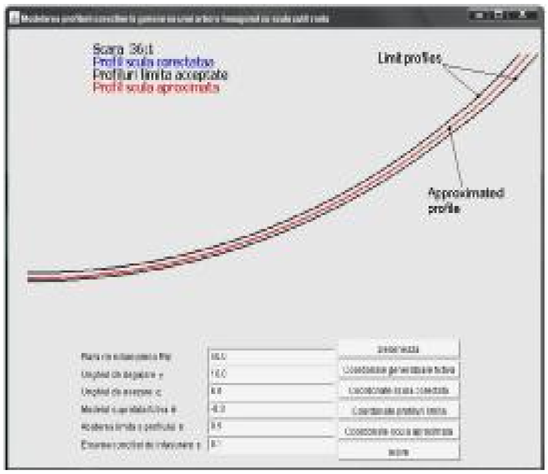

Fig. 10. *Approximated profile and limit profiles*

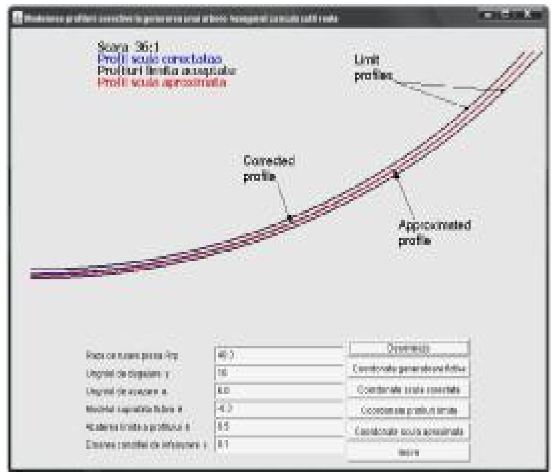

Fig. 11. *Corrected profile, approximated profile and limit profiles, over posed graphical representation*

Table 1. *Profile’s coordinates*

Crt. no.	**Corrected profile**		**Limit prfiles**				**Approximated profile**	
			superior		inferior			
	x	*h*	*x*	*h*	*x*	*h*	*x*	*h*
0	85.25426	0	84.75427	-0.00172	85.75426	0.001718	85.35898	0
1	85.25433	0.017881	84.75433	0.016349	85.75432	0.019413	85.35895	0.048038
2	85.25447	0.065763	84.75447	0.064981	85.75447	0.066545	85.35884	0.096077
3	85.25455	0.113645	84.75455	0.113613	85.75455	0.113677	85.35866	0.144115
4	85.25455	0.161527	84.75455	0.160809	85.75455	0.162245	85.35841	0.192152
5	85.25448	0.209409	84.75448	0.207941	85.75448	0.210877	85.35809	0.240189
6	85.25434	0.257291	84.75435	0.255073	85.75434	0.259509	85.35769	0.288225
7	85.25413	0.305172	84.75414	0.302204	85.75412	0.30814	85.35723	0.33626
8	85.25384	0.353053	84.75386	0.349335	85.75383	0.356771	85.35669	0.384293
9	85.25349	0.400934	84.75351	0.396466	85.75347	0.405402	85.35608	0.432326
10	85.25306	0.448813	84.75309	0.443595	85.75303	0.454031	85.3554	0.480357
M	M	M	M	M	M	M	M	M
511	77.58239	20.38798	77.22069	20.04276	77.9441	20.73319	77.63002	20.38977
512	77.55453	20.41717	77.19335	20.07141	77.91571	20.76293	77.60217	20.41882
513	77.53356	20.43908	77.17289	20.09278	77.89423	20.78537	77.58121	20.44062
514	77.50565	20.46814	77.14551	20.1213	77.86579	20.81499	77.55333	20.46954
515	77.48465	20.48995	77.12503	20.14257	77.84428	20.83732	77.53234	20.49123
516	77.4567	20.51889	77.09761	20.17096	77.81579	20.86681	77.50441	20.52003
517	77.43568	20.54058	77.0771	20.19213	77.79425	20.88904	77.4834	20.54162
518	77.40767	20.5694	77.04963	20.22039	77.76572	20.91841	77.45542	20.57029
519	77.38663	20.59099	77.0291	20.24145	77.74415	20.94053	77.4344	20.59177
520	77.35858	20.61968	77.00159	20.26959	77.71557	20.96976	77.40637	20.62031
521	77.33751	20.64116	76.98097	20.29063	77.69406	20.9917	77.38532	20.64169
522	77.31643	20.6626	76.96043	20.31152	77.67244	21.01368	77.36426	20.66302
523	77.28833	20.6911	76.93232	20.34002	77.64433	21.04219	77.33618	20.69137

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4. Conclusions

The corrective profiling of tools for enwrapping machining by rolling method may be an alternative to increase the surface's generation precision.

The proposed algorithm, allow, in certain limits, to make corrections of tool's form, in order to compensate the generating errors of blank, emerged due to some unknown causes.

Was realized a specifically software which allow the rigorous estimation of the value correction for tool's rake angle, in order to correct the generating profile of gear shaped tool's tooth.

Are presented numerical examples which proof the proposed algorithm's quality.

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Algoritm pentru profilarea corectivă a cuțitelor-roată

Rezumat

În lucrare, este prezentat un algoritm pentru profilarea corectivă a sculelor de tip roată, care generează prin înfăşurare, corecţie realizată prin modificarea suprafețelor active de aşezare sau de degajare.

Lucrarea prezintă un exemplu numeric pentru profilarea cuțitului-roată destinat generării unui vârtej plan de profiluri rectilinii (arbore cu secțiune transversală hexagonală).

Algorithme de correction pour le profilage du outil coteau roue

Résumé

Dans cette ouvrage est présenté un algorithme de correction du profil de l'outil couteaux roue qui génèrent par la méthode des surfaces enveloppes. La correction est réalisée par la modification de la face de dépouille ou la face de coupe du outil couteaux- roue.

On présente un exemple numérique pour la correction du profil d'un outil couteaux roue pour la génération de profils rectiligne (arbre hexagonal).

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