Comparison Between CAD Method and Analytical Method —Rack-Gear Tool's Profiling—

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ABSTRACT

In this paper we propose a CAD method, developed in CATIA design software, for profiling of tool's generating by enwrapping, especially for rack-gear tool.

The method is based on the creation of a virtual mechanism in keeping with the rolling condition of centrodes associated with enveloping profiles assuring that the tool's profile and blank's profile meet one of the fundamental theorems of gearing.

It was elaborated, in CATIA design environment, an algorithm and specialized software for determination of the generating rack-gear. In this paper is proposed the numerical validation of the results with an analytical method, unanimously accepted.

There are presented application examples for simple analytical profiles.

KEYWORDS: enveloping surfaces, rack-gear tool, graphical design method

1. Introduction

The profiling of tools generating by enveloping using the rolling method —rack gear tool and gear shaped tool— may be made by some methods:

- analytical methods, based on fundamental methods of surfaces enwrapping – first Olivier theorem, Gohman theorem, normals theorem, Willis [1], [2], [10], [13], [14];
- complementary analytical methods – "minimum distance" method, the "substitutive circles family" method, the "in-plane generating trajectories" method [3]-[5];
- graphical-analytical methods [6];
- graphical methods, using the capabilities of CAD software [7],[14]

We mention that the methods proposed and used for the study of reciprocally enveloping surfaces respect the enveloping fundamental theorem.

The proposed solutions lead to comparable results, in most cases identically, for the crossing profile tool's shape, generating by rolling ordered curls profiles associated with a couple of rolling centrodes.

2. Kinematics Method in CATIA Design Environment

It is proposed a new solution of the rack tool's profiling, using the capabilities of CATIA software, by making a kinematics entity which reproduces the rolling movement of centrodes: circle with the radius R_{rp}, associated with the profile's curl and a straight line, associated with the space of the rack tool.

The proposed solution is based on the facilities of the *Part* environment (*Part Environment*), in which the elements of a mechanism are synthesized, being able to simulate the enwrapping condition, in this case the condition of normals. These elements, created in *Part* environment, are introduced in a file of the *Assembly* environment, assuring the positioning of the mechanism elements in the start position, and then, in the *DMU Kinematics* environment (*Digital Mock Up*) to be defined the predefined kinematics couples.

The mechanism movement is made upon the command *Simulation*, establishing a number of intermediary positions *Shots*, creating with *Replay* command, a movie of the successive positions of the mechanism.

Upon the command *Trace*, the trajectory of any point can be traced starting from an element and regarding any other of the elements of the mechanism, including the global reference system, determining in this way, the gearing line between the profile to be generated and the rack tool's profile.

These trajectories represent curves on type *Spline*, obtained by successive points obtained by mechanism rolling. The coordinates of these points may be extracted as text files, see figure 1.

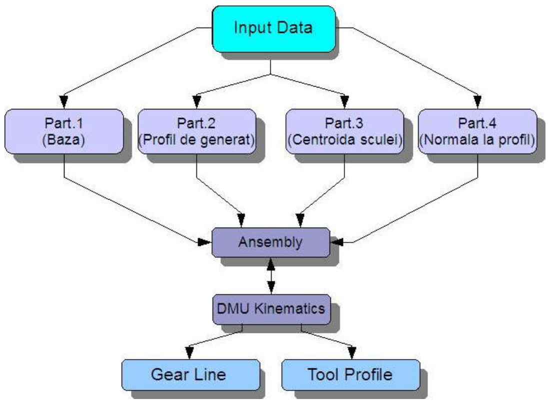

Fig. 1. *Algorithm for generating in the CATIA design environment*

The proposed solution has the advantage to use the capabilities of versatile software, which may offer very rigorous numerical results.

At the same time, being a graphical method, rough errors, due to the passing curves, which may be erroneously regarded as profile's zone, are easy to be identified and eliminated.

There are regarded three types of piece's profiles for which are designed as many types of virtual mechanisms in the CATIA environment (M.G.M.C).

These mechanisms are presented in table 1.

Table 1. *Types of M.G.M.C.*

M.G.C.M. type	Piece's profile type
M.G.C.M. for straight line profile	Straight line profiles
M.G.C.M. for circle's arc profile	Circle arc's profile, tangent or not in the contact points
M.G.C.M. for spline profile	Profiles composed by curves, given by points or known by equation

Analytical method

In principle, the problems of tool's profile determination reciprocally enveloping with an ordered profile's curl, associated with a circular centrode, presume the meeting of the generating process kinematics, see figure 2.

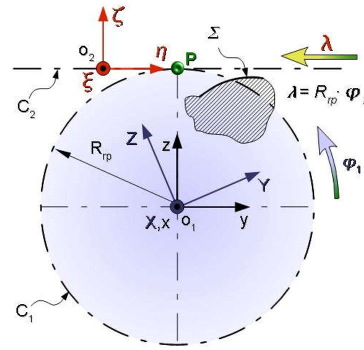

Fig. 2. *Rolling centrodes couple; Generation kinematics*

The two rolling centrodes, C_1 —circle, associated with the profiles ordered curls and C_2 — straight line, associated with the rack-gear tool, are in rolling movement, so, the following condition is respected:

$$\lambda = R_{rp} \cdot \varphi_1, \tag{1}$$

where λ is the linear velocity in the translation of C_2 centrode;

$R_{rp} \cdot \varphi_1$ — the value of velocity in point O_1— the gearing pole, from C_1 centrode, in the rotation movement around z axis;

φ_1 — variable angular parameter.

In the rotation of C_1 centrode the translation movements along the C_2 centrode and the rotation around Z axis are even.

There are defined the reference systems:

xyz is the global reference system, with z axis overlapped to the rotation axis of the C_1 centrode;

XYZ — mobile reference system, initially overlapped to the global reference system, joined with the ordered curls profile Σ;

$\xi\eta\zeta$ — mobile reference system, joined with C_2 centrode of rack-gear tool, with axis parallel to and of the same sense with the global reference system, xyz.

The kinematics of the rolling process of the two centrodes, C_1 and C_2, tangents in point O_1 — gearing pole— presume that the velocities of points belong to the two centrodes, temporarily situated in point O_1, to be equals.

In this way, the global motion of the $\xi\eta\zeta$ reference system, joined with the centrode C_2, is described by the transformation,

$$x = \xi + a, \tag{2}$$

where:

$$\xi = \begin{pmatrix}\xi & \eta & \zeta\end{pmatrix}^T;\ x = \begin{pmatrix}x & y & z\end{pmatrix}^T \tag{3}$$

represent the matrix of the current points in the space $\xi\eta\zeta$, respectively, xyz;

$$a = \begin{pmatrix}0 & -\lambda & -R_{rp}\end{pmatrix}^T \tag{4}$$

is the matrix formed with the coordinates of point O_1, in the global reference system, with λ as instantaneous velocity in the translation movement of C_1 centrode and R_{rp} the value of the circular centrode C_1 (rolling radius).

Also, the revolution movement of C_1 centrode is described by the transformation

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \omega_1^T(\varphi_1) \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (5)$$

where $\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$ is the matrix of the current point in space XYZ, and

$$\omega_1(\varphi_1) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\varphi_1) & \sin(\varphi_1) \\ 0 & -\sin(\varphi_1) & \cos(\varphi_1) \end{pmatrix} \quad (6)$$

is the rotation transformation matrix, around X axis, with angle φ_1 (counter clockwise rotation).

The assembly of equations (3) and (6), with the respect to rolling conditions (1), determine the relative motion,

$$\begin{pmatrix} \xi \\ \eta \\ \zeta \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\varphi_1) & \sin(\varphi_1) \\ 0 & -\sin(\varphi_1) & \cos(\varphi_1) \end{pmatrix} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} - \\ - \begin{pmatrix} 0 \\ -\lambda \\ -R_{rp} \end{pmatrix} \quad (7)$$

while the Σ profile, belongs to the profile's ordered curl, associated with the C_1 centrode, in the form,

$$\Sigma = \begin{pmatrix} 0 & Y(u) & Z(u) \end{pmatrix}^T \quad (8)$$

with u variable parameter, describing a profile's family in the rack-gear space:

$$(\Sigma)_{\varphi_1} \begin{vmatrix} \xi(u,\varphi_1) = 0; \\ \eta(u,\varphi_1) = Y(u)\cos(\varphi_1) - Z(u)\sin(\varphi_1) + \\ +R_{rp} \cdot \varphi_1; \\ \zeta(u,\varphi_1) = Y(u)\sin(\varphi_1) + Z(u)\cos(\varphi_1) - \\ -R_{rp}. \end{vmatrix} \quad (9)$$

It is associated with the (9) profile's family an enveloping condition defined in analytical form, based on the fundamental theorems or the complementary methods.

If it is accepted the specific condition of the in-plane generating trajectories, in the form,

$$\eta'_u \cdot \xi'_{\varphi_1} - \eta'_{\varphi_1} \cdot \xi'_u = 0, \quad (10)$$

where $\eta'_u, \xi'_{\varphi_1}, \eta'_{\varphi_1}, \xi'_u$ represent the partial derivative, calculated using (9), then the equations assembly (9) and (10), represent the rack-gear tool's profile.

For $\varphi_1 = const.$, are determined the coordinates of the contact point between the tool and the blank, regarding the tool's reference system.

Due to the fact that (10) condition represent, in principle, a link between the parameters u and φ_1,

$$u = u(\varphi_1) \quad (11)$$

the profile's family (9) is transformed into the form of:

$$\Sigma_{(\varphi_1)} \begin{vmatrix} \xi = 0; \\ \eta = \eta(\varphi_1); \\ \zeta = \zeta(\varphi_1). \end{vmatrix} \quad (12)$$

The form (12) represent the rack-gear tool's profile.

It was proposed, in order to validate the CAD method, as it was created this, the realization of a comparison, for simple profiles: straight line, circle's arc, involute profile.

3. The Generating of Straight Lined Profiles

In order to obtain the tool's profile for various polygonal shafts, for various side lengths, it is necessary to follow two stages. The first stage is to choose the side length and the diameter of the rolling circle as input data.

This thing may be done introducing in a text or Excel file the value, in following, the CATIA software will automatically modify the whole mechanism, with the new values. In the same stage, it is created the mechanism, the rolling of this and the tool's profile determination. The coordinates of points belonging to profile will be exported in a text or Excel file.

In figure 3, it is presented a polygonal shaft and the references system related to it.

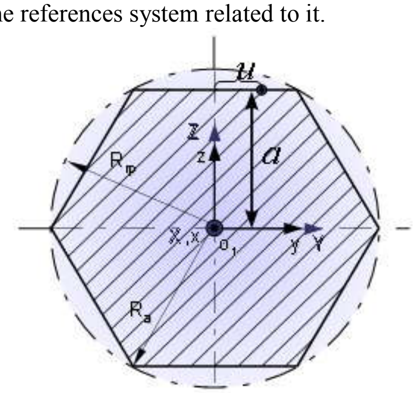

Fig. 3. *Crossing section of the hexagonal shaft*

M.G.M.C. for straight line segment

The virtual mechanism specific for this case (profile represented by a straight line segment), is presented in figure 4 and Table 2.

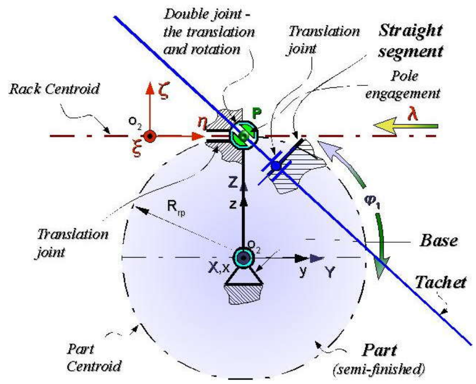

Fig. 4. *M.G.M.C. for straight segment and rack-gear tool*

The *Tool* element is a straight line which represent the centrode associated with the rack-gear and which rolls without sliding on the circle circumference which is the piece’s centrode.

The *Base* element is the fixed element which allows the piece’s translation and the sledge rotation. The *Sledge* element has a link with the *Base* and a link with the *Piece*. This couple is a translation couple of the rack-gear element along a guide of the fixed element *Base*.

In figure 5, it is presented the *Assembly* file with M.G.M.C. specifically, applied for the hexagonal shaft, which by the command *Simulation*, make the rolling of the two centrodes.

In figure 6, for 500 intermediary positions, the rack-gear tool profile is drawn, the whore coordinates are presented in table 3, for hexagonal shaft with the side 50 mm (rolling radius, R_{rp}=50 mm).

Table 2. *Couples used in DMU Kinematics environment*

Crt. no.	Joint type	Mechanism elements	
1	Fix	Base	-
2	Revolute	*Base*	Axa (*Piece*)
3	Prismatic	*Base*	Dreapta de rulare (*Rack-gear*)
4	Rack-gear = Prismatic + Revolute	GhidajDreaptaRulare, AxaArbore and Plan YZ (*Base*)	DreaptaRulare, AxaArbore şi Plan YZ (*Rack-gear*)
5	Prismatic	*Sledge*	Profile side L (*Piece*)
6	PointCurve	PolulAngrenarii (*Base*)	Normal (*Sledge*)
7	PointCurve	PunctContact (*Sledge*)	Profile side L (*Piece*)

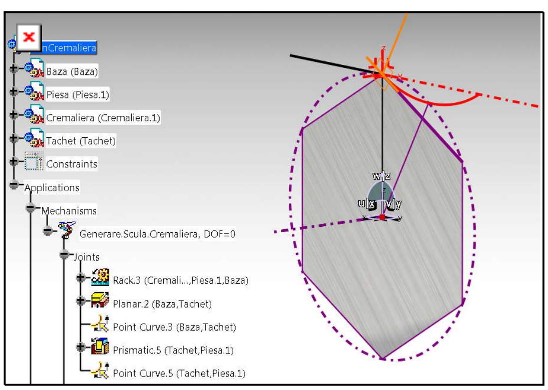

Fig. 5. *Assembly file with kinematics couples and tool’s profile*

The tool’s profile is obtained by command *Trace* and select as tracking element the *ContactPoint* point on *Sledge*, which will draw in the rack-gear reference system, the tool’s profile. This profile is automatically saved in a file named *SculaHexagon.part* and insert in the assembly file.

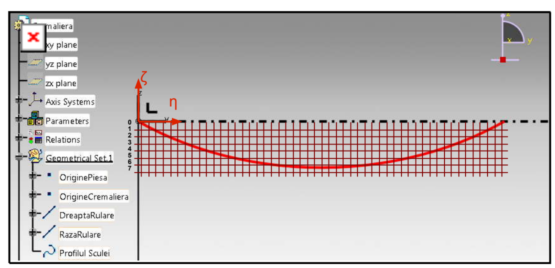

Fig. 6. *Tool’s profile in the ξηζ reference system*

Analytical method

Linking with figure 3 and equation (7), for the hexagonal shaft flank results:

$$\Sigma\left|\begin{array}{l} X=0; \\ Y=u; \\ Z=a, \end{array}\right. \qquad (13)$$

so, the Σ profile’s family equations in the rack-gear reference system, see (9), become:

$$(\Sigma)_\varphi \begin{cases} \xi = 0; \\ \eta = u\cos\varphi - a\sin\varphi + R_{rp}\varphi; \\ \zeta = u\sin\varphi + a\cos\varphi - R_{rp}. \end{cases} \quad (14)$$

The enwrapping condition, see (10), become

$$u - R_{rp}\,sin\,\varphi_1 = 0\,. \quad (15)$$

The equations assembly (14) and (15) represents the rack-gear tool’s profile.

The variations limit of the *u* parameter:

$$u_{min} = -\frac{R_{rp}}{2};\; u_{max} = \frac{R_{rp}}{2}. \quad (16)$$

In table 3, based on a specialized software, are presented the profile’s coordinates for a *u* parameter variation pitch,

$$\Delta u = \frac{u_{max} - u_{min}}{500}. \quad (17)$$

Table 3. *Points coordinates on tool’s profile (Kinematics method)*

Crt. no.	ξ [mm]	η [mm]	Crt. no.	ξ [mm]	η [mm]	Crt. no.	ξ [mm]	η [mm]
1	1.40E-06	-26.1799	**248**	6.698025	-0.28286	**496**	0.199296	25.83104
2	0.05004	-26.093	**249**	6.698477	-0.1695	**497**	0.149679	25.9186
3	0.099941	-26.0059	**250**	6.698703	-0.05562	**498**	0.099923	26.00594
4	0.149712	-25.9185	**251**	6.698701	0.057729	**499**	0.050028	26.09306
5	0.19934	-25.831	**252**	6.698471	0.171609	**500**	8.88E-07	26.17994

Table 4. *Points coordinates on tool’s profile (classical method)*

Crt. no.	ξ [mm]	η [mm]	Crt. no.	ξ [mm]	η [mm]	Crt. no.	ξ [mm]	η [mm]
1	0.0011	26.18057	**248**	6.69898	0.3402	**496**	0.20003	-25.832
2	0.05103	26.09385	**249**	6.69955	0.2268	**497**	0.1505	-25.92
3	0.10083	26.0069	**250**	6.69989	0.1134	**498**	0.10083	-26.007
4	0.1505	25.91972	**251**	6.7	0	**499**	0.05103	-26.094
5	0.20003	25.83232	**252**	6.69989	-0.1134	**500**	0.0011	-26.180

In figure 7 and table 4, are presented the two profiles of the rack-gear tool, determined by the two methods: kinematics method, proposed in this paper versus an analytical classical method.

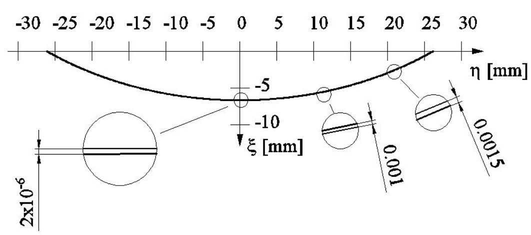

Fig. 7. *Rack-gear tool’s profile by the two methods: CATIA and classical method*

4. The Generating of Circle’s Arc Profile

The rack-gear tool’s profiling for a profile composed of circles arc, as sprocket, see figure 8, imposes to create in DMU Kinematics a specifically virtual mechanism for generation by enwrapping of a circle’s arc, see figure 9.

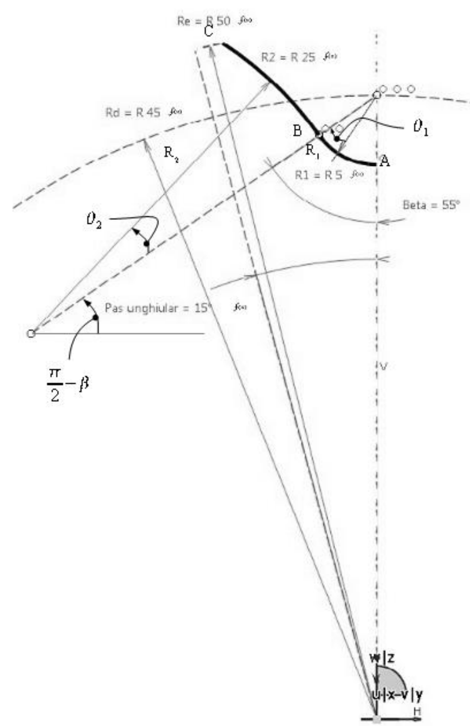

Fig. 8. *Profile’s geometry of a sprocket tooth flank*

For the tool's profile determination, which generates the flank of a sprocket tooth, the algorithm is the same as that for the previous profile. The Piece profile will contain two drafts with the flank profile, see figure 8.

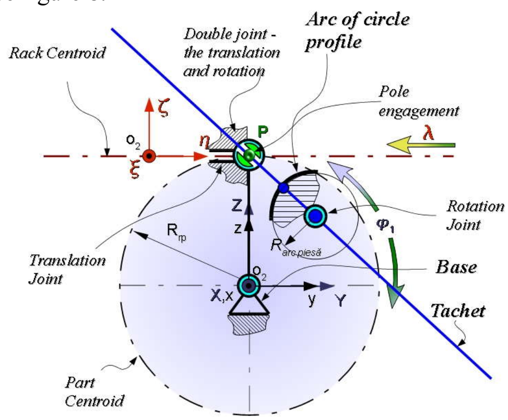

Fig. 9. *M.G.M.C. for circle's arc*

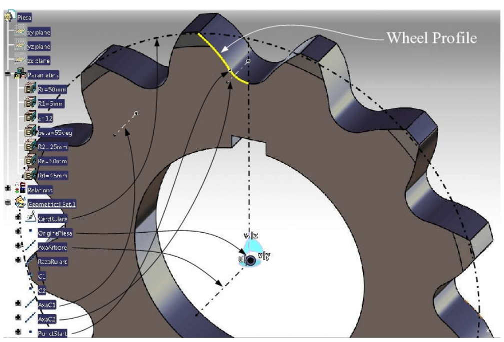

Fig. 10. *Sprocket—assembly—Piece's file*

The particularity regarding the virtual mechanism for generating in CATIA environment (M.G.M.C.) for straight line segments consists, in fact, in the translation couple between the *Sledge* and the *Piece* replaced by a rotation couple around an axis which cross the centre arc representing the profile.

The other elements and commands remain unchanged.

After the creation of the file *Pieces* in *DMU Kinematics* environment, the mechanism couples specific for the curved profiles are created. For this, the couple *Prismatic* from the straight lined profiles are replaced with the *Revolute* couples for the axis of the circle's arc which represent the profile.

This couple type allows the *Sledge* element to rotate around the axis of the circle's arcs (*AxaC1* and *AxaC2*), around a similar axis of the *Piesa* file while the *PointCurve* couple, between the *ContactPoint* couple of the *Sledge* file, the *PieceProfile* of the *Piece* file remaining as the leader element.

In the DMU Kinematics environment will be realised two mechanisms, see figure 10, for each arc of the composed profile, see table 5.

After the creation of the mechanism, of the simulation and after the record of the kinematics, with command *Trace*, is draw the tool's profile.

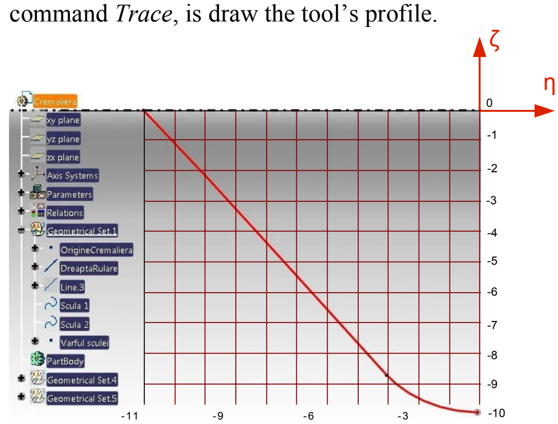

Fig. 11. *Rack-gear profile for sprocket*

In figure 11 and table 6, is presented the rack-gear tool's profile for the sprocket with the characteristics: R_r=R_e=55 mm; z=12 teeth; R_2=25 mm; R_1=5 mm; β=55°; R_d=45 mm.

Table 5. *Kinematics couples for the sprocket profile*

Nr. Crt.	***Joint type***	***Mechanism elements***	
1	*Fix*	Base	-
2	*Revolute*	Axis (*Base*)	Axis (*PIece*)
3	*Prismatic*	Rack-gear guide (*Base*)	Rolling line (*Rack-gear*)
4	*RollCurve*	Rolling circle (*Piece*)	Rolling circle (*Rack-gear*)
5	*Revolute*	AxaC1 and AxaC2 (*Base*)	AxaC1 și AxaC2 (*Piece*)
6	*PointCurve*	Gearing pole (*Base*)	Normal (*Sledge*)
7	*PointCurve*	Contact point (*Sledge*)	Profile's side L (*PIece*)

Table 6. *Coordinates of points on the rack-gear profile*

Nr. Crt.	*η[mm]*	*ζ[mm]*	*Nr. Crt.*	*η[mm]*	*ζ[mm]*	*Nr. Crt.*	*η[mm]*	*ζ[mm]*
1	-2.9610	6.7801	71	-0.5130	2.3978	36	1.6897	-0.9610
8	-2.6400	6.2515	78	-0.2569	1.9157	43	1.9671	-1.1672
15	-2.3974	5.8403	85	0.0117	1.4121	50	2.2592	-1.3523
22	-2.1598	5.4285	92	0.2956	0.8835	57	2.5641	-1.5155
29	-1.9260	5.0149	100	0.5979	0.3265	64	2.8802	-1.6559
36	-1.6946	4.5982	1	0.5979	0.3265	71	3.2055	-1.7730
43	-1.4641	4.1767	8	0.7680	0.0442	78	3.5383	-1.8662
50	-1.2327	3.7485	15	0.9655	-0.2299	85	3.8770	-1.9351
57	-0.9985	3.3111	22	1.1867	-0.4907	92	4.2197	-1.9795
64	-0.7594	2.8619	29	1.4289	-0.7350	100	4.6634	-2.0000

Analytical solution

According to figure 8, are defined the parametrical equations for the two circle’s arc, which constitute the sprocket flank:

$$AB\left|\begin{aligned}&Y=-R_1\sin\theta_1;\\&Z=R_d-R_1\cos\theta_1,\end{aligned}\right.\qquad \theta\in[0,\beta] \tag{18}$$

and

$$BC\left|\begin{aligned}&Y=-(R_1+R_2)\sin\beta+R_2\sin(\beta-\theta_2);\\&Z=R_d-(R_1+R_2)\cos\beta+R_2\cos(\beta-\theta_2).\end{aligned}\right. \tag{19}$$

In this way, from (7), may be deduced the profile’s family equations in the relative motion of the two centrodes C_1 and C_2, see figure 2:

$$(AB)_{\varphi_1}\left|\begin{aligned}&\eta=-R_1\sin(\theta_1-\varphi_1)-R_d\sin\varphi_1+R_{rp}\varphi_1;\\&\zeta=R_1\cos(\theta_1-\varphi_1)+R_d\cos\varphi_1-R_{rp}.\end{aligned}\right. \tag{20}$$

and

$$(BC)_{\varphi 1}\left|\begin{aligned}&\eta=-(R_1+R_2)\sin(\beta_1-\varphi_1)+\\&+R_2\sin(\beta-\theta_2-\varphi_1)-R_d\sin\varphi_1+R_{rp}\varphi_1\\&\zeta=-(R_1+R_2)\cos(\beta_1-\varphi_1)+\\&+R_2\cos(\beta-\theta_2-\varphi_1)+R_d\cos\varphi_1-R_{rp}.\end{aligned}\right. \tag{21}$$

The specific enwrapping conditions, determined by the in-plane generating trajectories (10) are:

- for $(AB)_{\varphi 1}$ family,

$$\varphi_1=\theta_1-\arcsin\left(\frac{R_d}{R_{rp}}\sin\theta_1\right); \tag{22}$$

- for $(BC)_{\varphi 1}$ family,

$$\varphi_1=\beta_1-\theta_2-$$
$$-\arcsin\left[\frac{R_d\sin(\beta-\theta_2)+(R_1+R_2)\sin\theta_2}{R_{rp}}\right] \tag{23}$$

The variation limits of parameters,

$$0\le\theta_1\le\beta,\ \beta=55^{o} \tag{24}$$

and

$$0\le\theta_2\le\theta_{2max}, \tag{25}$$

θ_2 is determined, from the intersection condition between the arc with radius R_2 with the external circle of wheel (R_c=R_{rp}=50 mm).

In figure 12 and table 7, are presented the form and coordinates of the rack-gear tool’s profile calculated according to (20)-(23) relations, versus the profile determined by CAD method, previously presented.

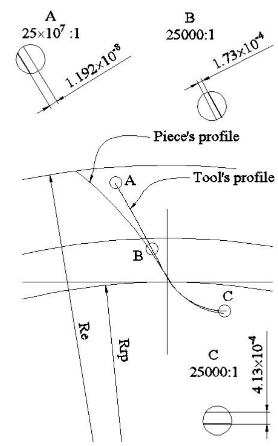

Fig. 12. *Rack-gear for sprocket generation*

Table. 7. *Coordinates of points on rack-gear profile*

ξ [mm]	η [mm]
-0.00273	-11.07982
0.1355	-10.94476
0.27482	-10.80921
0.41525	-10.67315
⋮	⋮
9.99403	-0.23024
9.99735	-0.15356
9.99934	-0.0768
10	0

5. Conclusions

The presented study proves the capabilities of the proposed method to describe the rack-gear profile form in a rigorous way.

Using the capabilities of the CATIA design environment, it is easy to draw the interference trajectories between the profile to be generated and the generating tool and at the same time the gearing line, only by changing the regarded element defining the contact point between the two conjugated profiles.

The proposed validation issue may be extended to the other generating proceses by enveloping, by the rolling method (generation with gear-shaped tool or generation with worm mill tool).

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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Comparație între metoda CAD şi metoda analitică
—Profilarea sculei cremalieră—

Rezumat

Se propune o metodă CAD, dezvoltată în mediul de proiectare CATIA, pentru profilarea sculelor generatoare prin înfăşurare, în speță scula cremalieră.

Metoda bazată pe imaginarea unor mecanisme virtuale care asigură că profilurile sculei şi semifabricatului satisfac una dintre teoremele fundamentale ale angrenării. A fost elaborat, în mediul de proiectare CATIA, un algoritm şi un soft specializat pentru determinarea profilului cremalierei generatoare.

Sunt prezentate exemple de aplicare pentru profiluri analitice simple.

Comparaison entre la méthode CAD et méthode d'analyse
—Outil grille profilage—

Résumé

Dans le présent document est proposé une méthode de CAO, développé en logiciel de conception CATIA, pour le profilage de l'outil, qui a généré par enveloppant. La méthode est basée sur la création d'un mécanisme virtuel de maintien de l'état glissant de centrodes associés à enveloppant profils assurer que les deux profils rencontrer l'un des théorèmes fondamentaux de l'engrenage.

Il a été élaboré, dans un environnement de conception CATIA, algorithmes et de logiciels spécialisés pour la détermination de la crémaillère de production.

Ils sont présentés des exemples d'application pour les profils d'analyse simple