



TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering  
Vol. 65, Issue Special IV, December, 2022

## GENERATING CURVED TEETH IN CAD SOFTWARE

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**Abstract:** *The paper presents the stages of generating solids that materialize gears with curved teeth and finally the gears obtained. These steps are performed in AutoCAD with AutoLisp function (that run in AutoCAD) and presupposes the existence of a generating tool and a semi-finished product. The way of obtaining the teeth is similar to the industrial processes of obtaining the gears or of the tools that process the gears. The algorithms presented and the AutoLisp functions that accompany them, allow to obtain gears with straight or curved teeth, regardless of the shape of the tooth or the appearance of the semi-finished product.*

**Keywords:** *CAD solids, toothed gears, generating solids, AutoLisp functions.*

### 1. INTRODUCTION

Gearboxes are among the most widely used machine components.

The variety of sizes, tooth layout, and the way the gear shafts are positioned, make the field to be addressed further [1-2].

The increase in transmitted power with the decrease in gear size has led to new gear tooth profiles or special tooth shapes [3-4]. All these are related to the simplest, most economically and energy efficient machining processes [5-7].

The theory of gear generation [1-2] presents general and particular aspects of tooth appearance and generation.

Gears with curved teeth generally have more complicated technological processes than gears with straight or inclined teeth.

Increasing emphasis is being placed on CAD/CAM/CAE generation and manufacturing. This results in lower cost prices while increasing economic efficiency [3,6,8].

Technological processes for tooth production include copying and rolling.

The copying process involves obtaining gears from an approximate shape and then milling the teeth, with disc or finger cutters, planning with template tools etc.

The rolling process involves the meshing between the tool and the semi-finished part approximating the gear. The teeth of the gears, depending on the purpose of the gearing, may have several profiles.

The most commonly used is the involute profile, which is obtained relatively simply by rolling without slipping. This profile also has the advantage that the gears being geared can be machined with the same tool.

The generation of gears with CAD software allows the rapid and extremely precise production of the solids that form the generating tools and, finally, the gears.

The simple way of obtaining them makes the method attractive, and it is also possible to generate other bodies that comply with the general theory of gearing [2].

In the following we will present how to obtain in AutoCAD the solids that materialize generating tools and gears with curved teeth, using AutoLisp functions.

AutoLisp is a programming language included in AutoCAD, through which we can transfer the computational relations of an analytical method into Lisp language. Thus, in a graphical environment, an analytical method has a graphical representation of the results.

## 2. GENERATING RACK TEETH

With the MAAG process, the gear teeth are practically obtained with a comb knife. The teeth of the tool have the dimensions shown in figure 1.

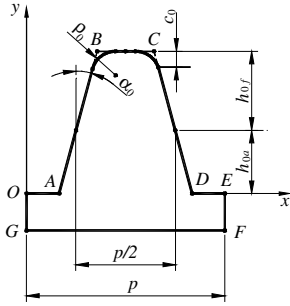


Fig. 1. Tooth size of the generating gear rack.

To obtain the solid that materializes such teeth in AutoCAD, proceed as follows:

- it is constructed the  $ABCD$  contour with the Pline command,
- the previous contour is connected with the command Fillet, with the radius  $\rho_0$ ,
- it is constructed the  $DEFGOA$  contour with the Fline command (the distances  $EF = OG$  have no fixed values),
- the two contours are joined into a single closed contour with the Pedit command,
- the EXTRUDE command is used to extrude the previous contour with a height  $l$  greater than the thickness  $b$  of the gear and an angle  $\alpha_0$ ,
- it is multiplied regularly with the ARRAY command the solid obtained, with the pitch  $p$  of the reference rack, on a sufficient number of columns to generate the gear.

All dimensions are a function of the modulus  $m$  of the reference rack:  $p = \pi m$ ,  $\alpha_0 = 20^\circ$ ,  $h_{0a} = m$ ,  $h_{0f} = 1,25m$ ,  $\rho_0 = 0,38m$ ,  $c_0 = 0,25m$ .

Figure 2 shows such a rack with straight teeth of  $m = 5$  mm, 10 teeth and a width  $l = 60$  mm.

With such a generating rack, gears with straight teeth and inclined teeth are obtained.

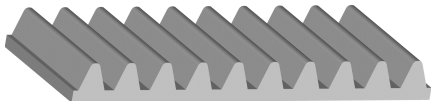


Fig. 2. The solid that materializes the generating rack.

To obtain the inclined teeth, the generating rack is rotated through an angle  $\beta$  (the angle of inclination of the teeth).

To obtain curved teeth it will be needed to use circle arches of the same radius.

Figure 3 shows the planar construction of the generating rack tooth with curved teeth.

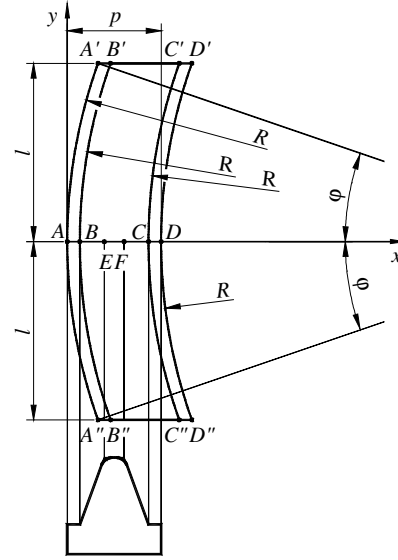


Fig. 3. Flat tooth construction of the generating rack with curved teeth.

Knowing the values for  $m$  (gear wheel modulus),  $b$  (gear wheel thickness) and  $R$  (tooth radius of curvature) and the dimensions of the straight-toothed reference rack, it is determined the coordinates of the points in figure 3.

Points  $A(x_A, y_A)$ ,  $B(x_B, y_B)$ ,  $C(x_C, y_C)$ ,  $D(x_D, y_D)$  and the angle  $\varphi$  have the expressions:

$$x_A = 0, y_A = 0, \quad (1)$$

$$x_B = \frac{p}{4} - h_{0a} \tan \alpha_0, y_B = 0, \quad (2)$$

$$x_C = p - x_B, y_C = 0, \quad (3)$$

$$x_D = p, y_D = 0, \quad (4)$$

$$\varphi = \sin^{-1} \frac{l}{R}. \quad (5)$$

In the same reference system, the upper and lower points have expressions:

$$A'(x_{A'}, y_{A'}) : x_{A'} = R - R \cos \varphi, y_{A'} = l, \quad (6)$$

$$A''(x_{A''}, y_{A''}) : x_{A''} = x_{A'}, y_{A''} = -l, \quad (7)$$

$$B'(x_{B'}, y_{B'}) : x_{B'} = x_{A'} + x_B, y_{B'} = l, \quad (8)$$

$$B''(x_{B''}, y_{B''}) : x_{B''} = x_{B'}, y_{B''} = -l, \quad (9)$$

$$C'(x_{C'}, y_{C'}) : x_{C'} = x_{A'} + x_C, y_{C'} = l, \quad (10)$$

$$C''(x_{C''}, y_{C''}) : x_{C''} = x_{C'}, y_{C''} = -l, \quad (11)$$

$$D'(x_{D'}, y_{D'}) : x_{D'} = x_{A'} + x_D, y_{D'} = l, \quad (12)$$

$$D''(x_{D''}, y_{D''}) : x_{D''} = x_{D'}, y_{D''} = -l. \quad (13)$$

For the construction of the solid that materializes the teeth of the generating rack, in AutoCAD, an AutoLisp function is prepared that performs the following operations:

- the construction with the Pline command of the arc  $A''A'$  of a circle of radius  $R$  and its multiplication at the points  $B$ ,  $C$  and  $D$ , the point  $A$  being the reference point,
- the construction with the Pline command of the line segments  $A'D'$ ,  $A''D''$ ,  $B'C'$ ,  $B''C''$ ,
- the Joint option of the PEdit command it is used to make the closed contours  $B'C'C''B''$ : (curve that will generate the tooth) and  $A'D'D''A''$  (curve that will generate the base of the tooth),
- the extrusion the contour  $B'C'C''B''$  with the EXTRUDE command, with the height  $h = h_{0a} + h_{0f}$  and angle  $\alpha_0$  of the extrusion,
- the rounding with the Fillet command of the head of the tooth  $\rho_0$  with the radius of the joint, using as selection points  $E(x_E, y_E)$  and  $F(x_F, y_F)$  of coordinates:

$$x_E = x_B + h \tan \alpha_0, y_E = 0, \quad (14)$$

$$x_F = x_C - h \tan \alpha_0, y_F = 0. \quad (15)$$

- the extrusion of the contour  $A'D'D''A''$  with the EXTRUDE command, with the height  $h' = -m$  and angle  $\alpha = 0$  of the extrusion angle, resulting in the tooth base,
- the joining, with the UNION command, of the two solids, resulting in a tooth of the generating rack,
- the multiplication with the ARRAY command, with the pitch  $p = \pi m$  of the reference rack, on a sufficient number of columns, 'Rack' to the resulting solid.

Figure 4 shows the solid materializing a generating rack with:  $m = 5$  mm,  $R = 90$ , 10 teeth and a width of  $2l = 60$  mm.

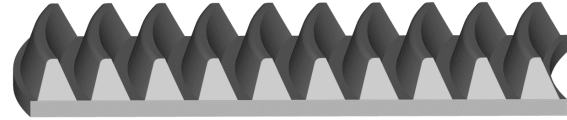


Fig. 4. Generator rack with curved teeth.

With this gear rack are obtained gears with curved teeth. For the conjugate gear wheel, the teeth of the generating rack should have a reverse curvature.

This is easily done either by mirroring the rack tooth with the MIRROR3D command or by mirroring the rack in figure 4. In both cases the mirror plane is the plane  $YOZ$ . The result is the solid in figure 5.

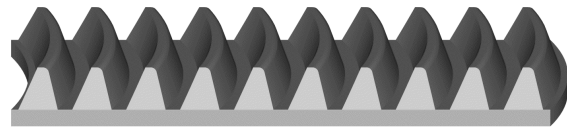


Fig. 5. Combined curved teeth generating rack.

The Lisp function used has the following content:

```
(Defun Cremaliera_Dinti_Curbi ()
(Setup ha m hf(* 1.25 m) hmic(+ ha hf) raza(* 0.38 m)
  alfa_rad(* alfa0 (/ pi 180)) sinx(sin alfa_rad) cosx(cos
alfa_rad) tg_alfa(/ sinx cosx) pas(* Pi m)
  xA 0 yA 0 A(List xA yA)
  xB(- (/ pas 4) (* tg_alfa ha)) yB 0 B(List xB yB)
  xC(- pas xB) yC 0 C(List xC yC)
  xD pas yD 0 D(List xD yD))
(Setup RazaDinte(* 3.0 bmic) sinfi(/ bmic RazaDinte)
  cosfi(Sqrt(- 1.0 (* sinfi sinfi)))
  ung_fi_rad(Atan sinfi cosfi)
  ung_fi_grd(* ung_fi_rad (/ 180 pi))
  xAprim(- RazaDinte (* RazaDinte cosfi))
  yAprim bmic Aprim(list xAprim yAprim)
  xAsec xAsec yAsec(* -1 bmic) Asec(List xAsec
yAsec))
(Command "Pline" Aprim "A" "R" RazaDinte Asec "")
(Setup Curba(EntLast))
(Command "Copy" Curba "" A D)
(Setup Curba3(EntLast))
(Setup xDprim(+ xAprim pas) yDprim bmic
Dprim(List xDprim yDprim) xDsec xDprim yDsec(* -1.0
bmic) Dsec(List xDsec yDsec))
(Command "Pline" Aprim Dprim "")
(Setup Linia3(EntLast))
(Command "Pline" Asec Dsec "")
(Setup Linia4(EntLast))
```

```
(Command "PEdit" Curba "J" Curba Linia3 Curba3
Linia4 "" "") (Setq bazaD(EntLast))
(Command "Pline" Aprim "A" "R" RazaDinte Asec "")
(Setq Curba(EntLast)) (Command "Copy" Curba "" A B)
(Setq Curba1(EntLast)) (Command "Copy" Curba "" A C)
(Setq Curba2(EntLast))
(Setq xBprim(+ xAprim xB) yBprim bmic Bprim(List
xBprim yBprim)
xBsec xBprim yBsec(* -1 bmic) Bsec(List xBsec yBsec)
xCprim(+ xAprim xC) yCprim bmic Cprim(List xCprim
yCprim)
xCsec xCprim yCsec(* -1 bmic) Csec(List xCsec yCsec))
(Command "Pline" Bprim Cprim "")
(Setq Linia1(EntLast))
(Command "Pline" Bsec Csec "")
(Setq Linia2(EntLast))
(Command "PEdit" Curba1 "J" Curba1 Linia1 Curba2
Linia2 "" "") (Setq Dinte(EntLast))
(Command "Extrude" Dinte "" hmic alfa0)
(Setq xSel1(+ xB (* hmic (Sin alfa_rad))) S1(List xSel1
0.0)
xSel2(+ xC (* hmic (Sin alfa_rad))) S2(List xSel2 0.0))
(Command "Fillet" "R" raza "")
(Command "Fillet" S1 "" "")
(Command "Fillet" S2 "" "")
(Setq dinte_3D(EntLast))
(Command "Extrude" bazaD "" (* -1.0 m) "0")
(Setq Baza_D(EntLast))
(Command "Union" Dinte_3D Baza_D "")
(Setq Dinte3D(EntLast))
(Command "Array" Dinte3D "" "R" "1" dinti pas)
(Command "Union" "All" "")
(Setq Cremaliera(EntLast))
(Command "Rotate3D" Cremaliera "" "x" "0,0,0" "-90")
(Command "Erase" "All" "R" Cremaliera ""))
```

### 3. THE GENERATION OF GEAR WHEELS

Obtaining profiles in AutoCAD is based on classic machining processes: rolling without sliding between a tool and a blank. In this way equal distances or arcs are covered.

The AutoLisp functions that allows to obtain solids in AutoCAD, solids that materialize teeth and gears, can be easily modified for other types of profiles.

The algorithm for obtaining a solid that materializes a gear in AutoCAD involves the following steps:

- step 1: generating the solid that materializes the tool,
- step 2: obtaining the solid materializing the blank and positioning it in the machining position,

- step 3: in a repetitive cycle, values are being given to the angle of rotation  $\varphi$  in the range  $\varphi \in [0^\circ, 360^\circ]$  with constant pitch  $\Delta\varphi$  and perform the following operations:

- step 3.1: it is copied the solid materializing the tool and position it in contact with the solid materializing the blank in the current position,
- step 3.2: it extracted the tooling solid from the blank,
- step 3.3: it is rotated the resulting solid by the angle  $\Delta\varphi$ .

The steps of constant rotation of the blank and translation of the tool are repeated until the entire angular range has been covered.

Compared to the classic technological process, the gearwheel is obtained in a single rotation (all "machining" addition is eliminated in one step). The function has the following sequence of steps:

- declaring the constants that define the gear and establishing the displayed space,
- calling the previous function called "Cremaliera\_Dinti\_Curbi",
- the generation of the solid materializing the semi-finished product: a cylinder positioned at point  $P(0,0,0)$ , with radius

$$R_e = \frac{mz}{2} + m(1+x) \text{ and height } g, \text{ to which}$$

the name "Semifabricat" is attributed.

- copying the solid named "Cremaliera", placing the copy at point (0,0) and assigning the name "Scot" to the new solid,
- in a repetitive "while" cycle, values are given to the angle of rotation  $\varphi$  in the range  $[0^\circ, 360^\circ]$  with a constant step of  $1^\circ$  and the following operations are performed:
  - the displacement of the rack is calculated with the relationship  $s = s + \Delta s$ , where the step is  $\Delta s = \frac{mz}{2} \cdot \frac{\pi}{180}$ ,
  - the copy of the rack from point  $R(s,0,0)$  is positioned,
  - with the AutoCAD SUBTRACT command it is extracted, from the solid titled "Semifabricat" the solid titled "Scot" and

assigned the name "Roata" to the new solid,

- the new solid it is rotated with  $1^\circ$  and the steps are repeated until the entire interval is covered.

At the end the solid is obtained which materializes the tooth wheel.

Figure 6 shows the photographic image of a gear wheel with curved teeth with:  $m = 5$  mm,  $z = 25$  teeth, tooth radius  $R = 60$  mm, unaligned tooth, tooth width  $b = 10$  mm.

From the solid obtained using the previous AutoLisp function were removed: 2 discs of 5mm thickness, having  $\varphi_e = 95$  mm and  $\varphi_i = 50$  mm, positioned on the sides of the wheel and 6 holes of  $\varphi = 20$  mm positioned equidistantly. The drive wheel bore has  $\varphi_G = 30$  mm in diameter.

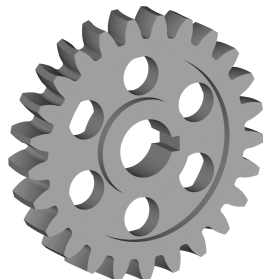


Fig. 6. Toothed wheel with 25 curved teeth.

Figure 7 shows the photographic image of the gear wheel combined with:  $z = 35$  teeth.

From the solid obtained with the AutoLisp function were removed: 2 discs of 5 mm thickness, having  $\varphi_e = 140$  mm and  $\varphi_i = 60$  mm, positioned on the sides of the wheel and 6 holes of  $\varphi = 35$  mm positioned equidistantly.

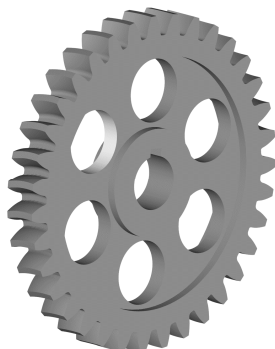


Fig. 7. Opposite gear with 35 curved teeth.

The drive wheel bore has is  $\varphi_G = 30$  mm in diameter.

Positioning the two gears at  $A = 150$  mm axle distance gives the photographic representation in figure 8.

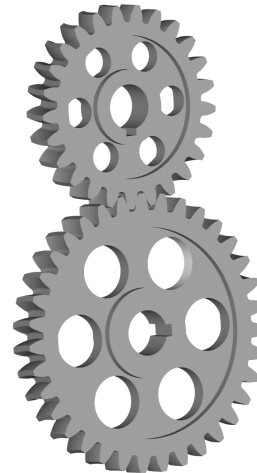


Fig. 8. Photographic representation of the gear with curved teeth.

In order to verify the accuracy of the operations performed, after positioning the solids that materialize the gear wheels in the gearing, the gear wheel  $z_1$  is rotated with the angle  $\varphi_1$ , the conjugate wheel is rotated with the angle  $\varphi_2 = \varphi_1 \frac{z_1}{z_2}$ , and with the AutoCAD INTER-

SECT command it is checked if there is a common area of intersection.

In the case of the two gears, the wheel  $z_1$  with 25 teeth is positioned at point (0,0) and the wheel with 35 teeth is positioned at point (150,0).

If the gear wheel  $z_1$  is rotated with  $\varphi_1 = 14^\circ$  and the gear wheel  $z_2$  is rotated with  $\varphi_2 = -10^\circ$ , in this position there will be no intersection area.

An AutoLisp function can also be used to rotate the two gears in gearing and interrogate the area of intersection, along the entire angular path.

The mass of the wheel  $z_2$  is 2.176 Kg and if after a complete rotation it remained constant, it means that the gearing is correct. The wheel mass was obtained with the AutoCAD MASS-PROP command. Only the value assigned to the mass is retained from the order listing: 297010.21.

The obtained value is for a body with dimensions in mm and unit density. For steel ( $\rho_{OL} = 7800 \text{ Kg/m}^3$ ), the obtained value must be multiplied by  $7.8 \cdot 10^{-6}$ , thus obtaining the mass in Kg. It can finally be concluded that the modeling is correct.

#### 4. CONCLUSIONS

Curved teeth are rarely used in cylindrical gears. The use of such symmetrical teeth offers the advantage of an increase in load-bearing capacity and a decrease in noise, to which is added the fact that there are no axial forces.

Modeling gears with solids has the main advantage of shortening the design time, the obtained models being then exported to finite element analysis software.

The method of obtaining them simulates a classical technological process of obtaining a gear wheel with a generating rack, without requiring advanced knowledge of the theory of generating gear wheels. The tooth profile thus obtained is the correct one.

The algorithm for obtaining the solids that materialize the gears is based on the ability of CAD software to use Boolean operations: addition, subtraction, intersection etc.

Due to the large number of such Boolean operations, the algorithm is supported by a programming language, AutoLisp in this case.

The functions described in the paper can also be used for other gears. For example, if instead of the solid materializing the gear rack with curved teeth, the solid materializing the gear rack with straight

teeth is used (Fig. 2.), gears with straight teeth or with inclined teeth are obtained.

The virtual gearing as on a machine tool specialized in gear machining is not only a didactic tool but also an opportunity to realize ideas with minimum consumption.

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#### GENERAREA DINȚILOR CURBI ÎNTR-UN SOFT CAD

*Lucrarea prezintă etapele generării solidelor care materializează roți dințate cu dinți curbi și, în final, roțile dințate obținute. Acești pași se efectuează în AutoCAD cu funcții AutoLisp (ce rulează în AutoCAD) și presupun existența unei scule generatoare și a unui semifabricat. Modul de obținere a dinților este asemănător cu procesele industriale de obținere a angrenajelor sau a sculelor care prelucrează roțile dințate. Algoritmii prezentați și funcțiile AutoLisp care îi însoțesc, permit obținerea unor roți dințate cu dinți drepecți sau curbi, indiferent de forma dintelui sau de aspectul semifabricatului.*

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