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PROFILING OF THE HOB MILL TOOL FOR GENERATING A PROFILE KNOWN IN DISCRETE FORM

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Abstract: In industrial practice, is sometimes needed to manufacture specific parts without blueprints. This part of engineering process is known as reverse engineering. Usually, this assumes that an existing piece is measured or scanned and based on this result is made a new part. If the part can be machined with universal cutting tools the manufacturing process don't rise problems, but in case of parts which needs specific tools, these must be designed to be suitable for machining the piece. In this paper, a tool profiling algorithm is proposed, which is based on the capacity to measure and represent some surfaces in a methodical cloud of points form. The proposed profiling algorithm is based on the "virtual pole" method. This method is used together with the intermediate surface theorem for profiling tools characterized by a helical primary peripheral surface. This article will represent a continuation of a research which was been published in 2021, in Bulletin of Polytechnic Institute from Jassy. In that published article, the profiling of the hob mill tool was presented in a theoretical way and the "virtual pole" theorem was applied for an any type of profiles. The proposed algorithm allowed the determination of the tool's profile reciprocally enveloping with a piece's profile known in discrete form. Now, in this paper, the discrete form profile will represent exactly a cycloidal disk from a cycloidal reducer whose coordinates were determined using specific reverse engineering processes. Considering that the determination of the relative movements between the tool and the part, as well as the determination of the enveloping condition are relatively complicated and can be a source of errors, the purpose of this work is to highlight the advantages of the "virtual pole" method compared to the other specific methods of tool profiling that generate by enwrapping. At the same time, it is investigated if the "virtual pole" method can provide a support for the identification of the intermediate surface, with the help of graphic design environments, for profiling, in this case, the worm tools, since the "virtual pole" method cannot be applied as such in the case of disk-type tools, worm tools and cylindrical-frontal tools, due to the fact that the theorem is intended for the study of planar gearing. The advantages of using the "virtual pole" method are obvious compared to the classical tool profiling methods. The results demonstrated the accuracy of the method, by the fact that, using the "virtual pole" method, the calculation time for profiling the hob mill tool for generating a profile known in discrete form, namely the profile of the cycloidal disk, is significantly reduced.
Key words: virtual pole, discrete form, hob mill, discretization, scanning process.

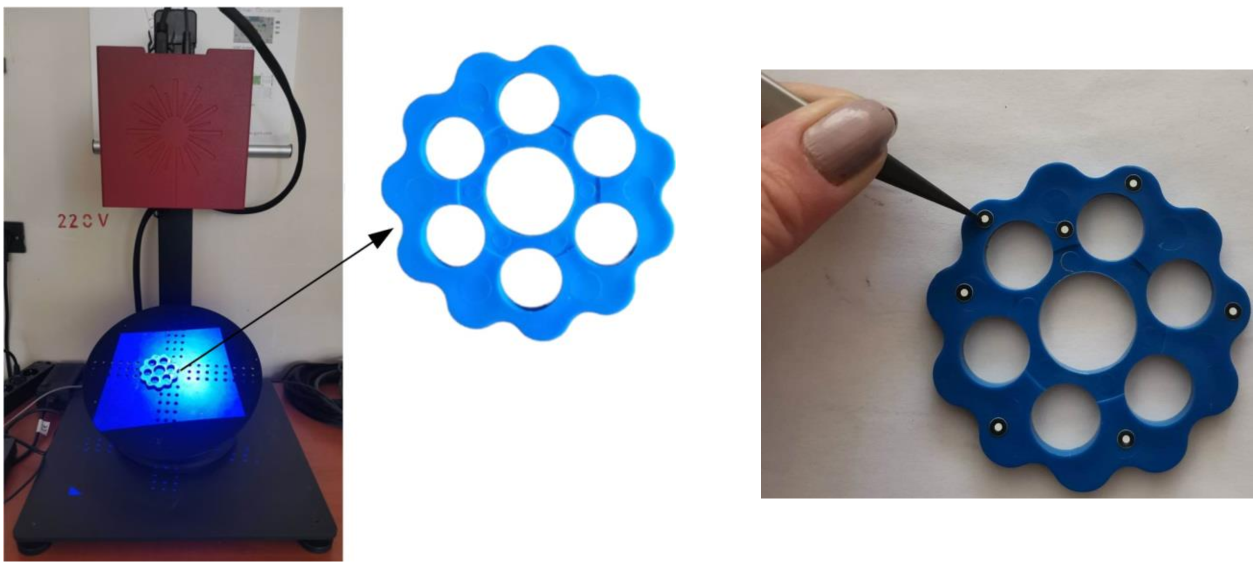
1. INTRODUCTION

Any type of surface can be numerically represented in a point cloud form [1,2]. The point cloud has certain coordinates that can be determined either by means of coordinate measuring machines or by means of 3D scanning equipments, these being some of the most common reverse engineering techniques [3,4].
There are two solutions for determining a surface. The first solution is the one in which a directory curve, known in discrete form, will be obtained, which, together with the generator, will precisely shape the measured surface [5,6].
The second solution to determine the surface is the one in which it will be modeled by means of polyhedral in which their vertices will be determined by the points belonging to the ordered point clouds.
The surface modeling represent, in this case, an approximation that will allow the determination of a normal, located at a point on the surface, this being a significant advantage, since various methods of profiling tools that generate by enveloping can be used, such as Willis's theorem, Gohman's theorem, minimum distance method, Olivier's method, method of planar generating trajectories and so on [1], [7-12].
In this paper, a tool profiling algorithm is proposed, which is based on the capacity to measure and represent

some surfaces in a methodical cloud of points form.
The case of generating with a hob mill tool is studied and a numerical application was made for the profiling of tools that generate the disk from the structure of a cycloidal reducer [13-15]. The application was made for the case where the profile to be generated is known in discrete form.
The paper represents a development of the research published in 2021, in Bulletin of Polytechnic Institute from Jassy in which the hob mill tool profiling was presented in a theoretical way in order to generate any profile known in discrete form [16].
One of the stages of tool's design is the tool's profiling which assume to determine the tool's cutting edge which will generate the desired profile of the piece.
The proposed algorithm is based on the "virtual pole" method which allows determining the profile of generating tools, reciprocally enwrapping with the profile to be generated. The method is based on the Willis theorem and allows to avoid the necesity to develop the equations of the reciprocally movements between piece and tool [17-22].
Profiling the hob mill assumes to determine the rack gear generating tool. The profile of this rack gear is further use for generating an intermediary surface which will be used for profiling the hob mill [23,24].
Now, the discrete form profile will represent the cycloidal disk from a cycloidal reducer whose coordinates were determined using specific reverse engineering processes [3,4], [25].
A cycloidal reducer is a device that reduces speed, ensuring a high reduction ratio and low gap between the active elements. It is used to transmit movement and torque in various mechanisms from automotive industry or robotics [26].
The disk from the structure of the cycloidal reducer has radial symmetry and its form is suitable for processing with tools that generate by enveloping, such as hob mills [27-30].
In this paper, the "virtual pole" method is used together with the intermediate surface method for profiling tools characterized by a helical primary peripheral surface.
Using the "virtual pole" method and with the help of reverse engineering techniques will demonstrate the fact that the calculation time for profiling the hob mill tool for generating the cycloidal disk from the structure of the cycloidal reducer, is significantly reduced, this eliminating an important part of the potential mathematical calculation errors that may occur during the profiling process.

2. MATERIALS AND METHODS

The cycloidal disk from the structure of the reducer was scanned using an equipment called *Atos Core*, an ideal system for 3D measurement of different types of parts up to 500 mm in size [31,32]. In Figure 1.a is showed the scanner and the measured piece.



a. *b.*

Fig. 1. The disk from the structure of a cycloidal reducer:
a - *Atos Core* equipment; *b* - application of the reference markers on the cycloidal disk.

The accuracy and the precision of the measuring system is at micron level, offering a fast scanning process, even in areas that are difficult to reach from an optical point of view (for example: channels, holes etc.), as well

as a high-quality graphic. Atos Core equipment measures non-contact the entire surface of the blank, generating a ”point cloud” that stores with great accuracy all the details of the measured part. The equipment uses a set of 2 cameras that work on the triangulation principle. Since both the cameras and the projector are calibrated, all three elements are used to calculate the coordinates. A more detailed description of the entire scanning process, as well as the characteristics of the Atos Core scanning system, were presented in the paper [32].
In order to realize the scanning process, the positions of object in the scanning process have to be recorded. For this reference markers are applied on the disk, Figure 1.b.
Reference markers are adhesive materials, which are placed both on the part and on the table of the scanning equipment (before the start of the actual scanning process) and are used in 3D scanning to mark the reference points used later in the process recording of the different positions in which the objects were scanned.
The images resulting from the scanning technique are processed using the *GOM Scan* software [32]. The software immediately displays the captured surface data in the 3D view.
To fully digitize an object, multiple scans from different angles are required. The software lists all scans in a single measurement series. Finally, 21 scans were obtained for the disk from the cycloidal reducer's construction, Figure 2.

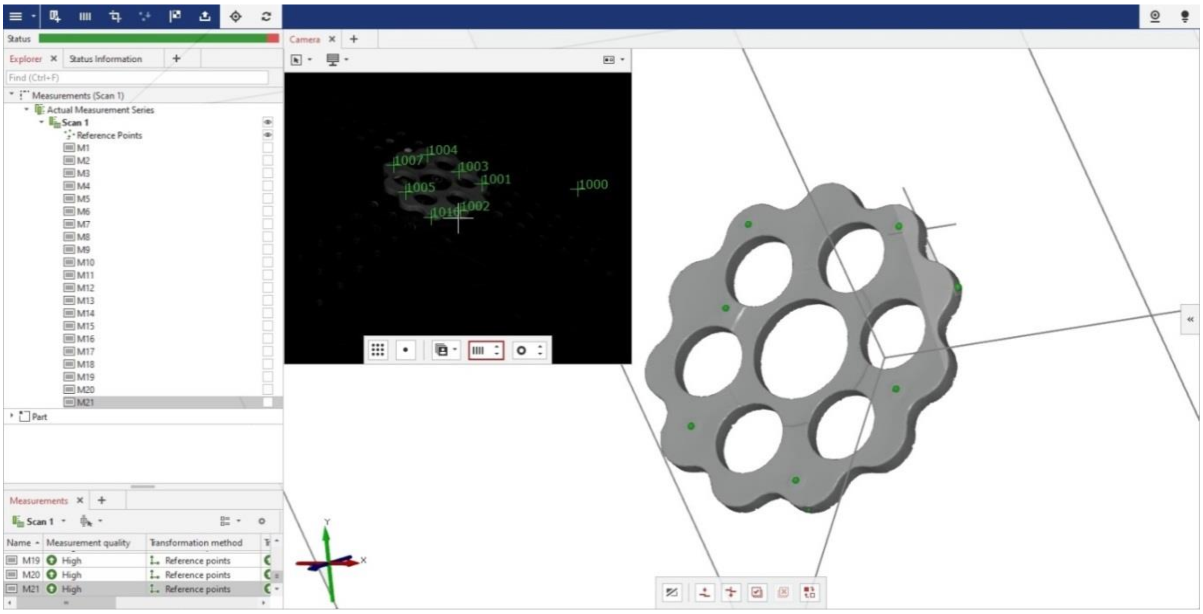


Fig. 2. The number of scans for the disk from the structure of a cycloidal reducer

After completing the scanning process of the cycloidal disk, a process called polygonalization is realized. This includes combining all the scans and obtaining the final numerical model [32], Figure 3.

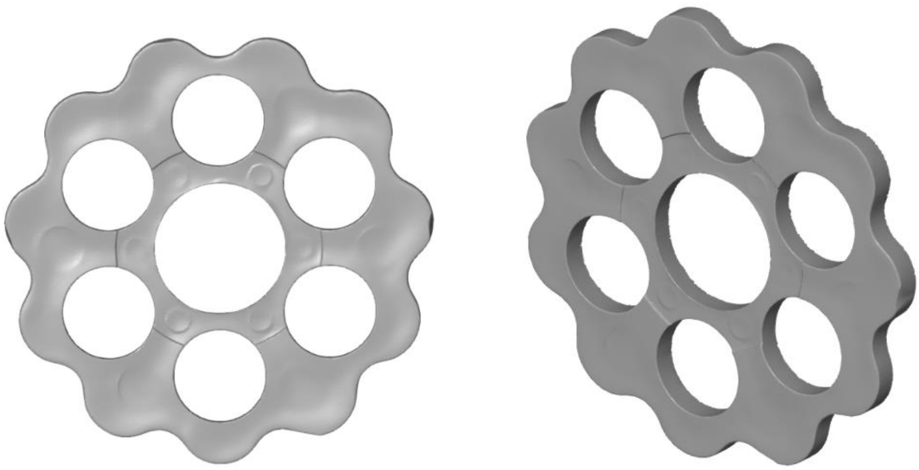


Fig. 3. The scanned cycloidal disk

Subsequently, in order to analyze the part, the *GOM Inspect* program [32] was used, this being a software designed for the evaluation of the data obtained by measurement through 3D scanning systems.

In order to determine the profile to be generated, in the *GOM Inspect* program, equidistant points were considered on one of the disk lobes from the cycloidal profile, located at a distance of *2 mm* between them, Figure 4, using the *Equidistant Points* command.

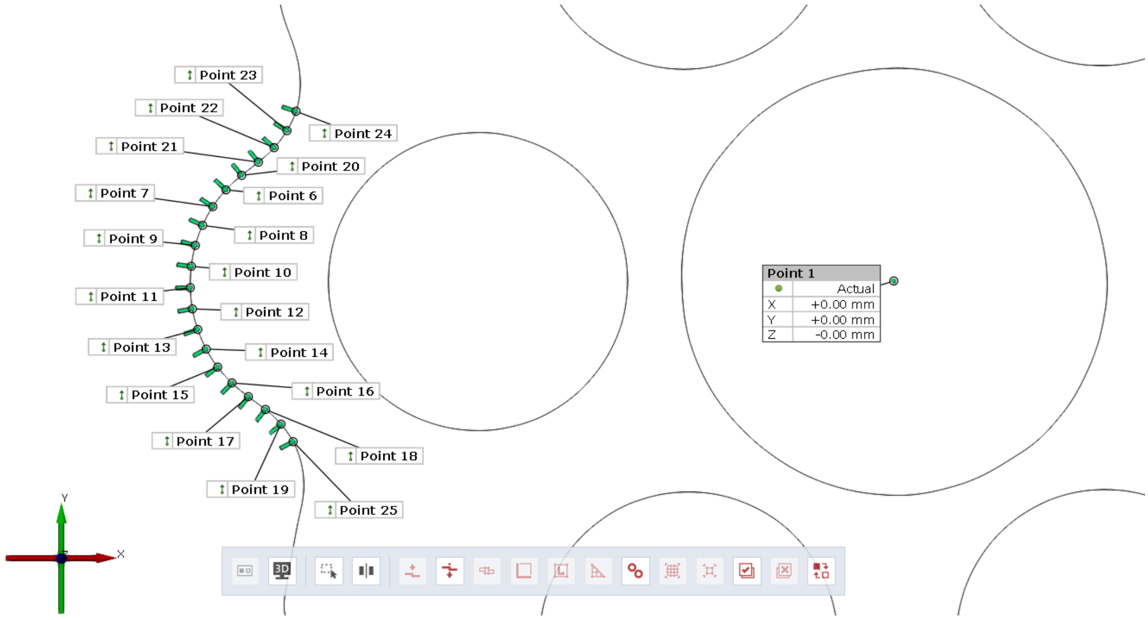


Fig. 4. Determination of the profile to be generated

The coordinates of these points were exported in a **.csv* file, to be used later in a program designed for performing numerical calculations called *Octave* [33], in order to determine the profile of the generating tool and the contact curve. Subsequently, a numerical application was made for profiling the worm tool designed to process a profile known in discrete form [16].

Figure 5 shows the profile of the piece and the reference systems used:

- xy, XY - the fixed and mobile coordinate systems (XY being joined with the part profile);
- $\xi\eta$ - coordinate system joined with the tool profile;
- C_1, C_2 - the centrodes associated with the part and the tool.

The rolling radius of the part is the outer diameter of the cycloidal disk, determined by scanning, $R_{rp}=33\ mm$.

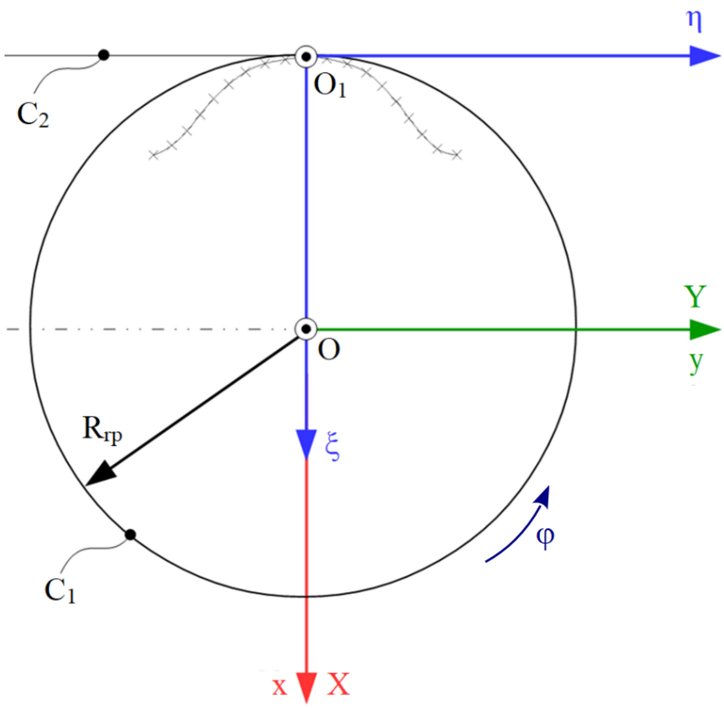


Fig. 5. Part profile and reference systems used

The equations of the C_1 centrode associated with the part are, Figure 5 [16]:

$$C_1: \left| \begin{array}{l} X = -R_{rp} \cdot \cos\varphi; \\ Y = R_{rp} \cdot \sin\varphi, \end{array} \right. \tag{1}$$

φ representing the rotation angle of the part system.

The gearing / contact curve, *C.A.*, represents the geometrical locus of the contact points between the two reciprocally enwrapping profiles, defined in the fixed reference system [16]:

$$C.A.: \left| \begin{array}{l} x = x(u,\varphi); \\ y = y(u,\varphi); \\ \varphi = \varphi(u), \end{array} \right. \tag{2}$$

where u is a variable scalar parameter.

The flank of the generating rack is determined by transferring, in the ξη system, the points on the contact curve, giving them the absolute movement [16]:

$$\xi = x + A; \quad A = \begin{pmatrix} -R_{rp} \\ -R_{rp} \cdot \varphi \end{pmatrix}. \tag{3}$$

Table 1 shows the coordinates of points belonging to the rack tool's profile and to the part's profile. The coordinates are referenced in the own reference system of the tool and, respectively, of the part.

Table 1. Coordinates of points on the rack tool profile and part profile

No.	**Tool profile**		**Part profile**	
	ξ [mm]	**η [mm]**	**X [mm]**	**Y [mm]**
1	3.972	-8.785	28.070	-7.500
2	3.664	-7.816	28.640	-6.680
3	3.116	-6.877	29.370	-5.990
4	2.415	-5.976	30.160	-5.390
5	1.725	-5.086	30.930	-4.750
6	1.151	-4.184	31.600	-4.010
7	0.716	-3.240	32.130	-3.160
8	0.393	-2.270	32.530	-2.240
9	0.195	-1.288	32.780	-1.280
10	0.119	-0.281	32.880	-0.280
11	0.162	0.714	32.830	0.710
12	0.316	1.718	32.640	1.700
13	0.593	2.696	32.300	2.640
14	0.982	3.642	31.830	3.510
15	1.516	4.573	31.210	4.300
16	2.167	5.467	30.480	4.980
17	2.842	6.323	29.690	5.600
18	3.400	7.206	28.960	6.280
19	3.779	8.144	28.360	7.070
20	-	-	27.940	7.980

Figure 6 shows the rack tool profile made in the *Octave* program. Here, the part profile is represented in green, the contact curve in blue and the tool profile is represented in red.

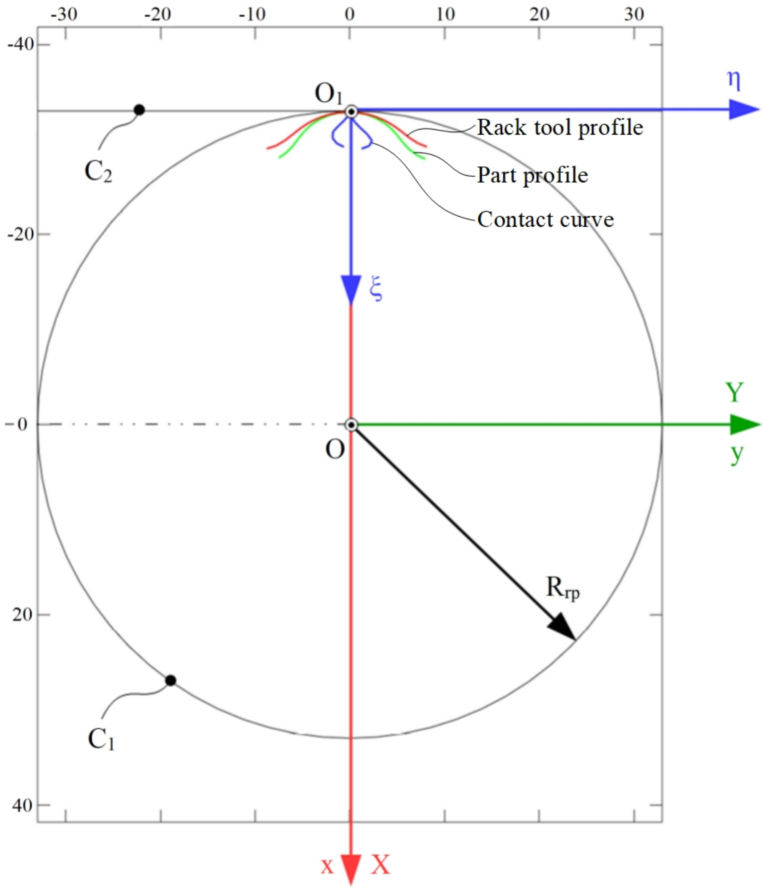


Fig. 6. Generating tool profile and the contact curve

Using equations (4) and (5), the coordinates of the points belonging to the primary peripheral surface of the worm tool are obtained.

$$S_M : \begin{vmatrix} \xi_1 = (\xi - R_{rh}) \cdot cos\,\varphi_1 - (\eta \cdot sin\,\theta - \zeta \cdot cos\,\theta) \cdot sin\,\varphi_1; \\ \eta_1 = \eta \cdot cos\,\theta + \zeta \cdot sin\,\theta + p_e \cdot \varphi_1; \\ \zeta_1 = -(\xi - R_{rh}) \cdot sin\,\varphi_1 - (\eta \cdot sin\,\theta - \zeta \cdot cos\,\theta) \cdot cos\,\varphi_1; \end{vmatrix} \tag{4}$$

$$\varphi_1 = arctan\left(\frac{\eta \cdot sin\,\theta - \zeta \cdot cos\,\theta}{R_{rh} - \xi}\right), \tag{5}$$

where:
- $\xi_1\eta_1\zeta_1$ represents the coordinate system joined with the worm tool;
- $\xi\eta\zeta$ - the reference system which is integral to the rack and in which the intermediate surface is defined, having the origin in O_1;
- R_{rh} - rolling radius of the worm;
- φ_1 - the rotation angle of the mobile coordinate system $x_1y_1z_1$ towards to $\xi_1\eta_1\zeta_1$;
- θ - the rotation angle of the worm axis towards to the η_1 axis;
- p_e - helical parameter.

At the same time, the axial section of the primary peripheral surface of the worm tool is obtained from relation (6), Figures 7 and 8.

$$SA: \begin{cases} \xi_1 = (\xi - R_{rh}) \cdot cos\,\varphi_1 - (\eta \cdot sin\,\theta - \zeta \cdot cos\,\theta) \cdot sin\,\varphi_1; \\ \eta_1 = \eta \cdot cos\,\theta + \zeta \cdot sin\,\theta + p \cdot \varphi_1; \\ \zeta_1 = -(\xi - R_{rh}) \cdot sin\,\varphi_1 - (\eta \cdot sin\,\theta - \zeta \cdot cos\,\theta) \cdot cos\,\varphi_1; \\ \varphi_1 = arctan\left(\dfrac{\eta \cdot sin\,\theta - \zeta \cdot cos\,\theta}{R_{rh} - \xi} \right). \end{cases} \tag{6}$$

The coordinates of the points on the characteristic curve and the axial section are shown in Table 2.

Table 2. The coordinates of the points on the characteristic curve and the axial section

No.	Characteristic curve			Axial section		
	ξ_1 [mm]	**η_1 [mm]**	**ζ_1 [mm]**	**ξ_1 [mm]**	**η_1 [mm]**	**ζ_1 [mm]**
1	-46.870	6.646	-1.779	-46.696	-7.227	0.000
2	-47.914	5.242	-2.220	-47.744	-5.863	0.000
3	-48.892	3.802	-1.549	-48.732	-4.454	0.000
4	-49.549	2.201	-0.855	-49.429	-2.883	0.000
5	-49.857	0.475	-0.217	-49.817	-1.209	0.000
6	-49.803	-1.281	0.414	-49.856	0.509	0.000
7	-49.365	-2.969	1.077	-49.570	2.204	0.000
8	-48.606	-4.498	1.823	-48.960	3.811	0.000
9	-47.523	-5.927	2.289	-48.049	5.269	0.000
10	-46.548	-7.319	1.578	-46.993	6.628	0.000

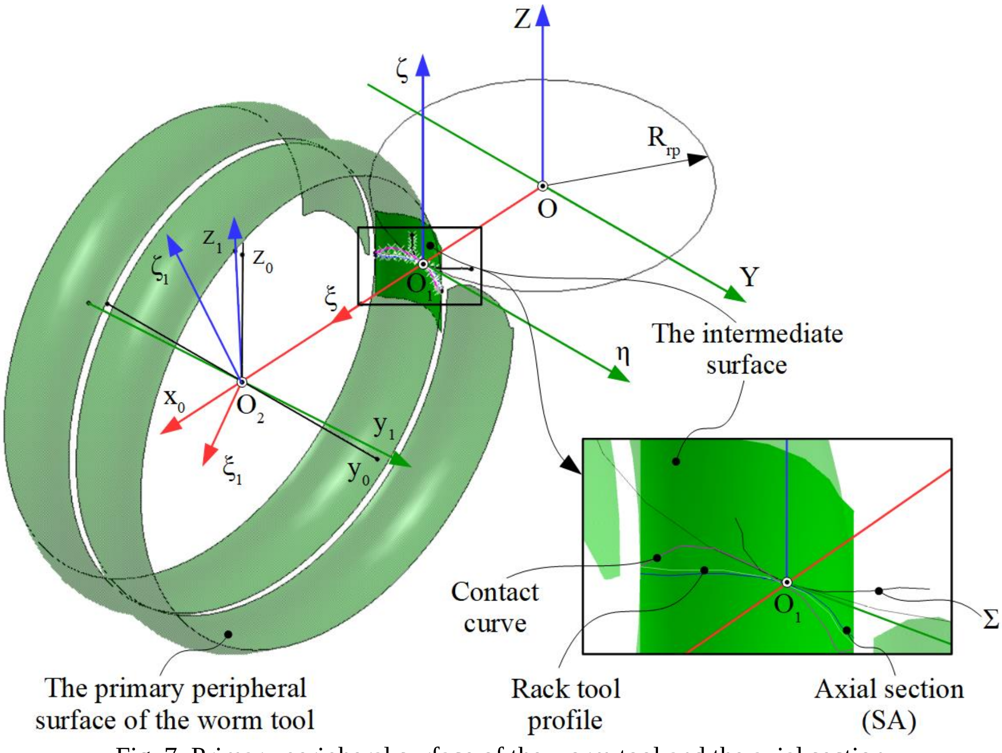


Fig. 7. Primary peripheral surface of the worm tool and the axial section

The worm tool has the axial section obtained from equations (6) is represented in Figure 8.
The rack tool profile, the theoretical cycloidal profile and the contact curve are presented in Figure 9. The coordinates of points used for generating the profiles presented in Figure 9 are calculated using an in-house made program, developed in *Octave* software.
The equations used for coordinates calculus are equations (2) for the characteristic curve and equations (3) for rack gear tool's profile.

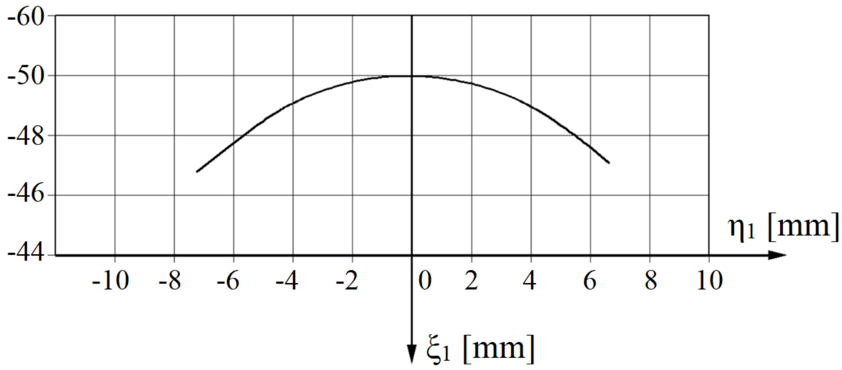


Fig. 8. The axial section of the worm tool

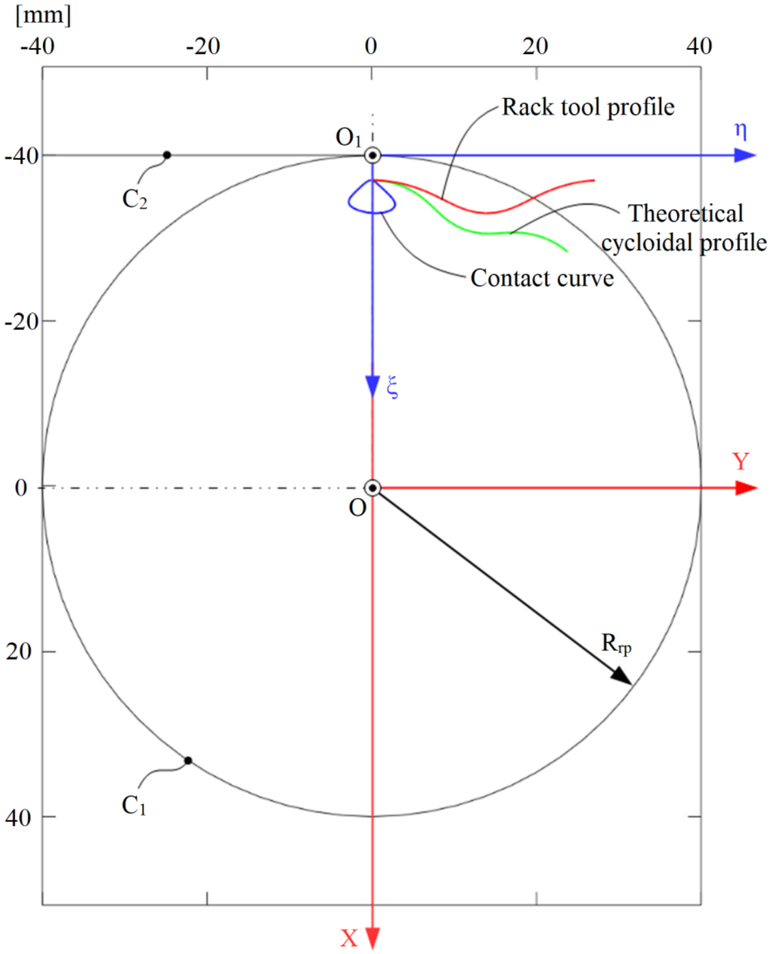


Fig. 9. The rack tool profile, the theoretical cycloidal profile and the contact curve

3. CONCLUSIONS

In many industries, the need to redesign parts or components from the structure of some assemblies appears because manufacturers must provide replacement parts for the models created in a short period of time. One of the more difficult stages of tool's design is the tool's profiling which assume to determine the tool's cutting edge which will generate the desired profile of the piece. Therefore, innovative solutions and methods are used to achieve this goal. One of them represents the 3D scanning techniques, namely the reverse engineering processes.
By combining these reverse engineering techniques together with one of the complementary methods developed in the field of tool profiling that generates by enveloping by the rolling method, namely the ”virtual pole” method, the profile of the tool that generates the desired profile of the part can be determined.
Therefore, in this paper, a tool profiling algorithm is proposed, based on the “virtual pole” method. This method is used together with the intermediate surface theorem for profiling tools characterized by a helical primary peripheral surface.
The proposed algorithm allows determining the tool's profile reciprocally enveloping with a piece's profile known

in discrete form, representing a cycloidal disk from the structure of a cycloidal reducer whose coordinates were determined with the help of a three-dimensional measuring equipment, called *Atos Core*.
At the same time, a numerical application was made in the *Octave* program for profiling the hob mill tool that generates the disk from the cycloidal reducer, using the advantages of the “virtual pole” method.
The “virtual pole” method is used together with the intermediate surface method for profiling tools characterized by a helical primary peripheral surface.
The results proved the value and the viability of the ”virtual pole” method, allowing to avoid the need to determine the family of profiles generated during the relative part-tool kinematics and therefore the need to identify the relative movements of these two elements. This eliminates an important source of potential errors and significantly simplifies the process of profiling the generating tool.

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