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MILLING HEADS FOR PROCESSING CURVED TEETH IN CYLINDRICAL GEARS

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Abstract: The paper presents a kinematic study of the simply planetary mechanism of the multi-cutter device adapted on a milling machine for processing curved teeth cylindrical gears. The means for reducing the generation errors are emphasized. For studying the kinematic and dynamic behavior of the designed device its modeling and simulation were achieved. In the paper were presented the kinematic scheme and dynamic behaviour of a cutting tool of changeable milling head type used for processing of flanks of teeth with hypocycloidal and cycloidal lines. The cutting tool is adapted on a machine for cylindrical gear tooth processing of FD Cugir family. Also, are presented some practical applications.

1. INTRODUCTION

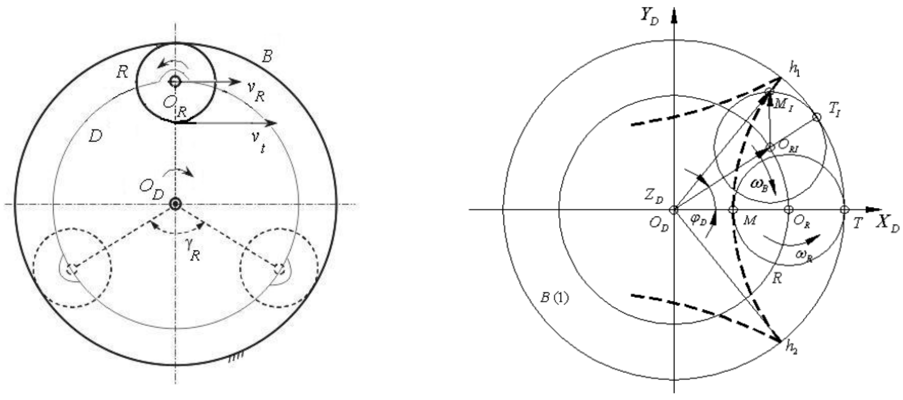
Cylindrical gearing with curved and bulged teeth have been developed and spread from the necessity of increasing the bending resistance and the load capacity of the tooth (20% 25%) in regard with the spur gears.

Some theoretical researches and applications were achieved concerning this gearing type. The methods are characterized by cutting tool and machine kinematics. They are mainly based on patents, some of them being presented in detail in [2] and [8].

The processing of the bulged teeth with curved flank lines in cylindrical gears or racks is achieved by milling using multi-cutters tools in mono-block construction or with applied cutters. In most cases, such a type of teeth cannot be processed by grinding, hence this implies some careful conditions of milling and abrading. The tooth flak lines are arc of circle, cycloid or hypocycloid [1], symmetrically placed on the gear width. The flank lines are generated kinematically or as trajectory of a point. The involute profile is generated kinematically by rolling. The division is discontinuous or continuous. For the generation of the two curves that define the flanks, some conditions regarding the form and position errors are imposed. These determine the accurate achieving of meshing and contact surface of flanks, noise level decrease, increase of durability and gearing precision [5], [7]. For this purpose, certain requirements are imposed: accurate adjustment of tool position in regard with the workpiece, elimination or diminishing of kinematic imprecision of mechanism in the machine structure, increasing of rigidity of clamping and driving systems of the tool and workpiece, improving of dynamic behaviour especially during cutting process, adequate choice of the process parameters. One specifies data regarding the cutting edge construction, their adjustment in tool assembly, errors arising in processing and their causes, cutting regime parameters, dividing the layer to be processed, forces and moments in cutting, tooth examination and others.

2. GENERATION KINEMATICS OF THE HYPOCYCLOIDAL FLANKS' LINE

For the kinematical generation of a closed hypocycloid, a milling head was designed and used. It consists of the planetary gear (rolling curve *R*) with the radius R_R – 1, inner teeth gear (base *B*) of radius R_B - 2 that is fixed, and the driving planetary carrier *D*



a **b**

Fig. 1. Hypocycloid generation kinematics: a – mechanism components; b – generation motions.

(Fig.1,*a*). The ratio $R_B/R_R = i_H = \{3, 4, 5, 6\}$ is an integer number and represents the number of loops of the hypocicloid, only one being active in processing - h_1h_2 (Fig.1,*b*).

Analyzing this mechanism by both *analytical* and *graphical methods* with tangential and angular velocities $v_R = (R_B - R_R)\cdot\omega_D$, $v_t = 2\ R_R\cdot\omega_R = 2\ v_1$ where ω_D is disk angular speed, in rad/s, it results:

$$n_R = \frac{R_B - R_R}{R_R}\cdot n_p\,. \qquad (1)$$

It was considered the case with gear modulus m = 2 mm. For certain values of n_D = 24; 30; 38 and 47.2 rpm and the ratio i_H / R_R = 3/80; 4/60; 5/48 and 6/40 mm we obtained the relative speed of rollers related to the disc D: n_{R_D} = 72, ..., 283 rpm.

On the basis of the vectorial equation of point the M_I position (Fig. 1,*b*) represented by the milling tool in the orthogonal system $O_DX_DY_DZ_D$ expressed in a parametrical way, we obtain the current point coordinates:

$$\begin{cases} X_D = (R_B - R_R)\cdot\cos\varphi_D - R_R\cdot\cos\left(\dfrac{R_B - R_R}{R_R}\cdot\varphi_D\right), \\ Y_D = (R_B - R_R)\cdot\sin\varphi_p + R_R\cdot\sin\left(\dfrac{R_B - R_R}{R_R}\cdot\varphi_D\right), \\ Z_D = 0. \end{cases} \qquad (2)$$

where φ_D is the motion parameter of the rolling circle center.

The dimensions of the two radii have to satisfy with high precisions the ratio i_H for the indicated values. Ax examples, two possible error cases were analyzed:

- If the rolling circle radius (R_R = 80 mm) has a small error and the real value is 79.9 mm, when R_B = 240 mm, the error on hypocycloid closing trace is 2.0 mm, that is unacceptable concerning the gear flank line shape;
- If the angular dimension between rollers (γ_R = 120 deg) has a small error of 0.1 deg, the angular error between hypocycloid traces will be about 0.111 deg, that is unacceptable concerning the gear flank line shape and pitch too.

For diminishing the errors in the design and fabrication of the milling head it was considered the precision level 6. Other constructive measures had in view the backlash reducing and creation of possibilities of compensating for the phase of the hypocycloid [3].

Figure 2 hows the milling head for groups of cutters adapted on the machine FD 320 A Cugir. The machine enables the generating motions executed by the tool and

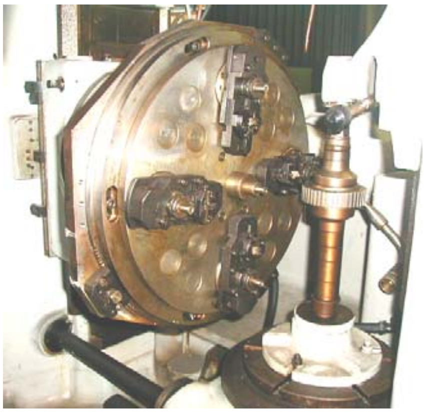


Fig. 2. Milling head (i_H = 4)adapted on machine tool.

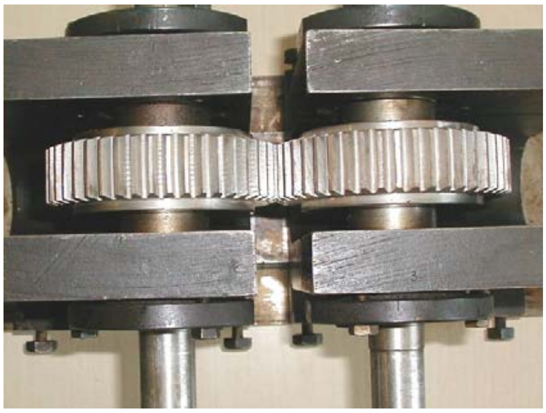


Fig. 3. Gearing with polyhypocycloidal teeth.

workpiece-gear and the interconnection between these motions. The machine kinematic structure contains two rolling kinematic chains for generating of the flank lines and profile.

The workpiece-gear has z_p=52 teeth and m=2,5 mm, the milling head has 4 groups of cutters and the geometrical characteristics: R_B=240 mm and R_R=60 mm. The cutting speed v_c=65,2 m/min. In Fig. 3 is presented a cylindrical gear having a curved gearing teeth. The contact spot is formed in the center of the adjointed flanks.

The behaviour during the work time (level of noise, the size and the position of the contact spot) is determined by the manufacturing precision of the gears (eccentricity, pitch and profile errors, direction error of the tooth, flanks' roughness).

3. GENERATION KINEMATICS OF THE CYCLOIDAL FLANKS' LINE

The cycloid c_1-c_1' is generated in the Γ_D plan as a trajectory of M_i points which are fixed by the rolling circle O_s wich has the centre on the NN straight line that represents the intersections of the plans Γ_D and Γ_G. (Fig. 4). This circle is rolling without sliding on the line d that belongs to Γ_D plane. The cycloidal line is transposed by rolling on Σ_{cil} surface of wheel part, that has radius R_R.

The generation of the cylindrical curved teeth in cycloidal arc is realised with a head milling cutter that uses a several cutting tool (i_c=1, 2, 3, 6) disposed equidistantly on the circumference of a circle of R_S radius. The head milling cutter is rotated with the angular speed ω_s and rolls on the straight line d with the linear speed v_{rul}.

From kinematical point of view to obtain the curved teeth on a cylindrical wheel it assumes three motions: two rotation motions and one translation motion. These motions

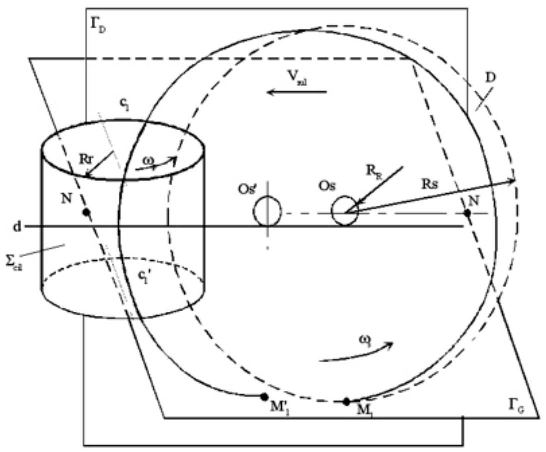


Fig.4. Generation of cycloidal line of the flanks

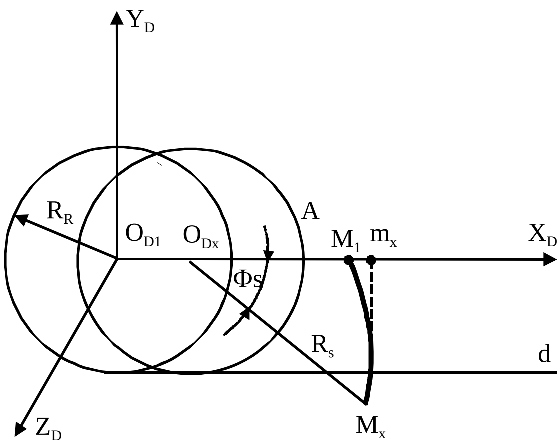


Fig.5. Generation motions.

are making as follows: the main rotation motion realized by milling cutter; the work piece rotation motion; the milling cutter translation motion with the rolling speed.

The generation hook that defines the cycloidal teeth has the flank defined by straight cutting edges. The flanks of the teeth are generated simultaneously by rolling with mobile straight line and continuous division. The rolling motion is continuous and the generating motion of involutes profile of flanks is discontinuous, so the flanks of teeth are obtained as successive points winding of cutting edges.

The coordinates of M_i points described by the milling head in its motion on cycloidal trajectory in in the orthogonal system $O_DX_DY_DZ_D$ (Fig. 5) are given by the following equations:

$$\begin{cases} x_D = (R_S + c \cdot k_{1,2} \cdot \dfrac{m \cdot \pi}{4} + k_{1,2} \cdot u \cdot \sin \alpha_0) \cos \Phi_S \\ y_D = -(R_S + c \cdot k_{1,2} \cdot \dfrac{m \cdot \pi}{4} + k_{1,2} \cdot u \cdot \sin \alpha_0) \sin \Phi_S \\ z_D = -u \cdot \cos \alpha_0 \end{cases} \quad (3)$$

From a technological point of view it is important to know the number of revolution of the workpiece versus number of revolution of milling cutter expressed by:

$$n_p = n_s \frac{i_c}{z_p} \left(1 + \frac{s_T}{2\pi R_r} \right) \quad (4)$$

In order to obtain on the wheel part curved teeth, the tool has a special construction. The experiments were made by using a milling cutter with three identicaly units of knives. Each of them is cutting the flanks of two adjacent teeth. The experimental model of milling cutter is presented in figure 6.

This project is favorable because it permits to change the knives and also allows radial, angular and vertical adjustments of them. More than this it can be used for any number of teeth and any module.

To avoid the changes of adjustment, the milling tool is mounted on the shaft of the device by using a flange. The support where are the knife-clips on, has a big construction necessary for the flying wheel role, so the possibility of vibrations during the cutting process has decreased.

The radial adjustment of the tools is realized by moving the knife-clips and then by blocking them with bolts and screw nuts introduced in T channels of the plate. The knives can be adjusted at a minimum radius of 46 mm.

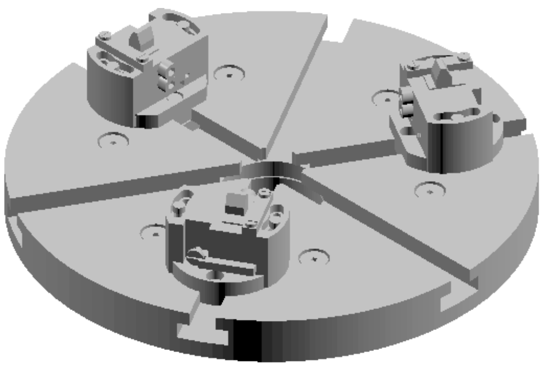


Fig.6. Milling head with three cutter tools

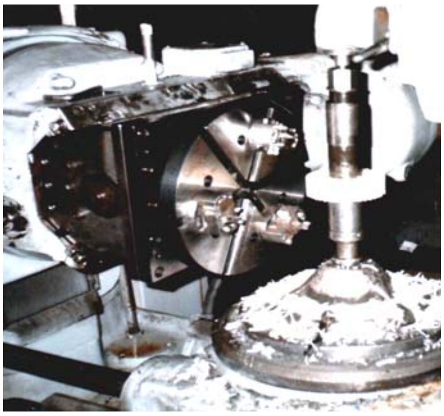


Fig.7. Milling head (i_c = 3) adapted on machine tool.

Fig 8. Gearing with cycloidal teeth

The simultaneously kinematic generation of the two curves that define the flanks, the cycloidal directory of flanks and the generator involute profile of flanks, needs a rigid mechanism between the rotation motion of milling cutter and the work piece rotation motion. The movement of the workpiece corresponds to the desirable ratio between the number of group of milling cutter tools and number of the teeth of work piece.

For an accurate profiling of the flanks, the milling cutter and the work piece must make a rolling motion as well. This motion is obtained by linear movement of tangential slide which is installed the adaptable device on (Fig 7), and must by correlated with a supplementary rotation motion from a differential mechanism. The correlation of these motions is realized with kinematical linkages adjusted by using changeable gear.

During rotation and shift of the head milling cutter, each cutting tool working in consecutive cavity of the teeth of the work piece, describing a cycloidal line on the workpiece. The teeth are obtained as an envelope of successive positions of cutting edges of the knives. In order to adjust the cutting depth it is necessary to fix the position of the work piece related to the milling cutter on radial directions. The radial advance is hand made at the beginning of every pass. The processed gears are presented in figure 8.

4. MODELING AND SIMULATION OF THE DEVICE ADAPTED ON MACHINE FD 320 A

The milling head was designed and executed as an experimental model in four variants having i_H = 3, 4, 5, and 6 [4]. This enables processing gears (precision class 8) with diameters between 50 and 125 mm and modulus m = 1.5, …, 3.5 mm.

For gearing running in gear testing of the processed cylindrical gearing with polyhypocycloidal teeth, a stand with open mechanical energetic flow was designed and used. The researches emphasized the formation and position of the contact spot and the level of noise. The milling head adapted on the tooth processing machine was modeled as a multi-body system in order to emphasize the kinematic and dynamic behavior.

On the main spindle of machine (Fig. 9) a shaft it was mounted supporting a bevel gear in contact with another one on a perpendicular shaft (driving spindle II, ratio 1:5). This is the shaft that moves the driving disk *D* carrying the satellite axes (III, IV, and V) on which the satellites rotates - spur gears in contact with the fixed crown. Together with the satellite axes there are the port-tools devices, on which the couples of cutters are mounted and adjusted in position to reduce the error factor. The bevel gear meshing was modeled as a joint of rolling without sliding type (cone on cone for the bevel gearing or cylinder in cylinder for the cylindrical gearing). The model tree is an open chain.

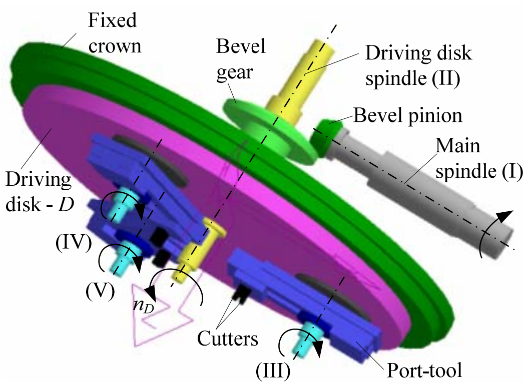


Fig. 9. Milling head with three groups of cutters.

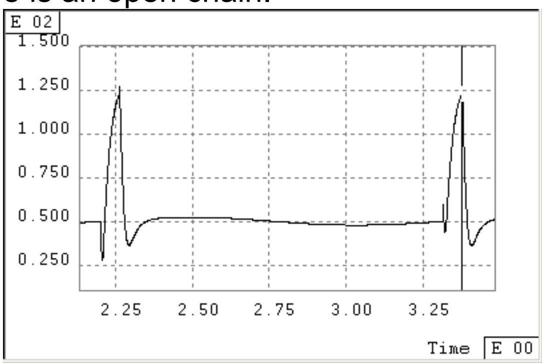


Fig. 10. Variation of moment on the disc D axis (body 1) at the cutting impact.

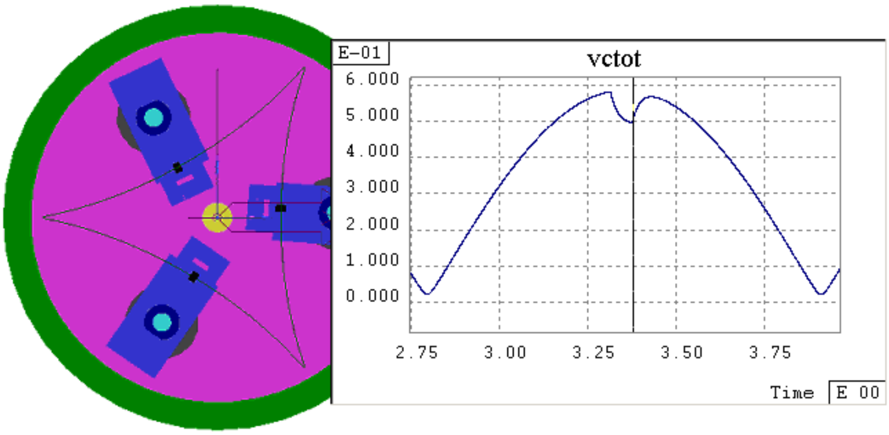


Fig. 11. Image with hypocycloid and variation of cutting speed at the contact tool-workpiece.

As input at the main spindle an imposed motion was supplied, which corresponds in rad/s to the chosen cutting speed v_c = 58.3 m/min ∈ (56.95 m/min, 72.1 m/min). This goes to a torque at the main spindle of 70 Nm. The cutting force was considered 100 N acting about full contact position between tool and workpiece in the range (–3°, +3°).

During simulation, the program provides information concerning positions, velocities, accelerations, point trajectories, the forces and moments applied to the articulations, the energies, as well as other data concerning the system, pre-defined by the software or defined by the user [6]. In Fig. 10 the torque variation on the body 1 (disc *D*) at the cutting impact is shown. The maximum torque is 126.8 Nm, with an increase of 77 Nm. The variation of cutting speed at the cutting contact (*vctot*) is shown in Fig. 11.

5. CONCLUSION

The design of the multi-cutter milling head has on its basis a simple planetary mechanism of high accuracy. For diminishing the errors some kinematical, constructive and adjusting solutions were designed. The 3D model of the milling head was achieved in SolidDynamics programme for obtaining the kinematic and dynamic behaviour of the device under variable loads given by the cutting force.

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