

## GEAR CUTTING ON CNC VERTICAL LATHES - KINEMATIC CAPABILITIES

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*Lucrarea prezintă studiul privind posibilitățile de prelucrare a roților cilindrice mari și foarte mari (cu diametrul exterior mai mare de 500 mm), a roților conice și a roților de curea pe strunguri verticale. De obicei, prelucrarea acestor danturi se face pe mașini de danturat mari. Prezentul studiu se ocupă cu determinarea structurii cinematice a strungurilor verticale prin reprezentarea schemelor structuralo-cinematice ale acestor mașini, care se pot adapta unui număr mare de mașini de acest tip. Pentru fiecare caz care a fost studiat sunt necesare capete de frezat sau de rectificat adaptate la arborii de frezare sau de rectificare.*

*This paper presents a study regarding the possibility of cutting the teeth of large and very large size (outer diameter bigger than 500 mm) cylindrical gears, bevel gears and timing pulleys, on CNC vertical lathes. Usually, the cutting of the teeth is made on large gear cutting machines. The present study concerns the determination of the kinematic structure of the CNC vertical lathes, by representing the kinematic structural diagrams of these machines, which are adaptable to a larger number of machines of such type. For every case that has been studied, milling or grinding heads that can be adapted to the milling/grinding spindle ends are required.*

**Key words:** gear, vertical lathe, rolling, closed kinematic chain

### 1. Kinematics of CNC vertical lathes

The heavy vertical turning lathes have very often the following constructive variants [1]:

- with one vertical working head on the movable crossrail (Fig. 1);
- with movable crossrail and two working heads (Fig. 2): one vertical head on the crossrail and one side-head on the right-hand column;

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- with two working heads on the crossrail, either both for turning or one for turning and the other for milling.

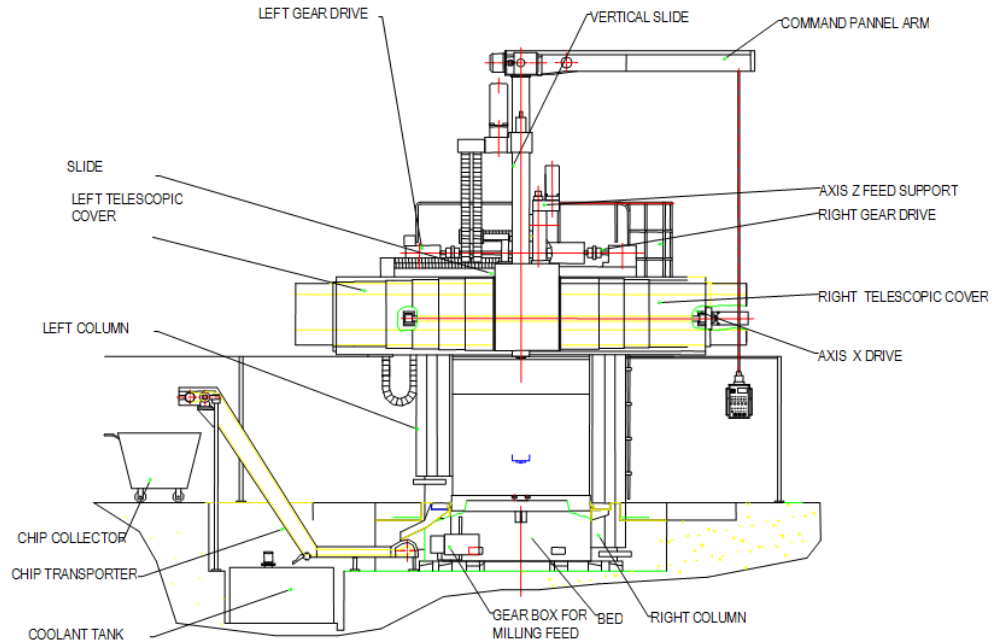


Fig. 1. Vertical lathe SC 17 with two columns, crossrail and one working head. General view.

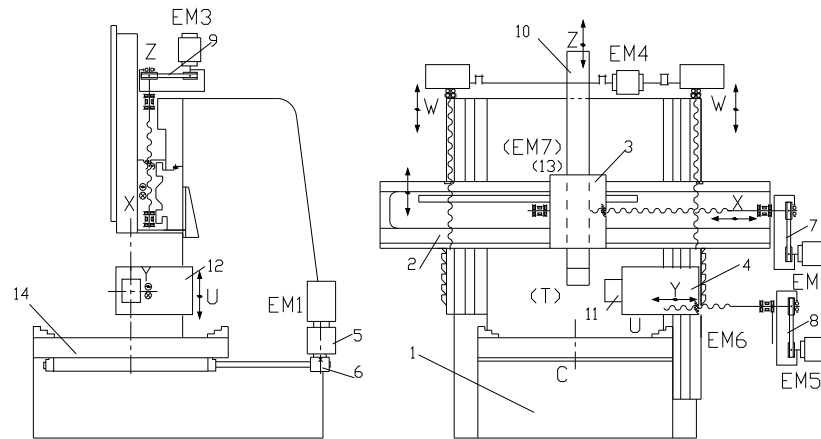


Fig. 2. Kinematic structure of the vertical lathe with one vertical working head and one side working head: 1 – bed; 2 – crossrail; 3 – vertical working head; 4 – side head; 5 – backlash-free gear-box; 6 – timing belt transmission from the structure of the main kinematic chain; 7, 8, 9 – timing belt transmission from the structure of X, Y and Z axes feed/positioning kinematic; 10 – vertical

working head travel; 11 – side head ram; 12 – feed/positioning chain; 13 – main kinematic chain for milling and drilling; 14 – table.

The study will consider only the variant with one vertical working head.

The kinematic structure of these machine tools consists of the following generating kinematic chains (Fig. 2):

- main kinematic chain for turning operation, driven by an AC motor with variable speed  $EM_1$  that ensures the main rotation motion of the workpiece clamped on the table 14;
- main kinematic chain for milling and drilling operations (13 – not shown) ensures rotation of the main milling spindle and includes an AC motor with variable speed and a two-speed gearbox;
- $X$ ,  $Y$  and  $Z$  axes feed/positioning kinematic chains with a kinematic structure specific to CNC machine tools: AC motor ( $EM_2$ ,  $EM_5$ ,  $EM_3$ ), belt transmissions (7, 8, 9) and ball screw mechanisms;
- Feed/positioning kinematic chain (12 – not shown) of the side head on vertical axis ( $U$  direction), driven by the electric motor  $EM_6$ .

The positioning of the crossrail on the columns ( $W$  axis) is achieved by means of an auxiliary kinematic chain (positioning) with the following structure: electric motor  $EM_4$ , clutches, reducers and screw-nut mechanisms.

The kinematic particularities of these vertical lathes are:

- integration of some mechanisms within the main kinematic chain, that ensure accurate control of table angular positioning (control on  $C$  axis);
- having the structure of the main kinematic chain identical with the feed/positioning kinematic chain on circular path makes possible the association in parallel with the feed/positioning kinematic chain on one of  $X$ ,  $Y$  and  $Z$  axes in order to get some complex generating kinematic chains (for rolling or threading), the condition of kinematic closing being ensured by the CNC equipment;
- each feed/positioning kinematic chain is driven by its own electric motor, having a simple kinematic structure that ensures the imposed positioning accuracy, static rigidity, dynamic and thermal behaviour specific to the technological accuracy of the workpiece.

For evidence, the usual structure of the main kinematic chain (Figs. 3, 4, and 5) having an AC or DC motor with variable speed, a two-speed or three-speed gearbox and a gear transmission (with internal or external teeth and characterized by substantial backlashes and high noise) that transfer the rotation motion to the main spindle (to the table) has been replaced with an electric motor with integrated gearbox and a belt transmission (Fig. 6).

DC or AC motors (Fig. 7,a and c) have a gearbox with planetary gears and transmission ratios  $i_{R1}=1/4$  and  $i_{R2}=1/1$ , the characteristics  $P=f(n)$  and  $M=f(n)$  being represented in Fig. 7,b for the two speed ranges (S1 – with opera-

tion time under unlimited load; S2 – with operation time of 30 min). When the bilateral clutch 4 is on position *a* (Fig. 7,e), the first speed range having the trans-

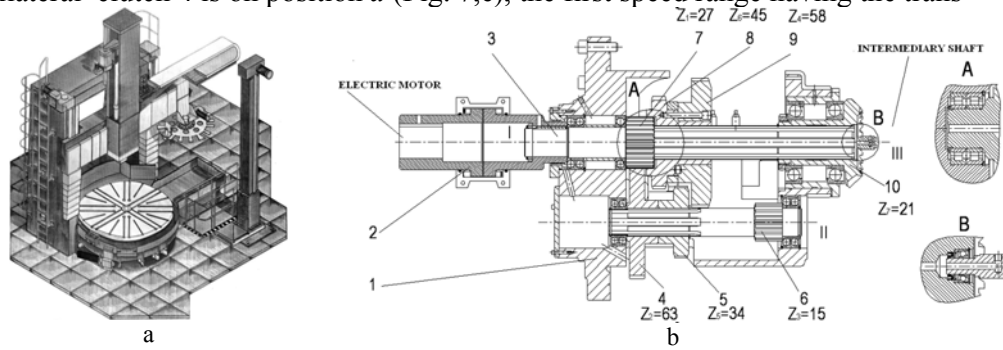


Fig. 3. Gearbox with intermediary device for 3 speed steps ( $i_{R1} = 27/27 = 1/1$ ,  $i_{R2} = (27/63)(34/45) = 1/3$ ,  $i_{R3} = (27/63)(15/58) = 1/9$ ): *a* – vertical lathe; *b* – cross section and details [2].

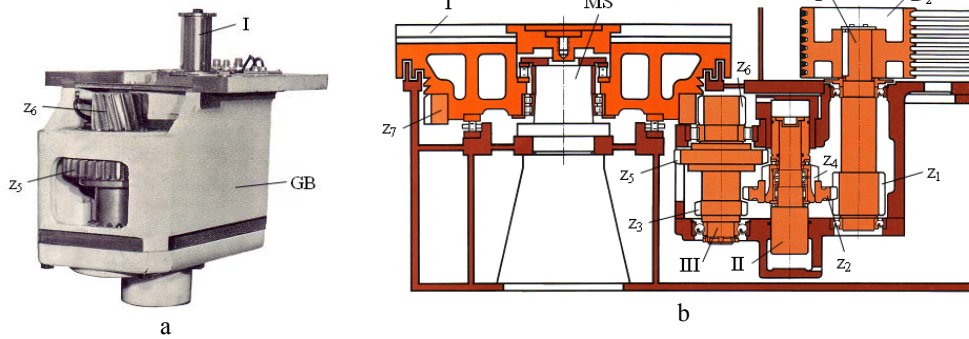


Fig. 4. Two-speed gearbox: *a* – actual gear box; *b* – main kinematic chain including gear box [3],  $i_{R1} = (z_1/z_2) \cdot (z_2/z_3)$ ,  $i_{R2} = (z_1/z_2) \cdot (z_4/z_5)$ .

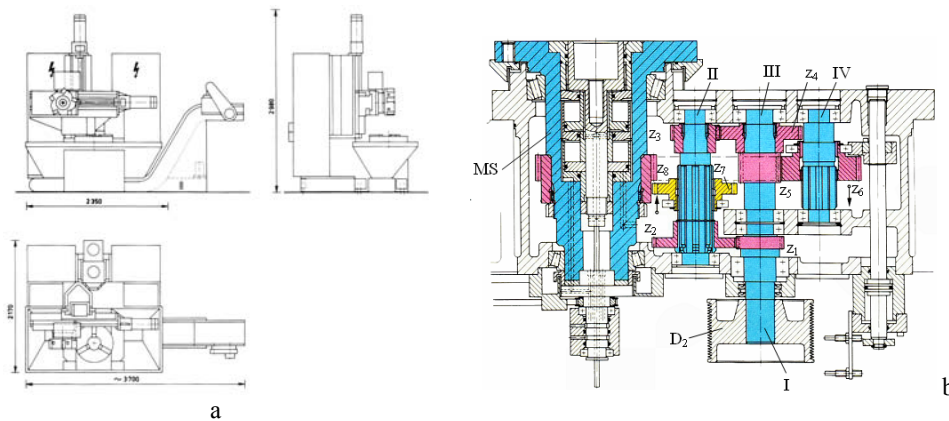


Fig. 5. Three-speed gearbox: *a* – vertical lathe; *b* – gearbox in the main kinematic chain [4]:  $i_{R1} = (z_1/z_2) \cdot (z_7/z_8)$ ,  $i_{R2} = (z_1/z_2) \cdot (z_3/z_4) \cdot (z_5/z_6) \cdot (z_6/z_8)$ .

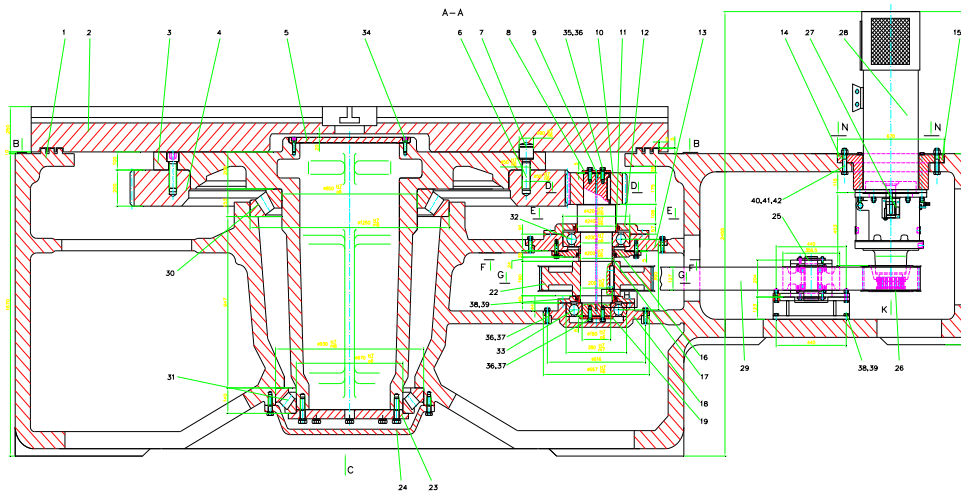
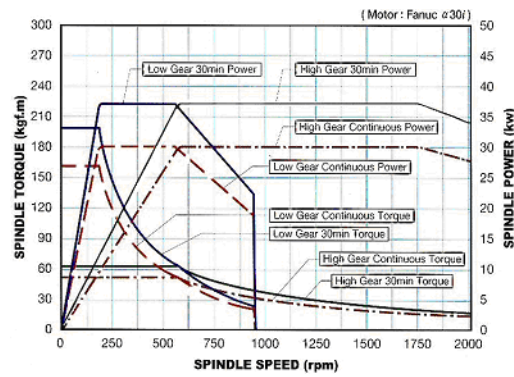


Fig. 6. Structure of a main kinematic chain with electric motor and an integrated gearbox [2].



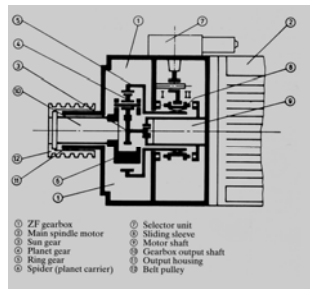
a



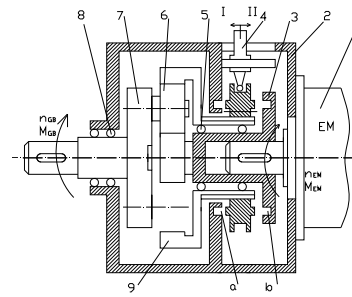
b



c



d



e

Fig. 7. A.C. motors with integrated gearbox [5]: a, c – constructive variants; b – characteristics  $P=f(n)$  and  $M=f(n)$ ; d, e – kinematic structures of the gearbox (1 – electric motor mounted directly on the gearbox; 2 – gear driven by the motor shaft; 3 – gear driven by the motor shaft; 4 – bilateral clutch; 5 and 8 – shaft bearing systems; 6 – planetary gears; 7 – output shaft; 9 – internal teeth gear).

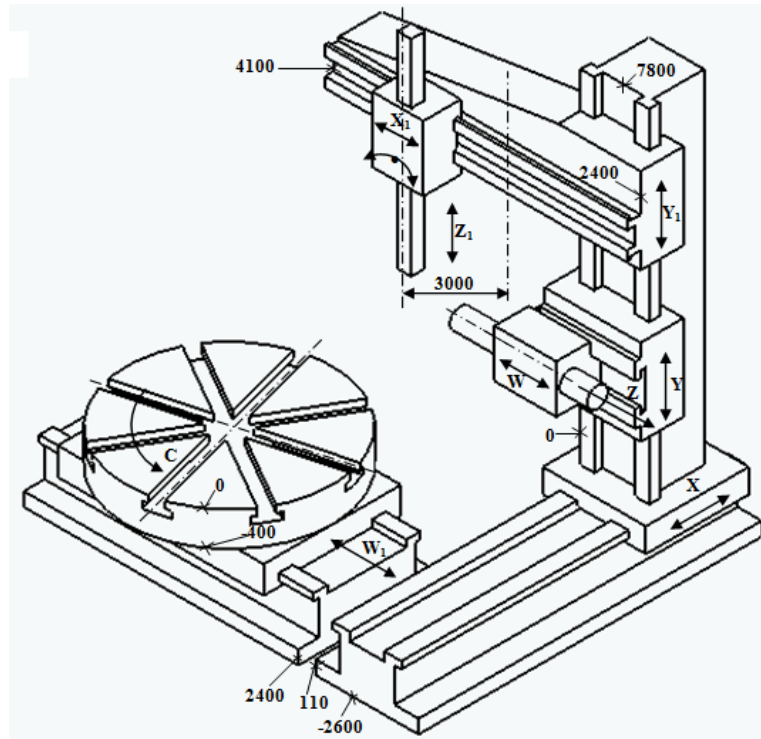


Fig. 8. Multi-functional machine-tool with mechanical and kinematic structure specific to the vertical lathes with single-column and to milling and boring machines with movable column.

mission ratio  $i_{R1} = 1/4$  is engaged by means of the planetary gears 6, while the gear 9 is locked. When having the clutch on position *b*, the planetary gears 6 and gear 9 enable the transmission ratio  $i_{R2} = 1/1$ . The motion from the gearbox output shaft 7 is usually transferred to the main spindle through a Poly V type belt transmission. This kinematic solution diminishes the thermal flow sent to the main shaft and improves the thermal behaviour of the assembly, making possible contour cutting and complex generating kinematic chains by associating in parallel, with the output parameters conditioned by the CNC.

Machining of large size cylindrical gears becomes possible also on multi-functional machine tools (Fig. 8) that have the basic mechanical structure of a single-column vertical lathe (Berthiez type) with a milling unit on the movable cross-rail and of a horizontal boring mill with movable column having the milling and boring unit located on the column. The kinematic structure of the vertical turning and boring machines is identical with the one shown in Fig. 2. There will be in addition the generating kinematic chains specific to CNC milling and boring machines.

## 2. Generating kinematics of the cylindrical gears

### 2.1. Cutting with materialized generatrix using involute profile end mills

Usually, the straight, helical and “V” type toothing of large size cylindrical gears (maximum external diameter  $D_{e\max} = 500\text{--}5\,000$  mm and maximum module  $m_{\max} = 35\text{--}50$  mm) are cut on gear cutting machines with involute profile end mills. For each mentioned type of teeth, the generatrix curve (involute profile of the toothing) is materialized on the cutting edge of the involute profile end mill, while the directing curve (a straight-line, a cylindrical helical line or a combination of two cylindrical helical lines with right-hand/left-hand direction, depending on the type of toothing: straight, helical or “V”) is obtained kinematically as an envelope of kinematic curves (plane cycloid or spatial cycloid).

Therefore, the kinematics for cutting cylindrical toothing requires the following generating motions (Fig. 9,a):

- rotation motion of the involute profile end mill, as the main motion ( $n_s \Rightarrow v_c$ );
- longitudinal feed motion ( $v_{fl} \Rightarrow B_1$ ), with the path parallel to the workpiece rotation axis;
- cross feed motion ( $v_{ft} \Rightarrow B_2$ ), for removing the cutting allowance.

When cutting finger bone gears or “V” type on cylindrical gears, the cylindrical helical-shaped directing curve is obtained by means of a threading chain, which ensures for the workpiece a rotation motion as a complementary generating motion ( $v_T \equiv v_{cg}$ ), correlated kinematically [6, 7] to the longitudinal feed motion ( $v_A \equiv v_{fl}$ ). The function of kinematic closing of the threading kinematic chain –  $v_T/v_A = \tan\beta$  – is accomplished by means of a rigid port-program of change gears type ( $\beta$  being the helix angle of the teeth).

Because cutting of teeth is discontinuous (tooth by tooth), the structure of the machine tools includes also a dividing kinematic chain, which enables the angular positioning motion of the workpiece ( $\gamma_p \Rightarrow D_1$ ) having the following kinematic characteristics:

- constant input parameter (usually  $y_i = 2\pi$ );
- output parameter  $y_e = \gamma_p = 2\pi/z_p$ ;
- adjustment through change gears.

When cutting cylindrical gears with involute profile end mills gear cutters on CNC vertical lathes, the generating kinematics is enabled as follows (Fig. 9):

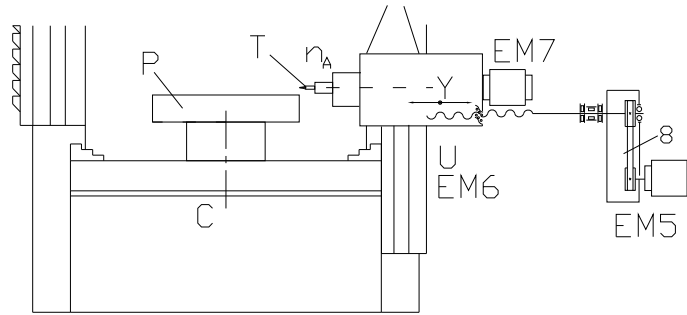


Fig. 9. Kinematic structure for cylindrical gear teeth generating using involute profile end mills.

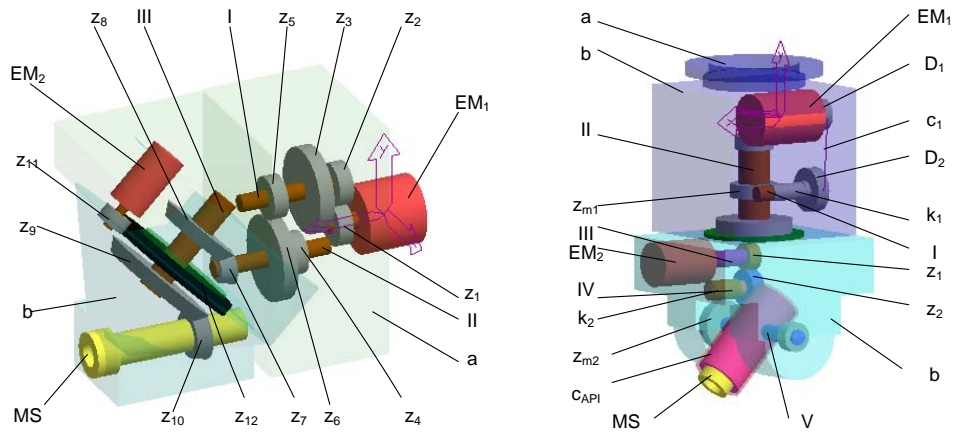


Fig. 10. Milling heads adaptable on the milling unit of the vertical lathe.

- main motion – by the main kinematic chain driven by the electric motor ME7 of the side support;
  - longitudinal feed motion  $B_1$  – by the feed/positioning kinematic chain on  $U$  axis, driven by the electric motor  $EM_6$ ;
  - cross feed motion ( $v_{ft} \Rightarrow B_2$ )– by the feed/positioning kinematic chain on  $Y$  axis, driven by the electric motor  $EM_5$ ;
  - thread cutting kinematic chain resulted by associating in parallel the feed/positioning kinematic chain on  $U$  axis with the feed/positioning kinematic chain on circular path ( $C$  axis), with the output parameters kinematically conditioned ( $v_T / v_A = \tan \beta$ );
  - accomplishing the dividing by CNC controlling of  $C$  axis.
- There are also other cutting possibilities using the involute profile end mills:



- by mounting a milling head (Fig. 10) – with horizontal or vertical position of the cutting tool rotation axis – to the end of the milling unit main shaft;
- by using a multi-functional machine (Fig. 8), where the generating motions of the side head (Fig. 9) are accomplished by those specific to a boring unit.

## 2.2. Cutting with materialized generatrix by using the involute gear cutters

Cutting of cylindrical gear toothing on CNC vertical lathes by using the gear shaper cutters is to be chosen for gears with medium modules and large number of teeth. Two generating kinematic variants are possible by using the generating motions of the side head or the vertical head – each one being equipped with a milling unit. In each case, the generating kinematic is identical to the one applied when cutting with gear shaper cutter. As a result, when cutting gears by using gear shaper cutters, the kinematic structure of the side head (Fig. 11) is the same as the one presented in Fig. 9,a for cutting with involute profile end mill.

Cutting of the cylindrical gear teeth by using the gear shaper cutters and the kinematic structure of the vertical head is suitable for helical teeth, because this head can be positioned in vertical plane by a tilting angle of the teeth,  $\beta$ . In addition, this becomes the only possibility of cutting cylindrical gears with internal teeth (straight or helical).

When cutting cylindrical gears by using the gear shaper on the vertical working head on CNC vertical boring mills, the generating kinematics is ensured as follows (Fig. 12):

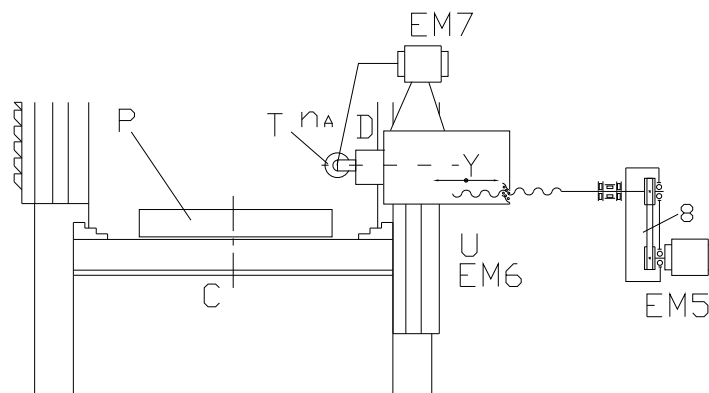


Fig. 11. Cutting the external toothing of cylindrical gears by using involute gear cutters and the side head.

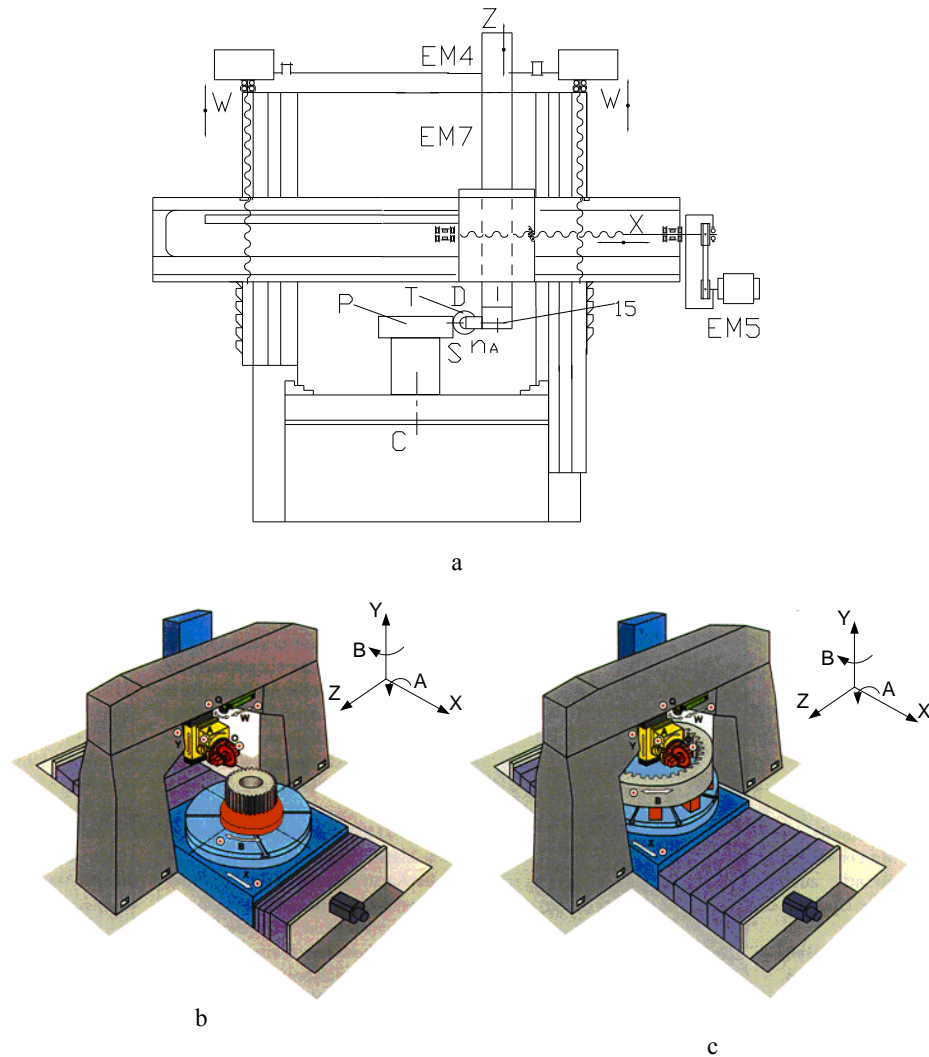


Fig. 12. Cutting cylindrical gears by using the involute gear cutters:  
*a, b* – cutting external teeth; *c* – cutting internal teeth.

- the main motion is supplied by the main kinematic chain, which is driven by the electric motor  $ME_7$ , a milling head 15 with angular positioning being mounted at the end of the main spindle for milling;
- the longitudinal feed motion  $B_1$ , which is obtained through the feed/positioning kinematic chain on the Z axis, driven by the electric motor  $EM_4$ ;
- the cross feed motion ( $v_{ft} \Rightarrow B_2$ ) is accomplished by the feed/positioning kinematic chain on the X axis, driven by the electric motor  $EM_5$ ;

- by getting the threading kinematic chain by associating in parallel – with the output parameters kinematically conditioned ( $v_T/v_A = \tan\beta$ ) – the feed/positioning kinematic chain on  $Z$  axis with the feed/positioning kinematic chain on circular path ( $C$  axis);
- CNC controlled dividing on  $C$  axis ( $\gamma_p = 2\pi/z_p$ ).

### 3. Cutting of the cylindrical gear toothing by rolling without sliding

#### 3.1. Cutting with the gear hobs

This method of generating supposes difficulties in getting closed kinematic chain of rolling type (accomplishment of the involute generatrix) and threading kinematic chain (accomplishment of the tooth direction along a cylindrical helix) and in achieving the conditions of kinematic closing specific to such kinematic chains, which, at this time, are obtained through a flexible port-program by means of the CNC equipment. The kinematic chains associating are independent kinematic chains (the main kinematic chain, the feed/positioning kinematic chain on straight or circular path) with a kinematic structure specific to CNC machine-tools. For example, Fig. 13 represents the kinematic structure of the association between the kinematic chain for rolling and the kinematic chain for threading, when cutting cylindrical gears with helical teeth, on CNC vertical lathes by using the gear hobs. The conditions of kinematic closing of the kinematic chain for rolling and the kinematic chain for threading are [8, 9, 10]:

$$\frac{n_p}{n_s} = \frac{k_s}{z_p}; \quad (1)$$

$$\frac{v_A}{v_T} = \frac{p_{scZ} \cdot n_s \cdot \sin\beta}{\pi \cdot m_n \cdot z_p \cdot n_p} = K \frac{\sin\beta}{m_n}, \quad (2)$$

where  $K = \frac{p_{scZ}}{\pi \cdot k_s}$ .

These are achieved by means of some modules of the CNC equipment. One notices that the kinematic chain for rolling is achieved by associating in parallel the main kinematic chain (it ensures the rotation of the gear hob with the speed  $n_s$ ) with the workpiece rotation ( $n_p$ ) ensured by the circular feed/positioning kinematic chain on the  $C$  axis (table rotation), the kinematic closing condition being expressed by Eq. (1). The kinematic chain for threading is achieved by associating in parallel the feed/positioning kinematic chain on  $Z$  axis with the circu-

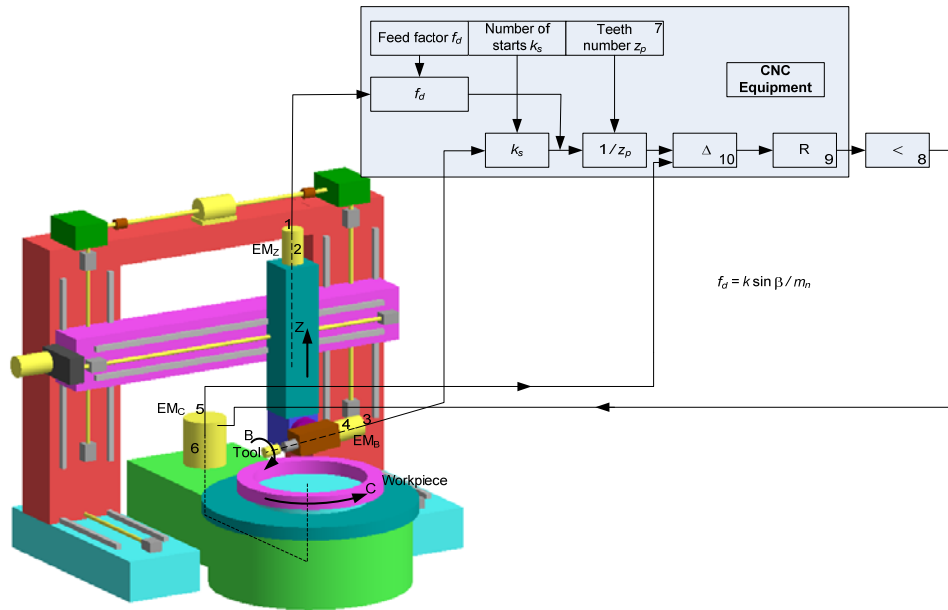


Fig. 13. Mixed association between the kinematic chain for rolling and the kinematic chain for threading, when cutting helical gears on CNC vertical lathes, by using hobs: 1 – rotary encoder on  $Z$  axis; 2 – driving electric motor for the axial feed kinematic chain; 3 – rotary encoder on  $B$  axis; 4 – driving electric motor for the main kinematic chain; 5 – rotary encoder on  $C$  axis; 6 – electric motor for driving the circular feed kinematic chain; 7 – module for data input; 8 – amplifier; 9 – regulator; 10 – adder;  $K$  – threading kinematic chain factor;  $\beta$  – tooth tilting angle;  $m_n$  – normal module;  $f_{dz}$  – feed per tooth;  $k_s$  – number of beginnings of the gear hob;  $z_p$  – gear teeth number.

lar feed/positioning kinematic chain on the  $C$  axis, the condition of kinematic closing being expressed by Eq. (2). The two closed kinematic chains, in their turn, are mixed associated through the adder 10 (it has the same role as the differential gear of the gearing machines with gear hobs with rigid port-program, where the conditions of kinematic closing are accomplished by means of the change gears).

### 3.2. Gear cutting by slotting with basic rack cutter or shaper cutter

For this type of gear cutting, achievement of the main motion on alternate straight trajectory should be kinematically and constructively accomplished. One of the solutions is to achieve the main motion through the feed/positioning kinematic chain on the  $Z$  axis ( $v_c \equiv v_A$ ), which supposes a special design for the screw-nut mechanism. The cutting tool  $T$ , a basic rack-type cutter (Fig. 14) or a shaper cutter (Fig. 15) is mounted on the turning ram or in the main spindle for milling/drilling ( $S$ ) of the milling ram, respectively. A second variant can be ob-

tained by mounting the slotting tools on a slotting head, mounted on the end of the milling/drilling spindle; this variant is applicable for small width of the tothing.

The kinematic chains for rolling, for the two types of cutting tools (Fig. 14 and Fig. 15) are achieved as follows:

- by associating the feed/positioning kinematic chain on the  $X$  axis (it accomplishes the tangential feed speed that helps generating the rolling line – a line) with the feed/positioning kinematic chain on the  $C$  axis (it accomplishes the base trajectory – a circle, by a complementary generating motion);
- by associating the main kinematic chain of the cutter (whose motion has become a circular feed motion) with the feed/positioning kinematic chain on the  $C$  axis.

The positioning motion on radial direction for the purpose of removing the cutting allowance is achieved by a positioning kinematic chain of the table saddle (not shown).

The positioning in vertical plane between the basic rack-type cutter and the workpiece-gear, as well as between the shaper cutter and the workpiece-gear is accomplished through the positioning kinematic chain of the crossrail ( $W$  axis).

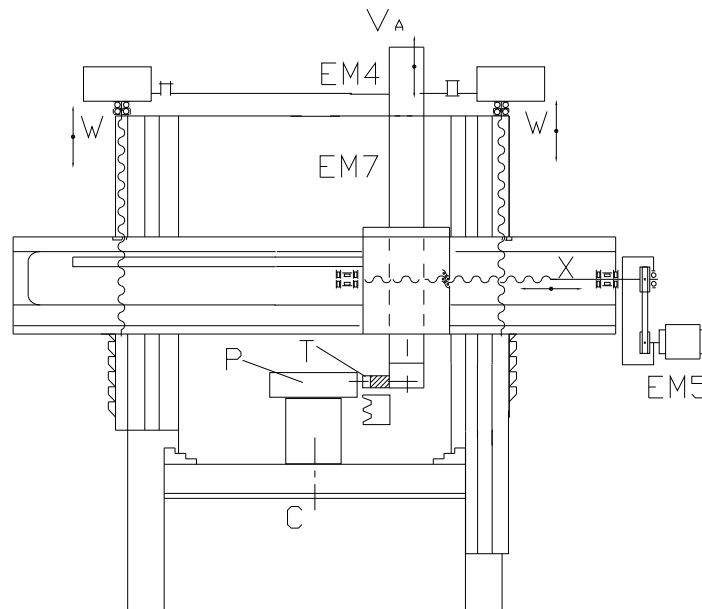


Fig. 14. Kinematics of generating the tothing of cylindrical gears by slotting using the basic rack-type cutter.

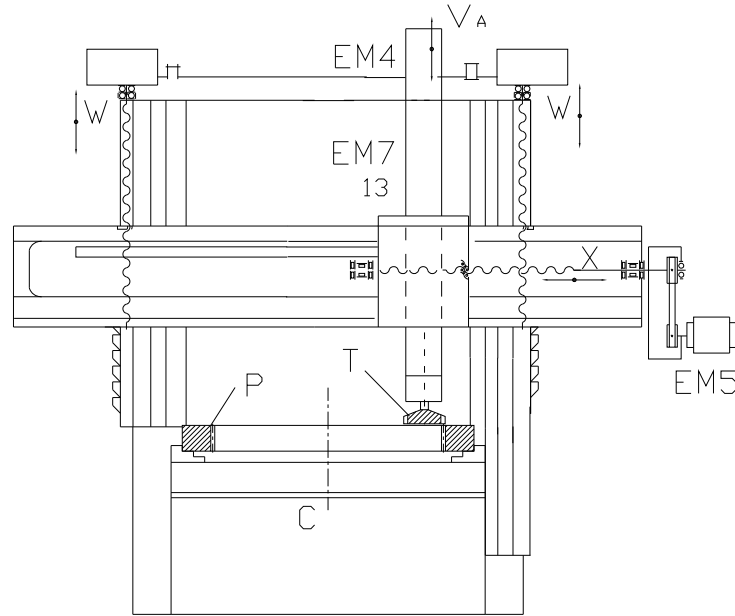


Fig. 15. Kinematics of generating the tothing of the cylindrical gears by slotting using the shaper cutter.

When gear cutting by using the gear hobs and the shaper cutter, the dividing is continuous, while using the basic rack-type cutter the dividing is discontinuous, the auxiliary dividing motion is accomplished through the control on the  $C$  axis (angular positioning of the workpiece-gear with the angle  $\gamma_p = 2\pi/z_p$ , by means of  $X$  axis (straight-lined positioning with the tothing pitch  $p = \pi \cdot m$ ).

#### 4. Cutting of the bevel gears through the method of materialized generatrix

Cutting of the bevel gear with straight or helical teeth on CNC vertical lathes is possible through the method of the generatrix (involute profile) materialized on the cutting edge of the involute profile end mill, under low precision conditions or for roughing operation. The generating motions and the auxiliary motions are accomplished in accordance with the kinematic structure specific to the vertical lathes with milling units (Fig. 16). The angle of the dividing cone of the gear is achieved by positioning the vertical support  $F$  on a vertical plane.

The analysis of cutting possibilities has been made only on kinematic grounds. A calculation for dimensioning or verifying the presented kinematic chains will be further sought of.

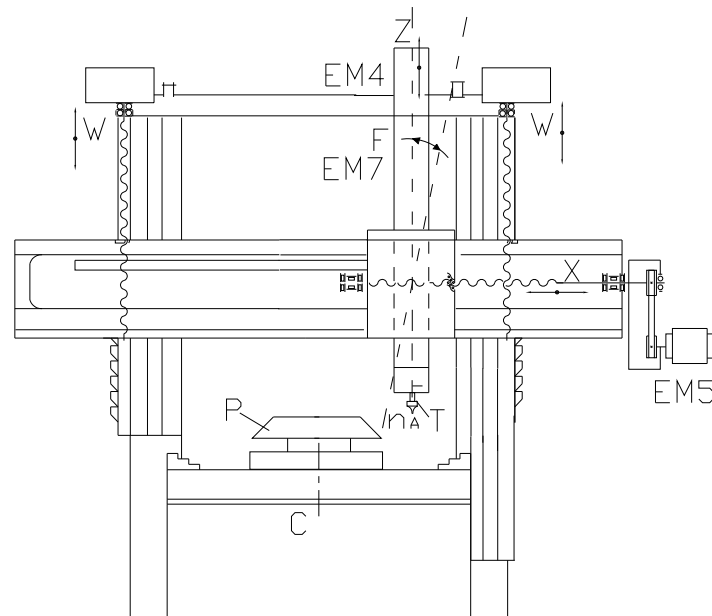


Fig. 16. Kinematic structure of the CNC vertical lathe for bevel gears cutting through the method with materialized generatrix.

## 5. Conclusions

When machining the semi-finished products required for cylindrical or bevel gears of large size on CNC vertical lathes, the possibility of cutting the teeth using the same workpiece clamping represents an advantage that should be materialized by means of a kinematic structure in accordance with the analysis made in paragraphs 2, 3 and 4. Usually, it is not about a mass or series production, therefore use of CNC vertical lathes is convenient and can replace the gear-hobbing machines.

By using modern mechanisms, such as integrated gearboxes and timing belt transmissions, the kinematic chains for rolling, threading and dividing are more easily to be mechanically obtained. The CNC equipment ensures the inter-conditioning required for getting the generating and directrix curves of complex shapes. Moreover, milling, slotting and grinding heads attachable to the milling or turning ram of the vertical working support are necessary.

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