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ADJUSTMENT OF THE MAIN KINEMATIC CHAINS OF HEAVY VERTICAL LATHES

Dan PRODAN[1,*], George CONSTANTIN[2], Anca BUCUREȘTEANU[3]

[1, 2, 3)] Prof., PhD, Eng., Machines and Manufacturing Systems Department, University "Politehnica" of Bucharest, Romania

Abstract: *In this paper the variants of adjusting of the main kinematic chains from the vertical lathes (carousel) are presented. Different possibilities of driving with electric motors are presented in a comparative manner by means of gearbox type gearboxes and belt or tooth belt transmissions. The paper presents the control systems used in older electric motors with a single speed, but also modern systems, in which asynchronous current motors are used having conntonously speed adjustment by frequency variation. It is emphasized the current role of gearboxes which is that of torque amplification and not of speed reduction. It is presented the criteria for choosing the optimal variant from a technical and economical point of view, depending on the specific technological requirements. Some experimental achievements are presented in heavy machine tools from the families of normal and vertical lathes (carousel) for the fabrication and re-fabrication of lathes, which can process pieces having diameters ranging from 800 to 10 000 mm.*

Key words: *main kinematic chain, heavy vertical lathes, gearbox, adjustment range.*

1. INTRODUCTION

Vertical lathes (carousels) are heavy-duty and very heavy-duty universal machine tools on which external and internal turning operations, flat turning, conical turning, threading, milling and even grinding [1, 2, 4, 6] can be performed.

Vertical lathes are part of heavy duty machine tools designed for machining of cylindrical pieces where the ratio between length and diameter is subunit, in the range 0.5–0.9. The diameters processed on these machines are usually in the range 800–20 000 mm and have lengths of 500–5000 mm.

Initially, the only machining operation on these machines was turning. Lately on these machines othre operations can also be acheved such as drilling, milling, grinding, teasing, etc. Expansion of the processing possibilities was possible especially after the appearance of the CNC systems.

In the paper there will be presented some considerations regarding the adjustment of the main kinematic chain (rotating table) with the mention that in the case of CNC machine, for some operations, it becomes a circular feed/positioning drive [1, 2, 7].

[*] Corresponding author: Splaiul Independenței 313, district 6, 060042, Bucharest, Romania
Tel.: 0040 21 402 9174;
Fax: 0040 21 402 9724
E-mail addresses: *prodand2004@yahoo.com* (D. Prodan), *george.constantin@icmas.eu* (G. Constantin), *ancab66@yahoo.com* (A. Bucureșteanu)

2. ADJUSTING THE SPEED AND TORQUE WHEN USING SINGLE-SPEED ELECTRIC MOTORS

The values of the cutting speed v_c and cutting force F depend on a number of factors including: the material of the workpiece and tool, values of the feed and depth of cut, tool life, and cutting conditions. Once all these are set, for correct machining it is necessary that the cutting speed and cutting force to be constant, regardless of the cutting diameter value [1, 2, 4, 6].

The real cutting speed is achieved on the trajectory of the cutting movement during the cutting process.

Regardless of the type of machining, the actual cutting speed is the result of the summation of the speeds of the movements on the trajectories whose combination determines the trajectory.

The main component of real speed is the main cutting speed.

The main kinematic chain is the generator kinematic chain which provides the main cutting speed, on the directrice trajectory or one of its components, being the main component of the actual cutting speed.

The main function of the main kinematic chain is that of adjustment, aiming at the actual cutting speed to be as close as possible to the technological cutting speed. The force developed during the cutting process is that determininng the necessary torque T at the workpiece diameter.

The real cutting speed has the expression:

$$v = \frac{\pi D n}{1000} \text{ [m/min]}, \quad (1)$$

where: D − cutting diameter [mm], n − main spindle speed [RPM].

During radial processing, the diameter of the blank is variable in the range:

$$D \in [D_m \, , D_M], \tag{2}$$

where: D_M – maximum diameter (start), D_m – minimum diameter (final).

From relations (1)−(3), for correct processing, it results:

$$v = constant, \tag{3}$$

$$n \in [n_m, n_M], \tag{4}$$

$$n_m = \frac{1000v}{\pi D_M} \text{[RPM]}, \tag{5}$$

$$n_M = \frac{1000v}{\pi D_m} \text{[RPM]}, \tag{6}$$

During processing, as the workpiece diameter decreases, the speed increases so that the product is constant.

Torque T developed by the main kinematic chain, according to the cutting force F has the value:

$$T = F \frac{D}{2000} [Nm]. \tag{7}$$

For keeping the cutting force F constant ($F = constant$), the torque T should take values in the range:

$$T \in [T_m, T_M]. \tag{8}$$

The torques T_m and T_M have the expressions:

$$T_m = F \frac{D_m}{2000} \text{[Nm]}, \tag{9}$$

$$T_M = F \frac{D_M}{2000} \text{[Nm]}. \tag{10}$$

If P denotes the power necessary for an optimal processing, it results:

$$FV = constant = P. \tag{11}$$

To achieve the drive, according to the structural scheme of Fig. 1, the electric motor EM supplies the speed n_{EM} and instant torque T_{EM}, respectively. If the gearbox is set for a transfer ratio i < 1, at the level main spindle level, neglecting the losses (efffiency η = 1), the n speed and torque T will be obtained. Ideally, the power P developed over entire processing from D_M to D_m should have a constant value.

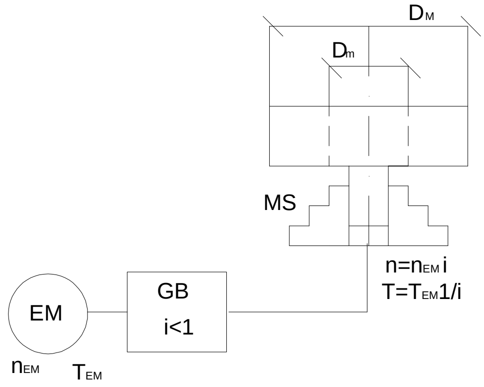


Fig. 1. Structural diagram of the main kinematic chain for vertical lathes.

In the case of the main kinematic chains driven by single-speed motors, the main spindle has a speed that is dependent on the motor type and the speed step selected at the gearbox.

In this case, keeping the notations in the previous relations, at the main spindle level it can be considered that the speed and torque evolve in the case of processong from D_M to D_m, as Fig. 2 shows.

In this case, the processing is not done with constant speed, strength and power values. Such processing is permissible if the diameter variations are small, the D_m and D_M being close. This is the case for narrow rings.

In this case, the characteristics of the electric motor (EM) and main spindle (MS) are shown in Fig. 3.

According to Fig. 3, for the motor and main spindle the following are distinguished: AA_1 – the starting point without the gearbox coupling, BB_1 – starting point of the idle motor coupled to the main kinematic chain, CC_1 – point at which the maximum torque develops. The useful area can be defined as $BCED$ or $B_1C_1E_1D_1$.

It is considered that in the points F and F_1 the kinematic chain blocking occurs.

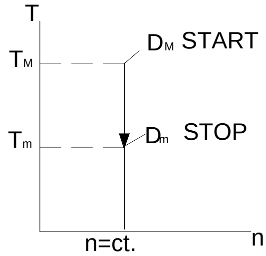
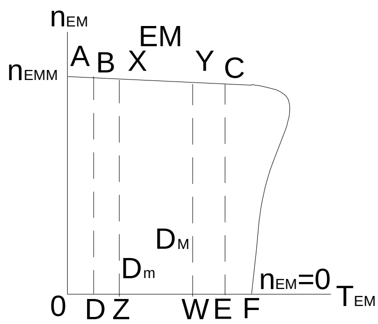


Fig. 2. Torque-speed dependence when using single-speed motors.



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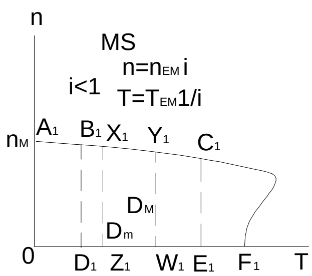

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Fig. 3. Characteristics of the electric motor (EM) and main spindle (MS) for single-speed electric motors and transmission ratio i of the gearbox.

The slope of the AC and A_1C_1 lines comes from the engine chracteristic. This is marked with s and is usually neglected considering that the AC and A_1C_1 lines are parallel to abscissa (T).

The number of pole pairs in these motors usually has the values 1 or 2. Thus, it can practically be considered that such an engine can have a maximum of two speeds at a certain drive frequency [1, 3, 4]. Under these conditions, for a given cutting speed value, at an initial D_M diameter and a final diameter D_m, a transefer ratio i is required to the gearbox. In this case, it is considered that the engine and main spindle speeds are constant between the points YX and Y_1X_1 respectively. Torque values vary between those corresponding to the points WZ and W_1Z_1 respectively. In Fig. 3 there were also noted n_{EMM} and n_M maximum idling speeds for the electric motor and main spindle respectively. For this type of actuation it can be considered that:

$$n = n_M = n_{EMM} i = n_{EM} i = constant, \qquad (12)$$

$$T \in [T_m, T_M], \qquad (13)$$

$$T = T_{EM} \frac{1}{i}. \qquad (14)$$

These motors usually have a single speed, maximum two and to ensure a satisfactory range of cutting speeds, the driving of the main spindle is made through gearboxes with a large number of gears. Gearboxes are complex constructions that include complex cast or welded housings, precision gears [1, 4, 6], shafts and bearings. Their price is high and implies the existence of a specific technology of realization. They provide as many speed steps as possible with subunitary transfer ratios i.

In these conditions, the torque amplification at the main spindle level is also ensured, often with higher values than required.

Figure 4 shows the kinematic scheme of a heavy vertical lathe driven by an electric motor with a single speed.

In Fig. 4 the following notations were made: I–VII – shafts; Z_1–Z_{17} – gears; D_1, D_2 – pully diameters.

The electric motor EM of the vertical lathe with the diagram shown in Fig. 4 has the power of 20 kW and single speed n_{EM} = 1470 RPM and transmits the movement through the D_1 and D_2 pulleys via the 12-speeds gearbox, bevel gears Z_{14} / Z_{15} and crown sprocket mechanism Z_{16} / Z_{17} to the main spindle MS. At the main spindle level the speed n is achived, being available the torque T.

The gearbox, coupled with belt drive, ensures twelve speeds in the range 7.5–150 RPM [1]. The calculated maximum torque is T = 25 000 Nm.

The gearbox results from the need of speed adjustment. It also leads to corresponding increases in the available torques.

In these machine tools, the feed drives [1, 2, 4, 6] receive motion from the main kinematic chain, which actually reduces the values of the torqaues previously calculated.

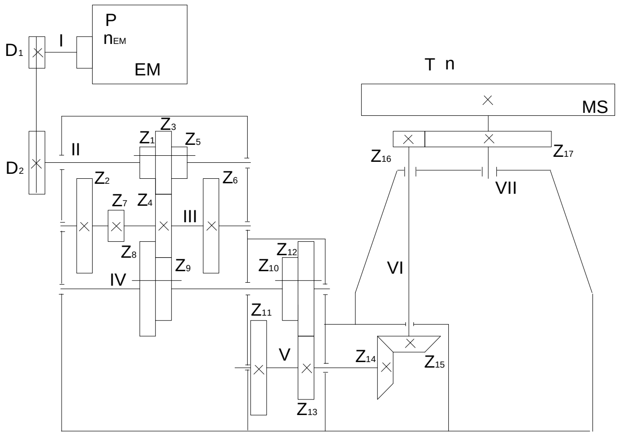

Fig. 4. Main kinematic driven by a single-speed electric motor.

Currently, such gearboxes are used increasingly rarely and never to CNC machines.

However, due to their specificity, heavy-duty machines can suffer refabrication. Given the price of these machines, built even more than 20 years ago, they are often rebuilt. On this occasion, single-speed motors are replaced with newer engines with continuously adjustable speed. In this case, often the original gearboxes are preserved, but abandoning many of the existing steps. It usually holds 2 or more maximum 4 from the initial ones. Their choice is made according to the presentetd criteria, depending on the machining characteristics, speed and cutting force. Replacing the old gearbox with a new one would involve costs that could compromise the entire refabrication.

3. SPEED AND CUTTING TORQUE ADJUSTEMENT WHEN USING ELECTRIC MOTORS WITH CONTINUOUSLY ADJUSTABLE SPEED

Nowadays, the most used control systems for the main kinematic chains for heavy lathes are gearboxes and electronic frequency converters.

By continuously adjusting the electric motor speed, it is possible to maintain constant the processing power at the main spindle when the diameter of the workpiece varies between the maximum diameter D_M and the minimum one D_m (Fig. 5).

The engine speed will increase from the minimum n_m to the maximum n_M starting from the diameter D_M to the diameter D_m in the case of large diameter machining and with large variations of cutting diameter, such as in the case of the wide rings. In this case, the torque decreases from maximum T_M to minimum T_m, the power being constantly constant.

If the elctric motor is considered to drive the main spindle by means of a gearbox set on a step having the ratio i and the efficiency of the kinematic chain is $\eta = 1$, the characteristics of Fig. 6 will be obtained for the engine and the main spindle.

In Fig. 6 the following notations were made: n_{EMN} – nominal motor speed [2, 3, 4], T_{EMM} – maximum torque developed by the motor. In the $ABCD$ and $A_1B_1C_1D_1$ surfaces respectively, the speed adjustment is made under conditions of maximum constant torque and increasing power on the DE and D_1E_1 lines respectively.

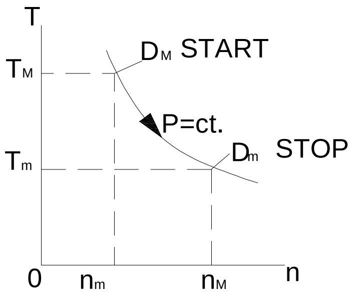

Fig. 5. Processing at constant power when using adjustable speed motors.

From the B, E and B_1, E_1 points, the adjustment will be at maximum constant power and decreasing torque. In the F, H and $F1$, $H1$ points, the maximum speed is achieved at maximum power and minimum torque.

According to Fig. 6, for the motor and for the main spindele respectiely, in the areas AB, A_1B_1 the maximum torque is constant and the power is decreasing. Note the points:

- B, B_1 – starting points of the electric motor (idle) coupled to the main kinematic chain,
- C, C_1 – points in which the maximum torque develops.

If the engine is operating at a lower engine speed than the nominal one (n_{EMN}), it is assumed that the adjusment is achived at maximum torque at the engine. If the motor speed exceeds the nominal speed, it is considered to be an adjustment at maximum constant power of the motor.

In order to determine the main kinematic chain variant, it is necessary to know: the desired speed range and the maximum required torque range. Speed adjustment for the entire range can only be achieved theoretically by adjusting the engine speed, but to meet the torque requirements, heavy duty and heavy duty vehicles require the presence of a gearbox. These are much simpler than those used for single-speed electric motors. These gearboxes have a maximum of four steps. The first stage usually provides a close ratio to 1/1. The largest demultiplication can be up to 1/20.

Figure 7 shows the kinematic diagram of the vertical lathes having diameters of the plate in the range 1400–3000 mm.

In Fig. 7 one also noted: I÷IV – kinematic chain axes, Z_1–Z_{10} – number of teeth of the gears. At the level of the main spindle the speed n is supplied along with the torque T.

Speed adjustment is achieved continuously at the electric moteor level and using three gears of the gearbox, according to the following equations:

$$n_{EM} - I - \frac{Z_1}{Z_1} - III - \frac{Z_7}{Z_8} - IV - \frac{Z_9}{Z_{10}} - MS, \quad (15)$$

$$n_{EM} - I - \frac{Z_1}{Z_2} - II - \frac{Z_3}{Z_4} - III - \frac{Z_7}{Z_8} - IV - \frac{Z_9}{Z_{10}} - MS, \quad (16)$$

$$n_{EM} - I - \frac{Z_1}{Z_2} - II - \frac{Z_5}{Z_6} - III - \frac{Z_7}{Z_8} - IV - \frac{Z_9}{Z_{10}} - MS. \quad (17)$$

The Z_1–Z_6 gears provide three transfer ratios: 1/1, 1/3 and 1/9 [2, 3].

In the case of an SC17 lathe, having a 60 kW engine, through the following three steps by continuously adjusting the following speeds are ensured:

$$i = 1/1\,,$$

$$n \in [20 - 200]\ [\text{RPM}],$$

$$i = 1/3,$$

$$n \in [6.48 - 648]\ [\text{RPM}],$$

$$i = 1/9,$$

$$n \in [2.22 - 22]\ [\text{RPM}].$$

The maximum developed moment is T_{MSMax} = 40 000 Nm. The gearbox is much simplified compared to the one shown in Fig. 4 having only three steps. In heavy lathes, a special contribution to speed reduction and torque amplification has the last crown gear mechanism, the gear ratio of which is less than 1/10. In these CNC machines, the feed kinematic chains are driven by independent motors. In this case, the power of the main kinematic chain is not diminished.

The three-speed gearbox is shown in Fig. 8. The gearbox shown in Fig. 8, where the previous notations have been preserved, works in a horizontal position, which requires the use of the Z_7 / Z_8 conical group. Due to the existing plays in this mechanism, as well as the in other spur gears and crown sprocket mechanism, in case of milling, a separate kinematic chain will be used for running backlash free [2, 7, 9].

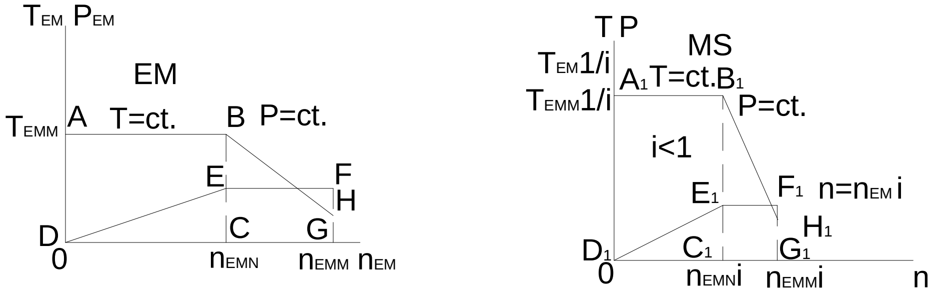

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Fig. 6. The characteristics of the electric motor (EM) and the main spindle (MS) in case of the use of variable speed electric motors and the transfer ratio i of the gearbox.

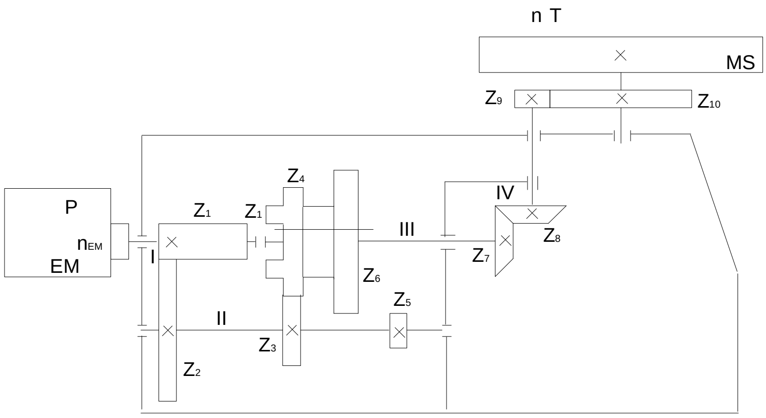
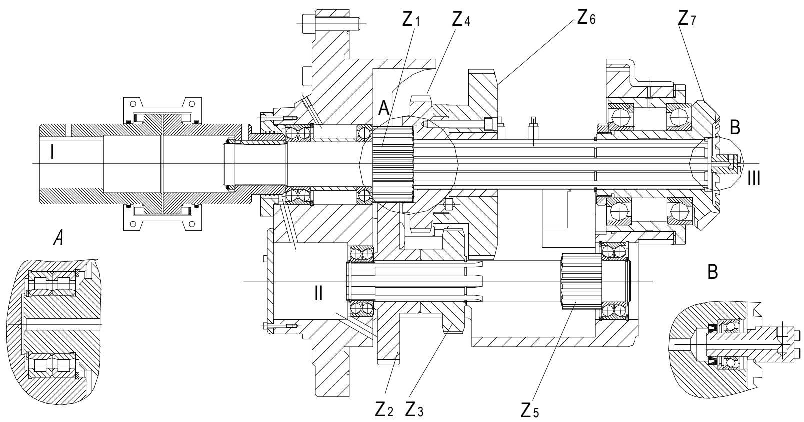


Fig. 7. The kinematic scheme of the main kinematic chain in heavy vertical lathes SC14–SC33.



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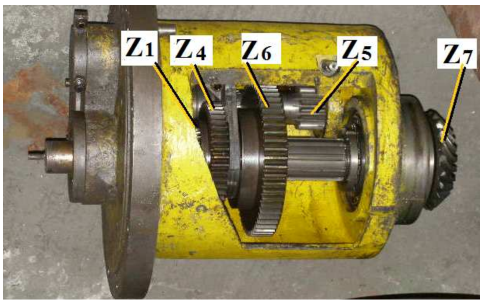

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Fig. 8. Three-speed gearbox used for vertical lathes in the SC14–SC43 series.

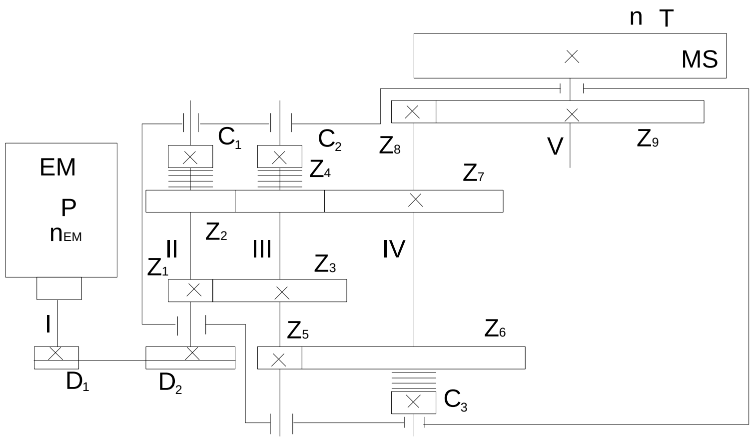


Fig. 9. Gearbox with vertical shafts and electromagnetic clutches.

To avoid the use of conical gears, vertical gearboxes can be used. A three-stage gearbox and elctromagnetic clutches [4, 6] are shown in Fig. 9.

In Fig. 9 it is also noted: I–V – shafts of the kinematic chain; Z_1–Z_9 – number of teeth of the gears; D_1 and D_2 – diameters of the pulleys; C_1, C_2, and C_3 – electromagnetic clutches. At the main spindle level the speed n is supplied along with the torque moment T.

The speed adjustment is done continuously from the motor and using three steps gearbox, according to the equations below, depending on the actuated electromagnetic clutch:

C_3 energized:

$$n_{EM} - I - \frac{D_1}{D_2} - II - \frac{Z_1}{Z_3} - III - \frac{Z_5}{Z_6} - IV - \frac{Z_8}{Z_9} - V - MS \quad (18)$$

C_2 energized:

$$n_{EM} - I - \frac{D_1}{D_2} - II - \frac{Z_1}{Z_3} - III - \frac{Z_4}{Z_7} - IV - \frac{Z_8}{Z_9} - V - MS \quad (19)$$

C_1 energized:

$$n_{EM} - I - \frac{D_1}{D_2} - II - \frac{Z_2}{Z_4} - III - \frac{Z_4}{Z_7} - IV - \frac{Z_8}{Z_9} - V - MS \quad (20)$$

The pulleys and gears Z_1–Z_7 provide three transfer ratios: 1/3, 1/7 and 1/16 [3]. Regardless of the chosen step, speed is reduced by 1/14 by the final ratio Z_8/Z_9.

Thanks to the development of electronic speed control systems, the gearboxes are becoming more and more simple. Thus the gearbox used by PIETRO CARNAGHI has only two steps. Through its construction and vertical assembly it is possible to remove bevel gears (elements that introduce considerable backlash). The kinematic scheme of a kinematic chain used in a vertical lathe with a plate with a diameter of 4300 m is shown in Fig. 10. The electric motor used has the power P = 100 kW, nominal speed n_{EMN} = 1500 RPM, maximum speed n_{EMM} = 4500 RPM and maximum torque T_{EMM} = 636 Nm.

Speed adjustment is made continuously through the engine and two steps of the gearbox, according to the equations:

$$n_{EM} - \frac{D_1}{D_2} - II - \frac{Z_1}{Z_2} - III - \frac{Z_2}{Z_3} - IV - \frac{Z_3}{Z_4} - V - \frac{Z_7}{Z_8} - VI - MS \quad (21)$$

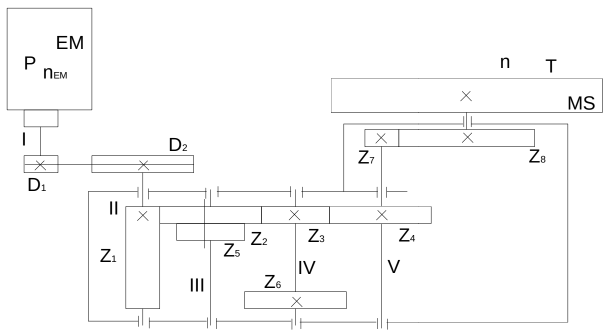


Fig. 10. The kinematic diagram of the main chain from a vertical lathe with a two-speed gearbox.

$$n_{EM} - \frac{D_1}{D_2} - II - \frac{Z_1}{Z_2} - III - \frac{Z_5}{Z_6} - IV - \frac{Z_3}{Z_4} - V - \frac{Z_7}{Z_8} - VI - MS \quad (22)$$

The Z_1–Z_8 gears provide two transfer ratios: 1 / 2.47 and 1 / 10.37 [3].

In the case of this lathe, the speeds obtained at the main spindle level are:

$$i = 1/2.47.$$

$$n_{MS} \in [1 - 100] \text{ [RPM]},$$

$$i = 1/10.37,$$

$$n_{MS} \in [0.27 - 24.09] \text{ [RPM]}.$$

Figure 11 shows a section of the gearbox without the belt transmission and the pinion crown end mechanism.

The sliding gear block Z_2Z_5 is the one through which the speed step is changed. Usually, these sliding blocks are hydraulically actuated and secured [2].

By comparing the two gearboxes shown in Figs, 10 and 11, we notice that the latter has a higher torque amplification at the expense of high speeds.

An important role in the modernization of lathes and other machine tools was the occurrence of power transmissions with toothed belt wheels and two-speed gearboxes, developed by specialized companies [5, 6, 8].

Of the modern mechanical transmissions, which largely removed the gear systems, the most spectacular evolving over time was the transmission of toothed belts. They were used initially only in the feed drives due to their low power transmission capabilities. In present, they are also used in the main kinematic chains and can transmit 100 kW power. Among the obvious advantages they have to gearing, one can notice:

- lower price,
- produced by specialized manufacturers,
- low noise in operation,
- can transmit motion at distances greater than the distance between the axis of a gearing,
- do not require lubrication,
- functioning with backlash free.

This last advantage requires them in the case of numerically controlled machines.

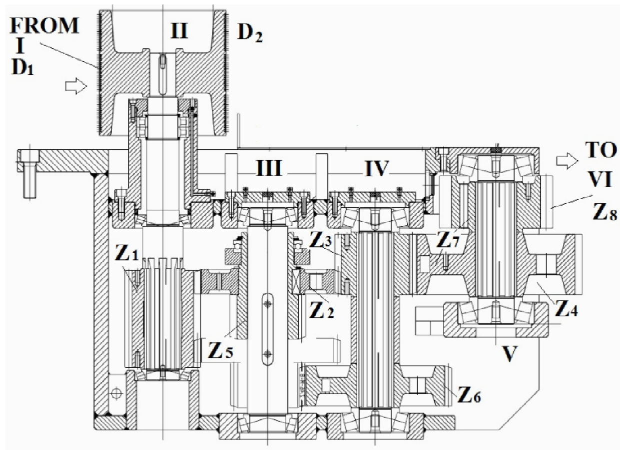


Fig. 11. Two-speed gearbox.

Where only two steps are sufficient for the technological process served, the gearboxes provided by the specialized firms can be used. They are selected from the catalogs [2, 3, 8] depending on the power to be transmitted and the necessary transfer ratios.

They have a number of advantages such as:

- Reduced backlash that allow them to be used also for vertical lathes that perform milling operations by eliminating circular feed drives;
- Lubrication circuit apart from the rest of the machine, which reduces heat transmission to the main shaft;
- Coupling to the main spindle through toothed belts, preventing transmission of vibrations;
- low noise;
- Simple and compact design with direct drive coupling;
- High efficiency, over 95%;
- Changing the speed steps is done with an integrated device in the gearbox, electrically, pneumatically or hydraulically operated.

The two-speed gearboxes and low backlash are usually made with two transfer ratios i_1 = 1/1 and i_2 =1 /3 (1/5) [2, 3] transfer ratios. These solutions are currently used on a large scale by different manufacturers. For vertical lathes from the SC11–SC22 range, it is even possible to remove the crown pinion end mechanism. Figure 11 shows the construction of such gearboxes.

The entire construction is made in the housing 1. The electric drive motor engages with the shaft 10.

The inner gear teeth 7 can engage the planet gears 2 on the planet gear carrier 6. In the case of transmission of the movement from the shaft 10 to the shaft 3 by means of the planatary transmission the provided ratio is i_2 = 1 / 5. The switching system 12, by means of fork 11, realizes the two steps. The central pinion 5 is coaxial with the shaft 10 and solidar with it. When the fork 11 is moved to the right, the outer toothed crown 9 solidarizes with the internal crown 8 which is fixed. In this case, the transfer between the input gear 10 and the output one 3 is directly (i_1 = 1/1). The shaft 3 is mounted in the housing by means of bearings 4. Such gearboxes can provide motor motion for up to 80 kW.

A gearbox similar to the one in Fig. 11 but made by another manufacturer [4] is shown in Fig. 12.

Figure 12 retains previous notations. These gearboxes can be used for transmitting power up to 80 kW and have i_1 = 1/1 and i_2 = 1/4 ratios.

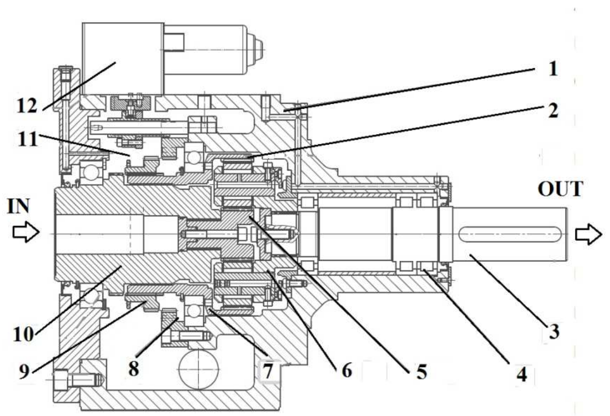
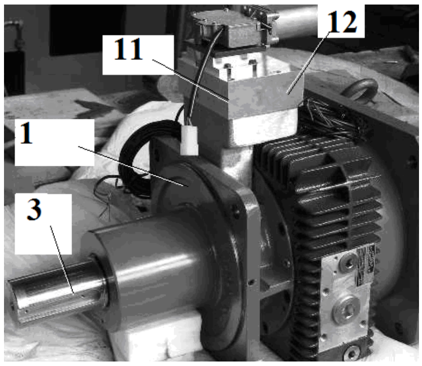


Fig. 11. Two-speed gearbox with i_1=1/1 and i_2=1/5.



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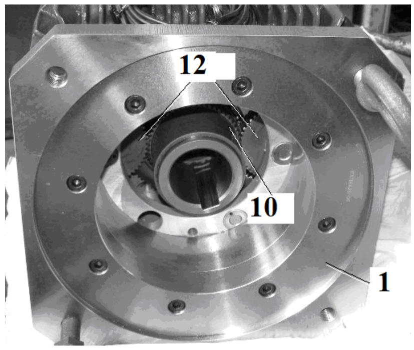

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Fig. 12. Two-speed gearbox with i_1 = 1/1 and i_2 = 1/4.

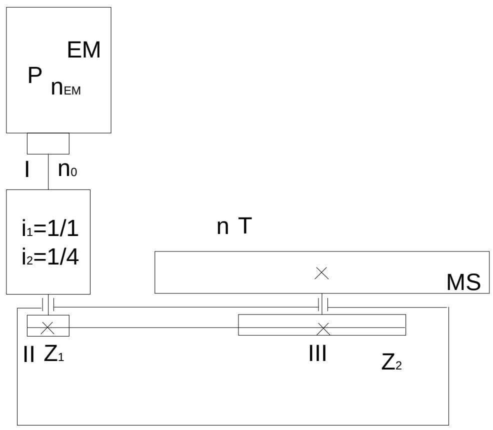


Fig. 13. The kinematic scheme of the main chain of a vertical lathe with a two-step gearbox and toothed belt without a pinion-crown mechanism.

In the case of vertical lathes of less than 2000 mm plate (SC11–SC17) it is possible even elimination of the end pinion crown mechanism [2, 4, 10]. Figure 13 shows the kinematic scheme of the main kinematic chain from a lathe of this type.

In Fig. 13 it was noted: Z_1 and Z_2 – tooth belt number of teeth; i_1 and i_2 – gearbox gear ratios used.

Speed adjustment is made continuously from the engine and using the two gearbox steps according to the equations:

$$n_{EM} - i_1 - II - \frac{Z_1}{Z_2} - III - MS, \qquad (23)$$

$$n_{EM} - i_2 - II - \frac{Z_1}{Z_2} - III - MS, \qquad (24)$$

Thanks to reduced backlash, the main kinematic chain can also be used as a circular feed drove CNC milling [2, 5, 7].

The selection of the two-stage and three-stage gearboxes used in SC11–SC22 lathes is based on the type of machining to be performed on the machine.

In the same asynchronous electric drive motor with speed-controlled frequency drive, there are no differences in speed adjustment, the two-stage gearbox being preferred. Problems may arise in terms of the developed torque, given that the maximum demultiplication of the two-stage gearbox is 1:4 and at that with three steps it is 1:9.

For example, it is considered the case with an electric motor having the characteristics:

$$n_{ENM} = 1500 \text{ RPM}, P_{EM} = 37 \text{ kW}, T_{MEM} = 236 \text{ Nm}. \quad [8]$$

In the case of using a three-speed gearbox, the maximum torque developed is 2124 Nm up to a speed of 166.6 RPM; 708 Nm up to 500 RPM and 236 Nm up to 1500 RPM.

Depending on the machine kinematics and the processing needs, the following variants are distinguished:

- the developed torque is sufficient (do not perform machining of hard materials);
- other demultiplication mechanisms are introduced;
- choose a larger power motor (torque).

In some cases, especially in machines where the main spindle is to be used for circular feed movements, two engines can be used, each with its own gearbox, as in Figure 14 [2, 3, 5].

In the two cases presented in Figs. 14,*a* and *b*, the two electric motors EM_1 and EM_2 are identical. The two gearboxes GB_1 and GB_2 are also identical and permanently set to the same transfer ratio (1/1 or 1/4). The movement ultimately comes from the pinions Z0 to the crown *Z*. In Fig. 14, the toothed crown *Z* is not shown. If the power of an motor is *P*, it is usually assumed that the maximum power of such a system is 1.5*P*–1.8 *P*. On these machines, the machine control system can also assure the take-over of the backlash between the pinions Z_0 and crown *Z* [9].

In the case of larger machines where it is necessary to drive with an engine of over 90 kW, the use of the two-stage boxes offered by the specialized manufacturers is excluded. For such machines, usually with the possibility of processing diameters larger than 5000 mm, one or even two specific gearboxes are used. If two engines are used, each will have its own gearbox.

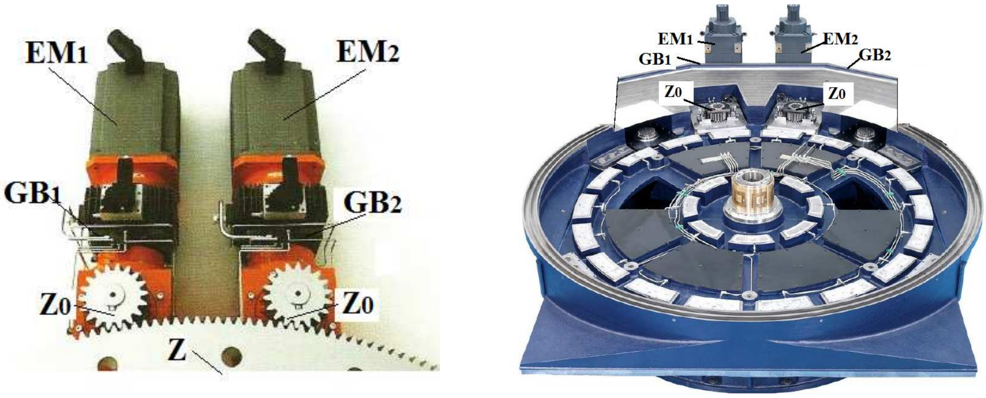
Figure 15 shows the diagram of a lathe with a 5600 mm plate diameter and which can process parts up to 300 t. This gearbox provides two turning steps, but due to its special construction, it can also provide the necessary speeds for the plate for cases where it is no longer acted as a main kinematic chain, but one circular feed (*C* axis). This is the case of milling machining. In this case, the axis C works independently or together with the translation axes (*X* and / or *Z*) in the case of interpolation.

The main kinematic chain is driven by the electric motor EM. It has continously adjustable speed in the range 75–1900 RPM. Hydraulic clutch C via the H_3 path ensures the transmission of the movement directly from the shaft I to the shaft II. From here, the movement is permanently transmitted to the shaft IV. Shaft IV supplies in turn the motion simultaneously to the shafts VL (left) and VR (right). They can transmit the motion to the VIL and VIR shafts in two ways, depending on the command given on one of the hydraulic paths H_1 and H_2. The pinions Z_9 transmit the motion from the VIL and VIR shafts to the main spindle VII. The kinematic flow scheme of the main kinematic chain is

$$n_{EM} I (C\ H_3) \frac{Z_1}{Z_1} - II - \frac{Z_2}{Z_3} - IV - \frac{Z_4}{Z_5} - VL, VR - (H_1) \frac{Z_5}{Z_6} - VIL, VIR - \frac{Z_9}{Z_{10}} - VII - MS, \quad (26)$$

$$n_{EM} I (C\ H_3) \frac{Z_1}{Z_1} - II - \frac{Z_2}{Z_3} - IV - \frac{Z_4}{Z_5} - VL, VR - (H_2) \frac{Z_7}{Z_8} - VIL, VIR - \frac{Z_9}{Z_{10}} - VII - MS. \quad (27)$$

For the electric motor *EM* (Fig. 15), the low speed step is obtained in the range 0.3–8 RPM. On the second stage, the speeds obtained are in the range 1.2–31 RPM. The couplings *C*, *CL*, *CR* are hydraulically operated [2].



a b

Fig. 14. Kinematic chains (circular feed motion) driven by two electric motors.

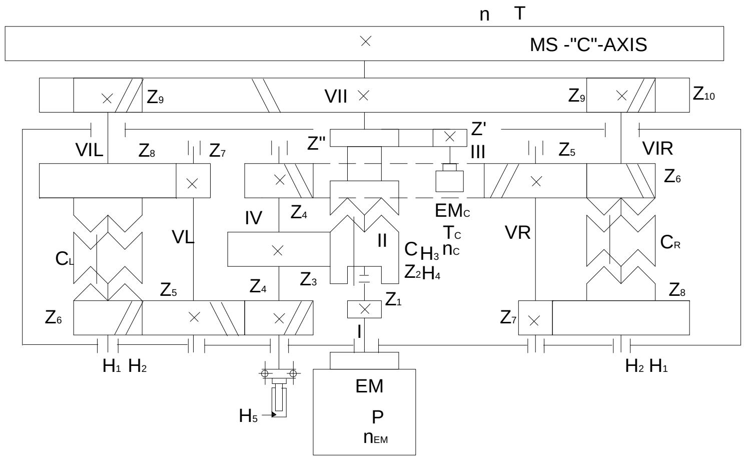


Fig. 15. The speed and circular feed gearbox of the vertical lathe with the 5600 mm plate.

When switching the clutch C in the upper position (*C*, H_4 +), the motor *EM* is disconnected and the circular feed motor *EMC* is engaged. This, by toothed belt transmission *Z'* / *Z*", rotates the shaft II at a speed and torque lower than those supplied by the motor *EM*. In this case, the anti-backlash system is activated [2] by sending oil under pressure on the path H_5. In this case, due to the opposite helix diection of the teeth of the two pinions Z_4 on the shaft IV, the backlash on the pitch circle of the two pinions Z_9 and Z_{10} in engagement is taken over.

Figure 16 shows the construction of the right part of the gearbox whose scheme has been shown in Fig. 15.

The pinions Z_9 have 20 teeth, module m = 16 mm and are the tooth helix is tilted on the right with 12°. The gears Z_6 have 64 teeth, module m = 6 mm and the theeth are inclined to the left and right with 30° respectively. The gears Z_8 have the module m = 10 mm and 72 teeth.

Figure 17 shows a view of the gearbox *GB* housing resulting in the belt transmission location and pinions Z_9.

The pullies of the belt transmission used in the feed drive have the ratio *Z'* / *Z*" = 16 / 100 and the electric motor EM_C has continusously adjustable speed in the range 0.15–930 RPM.

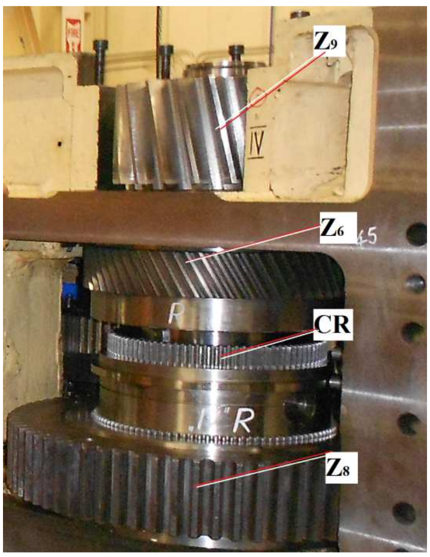


Fig. 16. Right side of the two-speed gearbox.

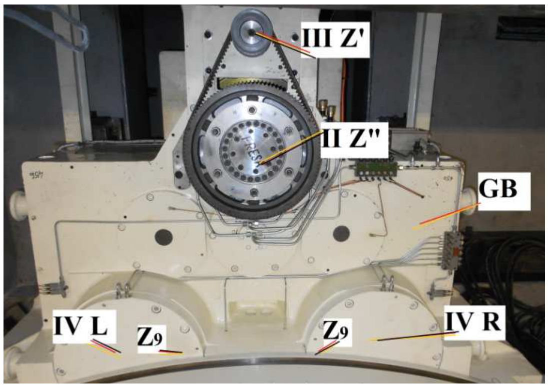


Fig. 17. Transmission of movement for the circular feed drive (axis *C*).

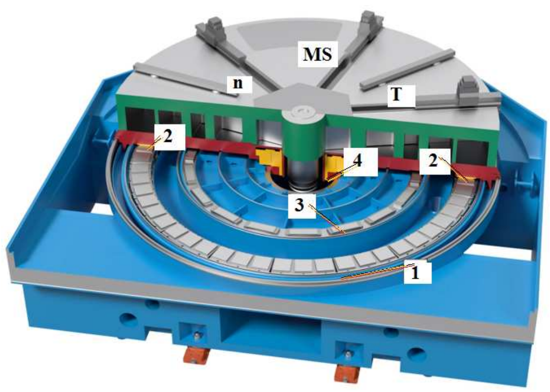


Fig. 18. Main kinematic chain of the *Direct drive* type.

It is worth mentioning that in the case of large machines with a plate over 5000 mm, this is usually supported by hydrostatic axial bearings insetead of bearings. The radial support can be made with bearings or also hydrostatic.

Recent research done by machine tools specialists focuses on simplifying the main kinematic chains by using *Spindle Motor* solutions. Figure 18 shows the working principle of this solution.

The electric drive motor has the stator 1 fixed to the bed. The main spindle MS is solitary with the rotor of the motor 2 and is axially and radially hydrostatically supported with hydrostatic mopdulated pockets 3 and 4. The machines built on this principle have the following characteristics:

- plate diameter 2500–8000 mm,
- drive motor power *P* of 100–240 kW,
- developed torque *T* of 31 000–333 000 Nm,
- main spindle speed 50–175 RPM.

These solutions, which are still in a testing phase, have the advantages of simplifying the cinematic chains and the entire construction. The modularization of stator 1, rotor 2 and hydrostatic pockets 3 allows the realization of an extended range of main spindle sizes.

4. CONCLUSIONS

By using the continuously adjustable speed electric motors, speed reduction can be made much easier electronically, with gearboxes providing adequate output torque amplification. In this case, the gearboxes have up to four speed steps.

In the case of the fabrication or re-fabrication of a vertical lathe, the choice of the mode of operation and implicitely the of the gearbox used asumes knowledge of the machining to be done. This involves knowing the basic parameters:

- range of diameters to be processed;
- power *P* required for the main spindle;
- required speed *n* range resulting from the specific cutting conditions and the machined diameters;
- torque value *T* required for a certain imposed cutting speed;
- existing gearbox type (in case of re-fabrication).

For machining up to 2000 mm in diameters, which does not require high torques (finish cut with small depth of cuts), for power up to 80 kW, the two-speed gearboxes offered by specialized firms are a recommended.

If machining is done under conditions requiring high torques (roudg cut, large depth of cuts, possibly irregular, crumbs from casting, etc.) and at over 80 kW power, the specific gearboxes with 2–4 steps are preferred.

In the case of very heavy machines with processing diameters more than 5000 mm, it is recommended that the main kinematic chains have one or two power sources represented by 1–2 motors supplying 100 kW and one or two specific gearboxes. These are characterized by that they have specific components for power transmission such as gears with modulus of 10–20 mm.

The use of toothed belts is limited by two considerations:

- maximum power (maximum torque) thay can transmit;
- maximum diameter of the belt pulleys supplied by manufacturers.

In the case of heavy-duty vertical lathes with multi-stage gearboxes, it is recommended that they be retained reducing the speed step number to a maximum of 2–4.

Choosing the optimal drive variant for these very heavy machines should take into account the technical criteria presented without neglecting the economic ones, knowing that the price of the transmission components of power over 20–30 kW is high.

REFERENCES

[1] Emil Botez, Masini-Unelte Vol.I,Vol.II, Editura Didactica si Pedagogica, Bucuresti 1977, 1978, CZ 621.9, CZ621.8

[2] D. Prodan, *Maşini-unelte grele. Sisteme mecanice şi hidraulice* (Heavy duty machine tools. Mechanical and hydraulic systems), Edit. Printech, Bucharest, 2010.

[3] ******* Catalogues and brochures: ZF, REDEX, BARUFFALDI,STOBER,TOCHIBA, BERTHIEZ,GPM TITAN INTERNATIONAL, PIETRO CARNAGHI, MORANDO, GE FANUC, SIEMENS.

[4] B. Perovic, Handbuch Werkzeug-maschinen (Machine tools handbook), Carl Hanser Verlag, Munchen, Wien, 2006.

[5] D. Prodan, N. Predincea, N., G. Constantin, & I. Tanase, *Gear Cutting on CNC Vertical Lathes. Kinematic Capabilities*, U.P.B. Sci. Bull., Series D, Vol. 73, Iss. 3, 2011, pp. 153–168.

[6] Prodan, D., Petre, M., Constantin, G., & Bucuresteanu, A, Eliminating the backlash of circular feed drives of cnc vertical lathes. *Proceedings in Manufacturing Systems*, *11*(1), 27.

[7] P.H. Joshi, Machine tools handbook, McGraw-Hill, New Delhi, 2007.

[8] D. Prodan, M. Petre, G. Constantin, & A. Bucuresteanu, Eliminating the Backlash of Circular Feed Drives of CNC Vertical Lathes,*Proceedings in Manufacturing Systems*, Vol. 11 (2016), Iss.1, pp. 27-34.

[9] D. Prodan, A. Motomancea, A. Bucuresteanu, E. Balan, *Modern Main Kinematic Chains for Machine Tools,* International Journal of Engineering and Innovative Technology (IJEIT), Vol. 4 (2015), Iss. 10, pp. 62-67.

[10] C. Gornic, *Cum se alege o masina-unealta (III)* (How to choose a machine tool), T&T Tehnica si Tehnologie, Vol. pp: 1453-8423