

ADJUSTMENT OF VERTICAL LATHES ROTATIONAL SPEED

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Abstract: *This paper presents some adjustment variants of vertical lathes main kinematic chain that have been used for more than 40 years and are still being used. These are presented comparatively by mentioning some values of adjustment ranges and torque couple necessary for the main kinematic chain. Initially, the gearboxes were built with sliding gears and couplings and they were used to decrease the rotational speeds in order to achieve the desired cutting speed. The rotational speeds decrease led indirectly to the amplification of the available torque. At the present moment, the vertical lathes CNC use modern gearboxes with planetary systems and frequency electronic converters which provide the decrease of rotational speeds and a proper amplification of torque output. At the same time, the number of steps of the gearboxes is reduced. The appearance of power transmissions with toothed belts had an important role in vertical lathes modernization. These improvements of the adjustment of main kinematic chain are necessary today, especially after numerical controls coming out, when the vertical lathes allow, besides turning, the machining of complex surfaces resulted from milling and grinding operations. In the end of the paper, there is presented an example of dynamic mathematical model for fixing the features of power and torque specific to vertical lathes CNC.*

Key words: *vertical lathes, gearbox, adjustment of rotational speeds, adjustment range, toothed belt power transmission.*

1. INTRODUCTION

The vertical lathes (vertical turning and boring machines) are universal heavy and very heavy duty machine tools on which can be made operations of external and internal turning, flat turning, taper turning, threading, milling and even grinding [1]. These machines were initially recommended for machining the parts with diameters much larger than their length by turning operations.

At the present moment, especially after numerical controls coming out, the vertical lathes allow, besides turning, the machining of complex surfaces resulted from milling and grinding operations.

Out of the main characteristics of these machines we can mention the following ones: machining diameters in the range of 800–25 000 mm, height of the machined parts in the range 700–6 000 mm, weight of the machined parts 1 500–400 000 kg.

Depending on their size and features, the vertical lathes are a variant constantly agreed by the users in transports, defense and electric power field especially. The manufacturers of such machines are among the well-known ones, especially the manufacturers of large and very large machines.

Some considerations will be presented in this paper in terms of adjustment of the main kinematic chain (table rotation) mentioning that in some cases (machining operations), this chain becomes a feed/positioning kinematic chain [2].

Overview of the different variants are following the evolution of vertical lathes building in Romania and not only.

For a long time, the adjustment of the rotational speeds using couplings and sliding gears represented the only practical solution in the case of a complicated adjustment of the speed of electric motors which drive the main kinematic chains.

The first electric motors were used with only one speed and very rarely two. DC motors used later and the AC speed adjustment by frequency, which monopolized the building of machine tools currently have changed the approach of adjustment.

Desired main spindle speeds can be often obtained by electric and electronic means, mechanical adjustment mechanisms such as gearboxes, becoming torque multipliers.

In recent times, along with the appearance of the production method called "integrated system" the manufacturers of machine tools increasingly turning to the 2-speed gearboxes produced by specialized companies.

They offer the possibility to obtain two steps of output rotational speed, covering areas necessary roughing and finishing on conventional machine-tools, but especially on the CNC.

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2. ROTATIONAL SPEED ADJUSTMENT OF VERTICAL LATHES

The value of the cutting speed for turning operations can be analytically calculated using the following relation [1]:

$$v = \frac{C_v}{T^{m_v} \cdot f^{x_v} \cdot s^{y_v}} \times K_{tot} \text{ [m/min]}, \quad (1)$$

where: C_v – is an experimentally determined constant value depending on the pair “semi-finished product-tool”; m_v , x_v , y_v – experimentally determined exponents depending on the cutting conditions; K_{tot} – total coefficient of cutting speed correction.

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

Regardless of the type of machining, the real cutting speed is the resultant of movement speeds summation on the trajectories, whose combination determines the main trajectory, or the summation of these ones with the feed movement.

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

The main kinematic chain is the generator kinematic chain that provides the main cutting speed along the master trajectory or along one of its components. The main cutting speed is the highest component of the real cutting speed.

In most machine-tools, the main function of the kinematic chain is the *adjustment* function, aiming at a real cutting speed whose value is as close as possible to the technological cutting speed.

The real cutting speed is expressed as:

$$v_r = \pi \times \frac{D \times n_{MS}}{1000} \text{ [m/min]}. \quad (2)$$

In the relation (2) it was noted: D – turning diameter, n_{MS} – the rotary speed of the main spindle MS [rpm]. In the case of vertical lathes, if there are high variations of diameter D , the product $D \times n_{MS}$ shall be constantly kept.

Currently, the most widely used systems of adjustment for the main kinematic chains of vertical lathes are the gearboxes and the frequency electronic converters.

Initially, the gearboxes, when the driving motors had a single speed, were intended to decrease this speed in order to achieve the desired rpm. The rpm decrease leads indirectly to the amplification of the available torque [3].

At the present moment, the rotational speed diminution can be done in a much more simple way, electronically, as the gearboxes provide a proper amplification of torque output.

Assuming that the transfer ratio of the gearbox GB driven by an electric motor EM , for a certain adjustment, is i ($i < 1$), we can consider [2]:

$$n_{GB} = n_{EM} \times i, \quad (3)$$

$$T_{GB} = T_{EM} \times i^{-1}. \quad (4)$$

In the relation above it was noted: n_{GB} – gearbox output rpm, n_{EM} – rpm of driving electric motor, T_{GB} – gearbox output torque, T_{EM} – electric motor torque.

3. ADJUSTMENT SYSTEMS OF ROTATIONAL SPEEDS USED FOR VERTICAL LATHES

The vertical lathe 153 type, according to ENIMS (manufactured in conformity with projects created earlier than 1960), has the main kinematic chain made according to the simplified kinematic diagram illustrated in Fig. 1 [1].

The electric motor EM with a power of $P = 20$ kW and the sole rotational speed $n_{EM} = 1470$ rpm transmit the motion to the main spindle MS by means of the belt pulleys D_1 and D_2 , via the 12 speed gearbox, the bevel gear Z_{14} / Z_{15} and the pinion-crown mechanism Z_{16} / Z_{17} . The rotational speed n_{MS} is achieved at main spindle level and the torque T_{MS} is reached.

In Fig. 1 it was also noted: I – VII – shafts of kinematic chain, $Z_1 - Z_{17}$ – number of teeth of those gearboxes.

The gearbox along with the belt drive makes possible the achievement of twelve speeds in range 7–150 rpm. The maximum torque calculated is $T_{MS} < 22000$ Nm.

In the case of this conventional machine, the feed kinematic chains receive the movement from the main kinematic chain, which reduces in fact the value of the torque calculated above.

A more recent solution, still used at the present moment, is given by Morando Company. This company has developed a 3-speed gearbox used for vertical lathes of SC 14 – SC 43 series. The drive motor has continuously adjustable speed (DC or AC motor) and its power ranges from 37 to 80 kW, depending on the machine type.

In Fig. 2 is shown the kinematic diagram of the main kinematic chain of a CNC vertical lathe that uses such a solution.

The electric motor EM has the adjustable speed n_{EM} within $[n_{min} - n_{nom} - n_{max}]$ range [3]. Further on we shall consider n_{EM} as instantaneous value of the rotational speed.

The main spindle achieves the n_{MS} speed and the T_{MS} torque is available.

In Fig. 2 it was also noted: I – IV – shaft of kinematic chain, $Z_1 - Z_{10}$ – number of teeth of those gears.

The rotational speeds adjustment is continuously made through the agency of the motor and of the 3-speed gearbox, according to the equations below:

$$n_{EM} - I - \frac{Z_1}{Z_1} - III - \frac{Z_7}{Z_8} - IV - \frac{Z_9}{Z_{10}} - MS, \quad (5)$$

$$n_{EM} - I - \frac{Z_1}{Z_2} - II - \frac{Z_3}{Z_4} - III - \frac{Z_7}{Z_8} - IV - \frac{Z_9}{Z_{10}} - MS, \quad (6)$$

$$n_{EM} - I - \frac{Z_1}{Z_2} - II - \frac{Z_5}{Z_6} - III - \frac{Z_7}{Z_8} - IV - \frac{Z_9}{Z_{10}} - MS. \quad (7)$$

The gearboxes $Z_1 - Z_6$ provide the three ratios of transfer: 1/1, 1/3 and 1/9 [4].

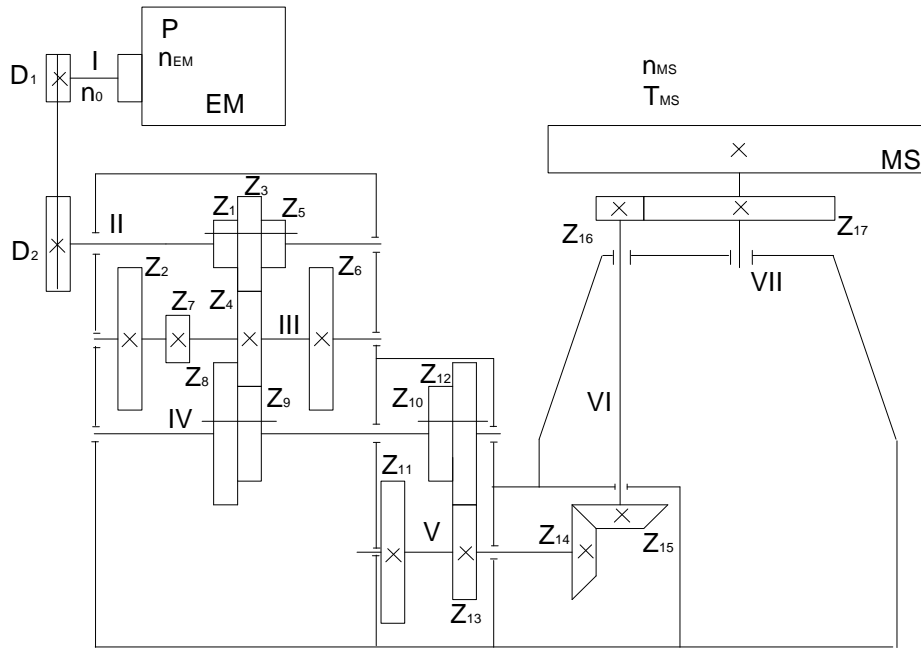


Fig. 1. Kinematic diagram of main kinematic chain of the vertical lathe 153.

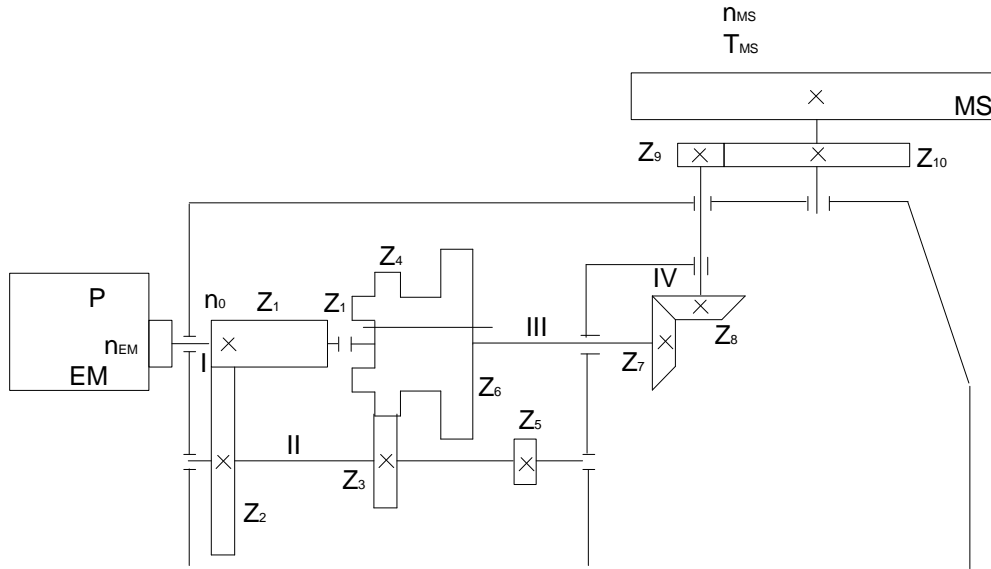


Fig. 2. Kinematic diagram of the main chain of a vertical lathe with 3-speed gearbox.

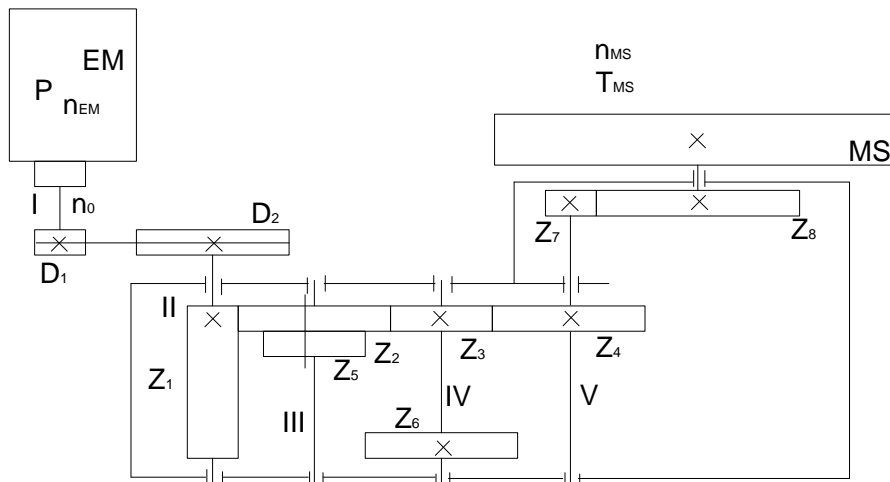


Fig. 3. Kinematic diagram of the main chain of a vertical lathe with 2-speed gearbox.

In the case of a lathe SC 17, with a motor of 60 kW, the three speeds are ensured by a continuous adjustment of the speeds below:

$$i = 1/1, n_{MS} \in [20-200] \text{ [rpm]},$$

$$i = 1/3, n_{MS} \in [6.48-648] \text{ [rpm]},$$

$$i = 1/9, n_{MS} \in [2.22-22] \text{ [rpm]}.$$

The maximum torque that is developed is $T_{MS \max} = 43\,000$ Nm. The gearbox is greatly simplified compared to the previous one as it has only three speeds out of 12. In the case of this NC machine, the kinematic chains for feed are driven by independent motors [3]. Because of the backlashes created inside the gearbox and the pinion-crown mechanism, a separate kinematic chain shall be used for taking over this backlash [2].

Due to the development of electronic adjustment systems of the speed, the gearboxes are becoming increasingly simple. Thus, the gearbox used by Pietro Carnaghi Company has two speeds only. Its construction enables the elimination of the bevel gears (elements that introduce considerable backlashes).

The kinematic diagram of a kinematic chain used for a vertical lathe with table diameter larger than 4 m is shown in Fig. 3.

The motor has a power of $P = 100$ kW, a rated speed $n_{nom} = 1\,500$ rpm, a maximum speed $n_{max} = 4\,500$ rpm and a rated torque $T_N = 636$ Nm [4].

The adjustment of speeds is performed either continuously through the agency of a motor or in two steps by means of the gearbox, according to the equations below:

$$n_{EM} - \frac{D_1}{D_2} - II - \frac{Z_1}{Z_2} - III - \frac{Z_2}{Z_3} - IV - \frac{Z_3}{Z_4} - V - \frac{Z_7}{Z_8} - MS, \quad (8)$$

$$n_{EM} - \frac{D_1}{D_2} - II - \frac{Z_1}{Z_2} - III - \frac{Z_5}{Z_6} - IV - \frac{Z_3}{Z_4} - V - \frac{Z_7}{Z_8} - MS. \quad (9)$$

The gears $Z_1 - Z_8$ provide two transfer ratios: 1/2.47 and 1/10.37 [4].

In the case of this lathe, the main spindle gets the following speeds:

$$i = 1/2.47, n_{MS} \in [1 - 100] \text{ [rpm]},$$

$$i = 1/10.37, n_{MS} \in [0.27 - 24.09] \text{ [rpm]}.$$

The maximum torque developed is $T_{MS \max} = 118\,000$ Nm. It is worth mentioning that the minimum torque of the motor is $n_{min} = 50$ rpm.

The construction of accuracy gears allows the use of the main kinematic chain for turning as a kinematic chain for feed too in the case of milling and drilling operations. The machine is in fact a CNC machining centre, with feed kinematic chains driven independently and a disc type tool magazine [4].

The appearance of power transmissions with toothed pulley belts and of the 2-speed gearboxes, manufactured by specialized companies (ZF, REDEX) [5, 6, 8] had an important role in vertical lathes modernization.

Toothed belts are now characterized by kinematic accuracy (negligible backlashes) and by the capacity to transmit high powers (> 100 kW). The 2-speed gearboxes with low backlashes are usually manufactured with two transfer ratios $i_1 = 1/1$ and $i_2 = 1/3$ (1/4) [5].

At the present moment, these solutions are widely used by different manufacturers [4, 8]. In the case of small size vertical lathes (SC 14 and SC 17) it is even possible to eliminate the final mechanism pinion-crown [4]. Figure 4 shows the kinematic diagram of the main kinematic chain of a lathe of this type.

The speeds are continuously adjusted by a motor or adjusted in two steps by means of the gearbox, in conformity with the following equations:

$$n_{EM} - i_1 - II - \frac{Z_1}{Z_2} - MS, \quad (10)$$

$$n_{EM} - i_2 - II - \frac{Z_1}{Z_2} - MS. \quad (11)$$

Due to the low backlashes, the main kinematic chain can be also used as kinematic chain for circular feed in case of CNC milling operations.

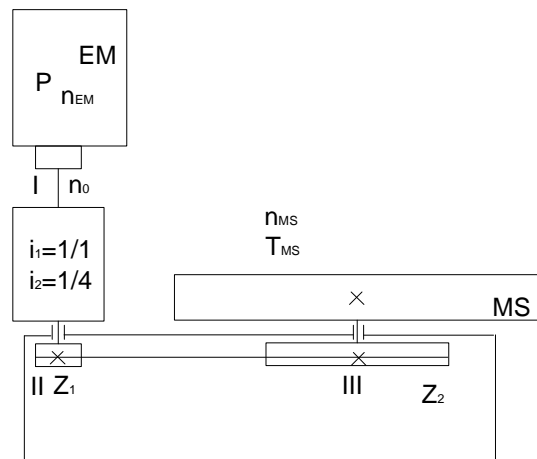


Fig. 4. The kinematic chain of the main chain of a vertical lathe with 2-speed gearbox and toothed belt, without pinion-crown mechanism.



Fig. 5. Vertical lathe with 2-speed gearbox with toothed belt, without pinion/crown mechanism.

Figure 5 shows such a lathe manufactured by the company GPM Titan International.

Out of the basic features of this machine, we can mention the following ones:

- maximum machining diameter – 1 450 mm;
- power of the main electric motor – 37/45 kW;
- speed range of main spindle (partially overlapped) 0.1–400 rpm;
- maximum torque – 61 200 Nm.

For the lathes larger than SC 17 it is necessary to keep the pinion-crown final mechanism because suitable gears for the toothed belts do not exist.

Figure 6 shows the schematic diagram of the main kinematic chain for such a lathe.

The speeds are continuously adjusted by a motor or adjusted in two steps by means of the gearbox, as per the equations below:

$$n_{EM} - i_1 - II - \frac{Z_1}{Z_2} - III - \frac{Z_3}{Z_4} - MS, \quad (12)$$

$$n_{EM} - i_2 - II - \frac{Z_1}{Z_2} - III - \frac{Z_3}{Z_4} - MS. \quad (13)$$

If these machines are also intended for milling/drilling operations it is necessary to make an independent kinematic chain for the circular feed.

Figure 7 shows the toothed belt transmission between the gearbox output shaft (II) and the intermediate shaft (III) of a SC 43 CNC lathe [4].

In Fig. 7 the following notations have been made: 1 – 2-speed gearbox (ZF), 2 – belt pulley (Z_1), 3 – toothed belt.

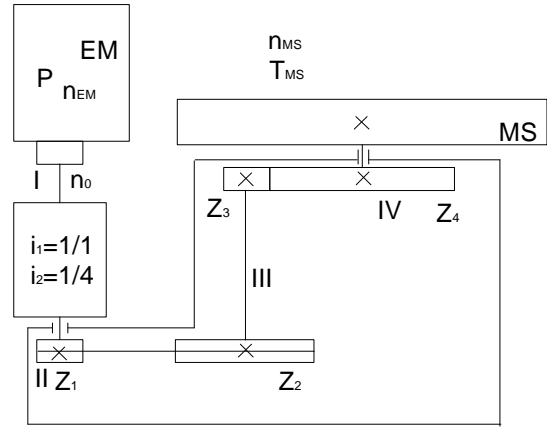


Fig. 6. Kinematic diagram of the main chain of a vertical lathe with 2-speed gearbox and toothed belt, with pinion-crown mechanism.

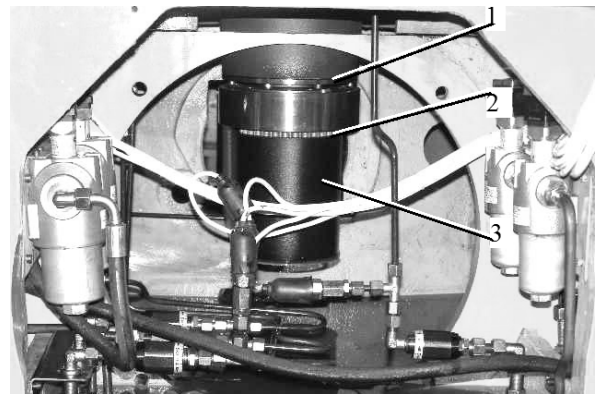


Fig. 7. Transmission with toothed belt between shafts II and III in Fig. 6.

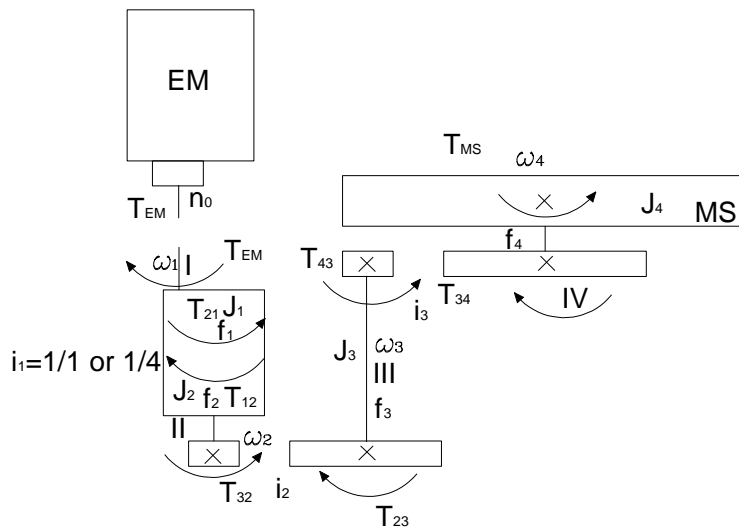


Fig. 8. Calculation diagram for the case shown in Fig. 6.

$$T_{EM} = T_{MS} + \frac{d\omega}{dt} \times (J_1 + J_2 \times i_1^2 + J_3 \times i_1^2 \times i_2^2 + J_4 \times i_1^2 \times i_2^2 \times i_3^2) + \omega_1 \times (f_1 + f_2 \times i_1^2 + f_3 \times i_1^2 \times i_2^2 + f_4 \times i_1^2 \times i_2^2 \times i_3^2) \text{ [Nm]}, \quad (14)$$

$$K = \frac{1}{f_1 + f_2 \times i_1^2 + f_3 \times i_1^2 \times i_2^2 + f_4 \times i_1^2 \times i_2^2 \times i_3^2} \text{ [(rad/s) / Nm]}, \quad (15)$$

$$\tau = \frac{J_1 + J_2 \times i_1^2 + J_3 \times i_1^2 \times i_2^2 + J_4 \times i_1^2 \times i_2^2 \times i_3^2}{f_1 + f_2 \times i_1^2 + f_3 \times i_1^2 \times i_2^2 + f_4 \times i_1^2 \times i_2^2 \times i_3^2} \text{ [s]}. \quad (16)$$

4. ASPECTS OF MAIN KINEMATIC CHAINS DYNAMICS IN VERTICAL LATHES

We take into account the kinematic chain in Fig. 6. In this case, the connections are ‘undone’ as in Fig. 8 in order to perform the dynamic study.

In Fig. 6 the following notations have been made:

- $\omega_1 - \omega_4$ – rotational speeds of shafts I – IV [rad/s],
- T_{EM} – torque at electric motor [Nm],
- T_{MS} – resistant torque at main spindle [Nm],
- $T_{21}, T_{12}, T_{32}, T_{23}, T_{43}, T_{34}$ – torques at shafts ends I – IV [Nm],
- $J_1 - J_4$ – reduced torques of inertia at shafts [kg m²],
- $f_1 - f_4$ – viscous friction coefficient (friction proportional to speed) [Nms/rad],
- $i_1 - i_3$ – transfer ratios [-].

After writing the balance relations, we obtain [7] relation (14).

Out of relation (14) one can determine the amplification K and its response time τ [7] with relation (15) and (16).

It is recommended that the real time of acceleration t_A verifies the relation:

$$t_A > 3 - 5\tau. \quad (17)$$

5. CONCLUSIONS

Vertical lathes were and still are some of the most popular universal machine-tools. The development of electric drives and the appearance of adjustment systems by means of frequency have led to the diminution of adjustment steps number of the gearboxes. In a practical way, speed adjustment can be made simply electrically, on the entire range of the motor; at the present moment, gearboxes have the role of torque amplifiers.

Gear transmissions are losing ground against toothed belt transmissions that became essential for several reasons out of which we can mention:

- lower price,
- reduced noise during operation,
- possibility to purchase them from specialized companies that ensure the desired kinematics accuracy and powers.

2-speed gearboxes (1/1 and usually 1/4) are to be preferred against specific gearboxes. They are characterized by:

- simplicity,
- various assembling possibilities,
- low backlash.

In the case of small lathes, the final pinion-crown mechanism can be even eliminated. In this case, the milling operations can be performed using the main kinematic chain for turning as kinematic chain for circular feed for milling operations.

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