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ELIMINATING THE BACKLASH OF CIRCULAR FEED DRIVES OF CNC VERTICAL LATHES

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Abstract: *Most circular feed and/or positioning kinematic chains used in CNC machine tools consist of: AC motor with speed adjustment through frequency, mechanical gearbox and a final pinion-wheel mechanism type. All the above mechanisms have functional backlashes that cumulated affect the positioning and processing accuracy. The paper presents some specific issues regarding the design, construction and operation of vertical lathes having such kinematic chains. Different variants of anti-backlash devices used by companies specialized in the production of vertical lathes are presented. Some hydro-mechanical solutions using two pinions for the final gear mechanism are presented in which the hydraulic unit is supplying the necessary torque that force one pinion to work on one flanks of the wheel teeth and the other one on opposite flanks. Some solutions with parallel pinion axes and also with coaxial axes of pinions are presented. The article presents some patents used in the field of cancelling backlash in final gears of feed drives of machine tools. Also, the papers brings in discussion the solution with eliminating backlash by using two pinions separately driven through two drives driven by own electric motors working in the Master/Slave regime. The machines and solution of cancelling 100% of the backlash are belonging to the group of vertical lathes with tables having diameters between 1250 mm and 20000 mm.*

Key words: *vertical lathe, backlash, anti-backlash designs, hydro-mechanical systems, electrical systems.*

1. INTRODUCTION

In CNC vertical turning machines, the electric motors are specially equipped with control devices working in double loop reaction in the feed drive. The final position is read from the rotary transducers, usually mounted on the machine table. Rotary encoder located on the motor shaft performs the second control loop.

Given the above conditions, at first glance, it would seem that any existing plays in the mechanical system does not influence the positioning/processing accuracy, rotary encoders being those that "corrects" these possible errors. This is true in case of feed in machining on a single axis. Special problems arise in simultaneous processing on at least two axes, in case of interpolation. Also, the backlash is a problem in the case of positioning. Theoretically, if the final play is constant and does not depend on the position and/or the load it can be "taken" electronically. Usually, in practice this is not possible primarily due the pinion-large bull gear final mechanism with a transfer ratio transfer $i < 1/10$ and its high modulus, the pits error being variable. The negative effect of this backlash is amplified also by the inertial effects that occur when large masses are rotating with high speeds.

Ideally, the backlash should be null [1, 2]. This play is actually a sum of backlashes coming from mechanical transmissions: gearing, toothed belt drives, etc. and the final transformation mechanism pinion-large bull gear.

In modern CNC machines, the number of mechanisms from the circular drive has reduced. In lathes with small tables (1400–1700 mm), the final mechanism pinion-bull gear is removed and replaced with a toothed belt drive [3–6]. Currently, there are toothed belt drives for high torques with backlash null.

The problem of backlash was subject of many patents [7–11]. The operating principle of the anti-backlash system given by the U.S. patent No. 4,036,074 [10] (Fig. 1) implies a pinion meshing with two idler gears that are meshing with a large bull gear. The pinion is forced moving to the centre between two idler gears. In this way, the idler gears are working in opposition (on opposite flanks of the bull gear teeth).

The patent U.S. Patent No. 4,072,064 [9] (Fig. 2) proposes a mechanical system using two pinions, one of them being supported by the other one. There is the possibility of angular displacement of the movable pinion with regard the other one by means of two wedges, one mobile through a bolt and the other one fixed. The opposition is created by a Bellevile spring.

Other inventions are presenting anti backlash gears of split type. The coil springs and retaining pins are eliminated and a resilient slug system being employed [7].

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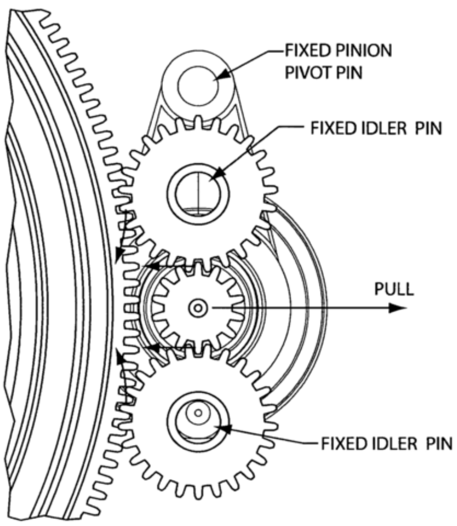
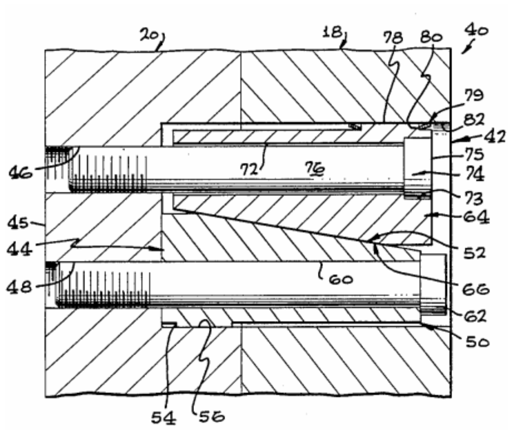


Fig. 1. Operating principle of an anti-backlash system with one pinion, two idler gears and a large bull gear [10].



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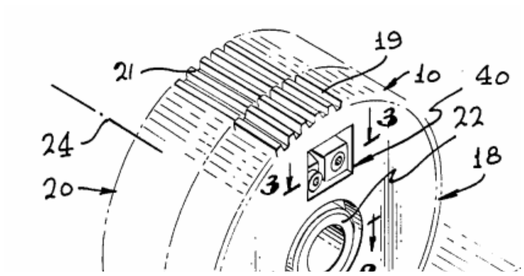


b

Fig. 2. Operating principle of an anti-backlash system with two coaxial pinions working on opposite flanks by means of a wedge and Bellevile spring [9]: *a* – two wedge system in axial section; *b* –axonometric view of the split gear.

O'neill in the U.S. Patent No. 3,127,784 [8], proposes a system for cancelling the backlash in meshing of a two gears by transfer of hydraulic fluid from an accumulator to a linear hydraulic motor that creates the necessary force between two segments of the slice gear that can work in opposition with regard to the flanks of the meshing gear teeth (Fig. 3).

Many other inventions are dealing with split gears and anti-backlash systems that use springs. The spring generates a constant force that leads to undue wear of the teeth.

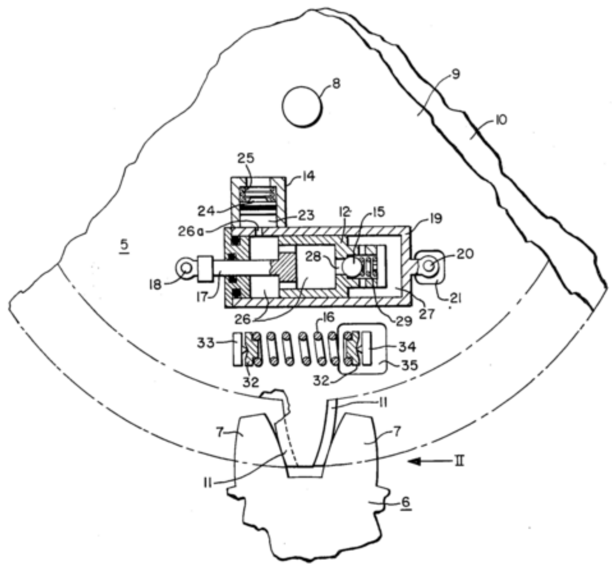


Fig. 3. Operating principle of an anti-backlash system with split gear and hydraulic piston and accumulator [8].

2. INFLUENCE OF BACKLASCH ON ACCURACY OF FEED/POSITIONING DRIVE

Figure 4 shows the gearing used in most vertical lathes as last mechanism of the feed/positioning drive (axis *C*).

Pinion 1 having the centre *O*, Z_0 teeth and rolling diameter D_0 engages, according to the direction in figure, the bull gear 2. This has the centre O_1, Z_1 teeth and rolling diameter D_1. If the transfer ratio of the mechanism is *i*, one can write:

$$\frac{n_1}{n_0} = \frac{D_0}{D_1} = \frac{Z_0}{Z_1} = i\ . \tag{1}$$

The backlash on pitch circle for this gearing is *j*. Due to this clearance, in changing the rotation direction of pinion 1, there is a delay between the time of reversing control and its realization. If this backlash *j* is not constant, it cannot be compensated in the electronic equipment [12], which affects the processing and positioning accuracy.

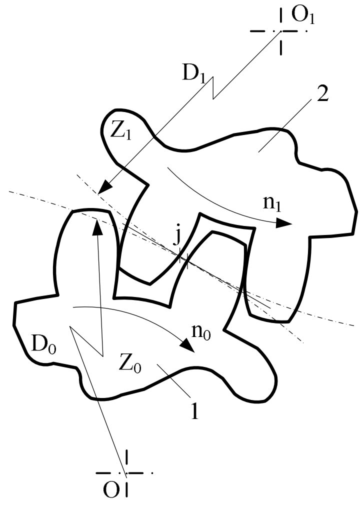


Fig. 4. Backlash on pitch circle in a gearing.

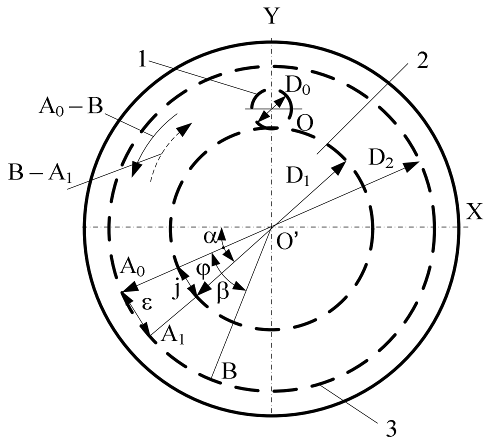


Fig. 5. Reversal error caused by the backlash.

The error ε, which will appear, depends on the position of the processed surface with regard to the centre of rotation *O*'.

Figure 5 shows schematically the case for achieving a positioning revolution from A_0 to B. After rotation, the command for returning to the point A_0 is given. Due to the backlash *j*, for the same revolution angle of the pinion, the point A_1 will be reached instead of A_0. The processing is done on the bearer diameter D_2. In Fig. 5 it was noted: 1 – shafts, 2 – bull gear, 3 – machined part, α – angle that defines the position of the point A_0, β – angular pitch between A_0 and B, φ – angular error, ε – linear error measured on the chord on the circle of diameter

If considered the axis system *XO'Y*, according to the diagram in Fig. 6, the error ε has horizontal and vertical components denoted ε_X and ε_Y.

According to Figs. 5 and 6, it can be considered as for the real dimensions to approximate the arch A_0A_1 with the chord A_0A_1:

$$\overline{A_0A_1} = \varphi \cdot D_1 \cong j\,. \tag{2}$$

In these conditions the following relations could be written:

$$\frac{j}{D_1} = \frac{\varepsilon}{D_2} = \sin\frac{\varphi}{2}\,, \tag{3}$$

$$\varepsilon = j \cdot \frac{D_2}{D_1}\,, \tag{4}$$

$$\varepsilon_X = \varepsilon \cdot \sin\left(\alpha + \frac{\varphi}{2}\right), \tag{5}$$

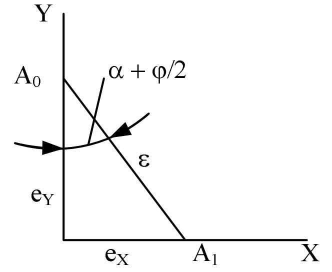


Fig. 6. Components of the linear error.

$$\varepsilon_Y = \varepsilon \cdot \cos\left(\alpha + \frac{\varphi}{2}\right). \tag{6}$$

From the above relationships it can be observed that the error is even greater as the backlash *j* is greater and the processing is performed further from the centre of rotation *O*'. The backlash *j* must be eliminated so that the error ε is close to zero. Total elimination of this error is not possible because it has a component resulting from the system elasticity. If the machine works simultaneously with axis *C* and at least another feed one (*X* or *Z*), at the processing with rotation direction reversing the errors may occur. The backlash can influence the dynamic behaviour of circular feed drive by the appearance of uncontrollable moves caused by the inertia in acceleration and braking phases.

3. ANTI-BACHLASH HYDRAULIC DESIGNS USED IN FEED DRIVES

For eliminating the backlash, the motion is brought to the bull gear level by two identical pinions relatively tensioned so as each is working on one flank of the tooth. There are many variants for tensioning the two pinions. It can be achieved mechanically, hydraulically or electrically. In most cases, the tensioning of the two gears is accomplished by hydraulic motors. The two pinions may have only one axis or two parallel axes.

Figure 7 shows the principle of operation of systems with gears with parallel axes.

The pinions 1' and 1" are identical and have the same number of teeth Z_0 and pitch diameters D_0. They rotate about the centres (axes) *O*' and *O*" in the same direction, being relatively tensioned through the hydraulic motor *HM*. They are engaging with the gear 2 that has Z_1 teeth and pitch diameter D_1 in the points M_1 and M_2 belonging to opposite flanks. Due to the pressure *p* of the hydraulic motor, the meshing is achieved simultaneously in the points M_1 and M_2 but on opposite flanks. In these conditions, even with existence of the backlash *j* in mechanism, in reversing the direction of rotation for both

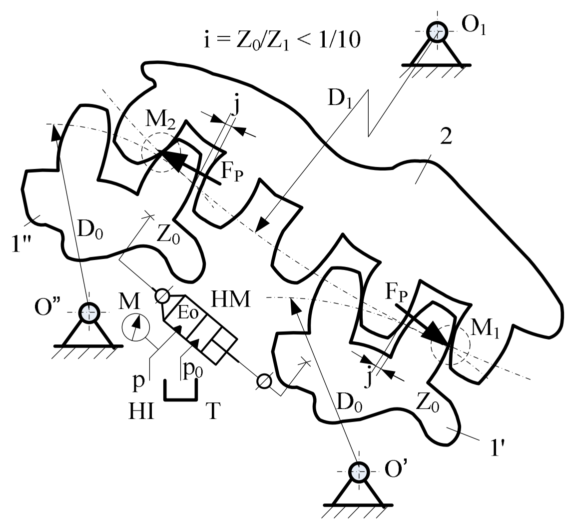
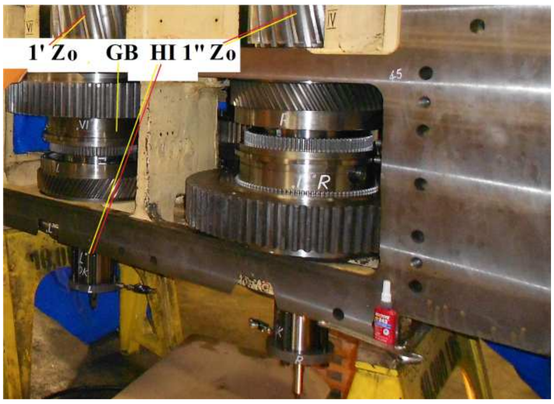


Fig. 7. Anti-backlash system with two pinions having parallel axes and hydraulic tensioning.

pinions, the contact between the pinions and bull gear is maintained permanently. The hydraulic systems *HI* supply the pressure p that causes opposing forces F_p. It must have a high enough value so that in starts, stops and reversal of direction, considering the compressibility of the oil E_0, the meshing to be permanent for minimization of the backlash j. In case of machining using the *C*, this pressure should be chosen such that the radial cutting forces not to lead to oil compression in the hydraulic motor *HM*, which could lead to errors. The pressure p can be adjusted in the hydraulic system, its value being monitored by the manometer *M*. The oil leaks are drained at atmospheric pressure p_0 in the tank *T*. The pressure p should not have excessively high values because this can cause premature wear of the gears. This anti-backlash hydraulic system can be integrated in the gearbox of the vertical lathe [13, 3] or may be a separate device. In both cases, the driving motor is different from that used in the turning main kinematic chain [12, 2].

Figure 8 shows a gearbox equipped with anti-backlash system used in a CNC vertical lathe with 5600 mm table. In turning, the hydraulic tensioning system is not active, the motion reaching the gears 1' and 1" through the gearbox *GB* directly from the main electric motor. When the system becomes necessary to be used as circular feed drive, the main electric motor is decoupled, the anti-backlash system is activated and the feed motor engages. By the toothed belt drive *GB*, the motion is brought to the large bull gear 2.



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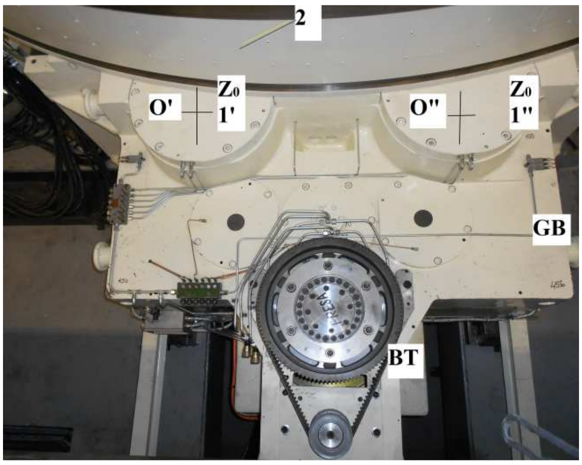

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Fig. 8. System for cancelling the backlash integrated in the gearbox having pinions with parallel axes.

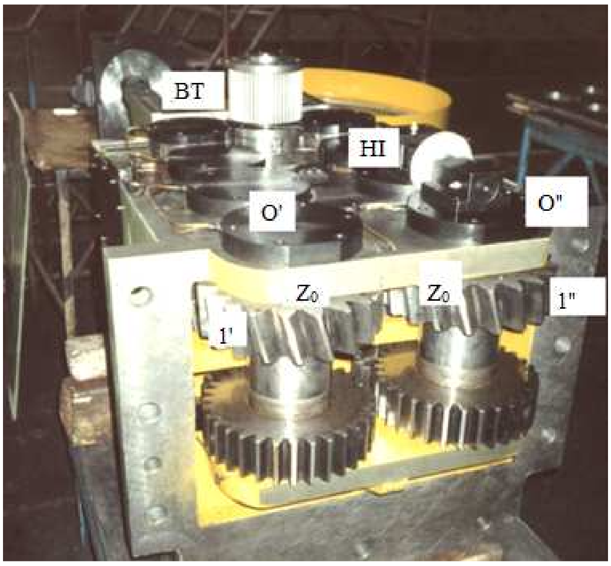

Fig. 9. Anti-backlash system used in a vertical lathe having the possibility of machining workpiece with the maximum diameter of 8000 mm.

The pinions have Z_0 = 20 and the wheel Z_1 = 315. In turning regime, the speed is supplied in the range 0.3–31 RPM and in the milling one in the range 0–1 RPM.

In some cases, such as for example in the remanufacturing of older machines, it raises the question of adding the circular feed drive in machines that were made initially only for turning operations. In this case, the feed drive and the anti-backlash system represent a completely new construction that is mounted on an existing machine tool. Figure 9 presents a feed box of a circular feed drive, independent of the gearbox, mounted on a vertical lathe which can machine parts with a maximum diameter of 8000 mm.

Through the toothed belt drive *BT* the motion is brought from an electric motor with adjustable speed to the feed box, which has in the final gearing the pinions 1' and 1" having Z_0 teeth. These are tensioned towards the bull gear using hydraulic unit *HI* not shown in this figure.

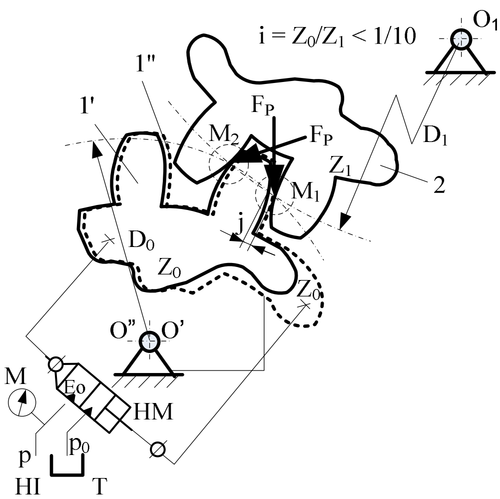

Fig. 10. Anti-backlash system with two coaxial pinions and hydraulic tensioning.

In many vertical lathes with maximum diameter of 5000 mm of the table, anti-backlash systems are used having two pinions with the same axis. In Fig. 10 it is shown their operation mode.

The pinions 1' and 1" are the same and have the same number of teeth Z_0 and have the pitch diameters D_0. They rotate about the centre $O' \equiv O''$ in the same direction and through the hydraulic motor *HM* are tensioned relatively being engaged with the gear 2 having Z_1 teeth and pitch diameter D_1 on opposite flanks in the points M_1 and M_2. Due to the pressure p of the hydraulic motor, the engagement is realized in points M_1 and M_2 simultaneously situated on opposite flanks. In these conditions, even in the presence of the constructive backlash j, in reversing the motion direction of the two pinions the contact between pinion and bull gear is kept permanently. The hydraulic unit *HI* supplies the pressure p that causes the opposing forces F_p.

The system construction is compact and is shown schematically in Fig. 11.

The pinions 1' and 1" are rotating the bull gear 2, which is solidary with the table 7. The motion is brought from the electric motor from the duplex worm 6, which engages with the worm wheel 5. On the axis III there is a hydraulic vane motor 3 [2] and the electric clutch 4 [2]. When the table 7 is rotated by the main kinematic chain (not shown in figure) the hydraulic unit is stopped and the clutch 4 is not operated. In the stage where it is desired the use of the circular feed drive, the hydraulic unit starts and the coupling 4 is actuated. The pinions 1' and 1" are tensioned and positioned on opposite flanks of the gear 2.

The kinematic scheme of the system is shown in Fig. 12.

The electric motor *EM* has adjustable speed n_{EM} = 0 to 2 000 RPM and a nominal torque T_{rated} = 62 Nm. According to the kinematic scheme shown in Fig. 12 the table speed n_2 is calculated using the relation:

$$n_2 = n_{EM} \cdot \frac{q}{Z} \cdot \frac{Z_0}{Z_1} \in [0; 5] \text{ RPM}. \quad (7)$$

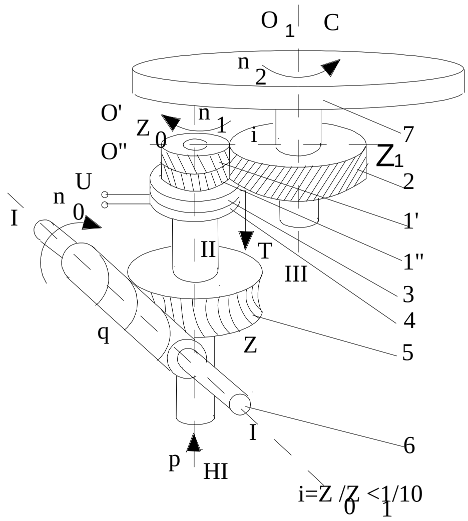

Fig. 11. Construction of the circular feed box.

Figure 13 shows the circular feed box made for lathes of the range SC14–SC43 (Fig. 13,*a*) and its mounting system (Fig. 13,*b*). The notations in Fig. 13 are the same as those in Figs. 11 and 12 The supply of oil under pressure (~ 60 bar) is performed at the bottom by means of a rotary coupling [6].

Lately, the vertical lathes with plateaus of maximum 2000 mm, the mechanism pinion-bull gear can be removed and replaced by a toothed belt drive. In this case, the main kinematic chain comprising an electric motor and a special gearbox [4] with two steps and low backlash can perform the function of circular feed drive. In this case, the electric motor and gearbox are working in vertical plane, the rotation motion being transmitted via a backlash free toothed belt drive free [12, 5]. In machine tools with tables greater than 2000 mm, this solution can not be applied due to the nonexistence of toothed belt drives that could be used.

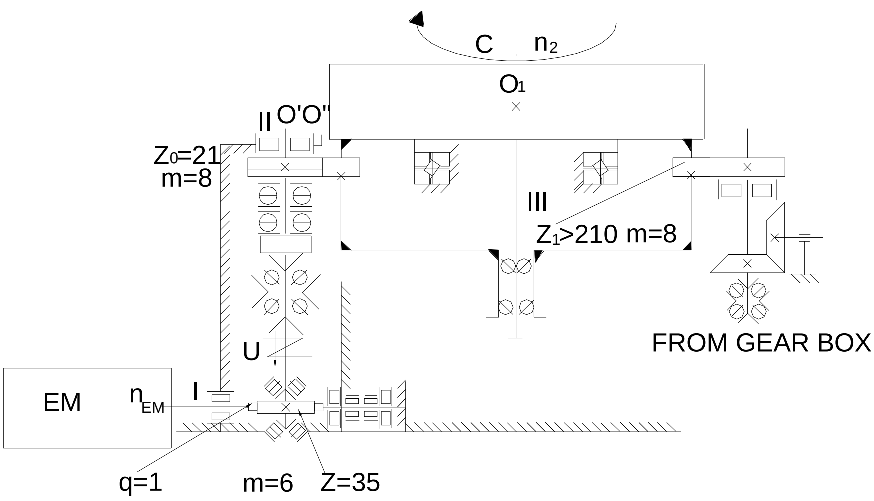

Fig. 12. The kinematic scheme of the circular feed drive.

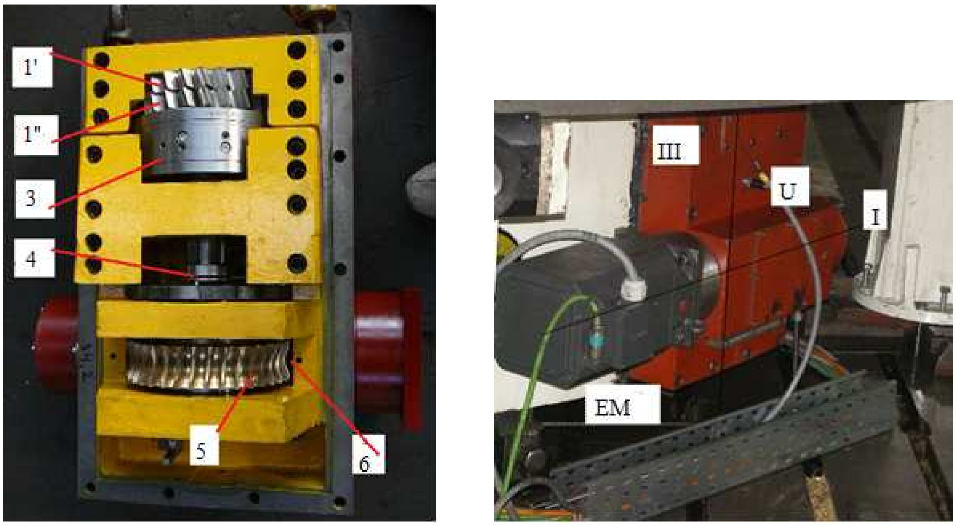

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Fig. 13. System with coaxial pinions with hydraulic tensioning.

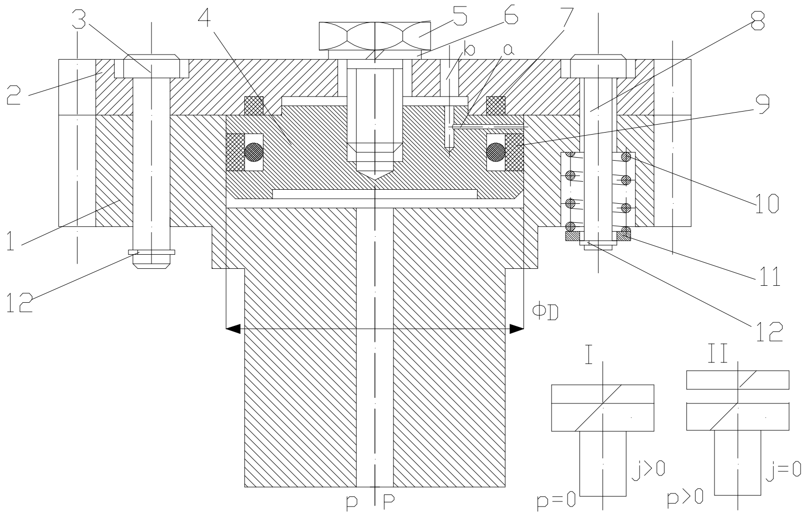


Fig. 14. Anti-backlash system with two coaxial pinions.

Usually, the maximum motor speed is electronically limited below the maximum value. The feed box construction is compact, in specific cast housing, being shown in Fig. 13.

In these machines, the last gearing belongs to both main kinematic chain in turning and circular feed drive in feed operations. Figure 14 shows schematically this variant and how it works [13].

The main pinion 1 and secondary pinion 2 are coupled by bolts 3. They are inserted pressed into pinion 2 and are sliding in pinion 3. The piston 4 is mounted on pinion 2 by bolt 5 and safety washer 6. The component 7 provides sealing between the pinion 2 and piston 4. Between the piston 4 and pinion 2 the sealing is provided by the component 9. The two gears are maintained in contact by preloaded springs 10. They are guided by the pins 8. The force caused by the preloading is taken by the washers 11. All pins are secured by retaining rings 12.

In turning, the pinions 1 and 2 are working on the same flanks of the bull gear. In machining by milling, the oil under pressure *p* is brought on the way *P*. The pressured oil is acting the piston 4 of diameter *D*, pushing it against pinion 2. The two pinions are having helical teeth. Due to this, the two pinions work on opposite flanks of the bull gear teeth eliminating the backlash. Any leaks are recovered on paths *a*, *b*.

If the helix angle with regard to the axis is β, the following relations may be considered:

$$F_A = p \cdot \frac{\pi \cdot D^2}{4} \quad , \tag{8}$$

$$F_N = \frac{F_A}{\sin \beta} \quad , \tag{9}$$

$$F_T = F_A \cdot \cot \beta \quad . \tag{10}$$

In the above relations it was noted: F_A – axial force, F_N – normal force to the teeth, F_T – tangential force.

The force F_A is dimensioned so as to ensure permanent elimination of the backlash regardless of the instantaneous reduced torque at the pinion axis. In these systems and others, it is necessary the presence of the rotary couplings that permit the supply of pressurized oil to rotating parts.

If vertical lathes with table greater than 5000 mm, other systems for elimination or minimization of backlash are used. Usually, in vertical lathes having milling possibilities, the plateaus have locking systems [2]. The firm blocking is used when the table should be kept firmly in a desired position. This is mandatory if drilling operations are achieved using the axis *Z*. There are heavy vertical lathes [12] that use locks for diminishing the backlash especially in the starting, stopping and reversing direction phases. In these cases, the locking systems are supplied by a low pressure, this transforming them in controlled brakes. The braking and firm locking pressures are in this case in the ration 1/10 [12]. The braking pads are lubricated and equipped with a control wear system [12, 2].

4. ANTI-BACKLASH DESIGNS USING TWO PINIONS AND ELECTRIC PRELOADING

These systems were used for the first time in the '80s and can provide positioning accuracy in circular feed drive of ± 4" or even better (ISO 230-2).

Currently, it uses two identical gears that engage permanently with the bull gear. With the appearance of electric motors that can be used for both main spindle driving and feed driving [1], the solution of eliminating the backlash can be applied successfully. Each pinion is driven through a reducer gear by an electric motor. The two motors are identical or not. In turning, the motors run so that it can be considered that the available power is the sum of provided powers, resulting a higher cutting capacity. In the milling phases, the motors are working in the mode Master/Slave.

In this case [12], one drive is considered as Master running in speed control. The other drive, the Slave, is running in torque/current control receiving the output of the speed controller as external toque/current reference. Thus, the pinions are working on opposite flanks of bull gear.

In reversing the rotation direction, an inversion of the two motor roles occurs, the slave becoming master and the master becoming slave. This switching is electrically controlled and done in less than 1/1000 s, its influence on the machine workpiece profile being imperceptible. The adjustment of the preloading force is made electronically.

Figure 15 shows the kinematic scheme of such a system and in Fig. 16 the construction of the system is shown.

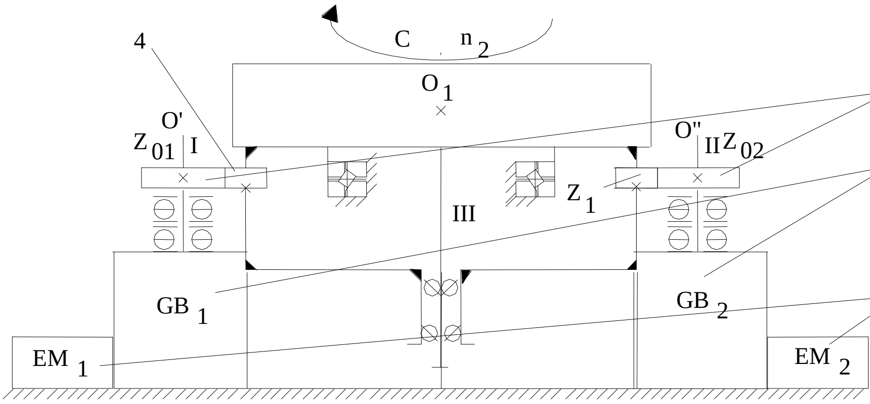
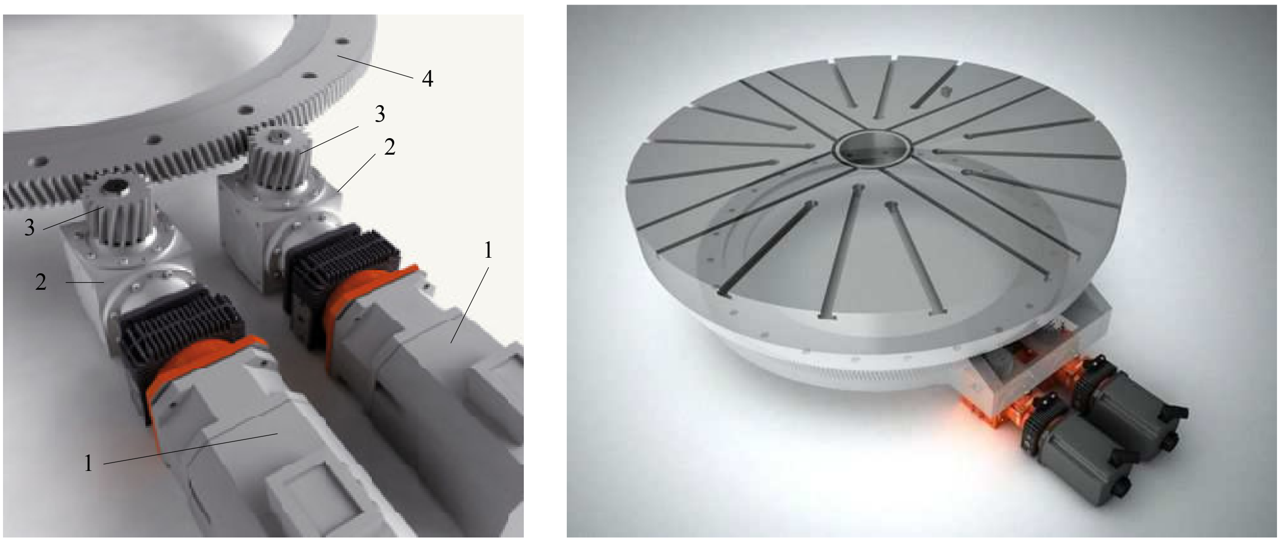


Fig. 15. Kinematic scheme of the circular feed drive using two pinions electrically preloaded.



a b

Fig. 16. Construction of an anti-backlash system with two pinions electrically preloaded: *a* – detailed components of the electric anti-backlash; *b* – detail of the table feed drive assembly of a vertical lathe (REDEX).

The electric motors 1 through gearboxes/feedboxes 2 [1, 12] acts the pinions 3. They are positioned on the flanks of the large bull gear 4. During the turning operations, the power output is the sum of those developed by the two drives. In case of the plateau rotation for milling or positioning, the drives are running in Master/Slave configuration.

5. CIRCULAR FEED DRIVE AS DIRECT DRIVE

Currently, there are manufacturers of vertical lathes that use a single electric motor that drives directly [14] the table without the need for gearboxes/feedboxes or neither pinion-bull gear mechanisms. The special electric motor is composed of segments being used both for turning as main drive and feed drive. The specific power and torque meet the requirements for both cases. Positioning accuracy is of ± 1". The capacity of acceleration is superior to all systems previously described. Thus, for a table of 4000 mm loaded with a workpiece of 40 t, the acceleration in the range 0–80 RPM is done in 6 s. Removing the speed/feed gearboxes and also the pinion-large bull gear mechanism eliminates high frequency oscillations, noise and thermal effects.

6. CONCLUSIONS

In cases when vertical lathes are used for milling and/or drilling operations, the main kinematic chain is disconnected and the table is driven by the circular feed chain. The errors occurring when reversing the motion direction of the table are due mainly to the existing backlash in the mechanisms pinion-wheel. For small lathes with tables less than 2000 mm, the final gearing can be replaced with a toothed belt drive.

For larger lathes, one provides hydro-mechanical or electrical anti-backlash designs. Systems for eliminating the backlash of this type are most used in machine tools made until 2000, many companies using them still in present. Among the disadvantages of these systems one can mention:

- the use of two hydraulic gears hydraulically tensioned does not completely eliminate the backlash and requires specific hydraulic units;
- the components of these systems are subject to heavy loads that lead to wear and require maintenance interventions;
- besides the anti-backlash system, it is required in addition an electric motor driving the circular feed chain in addition to those driving the main kinematic chain; this electric motor should be inactive in the turning phases;
- in heavy machine tools, two electric motors and two gearboxes are used in driving the main spindle. In this case, for milling operation a third electric motor is required.

In recent years, especially in machines with tables greater than 4000 mm, the minimization of backlash is done using electronic preloading. The electric motors are used for both turning and milling being controlled by the CNC equipment. The gearboxes used are simpler than the classic ones and have only two steps (usually $i_1 = 1$ and $i_2 = 1/4$). The preloading of the two pinions is easily adjustable and watchable than for those mechanically or hydraulically preloaded. By using this solution, the specific hydraulic unit is eliminated and the machine accuracy is increasing.

Due to specific electric motor, the future solution seems to be that based on the *Direct Drive* system.

The five-axis operations become possible on vertical lathes, they behaving like machine tools with multiple possibilities. Therefore, rectangular surfaces can be processed, according to NORMA NAS 979, with the same precision as on a machine tool of the milling and boring machine type.

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