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Modern Main Kinematic Chains for Machine Tools

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***Abstract* — This paper shows authors' research works in the field of drives for main kinematic chain in machine tools, generally, and heavy machine tools in particular. It displays several versions of drives which use modern elements and systems, like power toothed belt transmissions and two-stage gearboxes. Here, various kinematic diagrams are presented that may be used in newly developed machine tools, but also in upgrades (refurbishes) for existing machine tools. This paper describes several versions of two-stage gearboxes, designed by specialized manufacturers, highlighting their specific features. Calculation methods set forth herein take into and they are exemplified consideration kinematic requirements, but also power (torque) requirements. In the end of this paper, several experimental executions of main kinematic chains for an AF 105 machine are also described.**

***Index Terms* —gearbox, machine tools, main kinematic chain, power/rotation characteristic, torque/rotation characteristic.**

I. INTRODUCTION

The actual machining speed is exercised on the path of cutting motion during performance of machining process. Disregarding the type of processing, the actual machining speed results from the sum of movements on paths whose combination determine the guide path and the feed. The main component of the actual speed is the main machining speed [3], [9], [10]. The main kinematic chain is the generator kinematic chain that provides, on the guide path or on one of its components, the main machining speed, the most important component of the actual machining speed. In most machine tools, the main function of the main kinematic chain is the ADJUSTMENT, pursuing that the actual machining speed is as close as possible to the technological machining speed. Currently, the most frequently used adjustment systems for main kinematic chains are gearboxes and electronic frequency converter. Initially, when drive motors only had a fixed rotation speed, gearboxes were destined to reduce this rotation speed in order to achieve intended speeds. Indirectly, reduction of rotation speed increases available torque [1], [3]. Currently, reduction of rotation speed may be achieved much simpler with electronic means, gearboxes providing proper amplification of torque on output. If the gear ratio of a gearbox (*GB*) driven by an electric motor (*EM*) in a certain adjustment is considered to have the value i ($i < 1$), that we may consider:

$$n_{GB} = n_{EM} \cdot i \quad (1)$$

$$T_{GB} = T_{EM} \cdot i^{-1} \quad (2)$$

In the equations above, the symbols have the following meaning: n_{GB} – rotation speed at the gearbox's output, n_{EM} – rotation speed of the electric drive motor, T_{GB} – torque at the gearbox's output, T_{EM} – torque at electric motor level.

II. MODERN MECHANICAL TRANSMISSIONS FOR KINEMATIC CHAINS OF MACHINE

Among modern mechanical transmissions, which have largely replaced the geared systems, the most spectacular evolution in time was exercised by geared belt transmissions [6]–[7]. Initially used only in feed kinematic chains, due to the low power transmission capacity, they are currently used also in main kinematic chains, being able to transmit powers in the order of 100 kW. Some of the advantages proven over geared transmission are:

- lower price,
- built by specialized manufacturers,
- low operating noise,
- they are able to transfer motion to higher distances compared to the distance between shafts of a geared system,
- they do not require lubrication,
- They operate without mechanical return backlash.

This final advantage makes them ideal for machines with numerical control.

Where necessary, gearboxes may be used, usually with two stages, provided be specialized companies. They are selected from catalogues [5] based on transmitted power and required gear ratio.

They bring along a series of advantages, like:

- Reduced mechanical return play, allowing use in numerically controlled spindles;
- A lubrication circuit separate from the machine's lubrication system, reducing heat transmission to the main spindle;
- Connected to the main spindle driven by toothed belts, preventing transmission of vibrations;
- Low noise;
- Simple and compact structure, with direct coupling to the driving motor [2];

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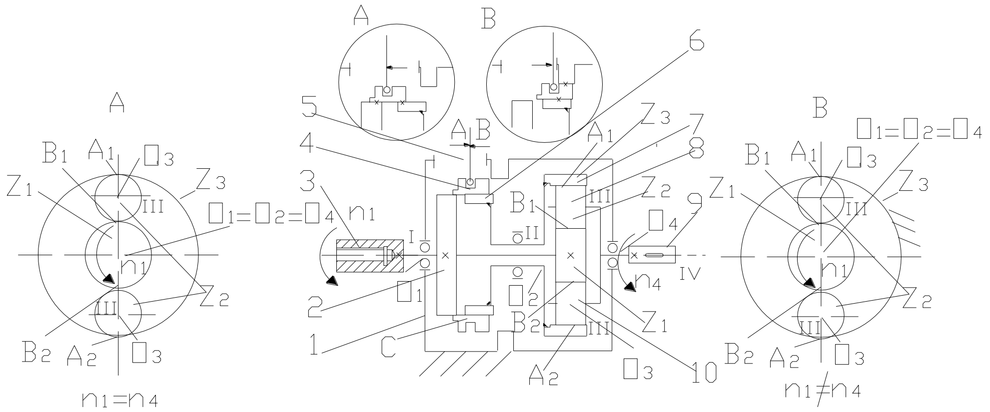
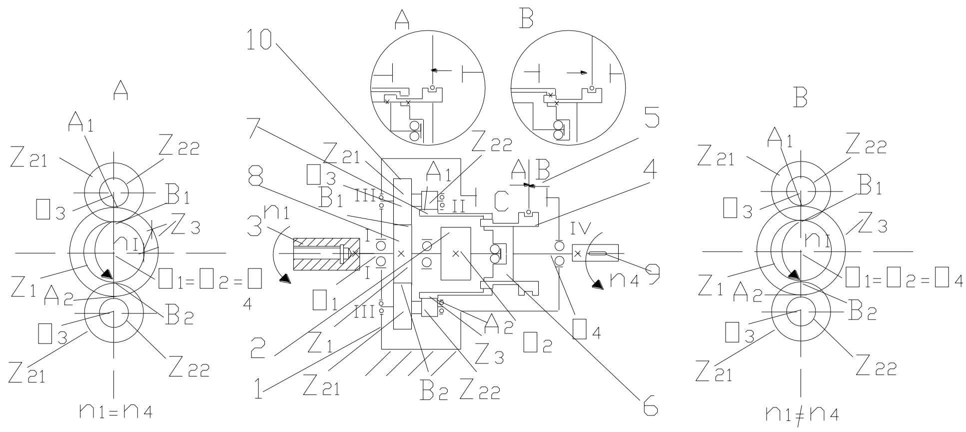


a.



b.

Fig.1. Kinematic scheme of gear boxes

1 – housing, 2 – gear, 3 – input shaft, 4 – lower teeth coupling, 5 – switching system, 6 – gear, 7 – internal tooth gear, 8 – pinion, 9 – output shaft, 10 – gears, *A*, *B* – gearbox stages, n_1 – input rotation speed, n_4 – output rotation speed, I, II, III, IV – shaft axes, Z_1, Z_2, Z_3, Z_{21}, Z_{22} – number of teeth of respective gears, A_1, A_2, B_1, B_2 – driving points, O_1, O_2, O_3, O_4 – rotation centers.

- High output, in excess of 95%;
- Gear shifting is achieved with a device integrated in the gearbox, actuated electrically, pneumatically or hydraulically.

Fig. 1 shows two kinematic diagrams used in such gearboxes.

For both kinematic diagrams, the following may be considered:

$$n_4 = n_1 \cdot i_{1GB} \quad (3)$$

$$n_4 = n_1 \cdot i_{2GB} \quad (4)$$

$$i_{1GB} = 1 \quad (5)$$

$$i_{2GB} < 1 \quad (6)$$

Usually, the value of i_{2GB} ratio is included between [1/5 -1/3].

These gearboxes may be installed in varying ways, depending on the machine tool type.

Most frequent options are shown below.

III. INTEGRATION OF TWO-STAGE GEARBOXES IN KINEMATIC CHAINS OF MACHINE TOOLS

In some machine tools, the electric motor drives the main spindle directly, with no reducing system. This is the case of the so-called “integrated spindles”, as shown in figure 2.

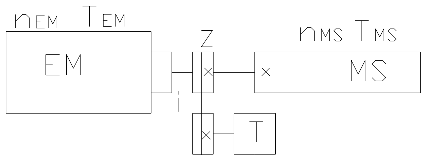


Fig.2. Kinematic scheme in the case of direct drive

EM – electric motor, *MS* – main spindle, *T* – rotary position transducer, n_{EM} – rotation speed of electric motor, n_{MS} – rotation speed of main spindle, T_{EM} – torque of electric motor, T_{MS} – torque of main spindle, *i* – gear ratio of toothed belt transmission between the main spindle and the rotary (threading) transducer, usually *i* = 1/1, *Z* – number of teeth in toothed belt gears.

In this case the following may be considered:

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$$n_{MS} = n_{EM} \quad (7)$$

$$T_{MS} = T_{EM} \quad (8)$$

$$i_T = 1 \quad (9)$$

Rotation speed and torque of the motor are found at the level of the main spindle.

If the electric motor is connected directly to the gearbox, the kinematic diagram achieved is as shown in figure 3.

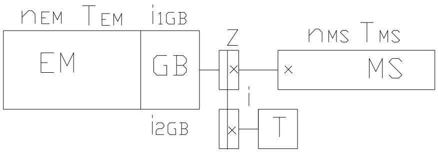

Fig.3. Kinematic scheme of the main kinematic chain with direct link between electric motor and gear box

Symbols used are similar to fig. 2, and *GB* is the two-stage gearbox and i_{1GB}, i_{2GB} – the two gear ratios of the gearbox (usually $i_{1GB} = 1, i_{2GB} < 1$)

In this case, at main spindle's level, the rotation speeds and torques of the motor shall be exercised if the gearbox provides the i_{1GB} ratio, and rotation speeds of the motor reduced by the i_{2GB} ratio if the gearbox is shifted into the second stage. In this case, torque at the main spindle shall be multiplied by the value i_{2GB}^{-1}:

$$n_{MS} = n_{EM} \cdot i_{1GB} \quad (10)$$

$$T_{MS} = T_{EM} \cdot \frac{1}{i_{1GB}} \quad (11)$$

$$n_{MS} = n_{EM} \cdot i_{2GB} \quad (12)$$

$$T_{MS} = T_{EM} \cdot \frac{1}{i_{2GB}} \quad (13)$$

Total gear ratio of the kinematic chain, depending on the stage selected on the gearbox, is:

$$i_T = i_{1(2)GB} \quad (14)$$

If an increase of torque is desired at main spindle's level, then a toothed belt transmission may be inserted between the gearbox output and the main spindle, as shown in figure 4. Symbols used are similar to figure 3; i_1 – gear ratio of the toothed belt transmission, Z_1,Z_2 – number of teeth of toothed belt gears $Z_1 < Z_2$). For this kinematic diagram, the following may be considered:

$$n_{MS} = n_{EM} \cdot i_{1GB} \cdot \frac{Z_1}{Z_2} \quad (15)$$

$$T_{MS} = T_{EM} \cdot \frac{1}{i_{1GB}} \cdot \frac{Z_2}{Z_1} \quad (16)$$

$$n_{MS} = n_{EM} \cdot i_{2GB} \cdot \frac{Z_1}{Z_2} \quad (17)$$

$$T_{MS} = T_{EM} \cdot \frac{1}{i_{2GB}} \cdot \frac{Z_2}{Z_1} \quad (18)$$

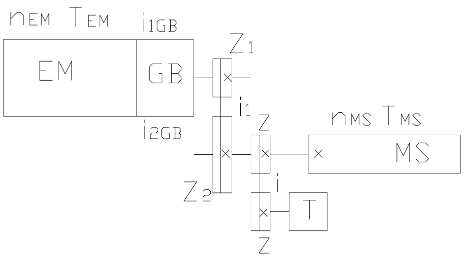

Fig.4. Kinematic scheme of the main kinematic chain with direct link and torque amplification

Total gear ratio of the kinematic chain, depending on the stage selected on the gearbox, is:

$$i_T = i_{1(2)GB} \cdot \frac{Z_1}{Z_2} \quad (19)$$

It may be noted that, compared to the previous diagram, rotation speeds achieved are lower but the torques are higher. The exclusive use of toothed belt transmission provide reduction of the mechanical return play [3], which has a high significance when processing complex surfaces (e. g. threads) and in case of interpolations. If a higher increase of torque is intended for the main spindle, the diagram in figure 5 may be used.

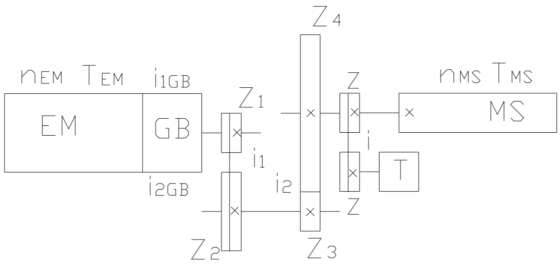

Fig.5. Kinematic scheme of the main kinematic chain with direct link and two-stage reduction

Symbols used are similar to figure 4; i_2 - gear ratio of the geared transmission, Z_3, Z_4 - number of teeth of gears $Z_3 < Z_4$).

Increase of torque and reduction of rotation speed are higher compared to the diagram in figure 4 due to the geared transmission Z_3/Z_4. For example, in case of vertical lathes with milling capabilities [3], where this diagram is used, $Z_3/Z_4 < 1/20$. It is worth mentioning that in this case, in order to improve accuracy, geared transmission is provided with mechanical or hydraulic systems to offset mechanical return play [3], [8] which are not shown in figure 5. Characteristics of this kinematic diagram are:

$$n_{MS} = n_{EM} \cdot i_{1GB} \cdot \frac{Z_1}{Z_2} \cdot \frac{Z_3}{Z_4} \quad (20)$$

$$T_{MS} = T_{EM} \cdot \frac{1}{i_{1GB}} \cdot \frac{Z_2}{Z_1} \cdot \frac{Z_4}{Z_3} \quad (21)$$

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$$n_{MS} = n_{EM} \cdot i_{2GB} \cdot \frac{Z_1}{Z_2} \cdot \frac{Z_3}{Z_4} \quad (22)$$

$$T_{MS} = T_{EM} \cdot \frac{1}{i_{2GB}} \cdot \frac{Z_2}{Z_1} \cdot \frac{Z_4}{Z_3} \quad (23)$$

Total gear ratio of the kinematic chain, depending on the stage selected on the gearbox, is:

$$i_T = i_{1(2)GB} \cdot \frac{Z_1}{Z_2} \cdot \frac{Z_3}{Z_4} \quad (24)$$

The electric motor may drive the two-stage gearbox through a toothed belt transmission, as shown in figure 6.

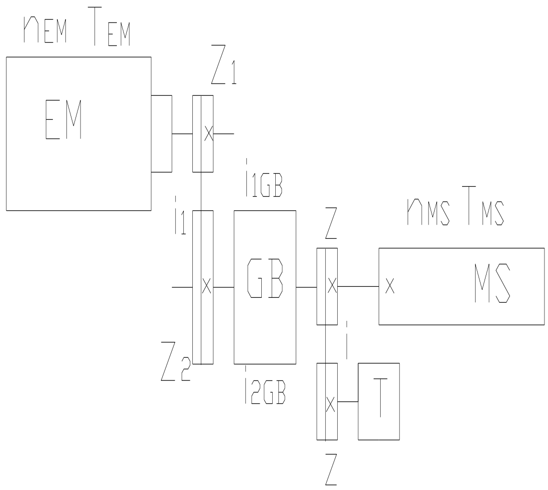

Fig.6. Kinematic scheme of the main kinematic chain with toothed belt transmission from electric motor to gear box

Symbols used are similar to figure 4.

In this case the input torque of the gearbox is amplified by Z_2/Z_1; characteristics in this case being:

$$n_{MS} = n_{EM} \cdot \frac{Z_1}{Z_2} \cdot i_{1GB} \quad (25)$$

$$T_{MS} = T_{EM} \cdot \frac{Z_2}{Z_1} \cdot \frac{1}{i_{1GB}} \quad (26)$$

$$n_{MS} = n_{EM} \cdot \frac{Z_1}{Z_2} \cdot i_{2GB} \quad (27)$$

$$T_{MS} = T_{EM} \cdot \frac{Z_2}{Z_1} \cdot \frac{1}{i_{2GB}} \quad (28)$$

Total gear ratio of the kinematic chain, depending on the stage selected on the gearbox, is:

$$i_T = i_{1(2)GB} \cdot \frac{Z_1}{Z_2} \quad (29)$$

If a geared transmission in inserted between the gearbox and the main spindle, an additional increase of torque is achieved, as shown in figure 7.

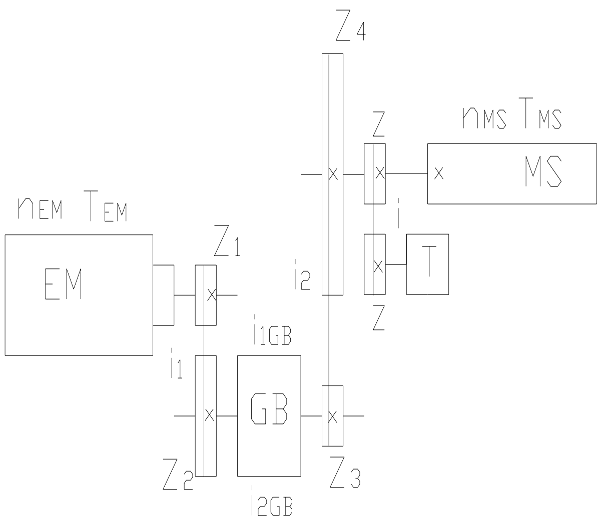

Fig.7. Kinematic scheme of the main kinematic chain with toothed belt transmission from electric motor to gear box and from this to main spindle

Symbols used are similar to figure 5.

In this case the input torque of the gearbox is amplified by Z_2/Z_1, characteristics in this case being:

$$n_{MS} = n_{EM} \cdot \frac{Z_1}{Z_2} \cdot i_{1GB} \cdot \frac{Z_3}{Z_4} \quad (30)$$

$$T_{MS} = T_{EM} \cdot \frac{Z_2}{Z_1} \cdot \frac{1}{i_{1GB}} \cdot \frac{Z_4}{Z_3} \quad (31)$$

$$n_{MS} = n_{EM} \cdot \frac{Z_1}{Z_2} \cdot i_{2GB} \cdot \frac{Z_3}{Z_4} \quad (32)$$

$$T_{MS} = T_{EM} \cdot \frac{Z_2}{Z_1} \cdot \frac{1}{i_{2GB}} \cdot \frac{Z_4}{Z_3} \quad (33)$$

Total gear ratio of the kinematic chain, depending on the stage selected on the gearbox, is:

$$i_T = i_{1(2)GB} \cdot \frac{Z_1}{Z_2} \cdot \frac{Z_3}{Z_4} \quad (34)$$

Depending on the type of the machine tool, on rotation / torque ratio, but also on constructive options required, the designer shall select one of the solutions for kinematic diagrams shown above.

IV. TORQUE / ROTATION AND POWER / ROTATION CHARACTERISTICS FOR MAIN KINEMATIC CHAINS USING TWO-STAGE GEARBOXES

Disregarding the option selected, torque / rotation and power /rotation characteristics for alternating current electric motor with frequency converter for rotation speed adjustment are shown in figure 8.

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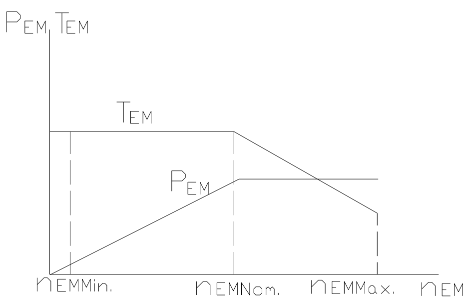


Fig.8. Electric motor characteristics

P_{EM} – electric motor power, T_{EM} – motor torque, n_{EM} – motor's rotation speed, n_{EMMax} – maximum rotation speed of the motor, n_{EMMin} – minimum rotation speed of the motor, n_{EMNom} – rated rotation speed of the electric motor.

If the total gear ratio of the kinematic chain is symbolized by i_T, torque / rotation and power / rotation characteristics achieved for the main spindle shall be as shown in figure 9.

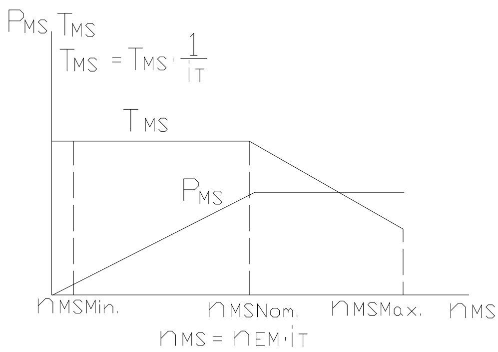


Fig.9. Torque/rotation and power/rotation characteristics of the main spindle

P_{MS} – theoretical power at main spindle level, T_{MS} – torque at main spindle, n_{MS} – rotation speed of main spindle, n_{MSMax} – maximum rotation speed of main spindle, n_{MSMin} – minimum rotation speed of main spindle, n_{MSNom} – nominal rotation speed of main spindle.

V. EXPERIMENTAL WORKS

When refurbishing a boring and milling machine built in the 1970s, decision was taken to use a two-stage gearbox and a toothed belt transmission. The original machine was conventional equipment which after refurbishment was converted into a CNC. Fig. 10 shows a gearbox of such machine, in initial construction.

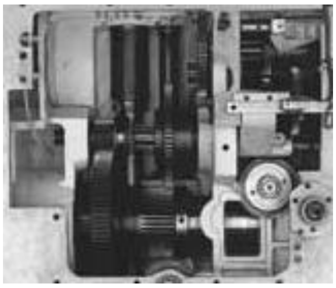


Fig.10. Original 16-stage gearbox

The gearbox shown in figure 10 provides 16 stages of rotation speeds [6], [7], [9] which can be shifted manually. Finally, at the main spindle level, rotation speeds varying between 2 - 2100 RPM could be achieved. The machine was equipped with a 15 or 20 kW electric motor. For refurbishment, the kinematic diagram in figure 11 was selected. It is based on the general layout shown in figure 4.

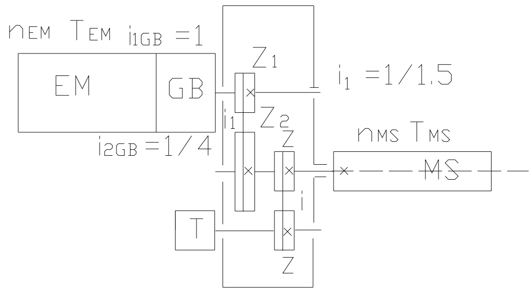


Fig.11. Kinematic scheme used to refurbish

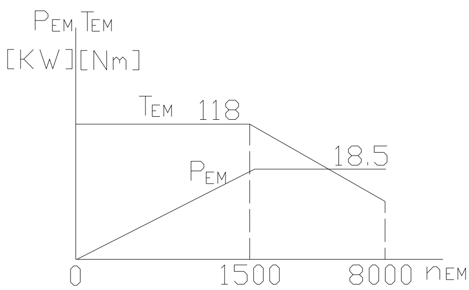
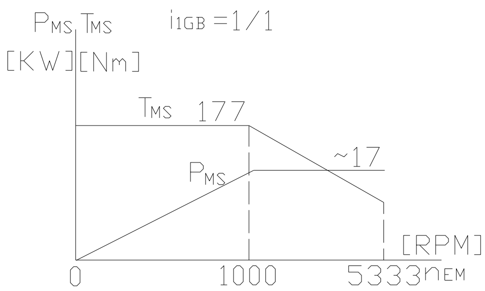
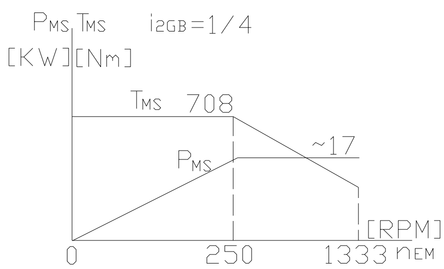


Fig.12. Characteristics of the new electric motor

Torque and power characteristics at main spindle level may be determined based on equations (15)-(19) depending on the stage selected in the gearbox, and they are shown in figure 13.



a.



b.

Fig.13. Torque and power characteristics at main spindle level

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After verification of machining parameters that are to be provided by the machine and requirements for bearing housing, decision was taken to limit motor's rotation speed to 2200 RPM. After the machine was dismantled, all spindles and gears were removed, the housing being re-machined for the new type of drive. In this newly re-machined housing the following were installed: the new gearbox, toothed belt transmission and the main spindle. Figure 14 shows the housing after final installation.

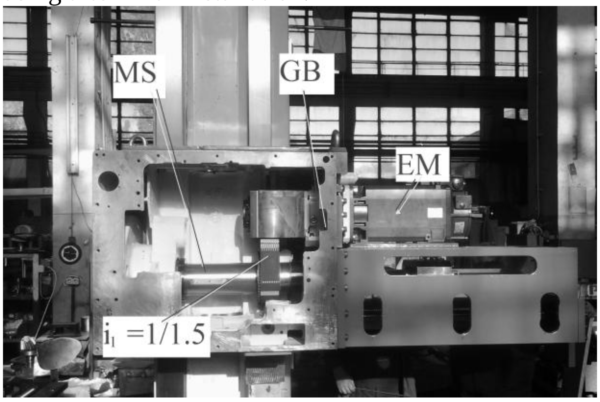

Fig.14. Final assembly

VI. CONCLUSIONS

Main kinematic chains of machine tools have become simpler due to the following:

- adjustment of rotation speed of the main motors in the [n_{MEMin}, n_{MENom}, n_{MEMax}] range may be performed continuously and using frequency converters,
- toothed belt transmissions may operate in highly accurate and safe conditions at high powers,
- two-stage gearboxes, with planetary systems, also provide possibility to transfer high and very high powers in optimum technical conditions (accuracy and mechanical return play within accepted tolerances, low noise, low size, high viability).

Kinematic chains which include motors with variable rotation speed, toothed belt transmissions and two-stage gearboxes are implemented both in new machine tools and in refurbished equipment. The rotation speed is adjusted basically by electric means, from the motor, the gearboxes and belt drives actually achieving an "amplification" of torque. In most cases, if an optimum solution is selected, performance of machines may exceed the performance of similar machines of classical structure, with higher accuracy and viability and lower noise. These solutions were applied by various manufacturers of machine tools when building machines like: vertical lathe, normal lathe, boring and milling machine, and AFP. The use of such kinematic chains, with a much simpler structure, reduces weight and complexity of processing of fixed housings and boring heads, especially for heavy machine tools.

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