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COMPENSATION FOR CROSS RAIL DEFLECTION IN HEAVY SINGLE COLUMN VERTICAL LATHES

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Abstract *This paper presents some of the theoretical-experimental research carried out by the authors on the occasion of the remaking of a heavy vertical lathe intended for the processing of diameters up to 10,000 mm. Considering this dimension, for vertical lathes with a single column, there is the question of reducing the deformation (fall) of the cross rail. In the paper some of the calculations and mathematical models used by the authors are presented in order to determine how to reduce deformations along with the experimental results.*

Key words: *heavy vertical lathe, fall compensation, mechanical-hydraulic compensation systems.*

1. THE INFLUENCE OF THE OF THE MOBILE CROSS RAIL DEFLECTION ON THE ACCURACY OF THE HEAVY VERTICAL LATHES WITH A SINGLE COLUMN

Heavy vertical lathes are machine tools designed to process surfaces by turning, milling and drilling, usually cylindrical blanks in which the ratio between height and diameter is in the range 0.5–0.9 [1, 2]. Figure 1 shows schematically the structure of such a machine tool.

The notations in Fig. 1 are the following: 1 – bed, 2 – plate, 3 – column guides, 4 – column slide, 5 – column, 6 – movable traverse, 7 – ram (carriage and slider assembly), *X*, *Z*, *C* – CNC axes of the machine, *P* – plane that defines the surface of the table (horizontal), *G* – weight of the ram (N, *n* – speed of the table 2, *m* – weight of the traverse distributed along its length (N/m), *L* – length of the traverse, *x* – current position of the ram on the traverse.

The machine main kinematic chain, which ends with table 2, is situated on bed 1. The table rotates with speed *n* in the *P* plane (*C* axis). Also, on the bed the guides 3 are paced on which the column slide 4 works. The column 5 is attached to this slide and together they can perform positioning movements, depending on the diameter of the semi-finished product. Also, the mobile cross rail 6 executes a positioning movement, this time depending on the height of the semi-finished product. It is considered that it has the weight (N/m) distributed on the length *L*. The ram 7 has the weight *G* and can move horizontally (*X* axis) but also contains a slide that performs the vertical movements – *Z* axis. The current position of the ram is determined by the *x* dimension.

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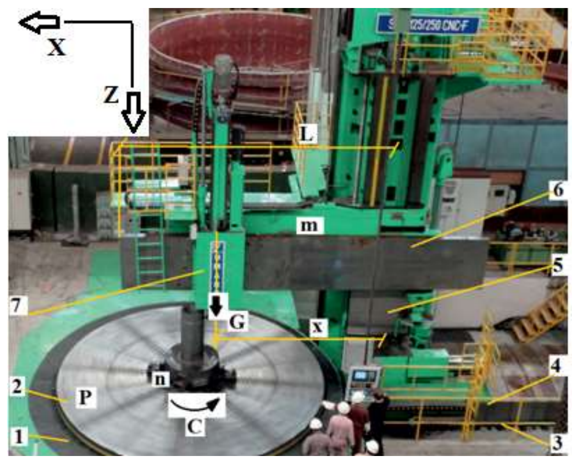

Fig. 1. Heavy vertical lathes structure.

The basic geometric conditions for carrying out specific processing can be summarized as:

- perpendicularity of the axes *X* and *Z*;
- parallelism of the *X* axis to the *P* plane.

From the two geometric conditions the condition of perpendicularity of the *Z* axis on the *P* plane results.

Due to the weight *G* and the distributed weight *m*, the cross rail bends and, depending on the position *x* of the ram, the deflection $f(x)$ and the angle $\varphi(x)$ occur as Fig. 2 shows. In Fig. 2 the notations from Fig. 1 have been kept, being added: $f(x)$ – cross rail deflection (fall) depending on the variable *x*, $\varphi(x)$ – angle of inclination of the cross rail to the horizontal due to the weight *G* and the load *m*.

For the study of the influence of these deformations, some simplifying hypotheses are made:

- the column is non-deformable;
- the crossbar is considered to be blocked without play on the column (embedded);
- for the position $x = 0$ it is considered that the deflection is given only by the distributed weight *m*;

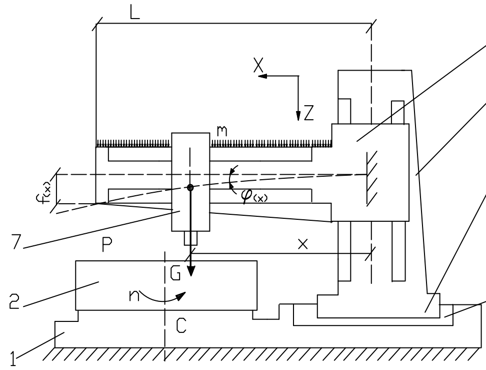

Fig. 2. Schematic of the vertical lathe.

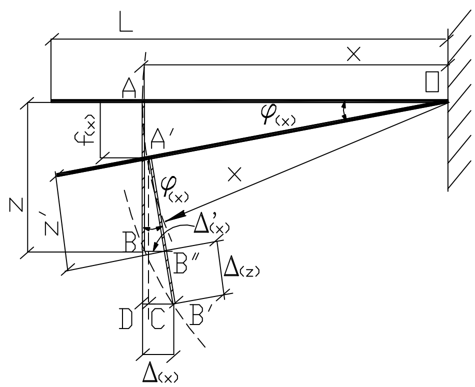

Fig. 3. Deformation mode of the mobile cross rail.

- in the previously defined position, the perpendicularity between the X and Z axes and the parallelism between the X axis and the P plane are ensured;
- the vertical position is defined by the position z.

Under the above hypotheses the deformations that appear are presented in Fig. 3.

The notations in Fig. 3 are as follows: L – cross rail length, x – horizontal tool position (relative to the column), z – vertical tool dimension (relative to the P plane), $\Delta(x)$, $\Delta(z)$ – errors on the two axes due to bending of cross rail, $f(x)$ – cross rail deflection corresponding to the position x, $\varphi(x)$ – φ angle that defines the rotation of the cross rail.

To determine the errors, it is considered that the cross rail rotates around point O describing an arc of a circle defined by the angle $\varphi(x)$. The angles AOA' and $CA'B'$ are also considered to have perpendicular sides. Under these conditions, the coordinates of the following points can be written in the XOZ axis system:

$$A(x, 0), \quad (1)$$

$$B(x, z), \quad (2)$$

$$A'(xcos\varphi_{(x)}, xsin\varphi_{(x)}), \quad (3)$$

$$C(xcos\varphi_{(x)}, x\ sin\varphi_{(x)} + zcos\varphi_{(x)}), \quad (4)$$

$$D(x, x\ sin\varphi_{(x)} + zcos\varphi_{(x)}), \quad (5)$$

$$B'(xcos\varphi_{(x)} - zsin\varphi_{(x)}, xsin\varphi_{(x)} + zcos\varphi_{(x)}). \quad (6)$$

Considering that x and z defined a position in the horizontal plane P, for point B, in the new conditions, the point B'' is obtained, also in the plane P. To reach this point on the Z axis, only a displacement corresponding to point B will be achieved, having the coordinates:

$$B''(\frac{x-zsi\ \ _{(x)}}{cos\varphi_{(x)}}, z). \quad (7)$$

If the Z position is kept, the plane P is exceeded and the corresponding error on the X axis is:

$$\Delta_{(x)} = x - xcos\varphi_{(x)} + zsin\varphi_{(x)}\ . \quad (8)$$

In order not to exceed the plane P, the position z is reached on the Z axis (point B'' is reached). In this case the error on the X axis is:

$$\Delta'_{(x)} = x - \frac{x-zsin\varphi_{(x)}}{cos\varphi_{(x)}}. \quad (9)$$

Considering that regardless of the fall of the cross rail it is desired to reach in the end the imposed position (point B of x and z coordinates), besides the correction applied on the Z axis (reduction), according to Fig. 4 a correction of the x position will be made (increase).

The notations in Fig. 4 are: L – cross rail length, x – uncorrected horizontal position of the tool (relative to the column), z – uncorrected vertical position of the tool (relative to the plane P), $\varphi(x)$ – angle that defines the rotation of the cross rail, z'' corrected tool vertical position (relative to the P plane).

In these conditions it is obtained:

$$OE = x'' = \frac{x}{cos\varphi_{(x)}} + \left(z - f_{(x)}\right)sin\varphi_{(x)}, \quad (10)$$

$$A''B = z'' = \left(z - f_{(x)}\right)cos\varphi_{(x)}. \quad (11)$$

By programming the x'' and z'' dimensions instead of the x and z dimensions, the deformation of the cross rail does not affect the positioning accuracy in the P plane. Determining the values of the new dimensions requires knowing the deformations (deflection $f(x)$ and angle $\varphi(x)$).

Even by applying the above corrections, although at first sight the accuracy of the machine is not affected by the bending of the cross rail, it can reach, at least theoretically, the desired point, in reality the problem is not completely solved. Considering that the cross rail is deformed, in the position determined by the elevation x

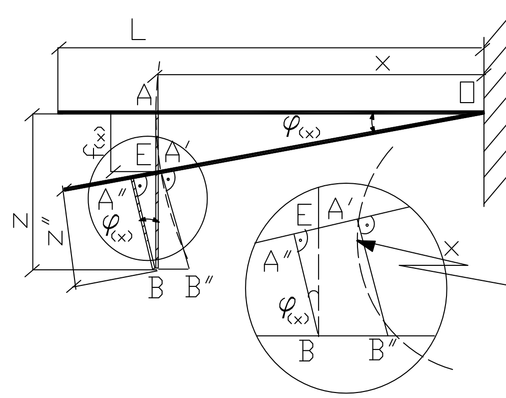

Fig. 4. Correction of positions x and z for compensation.

the perpendicularity of the Z axis with respect to the cross rail is kept, but not the perpendicularity on the plane P. As seen in Fig. 3 and 4 the Z axis is inclined with respect to the vertical with the angle $\varphi(x)$. If compensation (EA') is neglected, this angle has the expression:

$$\varphi_{(x)} = arctg\frac{f_{(x)}}{x}. \quad (12)$$

2. DETERMINATION OF THE MOBILE CROSS RAIL DEFLECTION

The mobile cross rail is considered to be a fixed beam loaded with a distributed mass m and a concentrated load G, as Fig. 5 shows [3].

The notations are: L – length of the cross rail, x – horizontal position of the tool (relative to the column), z – vertical dimension of the tool (relative to the plane P), G – weight of the ram, m – distributed mass of the cross rail, $f(x)$ the cross rail deflection of the corresponding position x, $\varphi(x)$ – the angle that defines the rotation of the sleepers, Iz – the moment of inertia of the cross rail (assumed constant along the entire length).

In the technical literature, for a cantilever having the modulus of elasticity Iz required as Fig. 5 shows, for determining the deformations the following expressions are considered:

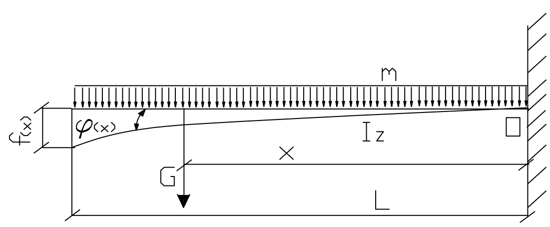

Fig. 5. Cross rail loading scheme.

$$f_{(x)} = \frac{Gx^3}{3EI_Z} + \frac{mL^4}{8EI_Z}, \quad (13)$$

$$\varphi_{(x)} = \frac{Gx^2}{2EI_Z} + \frac{mL^3}{6EI_Z}. \quad (14)$$

For the machine that was the object of the research, the mobile cross rail is a cast iron and ribbed construction with dimensions according to Fig. 6. The average thickness of the walls is 80–100 mm. The cross rail is a solid of equal resistance that fits in a parallelepiped having the dimensions 3500 × 1800 × 1650 mm^3.

Due to the shape and construction of the cross rail, the application of relations (13) and (14) implies the consideration of an approximately constant value of Iz along its entire length.

3. COMPENSATION FOR ERRORS OF THE MOBILE CROSS RAIL DEFLECTION

The total elimination of the errors induced by the deformation of the cross rail is impossible. There are various ways to reduce these errors, some of them being detailed further.

3.1. Processing of the guides that ensure the parallelism with the *P* plane at an angle that ensures the compensation of the deformations

This method is shown by Fig. 7.

The notations are: 1 – table of the grinding machine (horizontal), 2 – mobile cross rail, 3 – theoretical guides GT, 4 – processed guides GR, φ – angle at which the real guides are processed.

On the Table 1 of the guide grinding machine the cross rail 2 is attached. It is considered that the machine table ensures the perfectly horizontal positioning through the H plane which is always parallel to the P plane, in fact being the horizontal reference (provided by the foundation and adjustable jack levellers. If the theoretical 3 GT horizontal guides are processed after mounting as

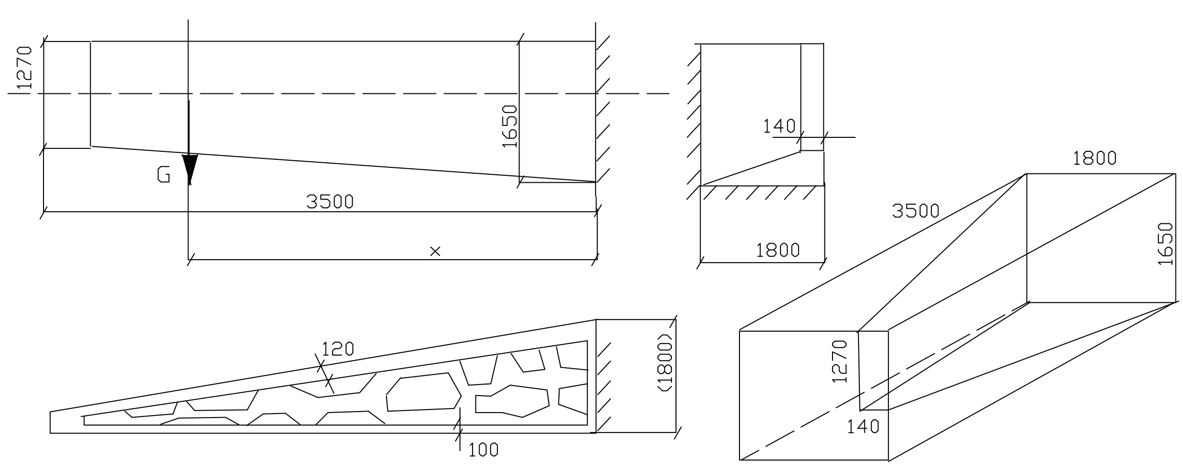

Fig. 6. Cross rail.

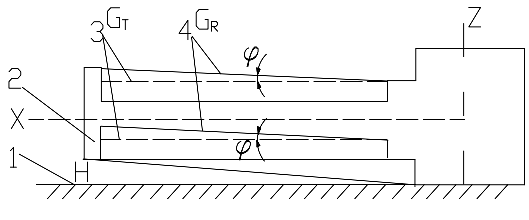

Fig. 7. Machining the guides along X-axis so as to ensure the compensation of the cross rail bending.

seen in Fig. 7, errors occur due to the transverse deformation. That is why the processing is done from an angle φ thus obtaining the real guides 4 GR. The angle φ is constant and represents an average value of the angle φ(*x*). The method involves the above calculations but also experimental measurements. If possible, it is recommended that these to be performed, where possible, on an existing similar machine. Given that the perpendicularity between the *Z* and *X* axes is not ensured on the whole stroke, the problems regarding the positioning accuracy are partially solved, but not the perpendicularity ones.

3.2. Initial inclination of the cross rail on the column guides with an angle φ

The notations in Figs. 8 are: *L* – length of the cross rail, *G* – weight of the ram, *m* – distributed mass of the cross rail, *X*, *Z* – working axes, *x* – position of the ram on the *X* axis, *B* – width of the guide of the cross rail on the column, *f* – deflection (linear deformation), φ – angle at which the assembling is made, *d* – dimension of the closing feathers. The rest of the notations are as in the previous figures.

If an angle φ (calculated or determined experimentally) is required, the closing wedges of the guides of the cross rail 6 on the column 5 will be processed so as to ensure the achievement of dimension *d* as figure shows.

The value of the dimension *d* is determined with the relation:

$$d = B\frac{f}{L}. \tag{15}$$

In the relation (15) it was also noted: *B* – width of the guide area of the cross rail on the column, *P* – horizontal plane (table plane), *f* – deformation of the cross rail (experimentally determined). By moving the ram 7 the cross rail is bent, theoretically ensuring the parallelism of the *X* axis with the *P* plane. So, the *X* axis rotates with respect to the *O* point.

3.3. Compensation of the cross rail deformation by tensioning it

The notations in Fig. 9 are the following [4]: 1 – bed, 2 – plate, 3 – column guides, 4 – column slide, 5 – column, 6 – mobile cross rail, 7 – ram, 8 – hydraulic cylinder, 9 – cross rail extension, 10 – tension bar, *S* – active surface of the cylinder, *p* – pressure on the active surface, *T* – hydraulic installation tank, *a* – height of the cross rail extension, *X*, *Z*, *C* – CNC axes of the machine, *P* – plane defining the surface of the plate (horizontal), *G* – weight of the ram (N), *n* – speed of the plate 2, *m* – mass of the cross rail distributed along its length (N/m), *L* – length of the cross rail, *x* – current position of the ram on the cross rail.

On the movable cross rail 6 there is a hydraulic cylinder which is supplied with oil at pressure *p*(*x*) on the active surface *S*. The cylinder pulls the extension of the cross rail 9 by means of the rod 10. The extension of the cross rail is of height *a*. The bending moment, in point *O*, created by the weight *G* with the arm *x* and by the distributed mass *m* with the arm *L*, is compensated by the moment given by the force *F*(*x*) having the arm *a*. In Fig. 9, besides the elements defined in Figs. 1 and 2, it was also noted: *p*(*x*) – supply pressure, *S* – active surface of the cylinder, *T* – tank of the hydraulic installation, *F*(*x*) – developed force, parallel to the *X* axis.

For a zero resultant torque it can be considered:

$$F_{(x)}a = Gx + \frac{mL^2}{2}. \tag{16}$$

The value of the force *F*(*x*) can be determined from relation (16) as a function of the position *x* of the ram. The required pressure is also a function of *x* and has the expression:

$$p_{(x)} = \frac{F_{(x)}}{\frac{\pi(D^2-d^4)}{4}}. \tag{17}$$

The numerical control equipment allows the measurement in real time of the dimension *x*, this dimension being the one that will determine the pressure necessary for the compensation. The pressure is regulated by means of a proportional reduction valve [5, 6]. Even if this dimension is measured continuously, in practice it is sent to the hydraulic equipment in the form

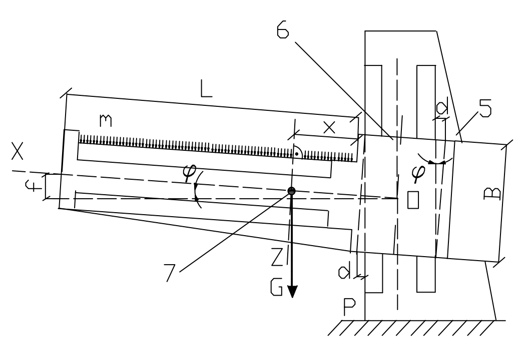

Fig. 8. Compensation for errors by mounting cross rail at an angle to the vertical.

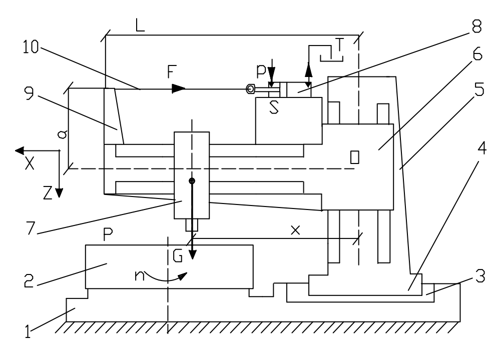

Fig. 9. Compensation for the fall of the cross rail with the help of a hydraulic installation.

of discrete signals with an imposed pitch (usually it is 100 mm). So, as the *x* position increases, the supply pressure of the cylinder also increases. For such an actuation it is recommended to use the proportional type of hydraulic equipment. The method is efficient and also solves the problem of keeping the perpendicularity of the *X* and *Z* axes. This method is also applied to AFP type machines [5, 7]. The major disadvantage of this method is the price of the necessary hydraulic equipment.

3.4. Deformation compensation with the help of CNC equipment

This method has already been mentioned previously [6]. It consists in correcting the theoretical positions *x* and *z* so that the positions *x*" and *z*" are obtained, according to relations (10) and (11). In this case, in order to enter the corrections, the values of the deflection $f(x)$ and the angle $\varphi(x)$ must be known. It is recommended to determine them experimentally and to introduce them discreetly with a certain step, as in the previous method. By this method, the positioning accuracy is improved, but the permanent perpendicularity of the *Z* axis on the *P* plane is not ensured.

4. EXPERIMENTAL RESEARCH

On the occasion of the remanufacturing of the SCM100 vertical lathe, in order to reduce the positioning and processing errors, the following compensations for the cross rail deflection were made [8]:

a. initial inclination of the cross rail on the upright guides with an angle φ;
b. compensation of the cross rail deflection by tensioning it [4].

After the completion of the construction of the remanufactured machine and after the application of the corrections presented above, the geometric precision conditions were checked. The values recommended by the norms are those for vertical lathes with two columns, machines in which the deformation of the cross rail is reduced by construction [5, 8]. Of these, the ones presented in Table 1 can be mentioned.

Table 1

Geometric parameters measured and recommended

No.	Measurement name	Obtained / recommended value (mm/m)
1	Plateau flatness (plan *P*)	0.04 / 0.04
2	Horizontality of the compensated cross rail	0.05 / 0.04
3	Rectilinearity of the ram movement (*X* axis)	0.04 / 0.04
4	Parallelism between X axis and *P* plane	0.05 / 0.04
5	Rectilinearity of the vertical movement of the slider (*Z* axis) with respect to the table axis (*P* plane)	0.03 / 0.03
6	Parallelism between *Z* axis and plateau axis (perpendicular to the *P* plane)	0.04 / 0.03

From Table 1 above it can be seen that, through the corrections applied, the accuracy of the machine tool with one column is not significantly lower than that of the machine with two columns.

5. CONCLUSIONS

Heavy machine tools are machine tools that, due to their size and price, are suitable for the remanufacturing process. Their size, complexity and price justify the investments needed for remanufacturing. This usually includes reconditioning the guide surfaces and changing the electrical, hydraulic and pneumatic elements. On the occasion of remanufacturing, new and modern solutions can be applied, which did not exist or were not applied to the initial manufacture. Usually, on the occasion of remanufacturing, the CNC equipment is changed. In the case of the hard remanufactured lathe, destined for the processing of parts up to 100 t by turning, milling, drilling, etc., the remanufacturing represented a preferable variant for the purchase of a new machine. On the occasion of the remanufacturing, the aim was to improve the processing and positioning accuracy, including the interpolation precision. For this purpose, theoretical research and real measurements were made. Of these, in the end, those that could be applied concretely were chosen: the initial assembly of the cross rail so that by deformation the *X* axis remains parallel to the *P* plane, the compensation of the cross rail deflection by tensioning it with a special hydraulic installation and the introduction of compensations, with a certain step on the *X* axis, in the control equipment. Considering the complexity of the construction, as well as the difficulties specific to the assembly of such a machine, the values obtained from the mathematical models were corrected based on the experimental measurements.

REFERENCES

[1] P.H. Joshi, *Machine Tools Handbook Design and Operation*, Tata McGraw-Hill Publishing Company Limited, New Delhi, India, 2007.
[2] B. Perovic, *Handbuch Werkzeug-maschinen*, Carl Hanser Verlag Munchen Wien, 2006.
[3] G. Buzdugan, Rezistenta Materialelor, Edit. Tehnica, Bucharest, 1974.
[4] D. Prodan, A. Bucuresteanu, A. Motomancea, Beam Sag Compensation in Single Column Heavy Vertical Lathe, Journal of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatonics, Nr.2 (2018), pp. 6–13.
[5] Dan Prodan, Masini Unelte grele. Sisteme Mecanice si Hidraulice, Editura Printech, Bucuresti 2010.
[6] *** Catalogs: GE Fanuc, SIEMENS, BOSCH REXROTH, Titan Masini Grele.
[7] D. Prodan, A. Ghionea, G. Constantin, *Sistem hidraulic de compensare pentru căderea pinolei la maşina AFP 180,* Conferinţa Internaţională de Comunicări Ştiinţifice Tehnologi Moderne, Calitate, Restructurare, Chişinău, Secţiunea 6, pp. 145–150, 2005.
[8] D. Prodan, S. Marinescu, *Refabricarea si Modelarea Masinilor-Unelte*. *Sisteme Hidraulice*, Edit. Tehnica 2005, Bucharest.