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HYDRAULIC BALANCING OF CROSSRAILS AND RAMS OF HEAVY DUTY MACHINE TOOLS

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Abstract: *This paper introduces some of the findings of the research made by the authors on the occasion of the manufacturing of a gantry type milling machine with displaceable table FLP 2200 CNC type. The designed balancing unit had to cope with the specific requirements of this type of machine, but it can be successfully used for other gantry type machine tools such as heavy vertical lathes and milling machines with displaceable gantry. Generally, in the case of heavy duty machine tools, the kinematic chains for feed / positioning that are working vertically must move large masses with velocities of 2−10 m/min, under high conditions of stability and accuracy. On the occasion of FLP 2200 CNC machine manufacturing, the authors have designed and made a single balancing unit. This fact was possible because the feed phases of the rams and the positioning phase of the crossrail are never overlapped and because the mechanical design met the conditions of maximum safety. Data is submitted about the necessity of balancing and the computational model of "discharge" of the feed / positioning kinematic chain when it is done hydraulically. It is presented the design of the hydraulic scheme used to balance both hydraulic rams and the crossrail. Also, simulating operation and the hydraulic diagram and the construction of this unit is presented. It is distinguished the need to use accumulators in the hydraulic circuit. Feed / positioning kinematic chains of the scenes must be driven by drive motors equipped with brakes.*

Key words: *heavy duty machine tools, hydraulic balancing, unloading of feed kinematic chains, positioning kinematic chain.*

1. GENERALITIES

The gantry type milling machines with displaceable table [1] belong to the category of heavy duty machine tools intended for the milling and drilling operations in the case of machining of heavy work pieces of large size. The machine for which the balancing hydraulic unit [2] has been made can machine work pieces with a weight up to 60 t; it has a displaceable table with the length of 8000 mm and the width of 2200 mm. The machine is CNC type and it has the following work axes: X axis – table movement, Y_1 and Y_2 axes – travels of the two saddles on the crossrail, Z_1 and Z_2 axes – vertical travels of the two rams, W − positioning movement of the crossrail, movement with pitch of 200 mm. Figure 1 shows the block diagram of such a machine.

The feed kinematic chain 3 (on X axis) moves the table 2 on the guide ways of the bed 1. The crossrail 6 can travel on the columns 4 by means of the positioning kinematic chain 9. The pulley systems 8 are clamped on the cross-beam 7; these systems perform the balancing of the crossrail by means of the cylinders 5. The crossrail 6

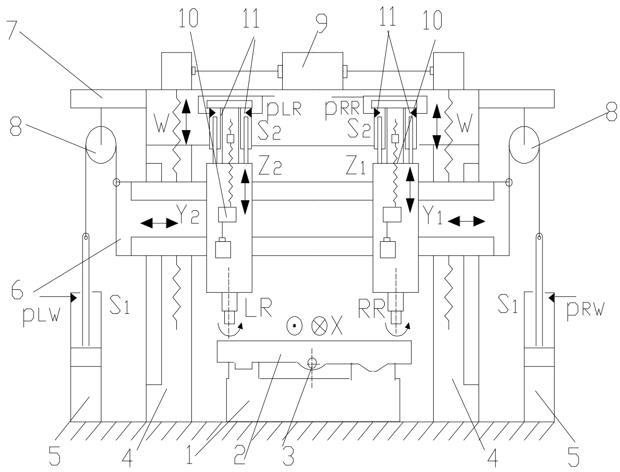

Fig. 1. The block diagram of gantry type milling machine FLP 2200: 1 – bed, 2 – movable table (it travels on X axis), 3 – feed kinematic chain of the table, 4 – columns, 5 – balancing cylinders of crossrail, 6 – crossrail, 7 – cross-beam, 8 – pulleys system, 9 – kinematic chain for crossrail positioning (positioning on W axis), 10 – feed kinematic chains of left side and right side rams (Z_1 and Z_2 axes), 11 – balancing cylinders of the two rams, LR – left ram, RR – right ram, p_{LW} and p_{RW} – supply pressures for the balancing cylinders of the crossrail (left side and right side), respectively, p_{LR} and p_{RR} – balancing pressures of left and right ram, S_1 – useful area of crossrail balancing cylinders, S_2 – useful area of rams balancing cylinders, X, Y_1, Y_2, Z_1, Z_2 – numerically controlled axes, W – positioning axis.

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is positioned by means of indexing devices and is locked by the cylinders that are not represented in the figure, depending on the height of the work piece.

The work pieces clamped on table 2 are machined by means of the milling (drilling) tools fastened in the tool holders of the *LR* and *RR* rams. These ones make the vertical feed movements Z_1 and Z_2 and, thanks to the corresponding slides, the horizontal feed movements Y_1 and Y_2. Therefore each tool can make a horizontal feed movement (Y) and a vertical feed movement (Z).

2. NECESSITY OF BALANCING

Generally, in the case of heavy duty machine tools, the kinematic chains for feed / positioning [3] that are working vertically must move large masses with velocities of 2–10 m/min, under high conditions of stability and accuracy. A commonly used solution of "unloading" of the respective kinematic chains is the hydraulic balancing [4]. Figure 2 shows (in a simplified manner) the working principle of the hydraulic balancing.

If there is no balance (Fig. 2,*a*), the feed kinematic chain will be sized so that the instantaneous force developed by it F_2 can equal the resistance force F_1. In most cases, the latter one is the sum of weight, inertia forces and/or cutting forces:

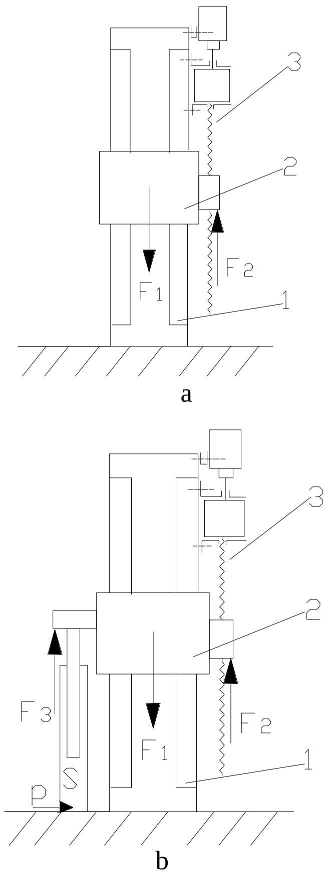


Fig. 2. Working principle of the hydraulic balancing: *a* – kinematic chain for vertical feed without balance; *b* – kinematic chain for vertical feed with hydraulic balance; 1 – guide ways for vertical movement, 2 – load displaced, 3 – kinematic chain for vertical feed, F_1 – resistance force, F_2 – force developed by the feed kinematic chain, F_3 – force developed by the balancing hydraulic system, S – useful area of balancing cylinder(s), p – pressure in the hydraulic unit.

$$F_1 = F_2 . \tag{1}$$

For a correct operation, check the necessary condition:

$$F_{2\max} = M_{EM} \cdot 2\pi \cdot \frac{i^{-1}}{p_s} \geq G \pm (F_I) \pm (F_C). \tag{2}$$

In the equation (2) it has been noted: $F_{2\max}$ – maximum force developed, M_{EM} – moment evolved by the motor of the feed kinematic chain [2], i – transfer ration of the mechanical adjustment system of feed kinematic chain (i < 1), p_S – pitch of the leading screw, G – weight of the moved load, F_I – inertia force, F_C – cutting force. Depending on the operation phase (rapid travel or cutting feed) and on the sense of movement, the values F_I and F_C are taken with + / – or they are missing.

The travel, regardless its sense and the system forces, is made with a velocity having the value:

$$v = n_{EM} \cdot i \cdot p_s . \tag{3}$$

In the equation above, it has been noted: v – feed or positioning velocity, n_{EM} – rpm of the electric motor, p_S – pitch of the leading screw (usually, this is a ball screw [5]).

If the feed kinematic chain is balanced, as in Fig. 2, b, one shall check if the conditions below are met:

$$F_1 = F_2 + F_3 , \tag{4}$$

$$F_3 = p \cdot S , \tag{5}$$

$$M_{EM} \cdot 2\pi \cdot \frac{i^{-1}}{p_s} + p \cdot S \geq G \pm (F_I) \pm (F_C), \tag{6}$$

$$v = n_{EM} \cdot i \cdot p_s = Q / S . \tag{7}$$

The following notations have been used in the equations above: p – supply pressure of the balancing cylinder, Q – flow of supply or exhaust from cylinder.

In the case of the hydraulic balancing, as it results from the equations above, the necessary moment at the electric motor is reduced and the feed kinematic chain do not need components as strong as in the case of the unbalanced drive. Usually, it is recommended that the balancing takes over as much as possible of the value of the weight (G) displaced.

3. HYDRAULIC BALANCING OF THE CROSS-RAIL AND RAMS OF FLP 2200 MACHINE

The following elements of this machine are balanced: the crossrail during the positioning travel (W) and the two rams in the feed and positioning travel (Z_1, Z_2). The cross-rail has a total mass of ~ 22 000 kg and each balancing ram has ~ 3800 kg. The positioning velocity of the crossrail is 1 m/min and the range of the feed/positioning velocities of the rams is 0–2.5 m/min. The crossrail is partially hydraulically balanced (the rest of the balancing is performed mechanically, by means of counterweights [2]) while the rams have a totally hydraulic balance.

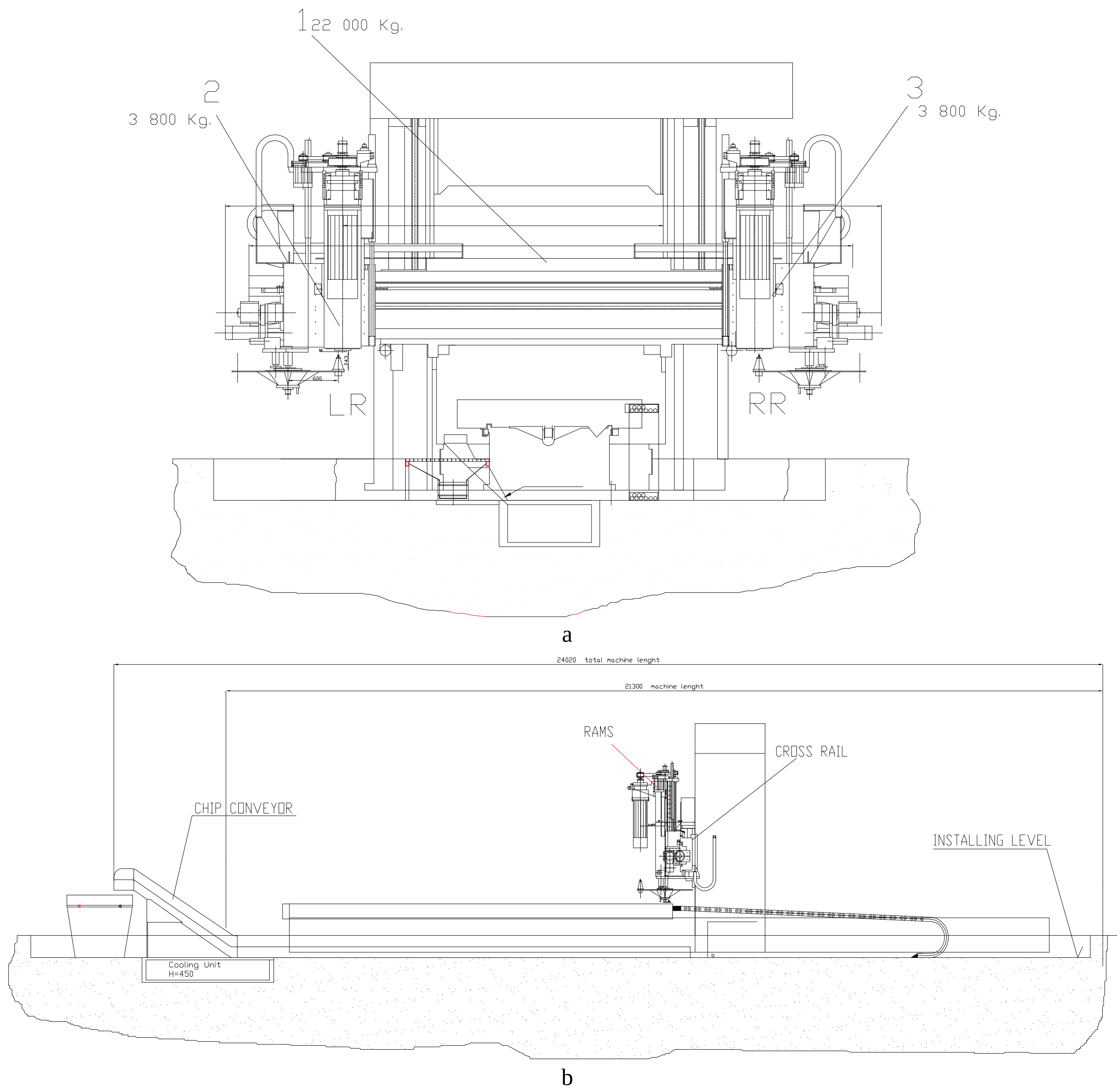


Fig. 3. View of FLP 2200 machine: *a* – front view; *b* – lateral view; 1 – crossrail to be balanced (22 000 kg), 2 – left ram to be balanced (3 800 kg), 3 – right ram to be balanced (3 800 kg).

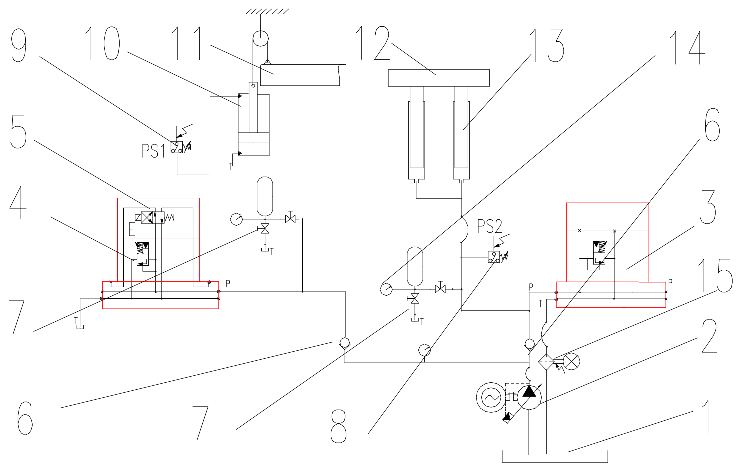


Fig. 4. Hydraulic diagram of the balancing unit (partial): 1 – tank, 2 – pump with pressure regulator, 3 – pressure relief valve for ram, 4 – pressure relief valve for crossrail, 5 – distributor with electric drive (*E*), 6 – check valves, 7 – accumulators, 8 – *PS*2 – pressure relay for ram balancing confirmation, 9 – *PS*1 – pressure relay for crossrail balancing confirmation, 10 – one of crossrail balancing cylinders, 11 – crossrail, 12 – ram, 13 – cylinders for crossrail balancing, 14 – pressure gauges, 15 – filter.

In Fig. 3 a view of FLP 2200 machine and the elements that are hydraulically balanced is shown.

The crossrail 1 in Fig. 2 is balanced by means of two hydraulic cylinders positioned at the extremities and each one of the rams 2 and 3 has two balancing cylinders plunger type [4].

4. HYDRAULIC DIAGRAM OF BALANCING UNIT

Commonly this type of machines has separate balancing units for crossrails and for rams.

Previous reserch [7] stated that in order to reduce the overall size and price of the kinematic chain elements, the solution is the crossrail balancing. The hydraulic balancing is made by means of two hydraulic cylinders symmetrically positioned. One shows the principle hydraulic diagrams, methodology of calculation and results of some simulations. For the crossrail balancing, a separate hydraulic unit for each of the two cylinders is available. Experimental achievements are shown for a portal milling machine of FLP 2000 type. The specific feature of this system for crossrail balancing is that it uses the regular hydraulic equipment and having low prices. The hydraulic units for such balancing can successfully replace the complex and expensive units used for feed kinematic chains, in the case of CNC heavy duty machine tools. As well, the authors presented a balancing hydraulic system for feed kinematic chains, which is acting on crossrail heads of the heavy gantry machine tools, usually used for axes *Z*.

On the occasion of manufacturing the machine FLP 2200, the authors have designed and made a single balancing unit. This fact was possible because the feed phases of the rams and the positioning phase of the crossrail are never overlapped and the mechanical design met the conditions of maximum safety. The feed kinematic chains of the rams are provided with motors with brake and an additional electro-magnetic brake on each ball screw. In these conditions, during crossrail positioning phase there is no risk of rams falling. In its turn, the crossrail is provided with indexing devices [2] and a locking system, which eliminates the risk of its falling when the rams are balanced.

The hydraulic unit includes two identical systems, each one performing the balancing of one ram and of one side (left or right) of the crossrail. Figure 4 presents one of these two systems.

4.1. OPERATION OF BALANCING HYDRAULIC UNIT

Figure 4 is used for understanding the operation of balancing hydraulic unit. When the pump 2 starts operating, it sucks the oil from the tank 1 and – through the check valves 6 – it loads the accumulators 14 and keeps the pressure in the circuit of the cylinders 13; the pressure is adjusted at the pump regulator [4]. The existence of this pressure is confirmed by the pressure relay 8 of the ram balancing circuit. Under these conditions it is possible to perform the rapid positioning of the ram or its feed travel.

If the feed kinematic chain of the ram stops, after breaking the motor and the leading screw, the electromagnet of distributor 5 shall be put under voltage. The pump 2 will supply the balancing circuit of the crossrail. The pressure in this circuit is confirmed by the pressure relay 9. In this phase, the crossrail is balanced and it can be unlocked and unindexed in order to position it again. After repositioning, the crossrail in locked in the new position indexed and the voltage is cancelled from distributor 5, coming back to the ram balancing. Filter 15 ensures the purity of the oil in circuit.

In the lifting phases, the ram and the crossrail will have the same pressure adjusted from the regulator of pump 2.

The necessary pressures for the falling phases will be adjusted at the pressure relief valves 3 and 4 but compulsorily by 10–15 bar higher than the pressure adjusted at the pump regulator. The pressures in different points of the circuit can be viewed by means of the pressure gauges 14.

The flow of the pump 2 must be higher than the flow necessary for the crossrail and ram lifting:

$$Q_P > S_1 \cdot v_1 = Q_1, \tag{8}$$

$$Q_P > S_2 \cdot v_2 = Q_2 . \tag{9}$$

Figure 5 presents the working theoretical characteristics for the balancing unit.

As mentioned above, two identical hydraulic units with the hydraulic scheme presented on Fig. 4 ensure the balance of the crossrail (only positioning) and balance of the rams. Selecting a certain phase of balancing is done by enabling or disabling the electromagnet *E* of the distributor 5. The confirmation of the active balancing is done using PS1 and PS2 relay pressure as in Table 1.

When the crossrail is moving, the rams are maintained in their respective axes by the electric motors of

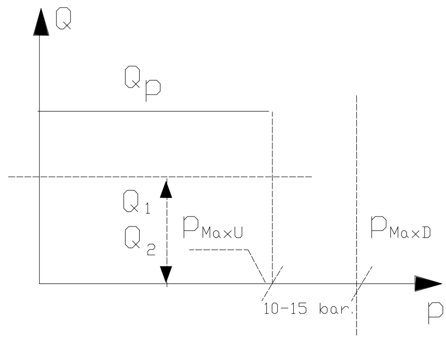


Fig. 5. Theoretical characteristics for the balancing unit: Q – flow, p – pressure, Q_P – pump maximum flow, Q_1, Q_2 – flows for the two balancing systems, p_{MaxU} – maximum pressure accepted during lifting and in STOP phase, p_{MaxD} – maximum pressure accepted during falling.

Table 1

Selection and confirmation of the balancing

No	**Phase**	**Pump** (2)	**E**	**PS1** (9)	**PS2** (8)
1	STOP	−	−	−	−
2	START	+	−	−	+
3	Balancing ram	+	−	−	+
4	Balancing crossrail	+	+	+	+

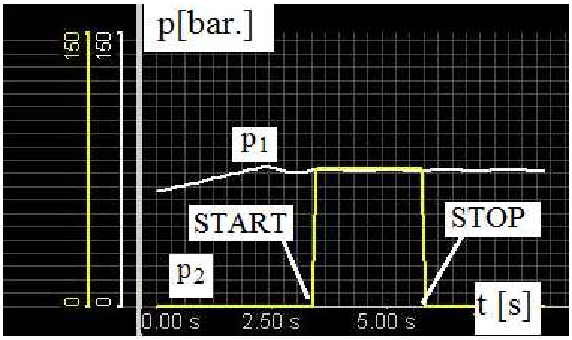


Fig. 6. Pressure development in ram balancing system (p_1) and crossrail balancing system (p_2).

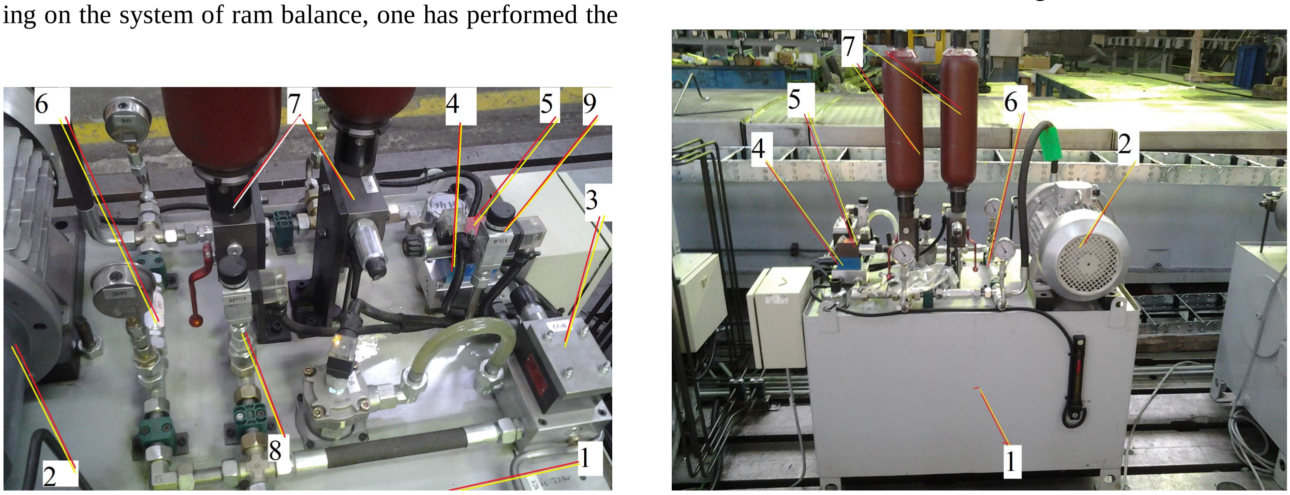
the feed kinematic chain (Z_1 and Z_2). After moving the crossrail on the desired position it is locked and indexed. At this moment the balancing of the crossrail is no longer required and the two hydraulic units will provide the balancing of the two rams on machining phases, and positioning phases.

For studying the influence of balance system clutching on the system of ram balance, one has performed the simulation of the whole unit in dynamic conditions, using a specialized program. If the pressure in ram balancing circuit is noted with p_1 and the pressure is the crossrail balancing circuit is noted with p_2, one can observe the interaction of these pressures in Fig. 6.

Figure 6 shows that in the clutching moment (START) of the crossrail balancing and in the unclutching one (STOP), the pressure in ram balancing system is not considerably affected, thanks to the presence of the two accumulators [6] that play a prominent role.

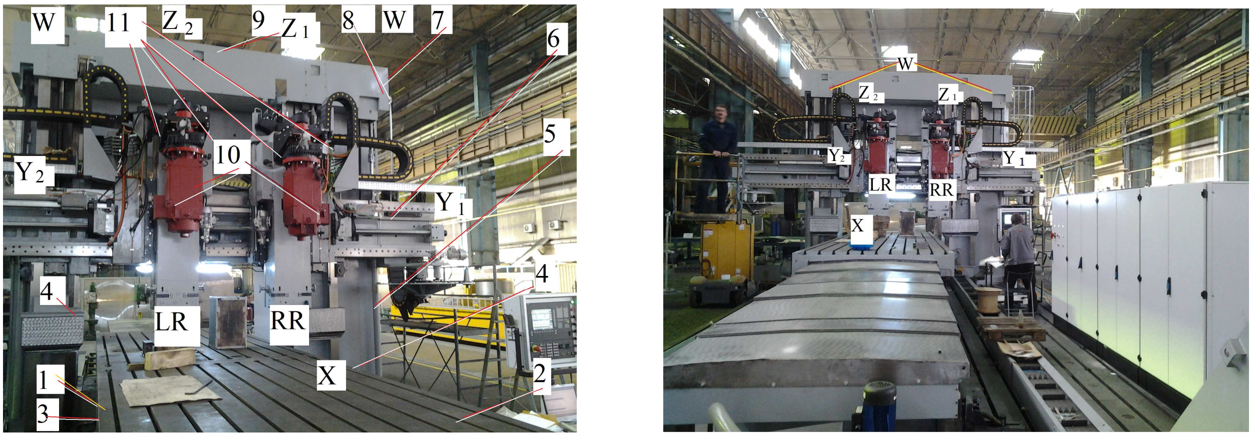
5. EXPERIMENTAL RESULTS

For making the hydraulic balancing of the crossrail and of the two rams of the milling machine with displaceable table, one has manufactured two identical hydraulic units. One unit makes the balancing of the left side ram and left side of the crossrail and the second unit performs the same functions but on the right side of the machine. The adjustments of the two units are totally independent. In Fig. 7 one of these two units is shown, the notations are the same as in Fig. 4.



a b

Fig. 7. Balancing hydraulic unit: *a* − top view; *b* − lateral view; 1 − tank, 2 − pump with pressure regulator, 3 − pressure relief valve for ram, 4 − pressure relief valve for crossrail, 5 − distributor with electric drive, 6 − check valves, 7 − accumulators, 8 − pressure relay for ram balancing confirmation, 9 − pressure relay for crossrail balancing confirmation.



a b

Fig. 8. View of the milling machine with displaceable table FLP 2200 CNC type: *a* – ram details; *b* – general view; X, Y_1, Y_2, Z_1, Z_2 − numerically controlled axes, W − positioning axis, 1 − bed, 2 − displaceable table (it travels on X axis), 3 − feed kinematic chain of the table, 4 − columns, 5 − crossrail balancing cylinders, 6 − cross-rail, 7 − cross beam, 8 − pulleys system, 9 − kinematic chain for crossrail positioning (positioning on W axis), 10 − feed kinematic chains for left and right rams (Z_1 and Z_2 axes), 11 − balancing cylinders of the two rams, *LR* − left ram, *RR* − right ram.

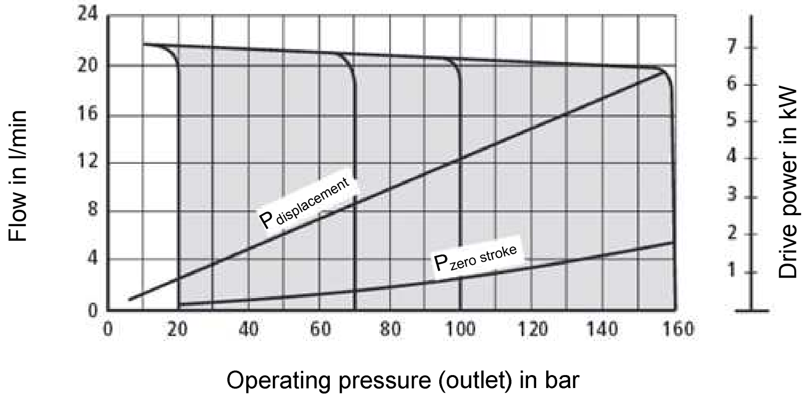


Fig. 9. Characteristic of the pump for balancing the crossrail and rams.

The units are placed behind the machine and supply the cylinders in Fig. 8 by means of the hoses. Figure 8 has the same notations as Fig. 1.

The characteristic of the pump (2) used to balance the rams and also the crossrail is shown in Fig. 9. The regulator of the pump is adjusted to 100 bar and pressure valves 4 and 3 (Fig. 4) are set at 120 bar. The pressure relays confirming the operation of the balancing systems (8 and 9 from Fig. 4) were adjusted to 90 bar.

6. CONCLUSIONS

In the case of the heavy duty machine tools requiring the hydraulic balancing of the crossrail that makes only positioning movements, it is possible to use only one unit for this function and for the hydraulic balancing of the rams. If such solution is adopted, the kinematic chains for feed/positioning of the rams shall be provided with drive motors equipped with brakes. It is recommended to place some supplementary electromagnetic brakes on the ends of the ball screws on *Z* axes.

The crossrail positioning is made by means of mechanical indexing devices and the locking shall be firm, on disk springs preferably, while the unlocking will be made hydraulically [2].

It is recommended that the hydraulic unit for balancing this type of machines to use adjustable flow pump with pressure regulator and pneumo-hydraulic accumulators [4, 6].

The balancing hydraulic units should be provided with accumulators and elements for confirming the balancing status, pressure transducers and relays.

The units should be calculated in static but also dynamic conditions, by means of specialized simulation programs.

The use of the second method of balancing presented in this article leads to a cost reduction of up to 40% with regard to the first one presented in work [7].

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