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HYDRAULIC BALANCING SYSTEMS WITH LOW POWER CONSUMPTION AND CONSTANT FLOW PUMPS

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Abstract

In this paper, authors show a cost-saving method of replacing variable flow pumps with pressure regulator within hydraulic balancing systems for heavy machine-tools, with simple, constant flow pumps. The system proposed is relevant for heavy machine-tools where large loads need balancing: cross beams, slides, enclosures, etc. The basic hydraulic schematics, calculation method and results of certain simulations are displayed here. A characteristic of these systems is the use of routine hydraulic equipment, thus providing low costs. Hydraulic equipment used in such balancing systems may successfully replace complex and expensive equipment used in feeding / positioning kinematic chains within CNC heavy machine-tools, like: Horizontal Boring and Milling Machines (HBM), Vertical Lathes (VL) and Gantry Machines.

Keywords: heavy machine-tools; feeding / positioning kinematic chain; hydraulic balancing; low power consumption.

1. Introduction

In case of heavy machine-tools, with vertically displaced heavy elements, hydraulic systems are used for discharging the feeding / positioning kinematic chains [1, 2, 3].

Hydraulic balancing is achieved with hydraulic cylinders. Figure 1 shows the hydraulic balancing of a cross beam within a portal milling machine [1, 4].

In figure 1 the following legend is used: 1 - balanced mobile cross beam, 2 - dual-output electric motor, 3 - reducing gears, 4 - feed screws, 5 - milling head(s), 6 - fixed cross beam, 7 - props, 8 - balancing cylinders.

The mobile cross beam 1 together with milling heads 5 have a large weight (possibly exceeding 15 t) which, in the absence of a balancing system, is displaced on the guides of props 7 by the motor 2 acting through reducing gears 3 and feed screws 4. The portal is closed with fixed cross beam 6. Cylinders 8 are used to accommodate fully or partially the displaced weight.

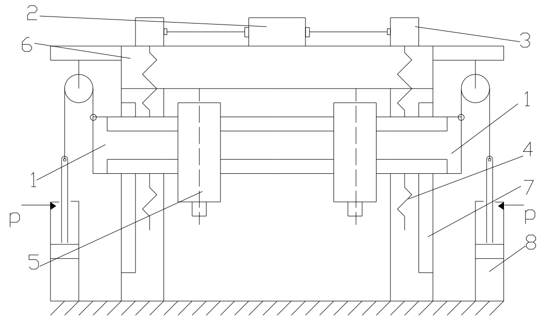


Fig. 1. Hydraulic balancing of mobile cross beams

Figure 2 shows the drive schematics for enclosure balancing.

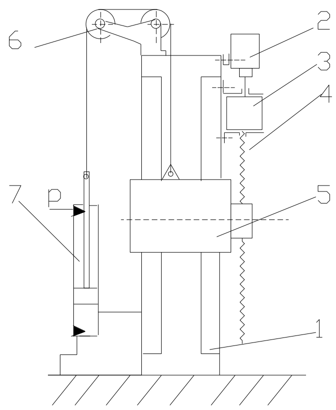


Fig. 2. Vertical displacement of hydraulically balanced loads

In figure 2 the following legend is used: 1 - prop with vertical guides, 3 - electric motor that drives the feed kinematic chain, 3 - feed box (reducing gears), 4 - feed screw, 5 - hydraulically balanced enclosure, 6 - sheaves and cables system, 7 - hydraulic cylinder. Enclosure 5 is displaced on guides of prop 1 by the feeding / positioning kinematic chain consisting of motor 2, reducing gears 3 and feed screw 4. For unloading the feed kinematic chain [5], enclosure 5 is balanced using the sheaves and cables systems 6, and cylinder 7.

The stationary force developed by each cylinder has the following expression (if losses are omitted):

$$F = p \cdot \frac{\pi \cdot (D^2 - d^2)}{4} \tag{1}$$

In equation above the following symbols are used: *D* - piston diameter, *d* - piston rod diameter, *p* - pressure in hydraulic system. Depending on each machine, the force developed by the cylinder may be lower than resisting forces (under-balancing) or higher (over-balancing).

In stationary conditions, the travel speed *v* dictated by the feed kinematic chain has the following expression:

$$v = n_{EM} \cdot i \cdot p_{BS} = \frac{4 \cdot Q}{\pi \cdot (D^2 - d^2)} \tag{2}$$

In (2) the following symbols are used: i - reducing gear's (feed box) transfer ratio, p_{BS} - lead of feed balls screw, Q - flowrate provided by the hydraulic balancing system.

2. Hydraulic balancing systems

Normally, for vertical feed kinematic chains, in case of enclosures, slides and even cross beams, if operating axes of CNC machine tools are involved [6], balancing systems with reducing valves, pressure regulating pumps or closed loop systems with accumulators are used [7]. All these systems involve expensive equipment and, given the operating schedule (full time), they raise equipment heating problems. Operating axes, controlled by the command system, must be actuated even in STOP stages, their position being maintained by elevation control read by transducer on the ruler. The hydraulic balancing installations used in such cases are under permanent stress, which requires special measures to mitigate heating.

These measures include [5, 7]:

- use of reducing valves, usually at lower loads;
- use of pressure-regulating variable flow pumps, an option that yields high quality results for affordable prices at pressures up to 100-150 bar for impeller pumps and up to 400 bar for axial piston pumps [8, 9];
- use of pneumo-hydraulic accumulator batteries, in which case the price is quite high and balancing is achieved with variable forces, depending on the position of displaced skid;
- use of complex, electro-hydraulic systems which involve the use of proportional hydraulic devices and/or electric power recovery systems. These systems are the most expensive and they are fit for very large machines.

In case of kinematic chains used exclusively for positioning, hydraulic balancing is not required to operate permanently. It is activated before each positioning and becomes usable only after the cross beam is unblocked and de-indexed [1].

3. Hydraulic balancing with variable flow pump and pressure regulator

The system in figure 3 is destined to feed the balancing cylinder of an existing machine-tool.

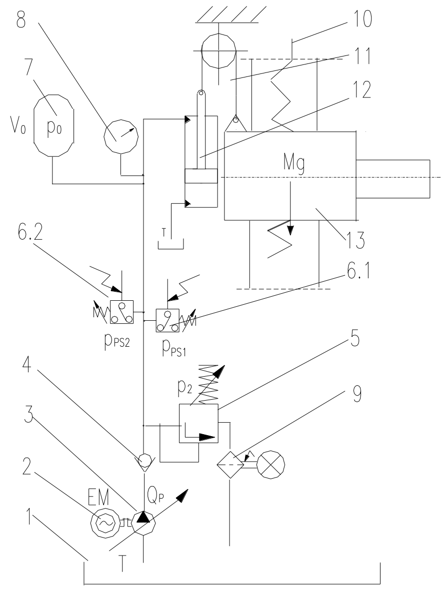
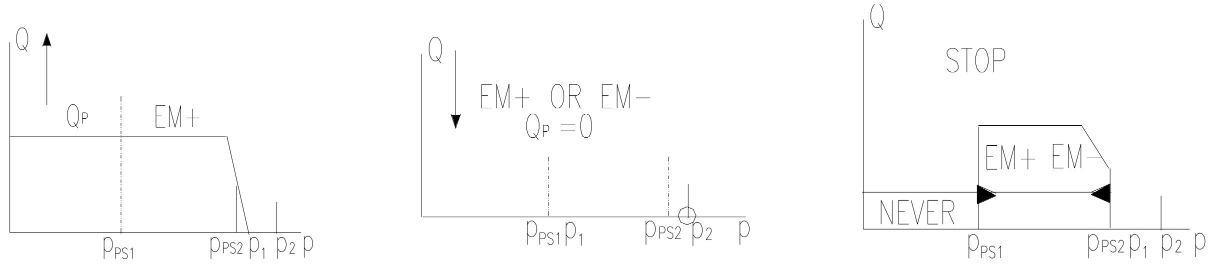


Fig. 3. Balancing system with variable flow pump

In figure 3 the following legend is used: 1 - tank, 2 - electric motor, 3 - variable flow pump, 4 - check valve, 5 - pressure valve, 6.1, 6.2 - pressure switches, 7 - accumulator, 8 - pressure gauge, 9 - filter, 10 - feed kinematic chain, 11 - sheaves system, 12 - hydraulic cylinder, 13 - mass balancing element M.

The variable flow pump 3, driven by the electric motor 2, sends oil to the balancing equipment from tank 1. Downstream from check valve 4, a pressure valve 5 is installed, set to a pressure higher that the pressure set on pump's regulator. Minimum and maximum balancing pressures are confirmed by the pressure switches 6.1 and 6.2. The accumulator 7, having the volume V_0 charged at pressure p_0, provides the flow peaks needed during startup phase [5]. Pressure gauge 8 allows reading the pressure. Return filter 9 provides oil purity. Cylinder 12, through the sheaves/cables system 11, discharges the feed kinematic chain 10 which displaces the enclosure 13 with mass M.

Operating features of the system that needs to provide the three stages, ascending, descending and STOP, are shown in figure 4.



a b c

Fig. 4. Operating features of balancing systems with variable flow pumps

In figure 4 the following legend is used: p - pressure, p_{PS1} - minimum balancing pressure, p_{PS2} - maximum balancing pressure, p_1 - pressure set on pump's regulator, p_2 - pressure set on pressure valve, Q - flowrate provided, EM - electric motor. In ascending stages, the maximum useful flowrate equals the maximum pump flow. In descending stages, check valve 4 closes and the pump supplies a very low flowrate, theoretically zero. In this case pressure is p_2. In STOP stages, in a correctly executed, zero-losses system, pressure is p_1 and the flowrate supplied by the pump is zero. The two pressure switches may actuate and stop the pump's motor when pressure drops. In this case the pump shall cover any possible losses. A pressure drop below p_{PS1} is a warning of a possible failure.

The system executed as per schematics in figure 3 is shown in figure 5, where the legend notations are maintained.

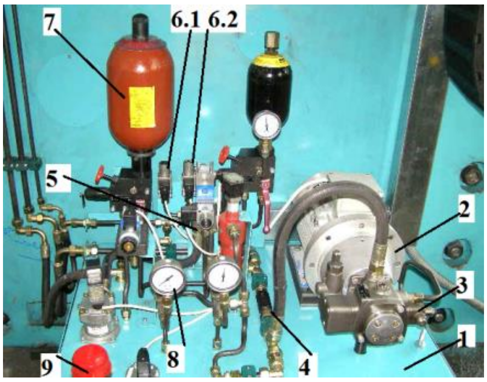
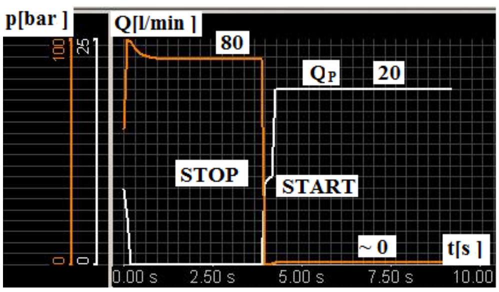


Fig. 5. Hydraulic balancing system with variable flow pump

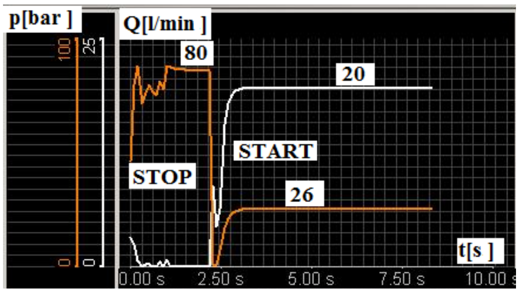
Maximum flowrate of pump is Q_P = 20 l/min. Set pressures have the following values: p_1 = 80 bar, p_2 = 90 bar, p_{PS1} = 70 bar, p_{PS2} = 75bar. The remaining elements in figure 5 are destined for performance of other hydraulic functions.

These installations are very frequently used in heavy machine tools [5]. Usually the pumps used are impeller pumps (up to 160 bar) or axial piston pumps (up to 400 bar). These are expensive pumps, produced by specialized manufacturers. In order to replace these pumps with simpler, gear pumps, which are also much less expensive, specific simulation software packages were used to analyze the dynamic behavior of balancing system shown in figure 3 [10]. In ascending stages, depending on the speed dictated by the feed kinematic chain, the system may supply flowrates between 0 and 20 l/min. Normally the maximum travel speed is limited to a value lower than the value corresponding to maximum flowrate.

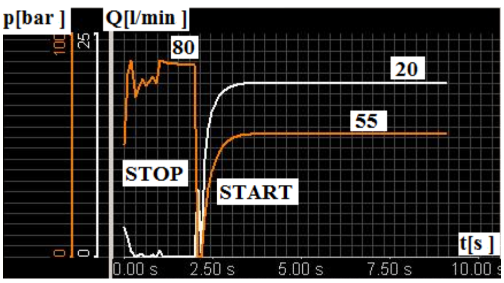
Next, a supposition is made as per (2), that the maximum achievable speed is of v = 10 m/min. In theory, at zero pressure, the flowrate supplied equals the maximum flowrate, like in figure 6a. This flowrate is usable up until pressure p_1 is reached, as set on the pump's regulator. Figures 6b and 6c show the operating features at 26 bar and at 55 bar.



a. p_1 = 80 bar, Q_P = 20 l/min, p = 0, v = 10m/min



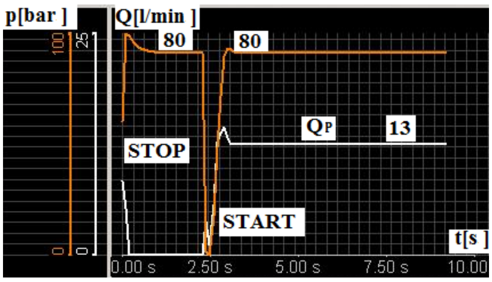
b. p_1 = 80 bar, Q_P = 20 l/min, p = 26 bar, v = 10 m/min



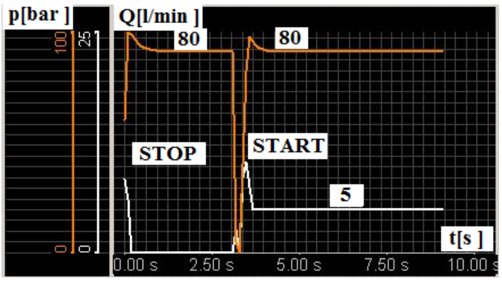
c. p_1 = 80 bar, Q_P = 20 l/min, p = 55 bar, v = 10 m/min

Fig. 6. Simulation of operational conditions of balancing systems with variable flow pump. Possible quick displacements

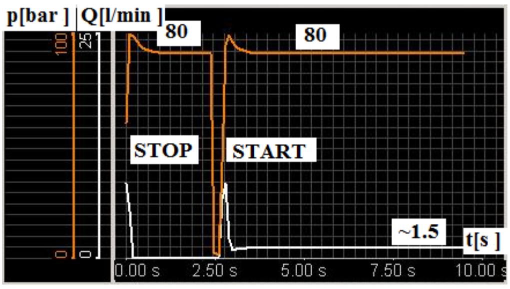
When the pressure set on regulator (p_1) is reached, the system reaches the operating phase of ascending stages. Figure 7 show the operating features for actual speeds dictated by the feed kinematic chain.



a. p_1 = 80 bar, Q = 13 l/min, p = 80 bar, v = 6500 mm/min



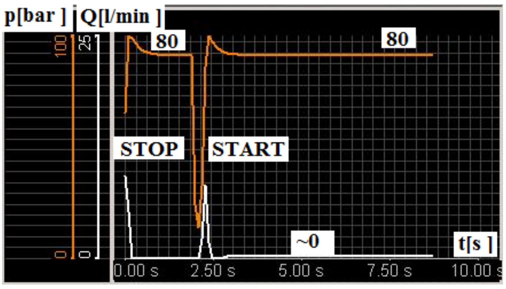
b. p_1 = 80 bar, Q = 5 l/min, p = 80 bar, v = 2500 mm/min



c. p_1 = 80 bar, Q = 1.5 l/min, p = 80 bar, v = 750 mm/min

Fig. 7. Simulation of operational conditions of balancing systems with variable flow pump. Quick displacements and ascending feed

The operating features of the system in descending and STOP stages are shown in figure 8.



p_1 = 80 bar, Q = 0 l/min, p = 80 bar

Fig. 8. Simulation of operational conditions of balancing systems with variable flow pump. Quick displacements and descending feed and the STOP stage

Based on simulations made, the flowrate / pressure function was drawn as shown in figure 9.

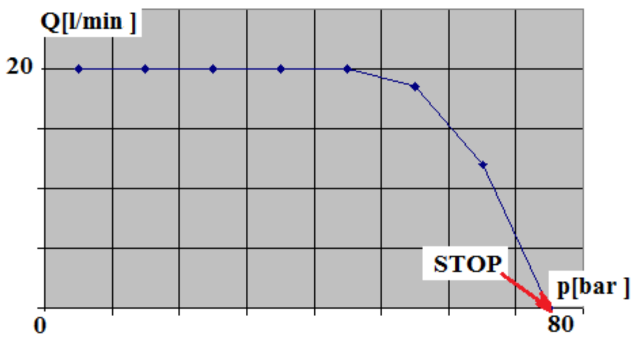


Fig. 9. Flowrate / pressure function of the balancing system using variable flow pump and pressure regulator.

4. Hydraulic balancing using constant flow pumps

The hydraulic system described below shall supply the same cylinder like the previous system, but it uses two constant flow pumps, which are normally gear pumps [4, 7, 9]. Hydraulic schematics is shown in figure 10.

In figure 10 the following legend is used: 1 - tank, 2 - suction filters, 3, 4 - constant flow pumps, 5 - electric driving motor, 6 - check valve, 7.1, 7.2 - pressure switches, 8 - hydraulic cylinder, 9 - accumulator, 10.1, 10.2 - pressure valves, 11 - hydraulic distributor, 12 - return filter, 13 - pressure gauge, 14 - sheaves system, 15 - feed kinematic chain.

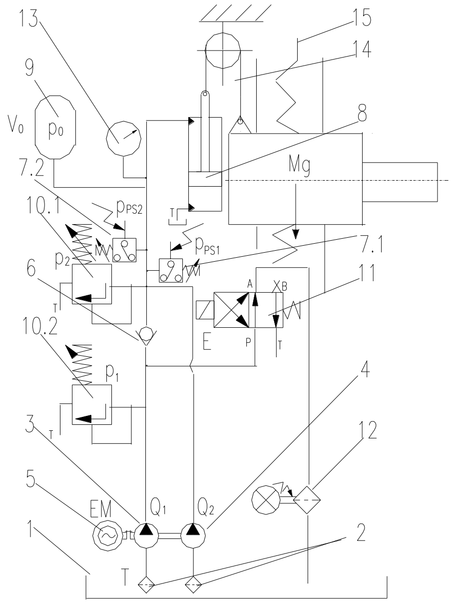


Fig. 10. Hydraulic schematics of balancing system using constant flow pumps

Pumps 3 (with flowrate Q_1) and 4 (with flowrate Q_2), driven by motor 5, take the oil from tank 1 and send it into the system through strainers 2. The high-rate pump 3 feeds the balancing circuit through check valve 6. The low-rate pump 4 feeds the balancing circuit directly. The pressure in balancing circuit is confirmed by the pressure switches 7.1 and 7.2. Maximum values of balancing pressure are adjusted using the pressure valves 10.1 and 10.2. It is recommended that p_2-$p_1 \geq$ 10 bar. The flow of larger pump 3 may be discharged back into the tank, without feeding the balancing circuit, through distributor 11. Maintenance of in-circuit pressure after shutdown of pumps is provided, in certain conditions [5, 7], by accumulator 9, which is supplied by the balancing circuit together with cylinder 8. When pump 3 discharges directly into the tank, oil is passed through the return filter 12. Pressure in the balancing circuit is read on pressure gauge 13. Cylinder 8 performs balancing of mass M using the sheaves system 14. Vertical travel is provided by feed kinematic chain 15.

Three operating phases may be noticed in the schematics above:

1. ASCENDING. The electric motor starts and, after relay 7.1 confirms that set pressure is achieved, voltage is applied to electromagnet E of distributor 11. The following condition must be checked:

$$Q_U = \pi \cdot \frac{D^2 - d^4}{4} \cdot v < Q_1 + Q_2 \tag{3}$$

In (3) the following legend was used: v - travel speed of cross beam, Q_U - necessary ascending flow.

The flow discharged through pressure valve 10.2 Q_{PV} is:

$$Q_{PV} = Q_1 + Q_2 - Q_U \tag{4}$$

The power loss in the ascending phase through the balancing system is:

$$P_{LU} = p \cdot Q_{PV} \tag{5}$$

2. STOP after ascension. In a first stage, voltage is removed from electromagnet E and then, if no positioning is performed next, motor 5 may be shut down. If pressure drops below the value set on relay 7.1, the motor is restarted until pressure set on pressure relay 7.2 is confirmed. Power loss in this phase is zero.

3. DESCENDING. To perform this phase, electric motor 5 is started and the system waits for pressure to be confirmed by pressure switch 7.2. In this stage electromagnet E is not actuated. If the travel speed is still v, the following may be considered:

$$Q_D = \pi \cdot \frac{D^2 - d^4}{4} \cdot v \quad (6)$$

$$Q_{PV} = Q_D + Q_2 \quad (7)$$

$$P_{LD} = p \cdot Q_{PV} \quad (8)$$

In equations above the following symbols are used: Q_D - flow necessary for descending, P_{LD} - power lost as heat. In this power only the element ΔP comes from the hydraulic system, where ΔP is:

$$\Delta P = p \cdot Q_2 \quad (9)$$

4. STOP after descending. If the required position is achieved, the positioning kinematic chain is shut down. The electric motor may be shut down.

In all these phases, accumulator 9 provides the peak flows for start-ups and maintenance of a certain volume of oil under pressure [7].

Operating features of the system that needs to provide the three stages, ascending, descending and STOP, are shown in figure 11.

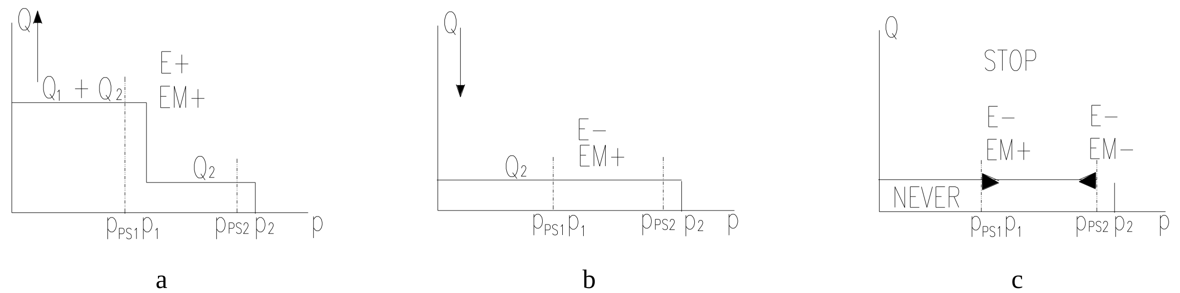


Fig. 11. Operating features of balancing systems with constant flow pumps

In figure 11 the following legend is used: p - pressure, p_{PS1} - minimum balancing pressure, p_{PS2} - maximum balancing pressure, p_1 - pressure set on pump's regulator, p_2 - pressure set on pressure valve, Q_1, Q_2 - flowrates supplied, E - distributor's electromagnet, EM - pump driving electric motor

The system executed as per schematics in figure 10 is shown in figure 12, where the legend notations are maintained.

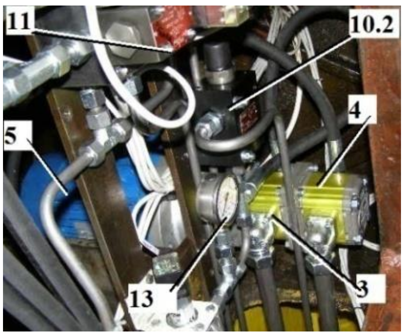


Fig. 12. Hydraulic balancing system with constant flow pumps

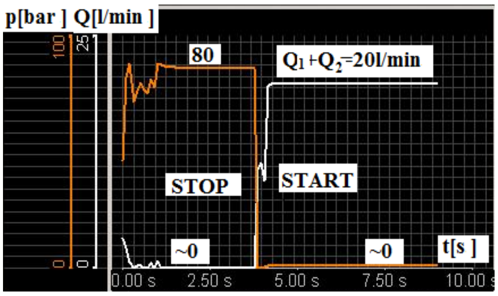
Maximum flowrate of the large pump is Q_1 = 14.5 l/min and of the small pump is Q_2 = 6 l/min. The set pressures have the following values: p_1 = 70 bar, p_2 = 80 bar, p_{PS1} = 65 bar, p_{PS2} = 75 bar.

In ascending stages, depending on the speed dictated by the feed kinematic chain, the system may supply flowrates between 0 and ~20 l/min delivered by pump 4 or both pumps.

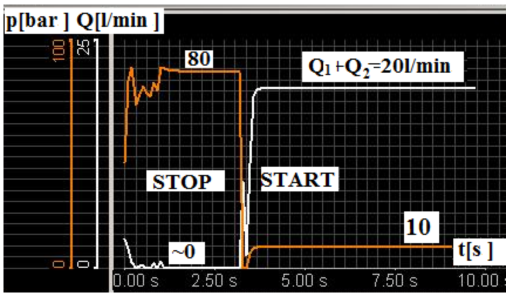
Next, a supposition is made as per equation (2), that the maximum achievable speed is of v = 10 m/min. It is considered that ascension is ordered after descending to 80 bar.

In theory, at zero pressure, the flowrate supplied equals the maximum flowrate, like in figure 13a. This flowrate is usable up until pressure p_1 is reached, as set on pressure valve 10.2.

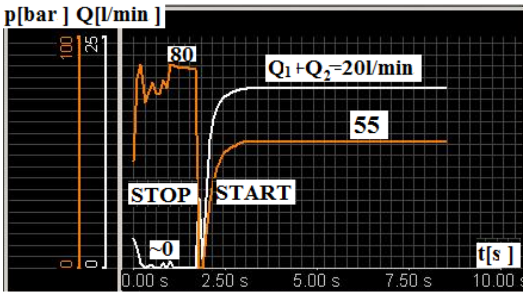
Figures 13b and 13c show the operating features at 10 bar and at 55 bar.



a. p_1=70 bar, p_2=80bar, Q_1+Q_2=20 l/min, p=0 bar, v=10 m/min



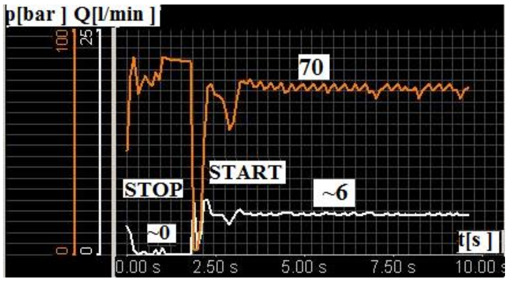
b. p_1=70 bar, p_2=80 bar, Q_1+Q_2=20 l/min, p=10 bar, v=10 m/min



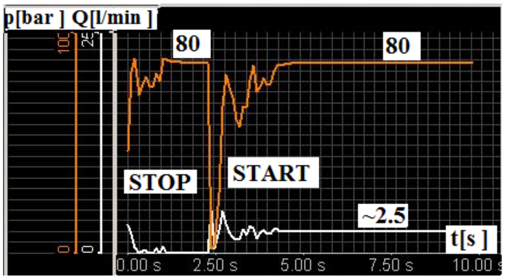
c. p_1=70 bar, p2=80 bar, Q_1+Q_2=20 l/min, p=55 bar, v=10 m/min

Fig. 13. Simulation of operational conditions of balancing systems with constant flow pump. Possible quick displacements in ascending phase

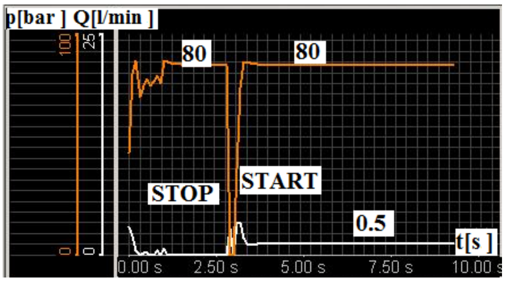
A correctly adjusted balancing system will operate in versions shown in figure 13 only for quick ascending displacements. When the pressure set on valve 10.2 (p_1) is reached, the system reaches the operating phase of ascending feed stages. Figure 14 show the operating features for actual speeds dictated by the feed kinematic chain.



a. p_1=70 bar, p_2=80bar, Q_2=6 l/min, p>p_1=70 bar, v=3000 mm/min



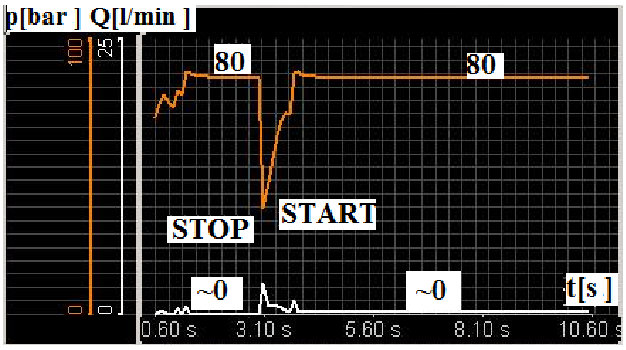
b. p_1=70 bar, p_2=80 bar, Q=2.5 l/min<Q_2, p=p_2=80 bar, v=1250mm/min



c. p_1=70 bar, p_2=80 bar, Q=0.5 l/min<Q_2, p= p_2=80 bar, v=250 mm/min.

Fig. 14. Simulation of operational conditions of balancing systems with constant flow pump. Quick displacements and ascending feed

The operating features of the system in descending and STOP stages are shown in figure 15.



p_1=70 bar, p_2=80 bar, Q=0, p=p_2=80 bar, v=0

Fig. 15. Simulation of operational conditions of balancing systems with constant flow pump. Quick displacements and descending feed and the STOP stage

Based on simulations made, the flowrate / pressure function was drawn as shown in figure 16.

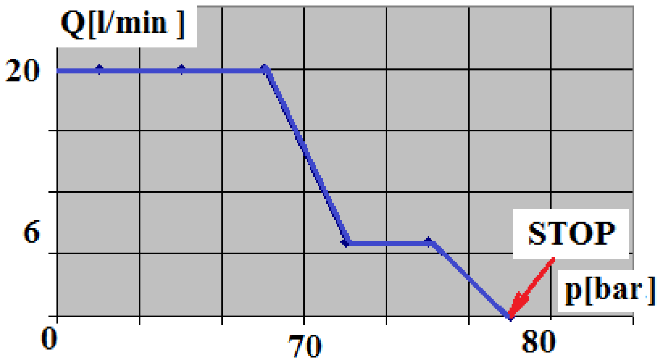


Fig. 16. Flowrate / pressure function of the balancing system using constant flow pump

In order to compare the two versions, it is considered that quick displacement of load has v = 8 m/min and feed displacement speed is of v = 100 mm/min, the balancing piston having a useful area of S = 20 cm^2. Comparative data is shown in tables 1 and 2.

	p [bar]	**Balanced load Ascending [daN]**	**Consumed power Ascending [kW]**	**Balanced load Descending [daN]**	**Consumed power Descending [kW]**	**Balanced load STOP [daN]**	**Consumed power STOP [kW]**
Variable flow pump	80	1600	2.4	1800	~0	1800	~0
Constant flow pump	65	1300	2.6	1600	max. 1	1600	0

Table 1. v = 8 m/min

	p [bar]	**Balanced load Ascending [daN]**	**Consumed power Ascending [kW]**	**Balanced load Descending [daN]**	**Consumed power Descending [kW]**	**Balanced load STOP [daN]**	**Consumed power STOP [kW]**
Variable flow pump	80	1600	0.1	1800	~0	1800	~0
Constant flow pump	80	1600	1.2	1600	max. 1	1600	0

Table 2. v = 100 mm/min

5. Conclusions

In case of positioning of high loads, in heavy machine tools, simple, inexpensive hydraulic systems may be installed which, if used infrequently, may replace the traditional balancing systems specific to feed kinematic chains.

Variable flow pumps are more expensive compared to constant flow pumps, but their use provides, among others, the following benefits: low noise levels, no other instruments necessary (valves, distributors, etc.).

The use of constant flow pumps increases system's power consumption, but provides, for slow feed speeds, a constant balancing force.

Opportunities for replacement of hydraulic system's components are better when using constant flow pumps, since the number of manufacturers is quite large.

In case the vertical displacement of load is performed only for positioning purpose and only rarely, like in the case of mobile cross beams of vertical lathes and heavy gantry machines, the use of constant flow pumps is preferred. In such case the load must be blocked after positioning. In this case, after blocking, the hydraulic system may perform other functions. The use of pneumo-hydraulic accumulators is recommended in this case too, as they improve system's viability.

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

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