Balancing the Vertical Feed Kinematic Chains by Means of Pressure Reducing Valves

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Abstract: *This paper presents the mathematical models necessary for the design of the hydraulically balanced vertical feed kinematic chains. The hydraulic balancing solution that uses constant flow pumps and 3-way pressure reducing valves is explained. The basic hydraulic diagram, the mathematical models in static and dynamic mode and examples of similar units are shown. There are also highlighted both the advantages and disadvantages of the hydraulic balancing systems.*

Keywords: *Machine-tools, hydraulic balancing systems, 3-way pressure reducing valves*

1. Introduction. Necessity of Balancing

In the case of heavy duty machine tools [1, 2], the vertical travel of masses (slides, rams, housings) requires the existence of appropriately sized kinematic chains. In most cases, these have the kinematic diagram shown in Figure 1.

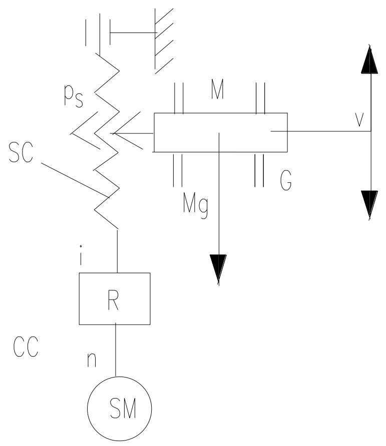


Fig. 1. Kinematic diagram of the vertical feed kinematic chain

The servomotor SM [1, 2, 3], actuated by the machine equipment, rotates the lead screw SC of pitch p_S, by means of the reducer R which has the transfer ratio *i*. The mass *M* is moved vertically on the guideways G. The electric motor rotates with the speed *n* and develops the instantaneous torque *T* for the total force *F* that includes weight *G*, force of inertia and forces of friction F_F. The instantaneous speed is *v*.
In the starting phase, it is considered that the acceleration is *a*, with the following value:

$$a = \frac{dv}{dt} \tag{1}$$

In these conditions, one can consider:

$$v = nip_S \tag{2}$$

$$T = \frac{iFp_S}{2\pi} \tag{3}$$

$$Ma + Mg + F_F = F \quad (4)$$

The feed kinematic chain is most stressed in the case of rapid upward movement. Therefore, this paper will focus on this case hereinafter.
The manufacturers of servomotors provide the data necessary for the calculation of these ones. Figure 2 presents the starting characteristic of such a servomotor [3].

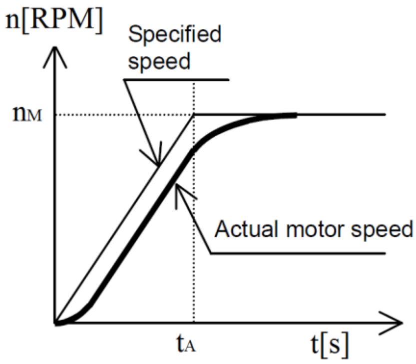


Fig. 2. Starting characteristic of a feed servomotor according to the catalogue of the manufacturer

In order to simulate numerically the realization of this characteristic, the following mathematical model is proposed, where the programmed rotational speed n_M is reached after the acceleration phase lasting t_A, with the ramp γ:

$$n = \begin{cases} \gamma t_A; t \leq t_A \\ n_M; t > t_A \end{cases} \quad (5)$$

In order to make a simulation, using the Matlab - Simulink package [4, 5, 6], a specific case was taken: a feed kinematic chain (Z axis) from the vertical lathes. In this case, the reference values are: M = 750 Kg, t_A = 0.2 s, n_M = 500 RPM, γ = 2500 RPM/s, i = 0.5, p_S = 10 mm.
Figure 3 shows the characteristic of the servomotor rotational speed.

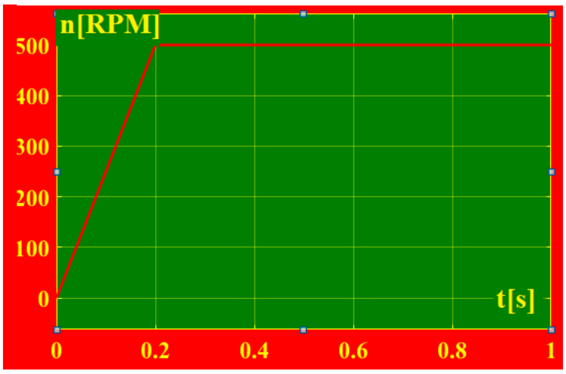


Fig. 3. The starting characteristic of the feed servomotor used in the simulation

Corresponding to this speed, the load increases with *v* speed according to the characteristic in Figure 4.
Mass *M* will move with a maximum speed of 2.5 m/minute which is the rapid moving speed for this type of machines.
The moment of force at the level of the electric motor will have the characteristic shown in Figure 5.
The torque developed by the servomotor in the acceleration phase is T = 6.12 Nm. After reaching the programmed value, it decreases to the value T = 6 Nm.
In this case, the dimensioning of the feed kinematic chain (CC) will be done taking into account these values. The weight of 7500 N, the forces of friction and inertia will be overcome by the electromechanical system.

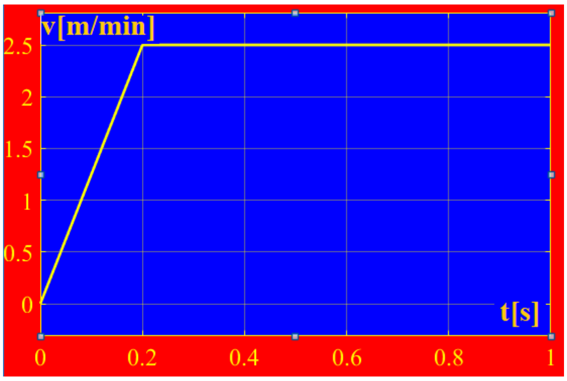


Fig. 4. Characteristic of the upward speed

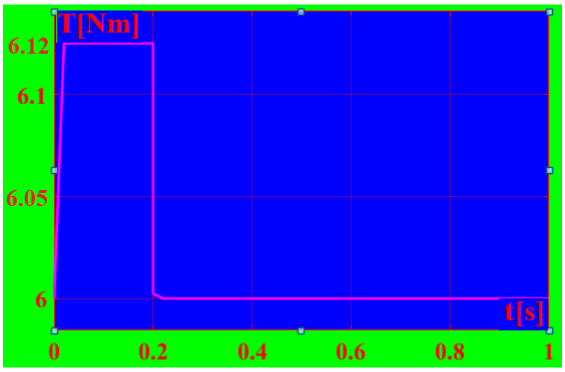


Fig. 5. Torque developed by the servomotor

2. Hydraulic Balancing of the Vertical Feed Kinematic Chain Using the Pressure Reducing Valves [7, 8]

The unloading of the feed kinematic chain is performed using a hydraulic system. The simplified diagram of this system is shown in Figure 6.

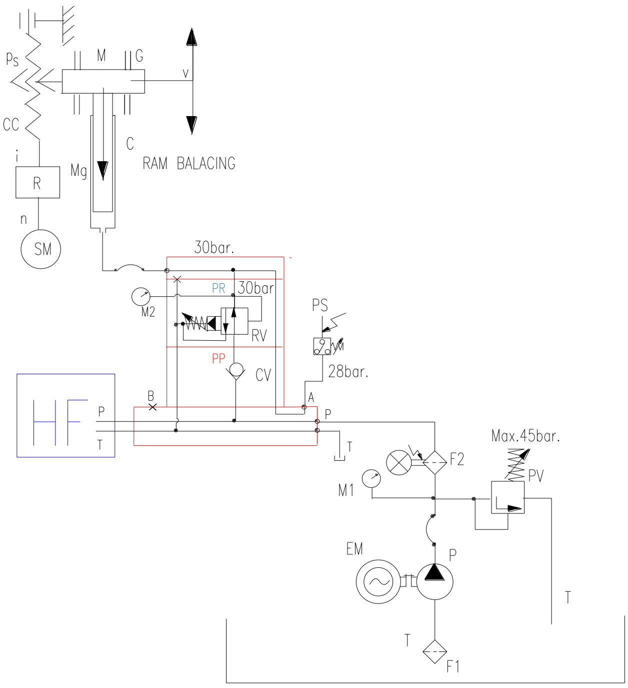
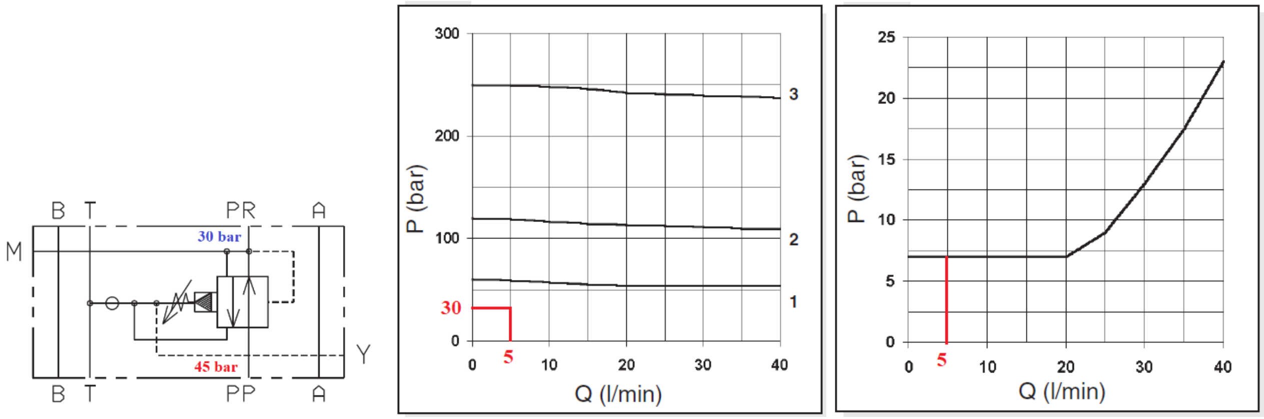


Fig. 6. Balancing hydraulic system with 3-way pressure reducing valve

The pump P is driven by the electric motor EM and sucks oil from the tank T through the suction filter F1. The maximum pressure in the system is regulated by the pressure relief valve PV. This pressure is viewed on the manometer M1. Oil is supplied to the balancing system through the F2 filter, then through the check valve CV and the pressure reducing valve RV [9]. The unit can also supply other consumers to perform other functions HF. The oil with reduced pressure supplies the cylinder C which, along with the feed kinematic chain CC, ensures the movement of the slide of mass M. The reduced pressure value [8, 9] is viewed on manometer M2. Pressure switch PS confirms the minimum working pressure presence. The figure shows too: PP – pressure at the pump and PR – reduced pressure.
The pressure reducing valve is chosen from the catalogue, depending on the intended flow rate and pressure. Figure 7 shows the defining elements for such a valve.



a. b. c.

Fig. 7. Characteristics of the pressure reducing valve

In the case of the chosen example, the required theoretical flow rate is 5 l/min at the reduced pressure of 30 bar. The pump pressure is 45 bar. The value of the pressure switch PS will be adjusted at 28 bar.
Figure 6a shows the detailed diagram of this valve which, if supplied at the pressure of 45 bar, ensures the flow rate of 5 l/min at the pressure of 30 bar. The chosen valve can work with a maximum flow rate of 40 l/min. The maximum pressure characteristic adjusted according to the flow rate for these valves is presented in Figure 6b. The minimum adjustable pressure at these valves is approximately 7 bar, as per Figure 6c.
The flow rate of the pump is chosen in such a way as to cover what is required by the balancing and the rest of the functions (HF), having a reserve of 10 ÷ 20%. Cylinder C has an active surface S = 20 cm^2.
In this case, the mathematical model for the entire actuation system, including the feed kinematic chain and the balancing hydraulic system, has the relations (1), (2), (3) and (5) to which will be added:

$$Ma + bv + Mg + F_F = p_R S + F \tag{6}$$

$$Q = Sv \tag{7}$$

$$Q_U = Q_S - Q \tag{8}$$

In the relations above it was also noted: *b* – the linearized coefficient of force losses proportional to speed (damping), *Q* – the flow rate supplied by the pressure reducing valve, Q_S – flow rate of the hydraulic source (pump and pressure relief valve), Q_U – the unused flow rate yet.
The characteristics of the rotational speed [RPM] and speed are the same as those in Figures 2 and Figure 3.
The torque required at the motor evolves as shown in Figure 8.

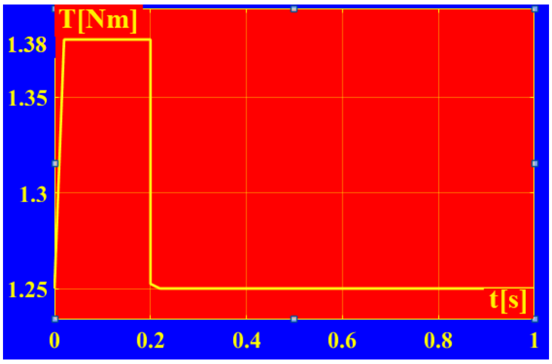


Fig. 8. Characteristic of the torque required for the motor in the case of hydraulic balancing

In the acceleration phase, the torque is T = 1.4 Nm. After reaching the programmed value, the torque decreases up to the value T = 1.25 Nm.
In this case, the dimensioning of the feed kinematic chain (CC) will be done taking into account these values, much reduced compared to the actuation without balancing system. The weight of 7500 N, the forces of friction and inertia will be overcome by the electromechanical system together with the hydraulic one.
For a pump that provides a constant flow rate [10, 11] of 9 l/min, the hydraulic unit can also supply other consumers as long as the sum of these ones, according to Figure 9, does not require a theoretical flow rate higher than 4 l/min in static mode.

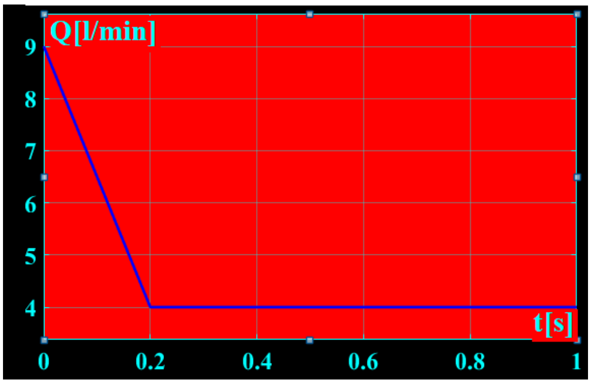


Fig. 9. Flow rate available for other functions

In these machines, by actuating the feed kinematic chain during the travel phase on Z axis [1, 2], other functions are no longer performed, as a rule. So, theoretically, the available flow rate is 4 l/min.
But the manufacturer of the pressure reducing valves mentions that these ones drain a flow in the range of 0.5 ÷ 0.7 l/min. In practice, the checking of flow rate is done taking into account other losses too, as shown below.
The flow rate of the pump is 9 l/min theoretically, but a safety margin of 15% is considered. So, in reality, the total usable flow rate is 0.85 x 9 = 7.65 l/min. If the losses through the draining of the pressure reducing valve are considered to be 0.65 l/min, it means that 7l/min are available in the entire unit. An amount of 5 l/min from the available amount are used for the rapid travels. Thus, during these phases, the flow rate available for other functions is 2 l/min.
The appropriate choice of pump flow rate is very important. A flow rate that is too low will not allow the necessary work phases, which will lead to improper balancing and therefore poor operation. A flow that is too high can entail the excessive heating of the unit by spilling the surplus through the pressure relief valve PV.
The balancing function is a permanent one. Therefore, it is activated when the pump motor is started and it is deactivated when the motor is turned off.

Comparing the characteristics of the servomotor torque in the feed kinematic chain in Figures 4 and Figure 7, the fact that the hydraulic system "helps" the electromechanical system becomes obvious.
Under these conditions, the feed kinematic chain (servomotor, reducer, ball screw) will be dimensioned accordingly. The elements of the feed kinematic chain will be less stressed, which leads to the choice of a servomotor and reducer for lower powers. The lead screw will be more flexible, with a smaller diameter. These facts result also in the diminution of the expenses for this kinematic chain. On the other hand, one must also take into account the expenses incurred for the making of the hydraulic unit, which does not exist in the case of the unbalanced systems.

3. Balancing the Rams of the Vertical Lathes

The balancing solution presented above is used in some vertical lathes whose ram does not exceed 1000 Kg and which have rapid travel speed lower than 3 m/min. Exceeding these values leads to the oversizing of the pumps and driving motors and implicitly to the increase of the lost power.
Figure 10 shows a SC 33 vertical lathe with two counterbalanced rams, each one with a pressure reducing valve.

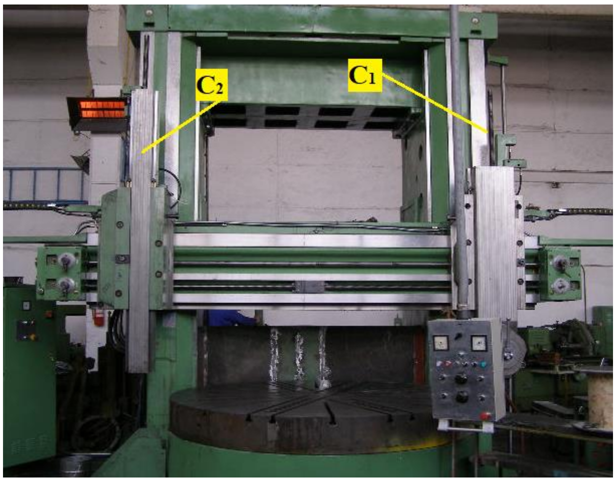


Fig. 10. Vertical lathe with two rams

Each one of the rams C_1 and C_2, together with the associated tool-holders, do not exceed the mass of 1000 Kg. Their maximum speeds are 2.5 m/min. The balancing pressure is adjusted in the range of 30 ÷ 35 bar. The maximum pressure set at the pump is 45 ÷ 50 bar. The pump provides a theoretical flow rate of 16 l/min. The driving electric motor of this one has the power P_{EM} = 2.2 KW.
The assembling shown in Figure 11 was made for balancing the two rams.

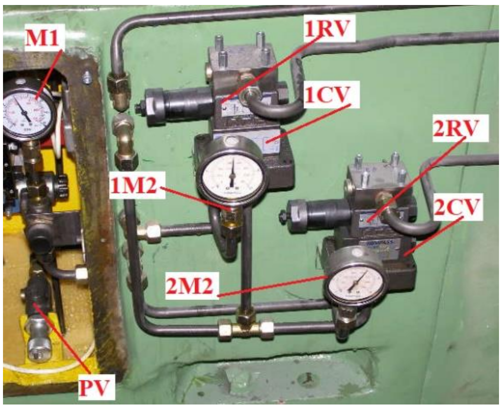


Fig. 11. Hydraulic unit for balancing the two rams of the SC 33 vertical lathe

The maximum pressure in the entire unit is regulated by means of the pressure relief valve PV. This pressure is viewed on the manometer M1. The pressure reducing valves 1RV and 2RV assembled on the check valves 1CV and 2CV, as shown in the diagram in Figure 5, are intended for the independent regulation of the two reduced pressures. These pressures can be read using the manometers 1M2 and 2M2. The adjustment of the balancing pressures is done for each feed kinematic chain independently, so that their servomotors do not detect torque differences greater than 10 ÷ 15% when ascending or descending.

4. Conclusions

The feed kinematic chains that operate vertically can be unloaded by means of the hydraulic balancing systems that use pressure reducing valves. They have the great advantage that they ensure balancing at constant pressure regardless of the direction of travel and the position of the balanced mass.

The pressure reducing valves are chosen depending on the required flow rate and pressure, according to the documentation of the manufacturer. In the case of using constant flow rate pumps, it is recommended to limit the values of pressure and flow rate so that the excessive heating of the unit be avoided.

For a good dimensioning of the elements of the kinematic chain, the balancing unit will ensure obtaining the required maximum speeds. A hydraulic balancing unit can serve several feed kinematic chains because it can be adjusted for each optimal balancing pressure.

The specialized programs, such as Matlab - Simulink and Automation Studio, allow solving the mathematical models specific to these systems.

In the case of the vertical lathes where the rapid travel speeds are lower than 3 m/min and the rail heads do no exceed the mass of 1 tone, the balancing systems with pressure reducing valves represent a functional and reliable solution with an acceptable price.

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