Modeling and Simulating the Operation of the Hydraulic Tool Holder Tightening/Releasing Systems Served by Accumulators

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Abstract: *In this paper, the authors present the theoretical research, the mathematical models, and also the results of the research carried out during the production of turning tool holder tightening/releasing systems used in vertical lathes. These mechanical-hydraulic systems are typically used for vertical lathes in the SC12 - SC43 range. The work is intended to create a mathematical model that will enable these systems to be more reliable and efficient. Some results of the simulation of system operation are also presented.*

Keywords: *Hydraulic systems with accumulator, tool holder tightening/releasing systems, machine-tools*

1. Presentation of the Installation

Vertical lathes [1, 2] are intended for metalworking in the presence of high-value machining forces and torques. The tool holders of these machines must ensure accurate positioning and high rigidity.
As a rule, the tool holders are tightened mechanically using a disc spring [1, 2]. To increase the tightening forces and the rigidity and reliability of the systems, mechanical tightening can be supplemented by hydraulic tightening. As a rule, tool holders are loosened hydraulically.
The pressures required to achieve the tightening forces are maintained by hydro-pneumatic accumulators. They are filled with nitrogen at a pressure determined by the requirements of the installation. During the various stages of work, the gas undergoes isotherm or adiabatic transformations [3, 4, 5, 6, 7, 8].
Hydro-pneumatic accumulators, apart from being additional energy sources, can also ensure increased operational safety, can take over thermal oil expansion, etc. [3, 4, 7, 9].
Figure 1 shows the hydraulic diagram of a tool holder tightening/releasing unit used for vertical lathes. The figure only shows this system, but the hydraulic source also serves other consumers: the indexing/unindexing system of the crossbar, the locking/unlocking system of the crossbar etc.
The constant flow pump P is driven by the EM electric motor and sucks oil through the F_1 filter from the T tank. The oil purity (10 μm) is ensured by the F_2 filter.
During operation, the pressure in the main circuit is displayed on the M_1 pressure gauge. The maximum pressure (p_M) is adjusted by means of the pressure valve PV.
By operating the S_1 electromagnet from the directional valve D_1, it is ensured that the pressure source (pump and pressure valve) is connected to the supply circuit of the tightening/release cylinder of the C tool holder.
The tool holder is tightened using the SK disc spring system and the pressure provided on the S_2 surface on path A. If pressure oil is supplied on path B, the force developed by it on the S_1 surface compresses the SK springs, thus achieving the release. Such positions of the C cylinder rod are confirmed by the L_1 and L_2 thrusts. On path A of the D_2 directional valve there are the PS_1 and PS_2 pressure switches set at pressures p_1 and p_2. Pressure p_1 is the minimum pressure that ensures tightening and pressure p_2 is the maximum pressure in this circuit.
Also here there is the V_0 volume Ac accumulator, initially filled with nitrogen at pressure p_0. The circuit with accumulator is sealed by the hydraulic pilot operated check valve HPOCV [5]. By operating the S_2 electromagnet, the D_2 directional valve releases the tool holder. In this case, pressure is sensed by the PS_3 pressure switch. It is adjusted at p_3 pressure. The pressure in the accumulator circuit is displayed using the M_2 gauge.
The above pressures shall observe the following conditions: $p_0 < p_1 < p_2 < p_M$ and $p_3 < p_M$.

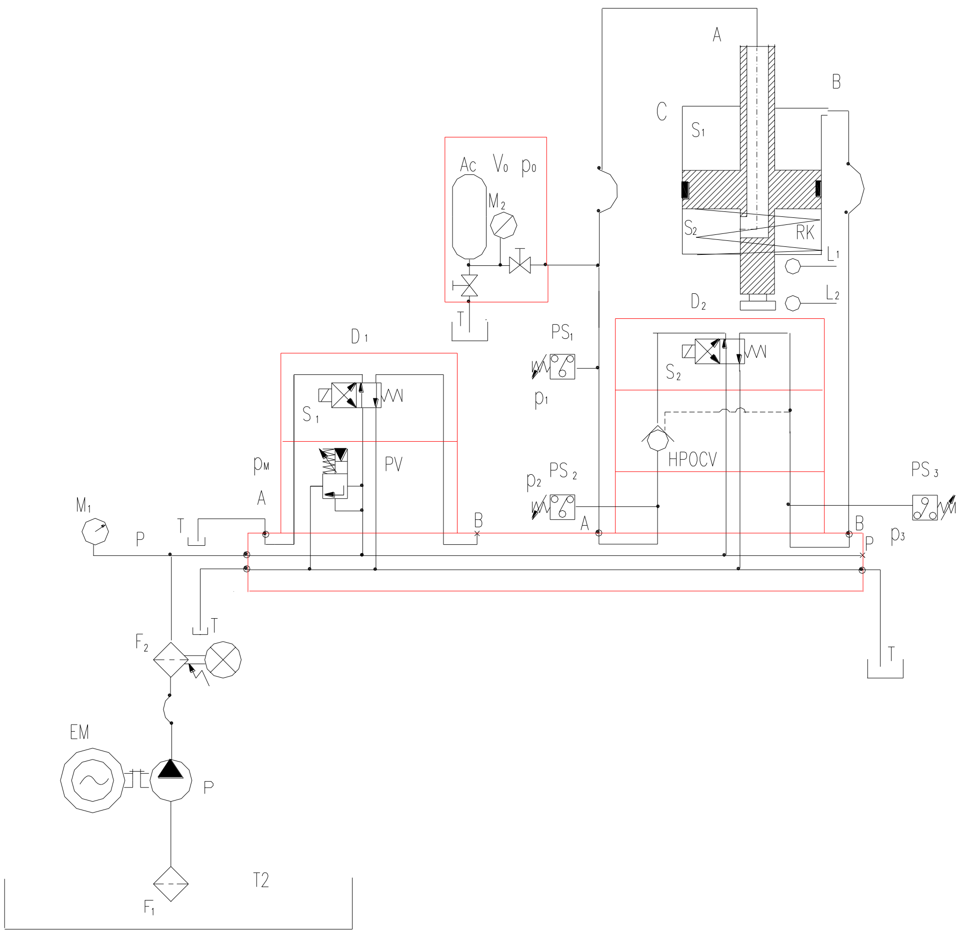

Fig. 1. The simplified hydraulic diagram of the tool holder tightening/releasing system

The operation of the installation shown in the diagram in Figure 1 is summarized in Table 1.

Table 1: The operation of the installation

	EM	S_1	S_2	PS_1	PS_2	PS_3	L_1	L_2	M_1	M_2
STOP	-	-	-				+	-	0	0 - p_2
Pump START	+	-	-				+	-	0	0 - p_2
Initial charge	+	+	-	+	+	-	+	-	p_2	p_2
Tool holder release	+	+	+	-	-	+	-	+	p_3	0
Tool holder tightening	+	+	-	+	+	-	+	-	p_2	p_2
Machine ON	+	-	-	+	+ → -	-	+	-	0	p_1 - p_2

The accumulator Ac provides proper operation, safety and reliability of the installation.
Figure 2 shows how the equipment in Figure 1 is placed on the machine, keeping the same notations.
In a lossless, properly executed and operated installation, the accumulator maintains the pressure required to tighten the tool holder as long as the tightened tool carrier is engaged in the desired cutting process.
If, however, over time, fluid is lost in the accumulator circuit, the system consisting of pump P, pressure valve PV and pressure switches PS_1 and PS_2 ensures, within certain limits, that the circuit of the accumulator on the path of the D_2 directional valve is refilled.

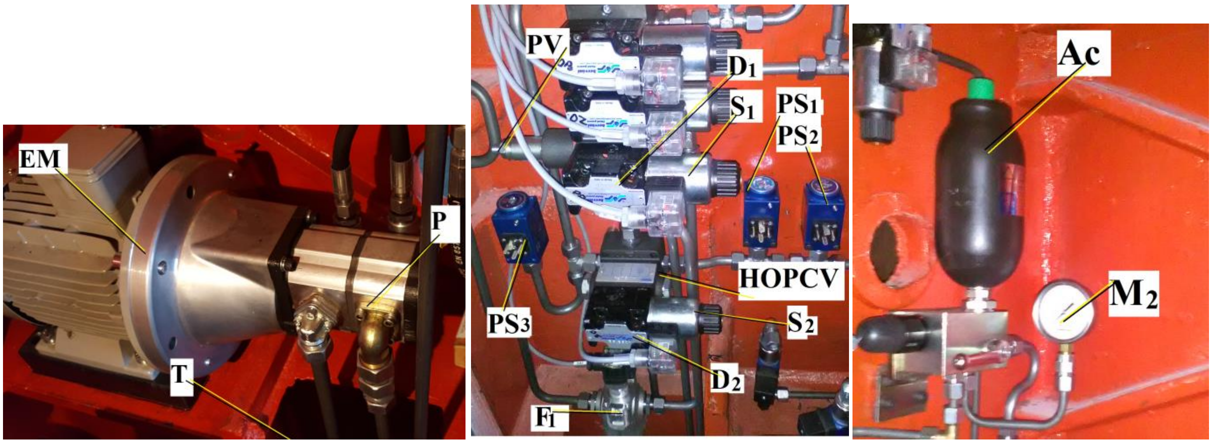

Fig. 2. The placement of the hydraulic equipment on the machine

2. Proposed Mathematical Models

The elementary source [6] consisting of pump P and pressure valve PV supplies a Q flow to the installation only when electromagnet S_1 of the D_1 directional valve is driven. The dependence of this pressure flow displayed on the M_1 pressure gauge is shown in Figure 3.

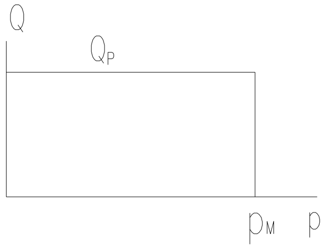

Fig. 3. The characteristic of the elementary source

The tool holder is tightened and released and the accumulator circuit is charged according to Table 1.
Under these conditions, the accumulator can be in the following situations:

a. initial charge or after the tool holder release command;
b. discharge of the accumulator due to accidental leakage through seals;
c. charging during tightening the tool holder to cover losses from the previous point;
d. discharge of the accumulator during the tool holder release phase.

a. Initial charging (when starting the machine) or after the tool holder release command

The source is considered to release liquid at pressure p_M. It enters the accumulator where gas is present, initially at pressure p_0, so as, finally, the PS_2 pressure switch commands the charge to stop when the pressure p_2 is reached. The accumulator pressure shall be considered to have a constant value equal to the average of the two. The flow rate discharged depends on the characteristics of the circuit portion and on the oil density [5, 6]. All these constants for the charging circuit shall be noted with K_1. The constant of the discharge circuit is defined in a similar way and will be noted with K_2. The constant of the circuit where losses occur shall be noted as K_3.
The charge diagram in this first case is shown in Figure 4.
During charging, losses are considered negligible.
The liquid volume sent to the accumulator ΔV_1 is:

$$\Delta V_1 = V_0\left(1-\frac{p_0}{p_2}\right) \tag{1}$$

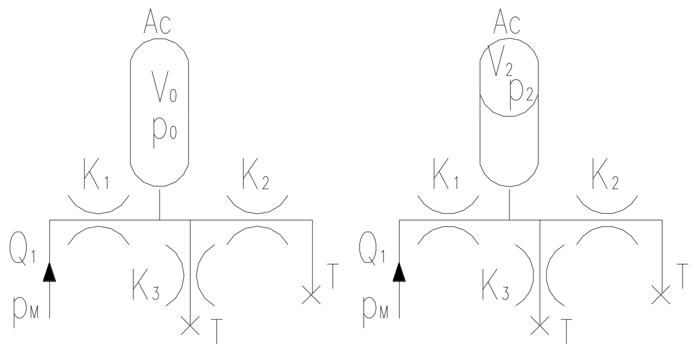

Fig. 4. Initial charge diagram

The charging time can be determined with the relation:

$$t_1 = \frac{\Delta V_1}{K_1\sqrt{p_M - \frac{p_0+p_2}{2}}} \tag{2}$$

The Q_1 flow intended to charge the accumulator results from the pump flow. The difference between them is discharged via the PV pressure valve.

b. Discharge of the accumulator due to losses

Broadly, this situation is shown in Figure 5.

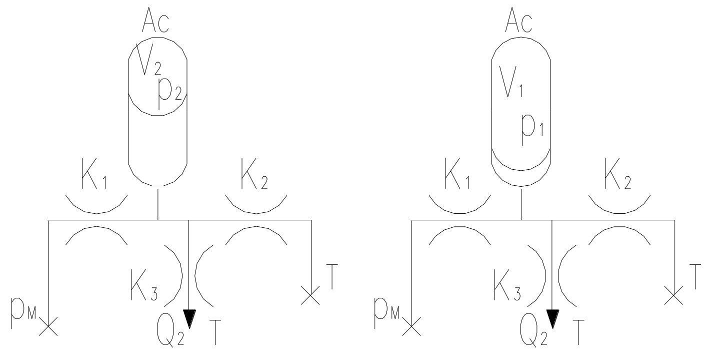

Fig. 5. Discharge diagram due to losses

Oil leaks occur from pressure p_2 until pressure p_1 is reached, which is indicated by the pressure switch PS_1 giving the recharge command.

The lost liquid volume is:

$$\Delta V_2 = \frac{p_0 V_0 (p_2 - p_1)}{p_1 p_2} \tag{3}$$

The time of discharge from pressure p_2 to pressure p_1 has the relation:

$$t_2 = \frac{p_0 V_0 (p_2 - p_1)}{p_1 p_2 K_3 \sqrt{\frac{p_1+p_2}{2}}} \tag{4}$$

The lost flow Q_2 goes to the T tank. At this stage, the pump discharges directly to the tank on the P-A path of the D_1 directional valve.

c. Charging during tightening the tool holder to cover losses from the previous point

For the installation to be effective, this phase should last as short as possible. The charge from pressure p_1 to pressure p_2 must be carried out within a few seconds. Otherwise, the pump will operate at p_M pressure, resulting in high energy consumption, noise and heating of the installation.

For these reasons, in the calculation scheme, shown in Figure 6, the charging is considered to be adiabatic, the adiabatic nitrogen coefficient being γ = 1.4 [3, 4, 5, 8].

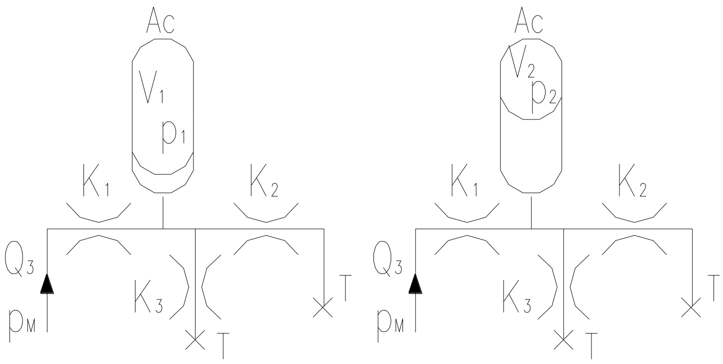

Fig. 6. Charging diagram to cover losses

During charging, a Q_3 flow from the p_M source pressure shall be considered to be sent to the accumulator. The pressure in the accumulator shall be assumed to be constant and equal to the average of the pressures p_1 and p_2.
In this case, the volume of oil sent to the accumulator ΔV_3 will be:

$$\Delta V_3 = \frac{p_0 V_0}{p_1}\left[1 - \left(\frac{p_1}{p_2}\right)^{\frac{1}{\gamma}}\right] \quad (5)$$

The charging time is:

$$t_3 = \frac{\frac{p_0 V_0}{p_1}\left[1 - \left(\frac{p_1}{p_2}\right)^{\frac{1}{\gamma}}\right]}{K_1\sqrt{p_M - \frac{p_1+p_2}{2}}} \quad (6)$$

d. Discharge of the accumulator during the tool holder release phase
In this phase, the directional valves D_1 and D_2 are activated simultaneously. The HPOCV valve opens and the accumulator discharges directly to the tank. The discharge diagram is shown in Figure 7.

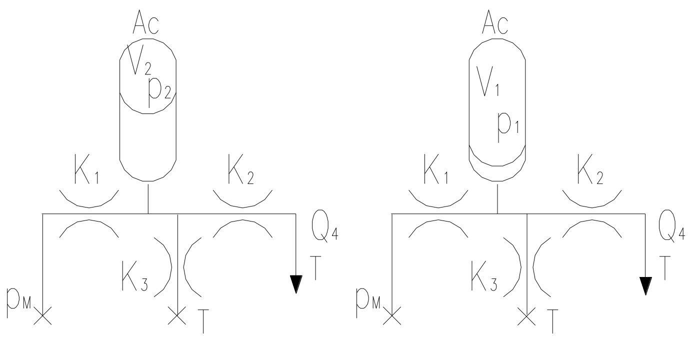

Fig. 7. The discharge diagram of the accumulator in the tool holder release phase

The volume discharged is the one in the relation (3).
The Q_4 flow rate shall be discharged directly to the tank at a t_4 time according to the relation:

$$t_4 = \frac{p_0 V_0 (p_2 - p_1)}{p_1 p_2 K_2 \sqrt{\frac{p_1+p_2}{2}}} \quad (7)$$

The accumulator becomes effective if charging to cover losses is very fast, namely adiabatic. During the remaining phases, the nitrogen in the accumulator can be considered to undergo isothermal changes. The efficiency of the accumulator in these conditions depends on the pump capacity and also on the type and size of the losses.

3. The Simulation of the Operation of the Tool Holder Tightening/Releasing System [10]

The mathematical models presented above allow a theoretical study to be carried out of the influence of the different parameters of the installation on its static operation, after certain simplifications and linearization. It has also been assumed that, when developing such models, losses are negligible during the charging phases of the circuit, which is not actually happening.
Simulation methods may be used for a more detailed study. They can take into account several variable parameters and give information on both static and dynamic behavior of the system.
For example, for the system shown in the hydraulic diagram in Figure 1, the following parameters were considered: minimum pressure (regulated at PS_1 pressure switch) p_1 = 50 bar, maximum pressure (regulated at PS_2 pressure switch) p_2 = 60 bar, maximum working pressure (regulated at PV pressure valve) p_M = 65 bar, the displacement of the pump is 4 cm^3 and is driven by an electric motor with a rated speed of 1500 rpm, the accumulator has a volume of V_0 = 2.5 l and is initially charged with nitrogen at pressure p_0 = 45 bar.
If the system is free of leakage, its initial charging shall be carried out as shown in Figure 8.

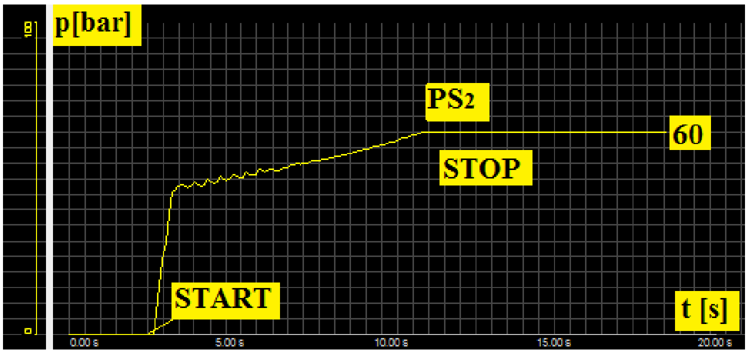

Fig. 8. The characteristic of charging the ideal circuit, loss free

It can be noted that after approximately 11 s the circuit is filled to the pressure p_2 = 60 bar. Charge stopping is controlled by the pressure switch PS_2. Under these conditions, as there are no losses, the pressure is preserved in the accumulator circuit until the tool holder is commanded to release.
For the same parameters, it is then considered that there are circuit losses with an average value of ΔQ = 1 l/min.
The amount of such losses, as seen in Figure 9, is variable. The pump refills the circuit after every delay of approximately 15 s.

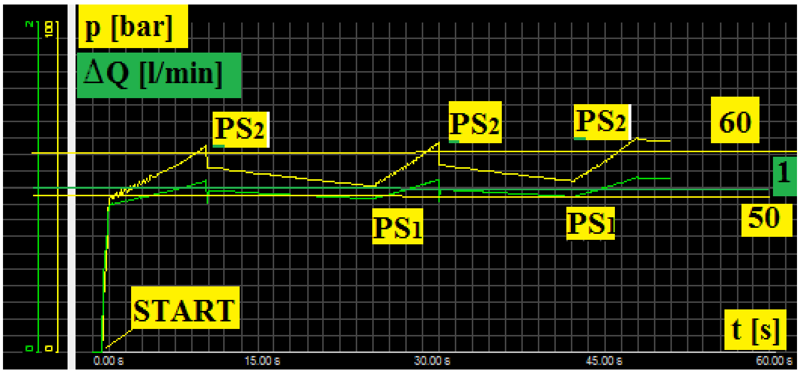

Fig. 9. The circuit charge/discharge characteristic with losses of approximately 1 l/min

The pressure switch PS_2 commands the coupling of the S_1 electromagnet from the directional valve D_1, and the pressure switch SP_1 commands it to be decoupled. If the circuit holds 15 s, the charging lasts for approximately 6 s.
If the losses are higher, e.g., ΔQ ~ 3 l/min, the operating mode of the installation is observed in Figure 10.

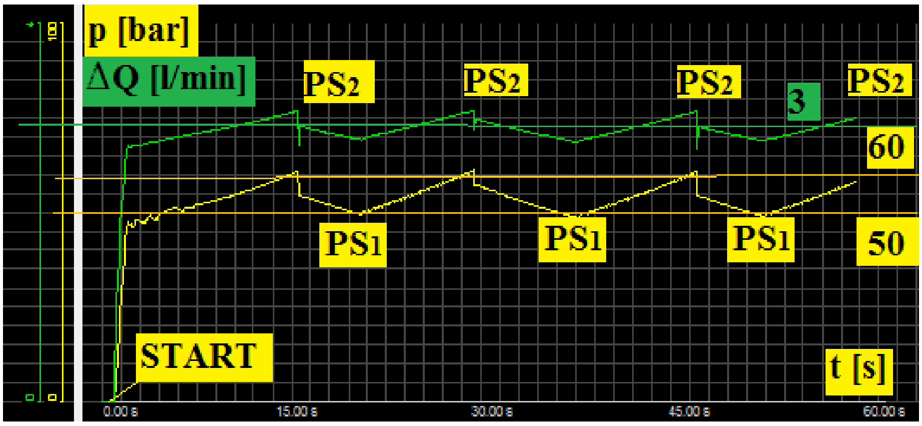

Fig. 10. The circuit charge/discharge characteristic with losses of approximately 3 l/min

In this case, the pressure is maintained only for 6 s after which, for approximately 12 s, it is necessary to couple the S_1 electromagnet. In this case, the pre-control system (i.e., the PV pressure valve and the D_1 directional valve in Figure 1) provided becomes unusable. If the installation is operating under these conditions, the causes of the losses shall be removed.

4. Conclusions

The hydraulic systems designed to tighten and release the tool holders of the machine-tools require high pressure forces. This pressure can be maintained with hydro-pneumatic accumulators. Within certain limits of pressure variations, these accumulators ensure that the systems function properly.
It is recommended that pressure sources include pre-control systems which engage at the minimum pressure and disengage at the maximum pressure required to tighten the tool holder. The pressure source shall be adjusted at a pressure above the maximum pressure required for tightening.
Pressure monitoring can be done discreetly, using pressure switches or continuously, using pressure transducers.
If fluid leaks occur over time, they can be covered by the pressure source - accumulator system. This can be done within certain limits, depending on the loss rate, pump capacity, accumulator capacity and working pressure range.
For a better choice of equipment and design of the installation, it is recommended that simulation methods should also be used before it is carried out.

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