Imitating modeling results of a recuperative hydraulic subsystem of the timber truck manipulator

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Abstract. The relevance of improving the efficiency of a timber truck used for timber transportation due to the use of a recuperative hydraulic drive in its design is substantiated. The analysis is made of the use of recuperative hydraulic drives of technological machines with mechanisms for the recovery of kinetic energy of rotation and potential energy of lowering the load. A mathematical and, based on it, simulation model has been developed for the hydraulic subsystem of the manipulator of a timber truck, including mechanisms of boom, handle and column recuperation that have also been developed. Dependencies are obtained that make it possible to determine the maximum amount of recuperated energy for one loading cycle by changing the volume of the pneumohydraulic accumulator, the height of the assortment, and the time of one loading cycle.

1. Introduction

The Russian Federation, due to its area and climate, has the largest renewable forest resources, which are the basis for the development of the timber industry. Timber removal by timber trucks is one of the most expensive technological operations in the production process of timber harvesting. The performance of timber trucks equipped with hydraulic manipulators of energy-intensive technological operations in difficult operating conditions of logging leads to a significant deterioration in their work. When loading and unloading assortments with a hydraulic manipulator during the rotation of the column, lowering the boom and the handle with the load, a locked flow of working fluid is created in their hydraulic cylinders. This flow of working fluid increases pressure and creates additional resistance in the hydraulic manipulator. This leads to inefficient use of the energy expended, since part of the kinetic energy of the rotation of the column and the potential energy of the boom and handle with the load is converted into heat and dissipated. A promising way to increase the efficiency of timber trucks under these operating conditions is the accumulation and reuse of these energy losses in hydraulic energy recuperation devices [1].

Baoyu Cao [2] and Debattta Das [3] in their works present promising schemes of hybrid recuperative hydraulic drives used in the construction of excavators. They allow you to convert excess hydraulic energy generated in hydraulic drives into electrical energy with its further accumulation in rechargeable batteries. Lei Ge [4] describes in his research the functioning of a recuperative control system for an excavator boom which allows accumulating hydraulic energy while lowering a boom with a load and then use it when lifting. This reduces the expended power of the drive motor and increases the efficiency of the process. M. Hekkila and M. Linjama [5] conducted a study based on simulation aimed at reducing the power of the primary engine of the excavator, which consisted in...
using a pneumohydraulic accumulator in its hydraulic drive, which allowed to accumulate the potential energy of the mass of the excavator boom when lowering it. Yunxiao Hao’s article [6] describes the recuperative hydraulic system of a GPER excavator with an HPES hydraulic cylinder. Based on the experiments, it is revealed that when the excavator is working, the recuperative hydraulic boom drive allows you to restore about 43.9 % of the energy. Lianpeng Xia [7] in his studies proposes to use a recuperative hydraulic drive to improve the energy efficiency of the excavator, which allows you to convert the potential energy of the boom when it is lowered into the hydraulic energy stored in the pneumohydraulic accumulator. Using the proposed recuperative hydraulic drive can reduce energy consumption by 50.1 %.

L. D. Bukhtoyarov [8] in his studies presents a simulation model of the operation of a manipulator with a damping device in the hydraulic system, which allows determining the time dependences in the main elements of the hydraulic system using the given parameters of the manipulator, damper, operating modes and operating conditions. The work by P. I. Popikov [9] presents a mathematical model of damping the working process of the hydraulic drive of the rotation mechanism of the column of the hydraulic manipulator, taking into account the calculation of the accumulation of hydraulic energy in the recuperative mechanism of rotation of the column. The above models in [8, 9] do not allow for the calculation and study of dependencies while the recuperative mechanisms of the column, boom, and handle of the hydraulic manipulator are functioning.

As a result of the analysis, it is found that recuperative hydraulic drives of timber truck manipulators, satisfying the requirements, as well as mathematical and simulation models of the functioning of all its recuperative mechanisms, allowing one to study the process of accumulation and beneficial use of hydraulic energy, have not been developed.

The aim of the study is to develop a mathematical model and a simulation one based on it, of the functioning of the recuperative hydraulic subsystem of the timber truck manipulator, which allows changing the main parameters of the recuperative hydraulic subsystem, technological parameters of the loading and unloading assortments to determine the dependences of the influence of the pneumohydraulic accumulator volume, the time of one loading cycle per loading cycle and lifting heights of assortments by the amount of recuperated energy.

2. Materials and methods

Based on the studies of hydraulic energy recuperation performed by the authors in the mechanisms of suspension recuperation, wheel hydromotors, towing and fifth wheel coupling, a promising scheme for the recuperative hydraulic drive of a timber truck manipulator was proposed [10]. To test its effectiveness, a mathematical and a simulation model based on it, of the functioning of the recuperative hydraulic subsystem of the timber truck manipulator, which allows changing the main parameters of the recuperative hydraulic subsystem, technological parameters of the loading and unloading assortments to determine the dependences of the influence of the pneumohydraulic accumulator volume, the time of one loading cycle per loading cycle and lifting heights of assortments by the amount of recuperated energy.
When the position of the pistons of the pneumohydraulic accumulator, hydraulic boom cylinders and rotary mechanisms of the column changes, the volumes $V_m$ of their cavities decrease or increase ($m$ is the index of the corresponding cavity). As a result, the pressure $P_m$ changes in these cavities. These transformations are related to the formula below:

$$\frac{dP_m}{dV_m} = -\frac{E}{V_m},$$

where $E$ – volumetric modulus of elasticity of the working fluid.

The flow of the working fluid in the recuperative hydraulic subsystem between two cavities connected to each other occurs at different pressures in them. Based on this, the flow rate of the working fluid $Q_{ij}$ is determined by the formula:

$$Q_{ij} = k_{ij} \cdot \text{sign}(P_i - P_j) \cdot |P_i - P_j|,$$

where $i$ and $j$ – cavity indices; $k_{ij}$ – the effective throttling coefficient; $\text{sign}(x)$ – the function that returns the sign of a variable $x$.

The expansion of hydraulic lines under the influence of working fluid pressure in the mathematical model is taken into account indirectly, by a decrease in the coefficient $E$.

To describe the pneumohydraulic accumulator, a set of equations is used, including the three equations presented below – the piston motion, the flow rate of the working fluid at the inlet, and the polytropic process in the gas cavity:

$$\dot{x}_p = \frac{1}{m_p} \left[ S_{PGA} \left( P_F - P_G \right) - h v_p - \left( R_{np}^0 + k_F P_F \right) \text{sign} v_p - c \left( x_p + x_{p0} \right) \right];$$

$$\dot{P}_F = \left( Q_F - S_{PGA} v_p \right) / k_F;$$

$$P_G = P_{G0} \left[ \frac{x_p}{L_{PGA} - b_p} \right]^n + P_{atm},$$

where $v_p$ – the speed of the piston separating the gas and liquid cavities; $m_p$ – weight of the movable part of the pneumohydraulic accumulator; $S_{PGA} = \pi D_{PGA}^2/4$ – working area of the piston of the pneumohydraulic accumulator; $D_{PGA}$ – the internal diameter of a cavity of the pneumohydraulic accumulator; $P_F$ – pressure in a liquid cavity of the pneumohydraulic accumulator; $P_G$ – pressure in a gas cavity of the pneumohydraulic accumulator; $h$ – the coefficient of viscous friction; $R_{np}^0$ – dry friction in the absence of pressure; $k_i = (\pi/20)D_{PGA}H$ – the coefficient of proportionality between the friction force and pressure in the working cavity; $H$ – lip seal height; $c$ – the spring constant; $x_p$ and $x_{p0}$ – the current coordinate of the piston of the pneumohydraulic accumulator and size of preliminary compression; $L_{PGA}$ – length of a working cavity of the pneumohydraulic accumulator; $b_p$ – thickness of the piston of the pneumohydraulic accumulator; $V_{PGA}$ – total amount of the pneumohydraulic accumulator; $Q_F$ – consumption of the working liquid coming to a cavity with liquid; $k_F = (\Delta V_{PGA} + x_p S_{PGA})/E_{pr}$ – the coefficient of elasticity of a cavity with working liquid; $E_{pr} = E_F/\left(1 + (D_{PGA}/\delta)(E_F / E_{atm})\right)$ – reduced volumetric modulus of elasticity of the cavity with the working fluid; $\Delta V_{PGA}$ – «dead» volume of the working chamber; $\delta$ – cylinder wall thickness; $P_{G0}$ – absolute gas pressure when fully charged pneumohydraulic accumulator; $n$ – the polytropic index; $P_{atm}$ – atmosphere pressure.

As a result, the general system of equations characterizing the operation of the recuperative
hydraulic subsystem of the manipulator will take the following form, given below. The main computational complexity of the application of the developed mathematical model is associated with the integration of differential equations. The calculation is performed in an iterative manner, using the computational functions of modern computers. At each integration step, elementary changes in the system are calculated: elementary movement of the bundle of assortments, elementary lifting of the boom of the hydraulic manipulator, elementary movement of the piston of the pneumohydraulic accumulator, elementary rotation of the column of the hydraulic manipulator. The following describes the sequence of calculation of the system parameters in an iterative way.

First, the piston position \( x_G \) in the left hydraulic cylinder of the column rotation mechanism is determined from the current value of the rotation angle \( \phi \) of the hydraulic manipulator column:

\[
x_G = x_{G0} + \phi \cdot R_e,
\]

where \( x_{G0} \) – a position of the piston at \( \phi = 0 \).

After finding the position of the piston \( x_G \) and knowing the position of the piston \( x_P \) of the pneumohydraulic accumulator, the volumes of the cavities of the hydraulic cylinder (\( V_L \), \( V_P \)) and the cavity with the working fluid of the pneumohydraulic accumulator (\( V_F \)) are determined:

\[
V_L = \frac{\pi D_G^2}{4};
\]

\[
V_P = (L_G - x_G) \frac{\pi D_G^2}{4};
\]

\[
V_F = (L_{PGA} - x_P - b_p) \frac{\pi D_{PGA}^2}{4},
\]

where \( L_G \) – length of the working cavity of the hydraulic cylinder.

The movement of the pistons in the pneumohydraulic accumulator and the hydraulic cylinders of the boom and the rotation mechanism of the column leads to a change in the volume of the cavities and pressures in them. The obtained pressures \( P_L, P_P, P_F \) at the integration step \( k \) are determined on the basis of equation (5), transformed in finite differences into the following form:

\[
P_m^k = P_m^{k-1} - E \frac{V_m^k - V_m^{k-1}}{V_m^k},
\]

where \( m \) – the cavity in which pressure is calculated (cavities «\( L \)», «\( P \)», «\( F \)»).

Next, the flow of the working fluid under the influence of the pressure difference in the cavities under consideration is taken into account. Taking into account the hydraulic subsystem diagram of a manipulator with a recuperative hydraulic actuator (figure 1), there are such options for the flow of working fluid as:

– the flow of working fluid from the cavity «\( L \)» of the hydraulic cylinder of the column rotation mechanism into the cavity «\( F \)» of the pneumohydraulic accumulator when braking the rotation clockwise:

\[
\begin{align*}
\text{if } P_L &> P_F, \text{ then } \\
V_L &= V_L - k_{LF} \sqrt{P_L - P_F} \Delta t; \\
V_F &= V_F + k_{LF} \sqrt{P_L - P_F} \Delta t;
\end{align*}
\]

– the flow of working fluid from the cavity «\( P \)» of the hydraulic cylinder of the column rotation mechanism into the cavity «\( F \)» of the pneumohydraulic accumulator when braking the rotation counterclockwise:

\[
\begin{align*}
\text{if } P_P &> P_F, \text{ then } \\
V_P &= V_P - k_{PF} \sqrt{P_P - P_F} \Delta t; \\
V_F &= V_F + k_{PF} \sqrt{P_P - P_F} \Delta t.
\end{align*}
\]

When turning the column of the hydraulic manipulator counterclockwise, the estimated flow rates of the working fluid are calculated in advance:

– the flow of working fluid from the hydraulic line of high pressure «\( GN \)» in the cavity «\( L \)» of the
hydraulic cylinder of the rotation mechanism of the column:

\[ Q_{GNL} = k_{GNL} \sqrt{P_{GN} - P_L}, \]  

(13)

If the flow rate \( Q_{GNL} \) exceeds the nominal \( Q_{NOM} \) flow rate of the hydraulic pump, the flow rate is adjusted:

\[ Q_{GNL} = Q_{NOM}, \]  

(14)

and after correction, a new volume of fluid in the cavity «L» is calculated:

\[ V_L' = V_L + Q_{GNL} \cdot \Delta t. \]  

(15)

Similarly, in the «column clockwise rotation» mode, the flow from the hydraulic line «GN» of the working fluid into the cavity «P» is calculated:

\[ Q_{GNL} = k_{GNL} \sqrt{P_{GN} - P_P} \cdot \Delta t, \]  

(16)

In the main modes of rotation of the column of the hydraulic manipulator, when one of the cavities «L» or «P» is supplied with working fluid from the pressure head hydraulic line, the second cavity (respectively, «P» or «L») is connected to the low-pressure hydraulic line «A». The discharge of the working fluid is modeled by the following equations:

– discharge from the «P» cavity into the low-pressure hydraulic line «A» in the «counterclockwise rotation» mode:

\[ V_P' = V_P - k_{PA} \sqrt{P_P - P_A} \Delta t; \]  

(17)

– discharge from the «L» cavity of the hydraulic cylinder of the column rotation mechanism into the low-pressure hydraulic line «A» in the «clockwise rotation of the column of the hydraulic manipulator» mode:

\[ V_L' = V_L - k_{LA} \sqrt{P_L - P_A} \Delta t. \]  

(18)

The found current values of the working fluid volumes \( V_L, V_P, V_F \) in the corresponding cavities are used for further calculations at the next integration step \( k + 1 \).

Based on the obtained values of the working fluid pressures in the cavities of the \( P_P \) and \( P_L \) hydraulic cylinders, the forces inhibiting the rotation of the column are calculated. Based on the found pressure \( P_F \), the force is calculated which drives the piston of the pneumohydraulic accumulator and causes a change in the pressure of the working gas.

The rotational motion equations underlying the mathematical model are second-order differential equations. To solve them, the second-order Runge-Kutta numerical method is used:

\[ \varphi^k = \varphi^{k-1} + \varphi^{k-1} \Delta t + \frac{\varphi^k (\Delta t)^2}{2}; \]  

(19)

\[ \dot{\varphi}^k = \dot{\varphi}^{k-1} + \dot{\varphi}^k \Delta t, \]  

(20)

where \( k \) and \( k-1 \) – current and previous integration steps, respectively.

To study the influence of the parameters of the recuperative hydraulic subsystem of the manipulator on the amount of accumulated hydraulic energy during loading of unloading assortments, a computer program was developed in the programming environment Borland Delphi 7.0 in Object Pascal, the functionality of which is: selection of parameters for the hydraulic manipulator, the recuperative hydraulic subsystem of the manipulator, and the technological process; conducting a computer experiment on the simultaneous raising (lowering) of the boom and rotation in the horizontal plane of the column of the hydraulic manipulator at a predetermined angle and return to its original position, with the possibility of connecting the hydraulic cylinders of the boom rotation mechanism to the pneumohydraulic accumulator when braking the movement; displaying pressure graphs \( P_C(t), P_L(t) \) and \( P_P(t) \), deviation of the load from the equilibrium position in the tangential and radial directions, the main indicators of the recuperative hydraulic drive [11].

The basic computer experiment consisted in a single reproduction of the cycle of loading an
assortment from a bundle of assortments on a supporting surface into the body of a timber truck. The boom of the hydraulic manipulator moved along the path indicated above, the mass of the assortment was taken equal to 300 kg. The first simulation results show that for a hydraulic manipulator with a boom length of 5 m and a load weight of 300 kg during one loading cycle, the recuperative hydraulic subsystem of the manipulator allows energy to be stored on the order of 2 kJ. The stored energy is enough to lift the same load to the height of about 68 cm. Given that the operational movement of the load in height is about 2 m, we can talk about the recuperation of about 34% of the energy. The proposed recuperative hydraulic subsystem of the manipulator also allows you to accumulate released energy when lowering the load during unloading and also use it in the future to lift the load.

In the proposed recuperative hydraulic subsystem of the manipulator, the operation of braking the lifting (lowering) of the boom and braking the rotation of the column is sent to the pneumohydraulic accumulator and passes into the energy of the compressed gas. Modern pneumohydraulic accumulators have an energy intensity of about 100 kJ, which allows you to store energy from about 30 to 40 loading cycles, and make 12 elementary load lifts of 300 kg to a height of 2 m.

Let us further consider how the parameters of the recuperative hydraulic subsystem of the manipulator and the technological parameters influence the efficiency of energy storage.

The volume of the pneumohydraulic accumulator $V_{PGA}$ affects the amount of stored energy for the possibility of delayed use. During the study, a single loading cycle is considered, during which the filling of the pneumohydraulic accumulator becomes more difficult as the energy supply increases. In order to study the effect of the volume of the pneumohydraulic accumulator on the recuperated energy, we carried out a series of seven computer experiments in which $V_{PGA}$ was varied at the levels of 1, 2, 5, 10, 20, 40, 60 liters.

With an increase in the loading speed, the characteristic kinetic energy of the hydraulic manipulator and a bundle of assortments increases, and consequently, the amount of accumulated energy in the recuperative hydraulic subsystem of the manipulator also increases. The speed of loading assortments is described by the inverse value: the time $t_{cp}$ of one loading cycle (moving the assortment into the body of a forest truck and returning the boom to its original position above the bundle of assortments on the ground). To study the effect of loading time on the efficiency of the recuperation system, we conducted a series of 8 computer experiments in which the $t_{cp}$ was changed from 6 to 20 s in increments of 2 s.

The potential energy of the assortment in the field of gravity depends on the height of the assortment $h_p$, which is necessary for moving the assortment from the bundle of assortments on the ground to the body of the logging truck and for transferring the assortment through the body limiters. This potential energy can turn into the energy of compression of the gaseous medium in a pneumohydraulic accumulator. Therefore, a series of computer experiments was conducted to study the effect of $h_p$ on the amount of stored energy $E_{CP}$ for one loading cycle. In a series of nine computer experiments, $h_p$ was changed from 0 to 4 m in increments of 0.5 m.

3. Results and discussion

The dependence of the influence of the volume of the pneumohydraulic accumulator $V_{PGA}$ on the amount of recuperable energy $E_{CP}$ for one loading cycle (figure 2) is established. It shows that the amount of incandescent energy of the working fluid $E_{CP}$ for one loading cycle does not change with a volume of a pneumohydraulic accumulator of 10-20 liters. With a large number of loading cycles (from 2 to 20), pneumohydraulic accumulators with a volume of more than 10 liters are the most suitable for accumulating and reusing the energy of the working fluid. The use of pneumohydraulic accumulators with a volume of less than 10 l in one loading cycle leads to a significant reduction in the amount of accumulated energy of the working fluid $E_{CP}$.

The dependence of the time of one loading cycle $t_{cp}$ of the assortment on the amount of recuperable energy $E_{CP}$ for one loading cycle (figure 3) is revealed. It shows that with a decrease in the loading cycle duration $t_{cp}$, the amount of recuperable energy $E_{CP}$ increases. This is due to the fact that due to an increase in the speed of lowering the boom, the handle with the load, their potential energy increases,
and with an increase in the speed of rotation of the column, kinetic energy increases, which leads to an increase in the amount of working fluid energy stored in the pneumohydraulic accumulator.

Figure 2. Influence of the volume of the pneumohydraulic accumulator $V_{PGA}$ on the recovered energy $E_{CP}$ in one loading cycle.

Figure 3. The influence of the time of one loading cycle of the assortment $t_{cp}$ on the recuperable energy $E_{CP}$ per one loading cycle.

The sigmoidal dependence of the influence of the lifting height $h_p$ of the assortment on the amount of recovered energy $E_{CP}$ for one loading cycle (figure 4) is obtained. With a small lifting height $h_p$ of the assortment, the manipulator moves mainly in the horizontal plane; therefore, the accumulation of hydraulic energy of the working fluid in the pneumohydraulic accumulator is carried out by smoothing transient processes when the manipulator column is rotated as a result of its acceleration and braking. In this case, the amount of recuperable energy $E_{CP}$ is 1.8 kJ. With an increase in the lifting height $h_p$ of the assortment, the amount of recovered energy $E_{CP}$ increases from 2.2 to 2.7 kJ. This is due to the fact that the potential energy of lowering the boom and the handle with the load is added to the kinetic energy of rotation of the column of the manipulator.

Figure 4. The influence of the height of the assortment $h_p$ on recuperable energy $E_{CP}$ for one loading cycle.

4. Conclusion

Thus, the developed mathematical model and the simulation model developed on its basis of functioning of the recuperative hydraulic subsystem of the truck’s manipulator, and the dependences obtained during its study make it possible to conclude that the maximum amount of recuperable energy $E_{CP}$ will accumulate in the pneumohydraulic accumulator when its $V_{PGA}$ volume is more than 10 l, with a decrease the duration of the loading cycle $t_{cp}$ and increasing the lift height $h_p$ assortment during loading and unloading of a timber truck.

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