Improving the efficiency of manipulator-type machines with an improved hydraulic drive

I Chetverikova¹⁺, P Popikov¹ and S Glushkov²

¹Forestry Mechanization and Machine Design Department, Voronezh State University of Forestry and Technologies named after G.F. Morozov, 8 Timiryazev street, 394087, Voronezh, Russian Federation
²Forest Research Institute, Bulgarian Academy of Sciences, 132 Cl. Ohridski street, 1756, Sofia, Bulgaria

*E-mail: teachercedo215@vglta.vrn.ru  https://orcid.org/0000-0001-9726-3218

Abstract. The article considers the possibility of increasing the efficiency of manipulator-type machines when harvesting wood by increasing the productivity, energy efficiency and reliability of the hydraulic equipment used. A combined method of transporting timber from logging sites by road and water transport using equipment with an improved hydraulic drive of the manipulator is proposed. The issue has not been worked through before. Using the example of the Northwestern Federal District, the author considers the development of forest areas located in the upper reaches of small and medium rivers. For the first time, original hydromechanical dampers and energy-saving devices are used in hydraulic drives of manipulators of forest machines to reduce dynamic loads and energy consumption for loading and unloading timber. This increases the efficiency of the use of manipulator-type machines, creating mobility, reducing equipment costs, the time spent waiting for unloading on sites for further rafting or shipment. The development of forest areas in a combined way will reduce capital investments for the construction of transport routes at the border of waterways by at least 3 times. All this will reduce the cost of harvesting in general and eliminate the use of additional loaders.

1. Introduction

All the main types of transport are concentrated in the investigated North-West region of the Russian Federation: road, sea, river, rail, air and pipeline. Transportation of timber from logging sites largely depends on the location of the cutting area. Forest harvesting is an important industrial and social task. However, this process is associated with significant transportation difficulties [1].

The main problem of the logging industry is the lack of forest roads at the logging sites, so the most common haulage of timber by road trains is not possible due to the lack of wide overall traffic lanes with a large radius at turns in the studied zones. According to well-known statistics, the movement of timber by road is advisable with a total distance of the transport route of no more than 200 km in view of the cost of the final product, and the removal of timber by a single car at a distance of more than 38 km is unprofitable. Rail transport is currently fully loaded and economically inefficient. In the conditions of the North-West, water transport of timber remains the most effective, since there is a fairly extensive water network in the region. Geographically, there are 12 navigable lakes, 19 navigable rivers, 2 most important navigable canals, reservoirs and many non-navigable waterways that can be used in certain conditions of the location of the cutting area. The presence of rivers and lakes in the forest zone of the
North-West of the Russian Federation makes it possible to increase the turnover of exported timber and to involve hard-to-reach resources in the development process.

It is proposed to use a combined method of timber transportation using manipulator-type machines with an improved hydraulic drive. The issue has not been considered previously. This method of transportation will reduce the loss of wood to zero, reduce costs and preserve the ecological balance. The improvement of the hydraulic equipment of manipulator-type machines will increase their reliability and performance in difficult conditions of the Savero-Western region.

The combined method includes two types of transport: from logging sites to the nearest points adjacent to water areas - automobile and then - water, taking into account the depth of the floatation and the volume of transported cargo. The period of sustainable logging and removal of harvested timber is relatively short. Transitions of the ambient air temperature from negative to positive values, characteristic of a sharply continental climate, stop the logging process in most of the felling areas due to thawing of frozen soils [2]. In view of this, the combined method assumes its seasonality, since raft timber rafting and ship transportation are possible only during the opening of navigation. The possibility of optimizing the volume of transported cargo during the spring flood is considered. The rise in the river water level will allow the use of large volumes of floating units due to the increased draft of both the vehicle and the floating cargo itself. During the inter-navigation period, forestry vehicles carry out the supply and unloading of wood to drainage rafts or flood-free areas with the further formation of floating units. The requirements for floating units, the peculiarities of the water transport of the forest in the conditions of small and medium-sized rivers impose certain restrictions on the formation of carnivorous units, their draft.

An important aspect is the productivity of forestry vehicles on problem soils of the North-West of the Russian Federation. There is a special need to improve components and mechanisms, which will allow machines to achieve maximum performance with the least risk of hydraulic equipment failure. That is why it is important for each type of cutting area to select the optimal towing scheme, to optimize the volume of aquatorial cargo and to improve the working bodies of the manipulators used [3-5], increasing their productivity and the technical level of machines in general.

The analysis of many scientific works of Russian and foreign researchers confirms the relevance and prospects of the scientific direction related to the improvement of hydraulic equipment, with an increase in its energy efficiency based on the introduction of various pressure surge damping devices and systems into the design.

In the work of Prabhat Ranjan, a promising hybrid system is proposed that allows using potential gravitational energy during the operation of the hydraulic drive of the excavator boom in the form of pressure energy of the working fluid accumulated in a pneumohydraulic accumulator. A study of this system has shown that it is 10% more energy efficient than using a traditional system [6]. Emiliano Pipitone performed a study of the kinetic energy recovery system for a car with an internal combustion engine. A preliminary assessment of this system, carried out on the basis of numerical modeling, allowed us to determine that the use of supercapacitors as energy storage makes it possible to save up to 20% of energy [7]. Jiansong Li in his work performed an analysis of hybrid hydraulic drives used in vehicles with electric, hydraulic and flywheel energy recovery systems. The results showed that the use of flywheel recovery systems in comparison with other systems has a higher specific power, energy efficiency, service life, as well as a lower impact on the environment [8].

For more than 20 years, imported wheel forwarders have been operating in the forests of the Northwest of the Russian Federation. To date, these machines have caused significant damage to forestry due to the destruction of undergrowth in clearings without the possibility of reforestation in the worked-out areas. The cost of wood raw materials is constantly growing, which is associated with the cost of operating and maintenance of foreign-made forestry machines, as well as with the strengthening of the dollar and euro [9]. That is why it is currently preferable to work on domestic environmentally friendly forestry vehicles, which are not inferior in productivity to imported forwarders, having adapted them to certain operating conditions.
Studies of the work process dynamics of harvesting machines were considered in the papers of famous scientists. Nesmianov I. A. and Khavronin V. P. [4] considered the dynamics of the hydraulic drive of the loading manipulator with elastic-damping bonds in the hydraulic system. Alexandrov V. A. [10] considered the emergency braking modes of the manipulator boom when working with loads, and the loading of the gripper mechanism. This process is accompanied by an additional dynamic load on the machine, which once again emphasizes the need to reduce it V. I. Posmetyev studied energy-saving hydraulic drives with a subsystem of energy storage of compressed air [5, 11]. However, the use of compressed air in the recurrence system causes a negative effect of heat-mass transfer and the appearance of moisture, freezing of motor elements with the expansion of compressed air [12].

Based on the conducted research, it can be concluded that scientific and design developments in the field of improving energy efficiency, reliability of machinery and equipment used in the forest industry are currently being actively conducted all over the world based on the use of promising energy-saving mechanisms and systems that convert and accumulate various types of energy. The design of working units of such machines, their improvement, is possible only in educational institutions of the corresponding profile, which is why we took on this task. Modern forestry vehicles should have high reliability, in particular, reliability, durability and maintainability. The use of a hydraulic drive for loading and unloading timber by manipulators has a number of advantages in contrast to, for example, mechanics or pneumatics. The hydraulic drive has high speed, decent rigidity, small size and weight.

We have improved the hydraulic drive of the manipulator machine in order to extinguish the generated pressure in the piston group, reduce vibrations, and thereby increase the reliability of the working body during machine operation. In this paper, proposals are made to minimize the transport costs of timber enterprises for the transportation of wood from logging sites located in forests near small and medium-sized rivers, through the use of a combined method of wood transportation.

So, the main disadvantages of the existing pressure surge damping devices of hydraulic manipulators are overheating of the working fluid and loss of energy due to its flow through additional channels of the damper. In addition, the efficiency of returning the lost braking energy of the column itself when turning and the efficiency of damping pressure surges of the working fluid in the system are reduced. Our task was to eliminate the existing shortcomings of the hydraulic equipment of the manipulators in order to increase the efficiency of energy accumulation and recovery and damping of pressure fluctuations of the working fluid in the start-brake modes, in particular, the mechanism for turning the manipulator column.

The purpose of the work was to substantiate the possible increase in the efficiency of manipulator-type machines in the conditions of the North-West of the Russian Federation by improving the hydraulic equipment used.

2. Methodology
The combined method of timber transportation considered for the North-West region is calculated when the cutting area is far from waterways in an area of up to 5 km, and the main distance to the floating point is overcome by waterways. It is proposed to transport timber directly from the felling area to the adjacent waterways with the further formation of floating units by towing tow or by patrol-remote method. It all depends on the depth of the rafting.

The modernized hydraulic manipulator LV-184 A, produced by Open Joint Stock Company Maikop Machine Building Plant (Russia) was chosen as the object of the study. The manipulator is designed for loading and unloading operations in the forestry, woodworking and other industries. The loading itself consists of 4 main operations: turning and lowering the boom, placing it over the required assortments and grabbing them, moving the assortments, then stacking them. When unloading, the structure of the working cycle of the hydraulic manipulator is similar to that of loading.

A forest transport machine equipped with a hydraulic manipulator brings sorting materials to the nearest dam and unloads them into a cohesive device, where floating units are formed. The performance of loading and unloading operations depends on the energy efficiency and reliability of a machine equipped with specialized hydraulic equipment. Involving small and medium-sized rivers in the
transport and technological potential, due to the depth of the floating course, it is important to form floating units of a small volume, approximately from 3 to 5 m$^3$. After the formation, the units are laid either on a flooded dam or on a non-flooded shore equipped with inclined guides for launching floating units into the water. An important aspect is the prevention of a large amplitude of swinging of the load, minimizing pressure surges in the piston group of hydraulic equipment. It is these parameters that directly affect the overall efficiency of using machines as a whole, their performance.

To limit the limiting fluctuations in the pressure of the working fluid when the piston of the hydraulic cylinder stops in intermediate positions when lifting or lowering the load, a hydraulic mechanical damper was developed. For the hydraulic drive of the column turning mechanism, a hydraulic pneumatic damping device has been developed. An additional damper with return springs dampens dynamic loads and swaying of the load when the slewing column stops in intermediate positions, and the pneumatic cylinders ensure smooth stops of the column in the extreme positions, while accumulating braking energy, and then returning it back to the system, i.e. there is a recuperation process.

We have carried out analytical studies of the working process of the mechanism for turning the column of a forestry manipulator with an energy-saving hydraulic drive, the design of which is protected by a patent for an invention [13]. For setting up systematic numerical experiments with the model, a computer program "Program for modeling an energy-saving hydraulic drive of a boom manipulator" was compiled. The output to the computer screen of the results of modeling the working process of the rotation mechanism of the column of the forest manipulator with an energy-saving hydraulic drive is shown in figure 1. The simulation model allows you to connect a pneumatic hydraulic accumulator in the mode of braking the rotation of the column and check the option of sharp blocking of the supply and drain hydraulic lines.

The main limitations of the program: operating pressure of the hydraulic system from 2 to 30 MPa, time resolution $2 \cdot 10^{-6}$ s. The optimal step of numerical integration is determined by repeatedly conducting experiments with a step that sequentially decreases 2 times and stopping at the step after which the simulation results are practically unchanged. These results are 1-2%. The program provides the output of schematic images of the manipulator and the load in three projections with the deviation of the load from the equilibrium position in the tangential and radial directions, graphs of pressure dependences in the left and right cavities of the hydraulic cylinders and grip fluctuations with a bundle of assortments. The details of the beginning of the experimental part are published in the source [14]. The universal program can be used both for the lifting mechanism and for the rotation mechanism of the manipulator boom.

Spikes appear on the graph of time dependences of pressure $P(t)$. The movement of the boom causes the load to swing in tangential and radial directions. The proposed energy-saving hydraulic drive allows not only to store and further use the braking energy, but also to reduce fluctuations in the load and pressure in the hydraulic system caused by the braking process of the column rotation.

The value of the energy accumulated during the working cycle and the efficiency of damping pressure impulses when braking the casing rotation is significantly influenced by the charging pressure of the pneumatic hydraulic accumulator $P_{PGA}$. To study the influence of $P_{PGA}$ on the efficiency indicators of an energy-saving hydraulic drive, a series of experiments was carried out on a computer. Within the series, $P_{PGA}$ was varied at levels of 1, 3, 5, 7.5, 10, 12.5, 15, 20 MPa. For the basic experiment, the following values of the main input parameters were chosen: pressure of the hydraulic pump $P_{Gn} = 20$ MPa; rated flow of the hydraulic pump $Q_{n} = 1330$ cm$^3$/s; cargo mass $m_c = 1000$ kg; boom weight $m_b = 250$ kg; column base mass $m_{ok} = 500$ kg; coefficient of viscous friction during rotational movement of the column $k_{Gk} = 100000$ Nꞏmꞏs/rad; the distance from the pivot axis O to the point G of the load application of the gravity $L_G = 6115$ mm; inner diameter of swing cylinders $D_G = 100$ mm; length of the working cavity of the swing cylinders $L_G = 670$ mm; effective throttling coefficient of pipelines $k_{Lg} = 2 \cdot 10^{-6}$ m$^3$ꞏsꞏPa$^{1/2}$; reduced volume modulus of elasticity of a cavity with a liquid $E = 10^8$ Pa.
Figure 1. Simulation results on a computer screen: (a) – three projections of the boom of manipulator, (b) – graphs of tangential $\Delta l_\tau(t)$ and radial $\Delta l_r(t)$ deviations of the gripper with a bunch of assortments from the equilibrium position relative to the boom, (c) – schematic representation of the hydraulic cylinders for turning the column and pneumatic-hydraulic accumulator, and (d) – time $t$ dependence of the graphs of pressure $P$ in various elements of the hydraulic system and gripper displacements with a bundle of assortments.

3. Results
Figure 2 presents the results of the conducted studies in the form of dependences of the influence of the throttling coefficient in the pipeline between hydraulic cylinders and a pneumatic accumulator on the stored energy per working cycle, the amplitude of the pressure surge in the hydraulic system and the amplitude of the load rocking in the tangential direction.

Figure 3 shows the dependences of the influence of the operating angle of rotation of the manipulator column on the stored energy per working cycle, the amplitude of the pressure pulse in the hydraulic system and the amplitude of the load rocking in the tangential direction.

The analysis of the results showed that the optimal charging pressure of the pneumatic hydraulic battery is 5 ... 10 MPa. At the optimal charging pressure of the pneumatic hydraulic accumulator, the energy-saving hydraulic drive stores about 300 J of energy during the working cycle, the pressure surges do not exceed 10 MPa, and the swinging amplitude of the load is 0.26 m. $k_{GGA}$ more than $10^{-7}$ m$^3\cdot$s$^{-1/2}\cdot$Pa$^-1/2$ the hydraulic drive provides an even greater reserve of energy and even better reduces pressure surges and swaying of the load, however, to achieve such a high $k_{GGA}$ coefficient, the cylinders and a pneumatic accumulator must be directly connected to the swing cylinders.
Figure 2. Influence of the throttling coefficient in the pipeline between the hydraulic cylinders and the pneumatic hydraulic accumulator $k_{PGA}$ on the stored energy for the operating cycle $E_c$ (a), the amplitude of the pressure surge in the hydraulic system $P_m$ (b) and the amplitude of the load swing in the tangential direction $A_{\tau m}$ (c).

Figure 3. Influence of the operating angle of rotation of the manipulator column $\phi_m$ on the stored energy for the working cycle $E_c$ (a), the amplitude of the pressure surge in the hydraulic system $P_m$ (b) and the amplitude of swinging of the load in the tangential direction $A_{\tau m}$ (c), respectively.

According to the research carried out, in a wide range of $10^{-6}...10^{-3} \text{ m}^3\text{s}^{-1}\text{P}a^{-1/2}$ in the hydraulic system and reduces load swing. The magnitude of the pressure surge in the hydraulic system $P_m$ practically does not depend on $\phi_m$ and is an acceptable value of about 3 MPa, and the swing of the load decreases to 0.2 m, which improves the efficiency of the manipulator.

Analyzing the research results, we can say that with the combined method of transporting wood, the use of equipment with improved hydraulic manipulators using hydromechanical dampers and energy-saving devices for loading and unloading makes the structure more reliable and energy-saving, which directly affects the productivity of machines and the cost of the final product.

4. Conclusion

Thus, considering the transportation of wood in the North-West, we can say that along with the use of vehicles in the presence of rivers and lakes in the forest zone, water transport of wood will remain promising, since it does not require additional costs for the construction of forest roads. Large-scale development of untouched forests through the use of possible methods of water and land transportation will simultaneously allow to involve in industrial production numerous stocks of ripe and overmature stem wood, the available areas of which are mainly located near the water areas of small and medium rivers of the Northwestern region of the Russian Federation. The development of woodlands in a
combined way will reduce capital investments for the construction of transport routes in the places where waterways meet.

Increasing the efficiency of manipulator-type machines can be achieved by improving the design of the installed hydraulic equipment. This becomes possible due to the use of new hydromechanical dampers and energy-saving devices, in particular, for the manipulator column rotation mechanism. Using universal manipulator-type machines with an improved hydraulic drive as a mono-technique for the proposed method, it is possible to achieve a significant reduction in the cost of logging in general and to abandon the use of additional loaders and specialized equipment. The novelty of the proposed solution is that during acceleration and braking of the rotary column, energy accumulates in the hydraulic accumulator, which returns to the hydraulic system during subsequent working processes of the manipulator, damping of pressure fluctuations of the working fluid improves, which allows to increase the productivity and reliability of the entire unit in severe conditions of forest objects in the North-Western region. Comparing the regenerative energy with the total energy expended in the rotation of the column, it was found that its share is approximately 25%. In the considered recovery system, an actuating fluid was used. In contrast to a recirculation system with compressed air [5, 11], the negative effects of heat transfer are not observed in this system.

In the context of the development of forestry in the country and the world as a whole, the improvement of manipulator-type machines in order to increase their technical, economic and resource-saving indicators will always be relevant. According to our research it has been established that the energy-saving hydraulic drive stores at least 180 J of energy per operating cycle, effectively dampens pressure surges in the hydraulic system and reduces the swing of the load to 0.2 m, which contributes to the efficiency of the loading and unloading process, increasing productivity, reliability and reducing economic indicators. Thus, in the future, the development of carnation units adapted to shallow water conditions and the improvement of the working bodies of domestic manipulators of vehicles will be one of the priority areas for us to contribute to the development of water and land transport of the forest.

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