Mathematical model of hydromanipulator of forest vehicle with recuperative hydraulic drive

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Abstract. The relevance of using a recuperative hydraulic drive to control the hydraulic manipulator of a timber truck used in conducting selective sanitary cutting of forest care has been substantiated. A mathematical model of the mechanical subsystem of a hydraulic manipulator with a regenerative hydraulic actuator is presented, which describes the movement of a hydraulic manipulator with an assortment in space. Successive states of boom, handle and column of hydraulic manipulator during loading of grades into body of forest truck at different moments of computer experiment time are considered. The research results obtained on the basis of the developed computer program are described.

1. Introduction

Forests occupy almost a third of the earth’s surface and are of great importance for the development of the country's productive forces. Wood taken from forests and other land covered by forest vegetation is an important part of the productive function. At this time, the logging industry massively uses machine technology for harvesting timber, among which a significant place is given to the technological process of harvesting timber with assortments. This technology most fully meets the environmental requirements for selective sanitary cutting of forest care. This circumstance leads to the fact that there is a need to develop new and improve existing designs of hydraulic manipulators for short log trucks based on wheeled vehicles. One of the promising ways to increase the efficiency and reliability of the working body with a load is to use regenerative mechanisms in their design, based on various methods of energy recovery, allowing to accumulate and reuse in their work, as well as when performing various technological operations, useless energy dissipated into the environment [1].

Lianpeng Xia [2] and Yanxiao Hao [3] in their studies substantiate the efficiency of using recuperative hydraulic drives of the excavator boom, which allow converting the potential energy of lowering the boom into the energy of the working fluid accumulated in a pneumatic-hydraulic accumulator. Ying-Xiao Yu [4] and Tranling Lin [5] presented in their works hybrid systems for recovering the potential energy of lowering the boom in the energy of the working fluid and the electrical energy stored in the supercapacitor. Tao Wong [6] presents the results of the functioning of the regenerative hydraulic drive of the excavator, which allows additionally converting the kinetic energy of braking of the excavator platform into electrical energy for further storage and use. Lu Lu and Bin Yao [7] describe the operation of the recuperative hydraulic drive they offer for controlling the boom of a hydraulic manipulator, which makes it possible to use potential energy when it is lowered by converting it into working fluid energy.

Based on the analysis of the existing designs of technological machines with hydroficated equipment by
the authors, it was revealed that, at the present time, recuperative hydraulic manipulators of hydraulic manipulators for forestry vehicles that have been developed have not yet been developed, which make it possible to convert kinetic energy for turning the rotary support device of the manipulator and potential lowering energy arrows and sticks in the process of loading and unloading assortments. The aim of the study is to develop a mathematical model and, on its basis, a computer program for operating a hydraulic manipulator of a timber truck equipped with the proposed design of a regenerative hydraulic actuator, which allows, by changing the basic geometric, functional and inertial parameters of the hydraulic manipulator, to reveal the dependences of the influence of the mass of the boom, handle with load, boom angle, angle turning the column on the amount of recovered energy.

2. Materials and methods

Based on the research conducted by the authors of the hydraulic drive of a logging vehicle with energy recovery in the recuperative mechanisms of the boom, stick, slewing ring of the hydraulic manipulator, suspension, hydraulic motors of the wheels and the towing device, a promising diagram of the recuperative hydraulic drive of the logging truck was proposed (figure 1) [8, 9].

![Figure 1. Scheme of a recuperative hydraulic drive of a timber truck hydraulic manipulator: 1 – recuperative boom mechanism, 2 – recuperative arm mechanism, 3 – recuperative mechanism of the rotator, 4 – pump-battery assembly.](image)

In order to assess the possibility of equipping the hydraulic manipulator with a hydraulic energy recovery system and determine its optimal parameters, the task is set to develop and investigate a mathematical model of functioning of the mechanical subsystem of the manipulator of a forest vehicle with a recuperative hydraulic drive. Mathematical modeling is based on the calculation methods of classical mechanics and hydraulics [10].

Within the framework of the mathematical model of the mechanical subsystem of a hydraulic manipulator with a regenerative hydraulic drive, the main physical processes occurring in its mechanical subsystem are described. The structure of the hydraulic manipulator is presented in a mathematical model by a system of algebraic and differential equations. The solution of this system of equations is carried out on the basis of numerical integration.

Despite the fact that the boom, as a mechanism, consists of two links, in the mathematical model, the assumption is that the boom is a single link and is a single solid body (figure 2). In this case, in the
In the mathematical model of the mechanical subsystem of a hydraulic manipulator using the equations of classical dynamics are described: the movement of the boom relative to the column, the rotation of the column (absolutely solid) relative to the vertical axis $Z$, the swinging of assortment $D$ relative to the attachment point of the grapple on the arrow of the hydraulic manipulator $C$. The value of $\phi$ is measured from the axis.

![Diagram of hydraulic manipulator](image)

**Figure 2.** The design scheme for the representation of a hydraulic manipulator with a recuperative hydraulic actuator in a mathematical model.

The mathematical model considers such mechanical processes as rotational movement of a hydraulic manipulator column relative to the vertical axis, boom displacement relative to the hydraulic manipulator column, swaying of assortment $D$ relative to the grapple attachment point on the hydraulic manipulator boom $C$. The classical dynamics equations were used to represent the mathematical model. The hydraulic manipulator column is described as an absolutely rigid body rotating about the $Z$ axis. The position of the hydraulic manipulator column in a mathematical model is determined by the angle $\phi$ determined from $X$ in the counterclockwise direction. To describe the rotation of the column uses the basic equation of the dynamics of rotational motion:

$$J \frac{d^2 \phi}{dt^2} = \sum i M_i,$$

where $J$ – moment of inertia of the column relative to the axis $O$; $M_i$ – obstructive and propelling various types of torques.

In more detail the description of the equation of rotational motion of the hydraulic manipulator column will take the following form:

$$J \frac{d^2 \phi}{dt^2} = M_{GC} - M_G - M_\rho - k_{\phi} \frac{d\phi}{dt} + M_{sl} + M_u + M_w,$$

where $M_{GC}$ – torque transmitted by hydraulic boom cylinder to rotary column of hydraulic manipulator; $M_G$ – moment passed when moving assortment; $M_\rho$ – friction torque in the pivot bearings of the hydraulic manipulator column; $k_{\phi}$ – coefficient of reduction of viscous friction in hydraulic cylinders of the mechanism of rotation of a column of a hydraulic manipulator; $M_{sl}$ – torque from the slope of the bearing surface, depending on the angle $\phi$ of the rotation of the boom of the hydraulic manipulator, measured by
the location of the hydraulic manipulator on the supporting surface with a slope; \( M_w \) – moment of force from wind load, which is a complex function, depending on the configuration of the manipulator and the load, and the orientation of the boom with respect to the direction of the wind.

In the mathematical model, a separate dynamic calculation is not made for the piston-rod group of hydraulic cylinders of the column turning mechanism, but its inertial characteristics are taken as small additions to the moment of inertia of the boom of the hydraulic manipulator and the moment of friction of rotation. The calculation of the moment of inertia of the hydraulic manipulator column is carried out taking into account the introduction of the following assumptions: we consider the column as a body including two regular geometric components: a manipulator boom, represented in the form of a homogeneous rod with length \( L_G \) and mass \( m_C \); manipulator column, presented in the form of a solid cylinder of radius \( R_{cyl} \) and mass \( m_{cyl} \). Based on these assumptions, the moment of inertia of the hydraulic manipulator column is determined by the following formula:

\[
J = \frac{1}{3} m_c L_G^2 + \frac{1}{2} m_{cyl} R_{cyl}^2. \tag{3}
\]

The torque generated by the hydraulic cylinders of the rotation mechanism of the hydraulic manipulator column is determined by the following formula:

\[
M_{GC} = F_{GC} \cdot R_{gw} \tag{4}
\]

where \( R_{gw} \) – the radius of the gear rack and pinion transmission mechanism of rotation of the column hydraulic manipulator; \( F_{GC} \) – force created by the hydraulic cylinders of the rotation mechanism of the hydraulic manipulator column calculated by the formula:

\[
F_{GC} = (P_L - P_P) \frac{\pi D_G^2}{4}, \tag{5}
\]

where \( D_G \) – hydraulic cylinder inner diameter; \( P_L \) and \( P_P \) – working fluid pressure in the left and right cylinders, respectively, of the column rotation mechanism.

The principle of operation of the recuperative hydraulic drive consists in accumulating the energy of the working fluid released when breaking the rotation of the hydraulic manipulator column or breaking the boom rotation. During rapid deceleration of the rotation of the column, the second derivative \( \frac{d^2\phi}{dt^2} \) has a high negative value, and the boom of the hydraulic manipulator with the assortment has a high reduced moment of inertia \( J \). Therefore, the column under braking has a significant deceleration moment \( M_{GC} \):

\[
M_{GC} = J \frac{d^2\phi}{dt^2} + M_G + M_p + k_{\phi} \frac{d\phi}{dt} - M_{fr} - M_w. \tag{6}
\]

The high braking torque \( M_{GC} \) leads to a significant increase in pressure in one of the hydraulic cylinders (in particular, the pressure difference \( P_L - P_P \)):

\[
(P_L - P_P) = \frac{4}{\pi D_G^2 R_{gw}} \left( J \frac{d^2\phi}{dt^2} + M_G + M_p + k_{\phi} \frac{d\phi}{dt} - M_{fr} - M_w \right). \tag{7}
\]

A surge in pressure in a hydraulic cylinder that rotates a turn has an adverse effect on the hydraulic system and can cause hose breaks and loss of fluid. The recuperative hydraulic actuator can significantly reduce the sharp fluctuations in the pressure of the working fluid due to its direct direction to the pneumatic-hydraulic accumulator from the braking hydraulic cylinder.

The moment created by a pack of assortments is determined by:

\[
M_G = L_G \left(-F_{GX} \cdot \sin \phi + F_{GY} \cdot \cos \phi\right), \tag{8}
\]

where \( F_{GX} \) and \( F_{GY} \) – cartesian components of the force acting from a bundle of assortments on the
boom of a hydraulic manipulator; \(L_G\) – the distance between the attachment point on the grapple boom and the axis of rotation of the hydraulic manipulator column (figure 2).

As a result of this, the equation of rotational motion of the hydraulic manipulator column will take the following form:

\[
\frac{d^2 \phi}{dt^2} = \frac{1}{3 m_L L_G^2 + \frac{1}{2} m_M R_f^2} \left\{ R_{\phi G}(P_L - P_r) - \frac{\pi D_G^2}{4} - \frac{L_G}{2} \left( -F_{G\phi} \cdot \sin \phi + F_{G\phi} \cdot \cos \phi \right) - M_p - k_{\phi} \frac{d \phi}{dt} + M_d + M_w \right\}. \tag{9}
\]

Similarly, the rotation of the boom \(OC\) in a vertical plane relative to the hinge \(O\) is described. The main difference is the calculation of the moment relative to the hydraulic cylinder and the absence of the moment from the slope of the bearing surface.

In the mathematical model, the assortment of mass \(m_M\) lifted and moved by a hydraulic manipulator, is described either by a material point, at small values of dimensions, or in the form of a rod of length \(L_r\). In the mathematical model, the assortment is associated with an arrow due to a weightless viscoelastic rod simulating a gripping device. The rod is located between the point \(G\) of the grapple mounting on the boom and the point \(M\) of the center of gravity of the assortment. According to the law of dynamics of translational motion, the vector equation of motion of the center of gravity of the assortment will take the following form:

\[
\frac{d^2 \vec{r}_m}{dt^2} = \frac{1}{m_M} \left\{ \left( -c_M (GM - L_M) - d_M \frac{d(GM - L_M)}{dt} \right) \frac{GM}{GM} + m_M \vec{g} \right\}, \tag{10}
\]

where \(\vec{r}_m\) – radius vector of point \(M\) in the cartesian coordinate system \(XYZ\); \(c_M\) and \(d_M\) – stiffness and viscosity coefficients of viscoelastic interaction through a capture device; \(GM\) – vector starting at \(G\) and ending at \(M\); \(GM\) – distance between points \(G\) and \(M\); \(\vec{g}\) – gravity acceleration vector.

In this equation, the expression in the external brackets is the force acting on the assortment. The force acting from the assortment on the boom hydraulic manipulator is determined by the expression:

\[
F_G = \left( c_M (GM - L_M) + d_M \frac{d(GM - L_M)}{dt} \right) \frac{GM}{GM} - m_M \vec{g}. \tag{11}
\]

The components of this force \(F_{GX}\) and \(F_{GY}\) take part in the equation described above. In mathematical modeling, the assortment is described in the form of a mass evenly distributed along a rod of length \(L_r\), with a center of gravity at point \(M\). This should take into account the possibility of rotating the assortment relative to the center of gravity in the vertical and horizontal planes. Therefore, to describe the movement of the assortment, you must use the following two equations:

\[
\frac{d^2 \psi}{dt^2} = \frac{12}{m_M L_r^2} M_{\psi}(t) - d_{\psi} \frac{d \psi}{dt}, \tag{12}
\]

\[
\frac{d^2 \chi}{dt^2} = \frac{12}{m_M L_r^2} M_{\chi}(t) - d_{\chi} \frac{d \chi}{dt}, \tag{13}
\]

where \(\psi\) – the angular deviation of the assortment in the horizontal plane relative to the direction of the boom of the hydraulic manipulator; \(\chi\) – angular deviation of the assortment in the vertical plane relative to the horizontal position; \(M_{\psi}(t)\) and \(M_{\chi}(t)\) – moments of external forces acting on the assortment; \(d_{\psi}\) and \(d_{\chi}\) – coefficient of viscous friction during rotation of the grapple with the assortment in the vertical and horizontal planes.

To increase the speed of solving the differential equations included in the developed mathematical
model, as well as to conduct a computer experiment with a mathematical model, a computer program was created in the Border Delphi 7.0 programming environment in the Object Pascal language. This program allows, by changing the basic geometric, functional and inertial parameters of a hydraulic manipulator with a regenerative hydraulic drive, to imitate its operation in loading or unloading cycles, as well as to optimize the basic parameters of the regenerative hydraulic drive.

In the simulation model, a typical process of loading assortments with a hydraulic manipulator into a timber truck is reproduced. The hydraulic manipulator grabs the assortment from the bundle of assortments, deviating 90° from the direction of the forest truck, and lowering the arrow to grab the assortment with a grab (figure 3). After that, the boom of the hydraulic manipulator turns upward and at the same time returns to the longitudinal axis of the logging truck. To raise the assortment through the side stops of the truck body, the boom of the hydraulic manipulator rotates with a margin up. To create such a trajectory in the simulation model, the time dependences of the corresponding flow rates of the working fluid in the hydraulic cylinders for lifting and turning the boom are calculated. A similar boom path was used when unloading a timber truck with a hydraulic manipulator. However, further only the loading mode is examined, as it is more energy-consuming compared to the unloading mode.

The process of loading the range takes 6.0 s in the model. After loading the range, the boom of the hydraulic manipulator returns to the initial position. The operation of the recovery system is calculated both for the process of loading the grade and for returning the boom to the initial position. Thus, the recovered energy for the entire loading cycle is determined.

During movement by the boom, the grade is rocked relative to the hinge of the gripper grip, which is reproduced with sufficient adequacy in the simulation model. In particular, when the boom stops above the

Figure 3. The successive states of the hydraulic manipulator in the process of loading the assortment into the forest truck (time points \( t \) of the computer experiment are indicated): \( a \) – top view (projection on the \( XY \) plane); \( b \) – starboard view (projection on the \( YZ \) plane); \( c \) – rear view (projection on the \( XZ \) plane).
body of the forest vehicle at the time of 5.4 s, the grade continues to oscillate and in the model is released later, at the time of 6.0 s (figure 3). The effect of the swinging significant mass on the boom and hydraulic system is taken into account in the model, and this action affects the recovered energy.

The main indicator characterizing the efficiency of the recovery system is $E_{CP}$ energy stored in a pneumohydraulic accumulator during one loading cycle (or $E_{CP}$ energy per unloading cycle):

$$E_{CP} = \int_{0}^{t_{CP}} P_{PGA}(t) Q_{PGA}(t) \, dt,$$

where $t_{CP}$ – duration of one loading cycle; $P_{PGA}$ – pressure in the pneumohydraulic accumulator; $Q_{PGA}$ – the rate of flow of the working fluid in the pneumohydraulic battery. Energy $E_{CP}$ is determined during the first loading cycle, since for subsequent cycles, as the pneumatic-hydraulic accumulator is filled, the energy stored during the cycle gradually decreases.

The inertial properties of the hydraulic manipulator, which affect the acceleration and deceleration of the hydraulic manipulator links, depend on the mass of the assortment or the bundle of assortments, and, accordingly, should significantly affect the recovered energy. In order to study the effect of the assortment mass $m_{B}$ on the efficiency of the recovery system, a series of computer experiments were carried out, in which $m_{B}$ was changed from 100 to 500 kg with a step of 100 kg.

3. Results

There is obtained dependence of lifting angle $\alpha$ of hydraulic manipulator boom on turning angle of its column, which makes it possible to trace changes in values of these angles during unloading of grades by hydraulic manipulator (figure 4). Values of corners $\alpha = 0^0$ and $\phi = 0^0$ correspond to the provision of an arrow and column at the initial moment of capture by the assortment grab from a pack. The maximum values of corners $\alpha = 37^0$ and $\phi = 52^0$ correspond to the provision of an arrow and column at the time of overcoming by assortment of side limiters of a body of the forest car. Values of corners $\alpha = 15^0$ and $\phi = 90^0$ correspond to the provision of an arrow and column at the time of contact of assortment with a body of the forest car.

Dependence of mass of $m_{B}$ grade on the amount of recuperated hydraulic energy $E_{CP}$ in the pneumohydraulic accumulator per one loading cycle is revealed, which allows performing optimal use of recuperative hydraulic drive (figure 5). With an increase in the mass of the assortment $m_{B}$, the hydraulic energy stored in a single loading cycle, $E_{CP}$, increases almost linearly. Because of such a strong dependence, there arises the problem of selecting the optimal recuperative hydraulic drive. So, if submerged assortments differ significantly in diameter and length, it is impractical to use the
accumulation and return of recovered energy in the same cycle and it is necessary to use a high-capacity pneumohydraulic accumulator to save energy for several (2-20) cycles and use it after of this. If the submerged assortments are close in geometric parameters, it is advisable to organize the accumulation and use of energy within one loading cycle, which makes it possible to use small-volume pneumohydraulic accumulators.

It should be borne in mind that moving the boom even without an assortment, or with a light load (up to 50 kg), only because of the inertial properties of the hydraulic manipulator itself, allows you to store about 0.7…1.0 kJ of energy per round-trip cycle »Without load, but along the loading path of the assortment. Therefore, equipping a hydraulic manipulator with an energy recovery system is advisable in a wide range of modes of its operation: for both light and heavy loads.

4. Conclusion
Thus, the developed mathematical model of the hydromanipulator of the forest vehicle and the dependencies obtained during its study in the computer program allow to conclude, That the maximum efficiency from the use of the proposed recuperative hydraulic drive of the forest truck will be achieved during loading and unloading of varieties with the highest permissible mass, With minimum values of boom and column position angles at the moment of grabber grabbing, And with maximum values of angles of their position at the moment of lowering the grade into the body of the forest truck.

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