Simulation modeling of recuperative cone unit with ball bearing of road train

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Abstract. The ways of increasing the efficiency of tractors aggregated with mounted devices with disk implements during forest restoration activities are determined. A promising design of a recuperative mounted system of a tractor is proposed. A mathematical model is developed that describes the operation of the proposed mounted system during soil cultivation by a tractor. The dependencies of the influence of design and operational factors on the performance indicators of the proposed mounted system are revealed. It is established that with a hydraulic cylinder diameter of 60 mm of the mounted device of a disk implement, the value of the recuperated power reaches 0.55 kW. With an increase in the speed of the tractor, the height and density of obstacles, the intensity of pumping the working fluid into the pneumatic accumulator by the hydraulic cylinder increases, therefore, the recuperated power also increases.

1 Introduction

Russia holds the leading position among all countries in the world in terms of forest resources. Annual planned and illegal logging, forest fires and diseases lead to significant losses of forest resources and currently require measures related to reforestation. The main objects of the forest cultural fund of Russia, where reforestation measures are carried out, are unstumped fellings and burnt areas. Such measures at the considered objects, characterized by the presence of many different obstacles and irregularities, are carried out by tractors aggregated with mounted equipment. Taking into account the trends of increasing fuel costs, scientific research of many scientists is aimed at finding ways to reduce it, as well as increase the productivity and service life of tractors, as well as mounted soil-cultivating machines and tools aggregated with them.

Avello Fernandez L. in his work established the influence of the design parameters of the tractor's mounted system on the change in the forces acting on the moving tractor during the interaction of the mounted implement with the cultivated soil [1]. Changqing Liu in his article substantiated the possibility of improving the dynamic characteristics of the tractor through the use of the proposed algorithm for controlling the accuracy and stability of the electrohydraulic system of the tractor's mounted device [2]. De Simone M. C. proposed in his work an easy-to-maintain and inexpensive-to-produce autonomously controlled electric tractor, aggregated with various mounted equipment [3]. Deng X. in his

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study assessed the dynamic characteristics of a tractor equipped with an electric motor, the advantages of which are a significant reduction in harmful emissions during operation, as well as a sufficient power reserve for a given workload [4]. Jang M.-K. As a result of studying the influence of various factors on the possibility of lateral overturning of a tractor aggregated with mounted equipment, it was revealed that with an increase in the center of gravity of the tractor, an increase in the speed of movement, an increase in the transverse slope of the road, as well as the height of the obstacles to be overcome, the probability of lateral overturning of the tractor increases [5]. Liu C. in his article established that the use of the developed and described in the work method of active control of the process of damping loads arising in the hydraulic drive of a tractor aggregated with mounted equipment allows to reduce the negative impact of dynamic loads acting on the tractor, to improve the smoothness, comfort and safety of the unit's movement [6]. Luo Z. in his work evaluated the developed method for controlling the pressure of the working fluid in the hydraulic cylinder of the electrohydraulic mounted system of the tractor, which showed that the use of such a method makes it possible to reduce energy losses from the interaction of the mounted device of the implement with the soil while maintaining the required depth of penetration of the working bodies of the tillage implement, and also to improve the maneuverability of the tractor [7]. Zhou B. in his work substantiated the efficiency of using the proposed navigation system in tractors, which allows for the optimization of the movement process in real time, with improved accuracy, tracking of the speeds, trajectories and movement conditions of the tractor [8].

Analysis of scientific works shows that it is possible to achieve an increase in the efficiency of tractors aggregated with mounted equipment due to the following innovative developments: optimization of the design parameters of the tractor mounted system; use of new algorithms for controlling the accuracy and stability of the electro-hydraulic system of the mounted device; use of electrified tractors; taking into account road conditions during tractor operation; damping of dynamic loads acting on the tractor; use of energy-saving hydraulic drives; use of navigation systems that optimize the functioning of the tractor.

It is known that in the process of reforestation, when a tractor moves along unstumped clearings, the greatest efficiency is provided by mounted forest disk implements. This is due to the fact that such implements not only provide high quality soil cultivation, but are also more adapted to rolling over numerous obstacles. Despite this, the movement of a tractor in such conditions with mounted disk implements is accompanied by: collision of working bodies with obstacles, the impact of significant dynamic loads on the parts of both the implement itself and the mounted system and the tractor as a whole, a decrease in their reliability, deterioration in the productivity of the tillage unit, irreversible loss of kinetic energy of the mass of the disk implement, and, as a consequence, an increase in fuel consumption. In this regard, the development of promising recuperative mounted systems for a tractor that reduce the loads affecting the disk implement when encountering obstacles, as well as the conversion and accumulation of the recuperated energy of the working fluid, is an urgent and timely task.

The aim of the work includes: development of a promising design of a recuperative mounted system of a tractor; development of a mathematical model describing the operation of the proposed mounted system during soil cultivation by a tractor; research based on computer modeling of the influence of operational factors on the performance indicators of the recuperative mounted system of a tractor.

2 Methods and Materials

The authors' many years of experience in the development and research of recuperative systems and devices for transport and technological and forestry machines allowed them to

develop a promising design of a recuperative mounted system for a tractor (fig. 1). The use of such a mounted system allows: to reduce fuel consumption by the tractor by converting the potential energy of the disk implement mass into the energy of the working fluid with its subsequent accumulation in the pneumatic hydraulic accumulator and useful use in the work process; to increase the productivity of soil cultivation by the tractor; to reduce dynamic loads perceived by the mounted device and disk implements; to remotely change and hold disk implements at a given depth of soil cultivation, and, thereby, to improve the quality of its cultivation.

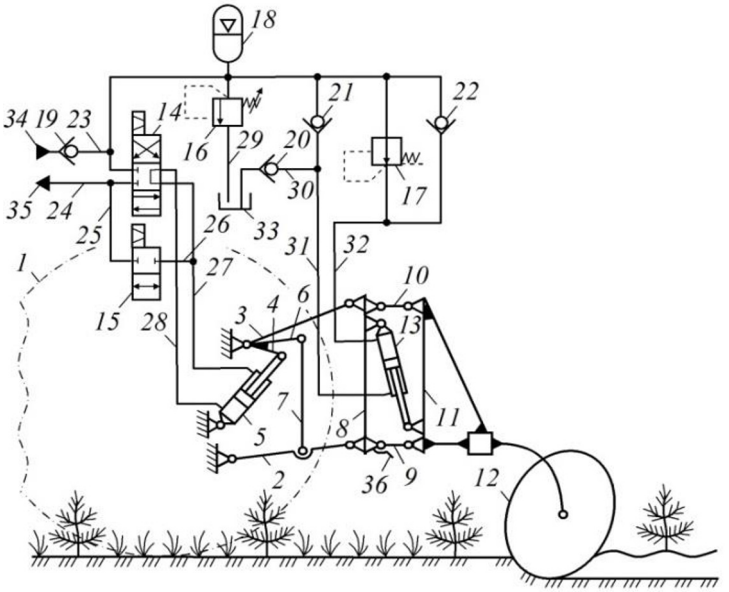


Fig. 1. Recuperative mounted system of the tractor: *1* – tractor; *2*, *3* – rods; *4*, *6*, *9*, *10* – levers; *5*, *13* – hydraulic cylinders; *7* – diagonals; *8* – triangular truss; *11* – frame; *12* – disk working bodies; *14*, *15* – hydraulic distributors; *16* and *17* – adjustable safety and pressure-reducing valves; *18* – pneumohydraulic accumulator; *19-22* – check valves; *23-32* – pipelines; *33* – hydraulic tank; *34*, *35* – pressure and drain ports.

When developing the mathematical model, the tractor wheels were considered as separate bodies performing rotational motion, as well as displacements in the vertical plane relative to the tractor body. The motion of the tractor body in the mathematical model is represented by the following system of equations:

$$\begin{cases} \dfrac{\partial x}{\partial t} = const = v_{trac.}; \\ y = const = 0; \\ m\dfrac{\partial^2 z}{\partial t^2} = F_1 + F_2 + F_3 + F_4, \\ J_x \dfrac{\partial^2 \phi_x}{\partial t^2} = \left(F_1 + F_2 - F_3 - F_4\right)\dfrac{a}{2}; \\ J_y \dfrac{\partial^2 \phi_y}{\partial t^2} = \left(F_1 - F_2 + F_3 - F_4\right)\dfrac{b}{2}; \\ \phi_z = const = 0, \end{cases} \quad (1)$$

where x, y, z – cartesian coordinates of the tractor's center of gravity; φ_x, φ_y, φ_z – angles of rotation of the tractor relative to the coordinate axes; $v_{trac.}$ – tractor speed; F_1-F_4 – forces acting from the wheels in the vertical plane on the tractor body; a – lateral distance between tractor wheels; b – longitudinal distance between tractor wheels.

The forces acting between the wheel and the tractor are determined by the following relationship:

$$F_i = c_{rigid.i}\left(z_{cur.i} - z_{equil.i}\right) - d_{rigid.i}\left(\frac{\partial z_{cur.i}}{\partial t} - \frac{\partial z_{equil.i}}{\partial t}\right), \tag{2}$$

where $c_{rigid.i}$ – wheel hardness; $z_{cur.i}$ – current coordinate of the center of the i-th wheel; $z_{equil.i}$ – equilibrium coordinate of the center of the i-th wheel.

$$F_{surf.i} = c_{surf.i}\left(z_{surf.i}\left(x_i, y_i\right) - \left(z_{equil._i} - R_{wheel}\right)\right) - d_{surf.i}\left(\frac{\partial z_{surf.i}\left(x_i, y_i\right)}{\partial t} - \frac{\partial z_{equil._i}}{\partial t}\right), \tag{3}$$

where x_i and y_i – cartesian coordinates of the center of the i-th wheel; R_{wheel} – wheel radius.

The force acting on the disk of the implement's mounted device is determined by the following relationship:

$$F_k = h_{kaver.}c_d - \frac{dh_{kaver.}}{dt}\theta_d, \tag{4}$$

where $h_{kaver.}$ – average value of disc penetration; c_d и θ_d – rigidity and damping coefficient of the attachment of the disc implement with the supporting surface.

The equations describing the operation of the hydraulic cylinder of the disk implement attachment are as follows:

$$\dot{v}_k = \left[p_i F_i - p_j F_j - h v_k - \left(R^0_{fric.} + k_i p_i + k_j p_j\right)\ sign\ v_k - R_{rod.}\right] / m, \tag{5}$$

$$\dot{z}_k = v_k,\ 0 \le z_k \le L_{hydr.cyl.}, \tag{6}$$

$$\dot{p}_i = \left(Q_i - F_i v_k\right) / k_{elas.\ i}, \tag{7}$$

$$\dot{p}_j = \left(F_j v_k - Q_j\right) / k_{elas.\ j}, \tag{8}$$

where m – reduced mass; F_i, F_j – working areas of the cavities of the hydraulic cylinder; h – coefficient of viscous friction; $R_{rod.}$ – rod force; $R^0_{fric.}$ – dry friction force.

The equations describing the operation of the pneumatic hydroaccumulator are as follows:

$$\dot{v}_k = \left[F\left(p_i - p_j\right) - h v_k - \left(R^0_{mp} + k_i p_i\right) sign\ v_k - c\left(z_k + z_0\right)\right]\ / m, \tag{9}$$

$$\dot{z}_k = v_k;\ 0 \le z_k < L_a = V / F, \tag{10}$$

$$\dot{p}_i = \left(Q_i - Fv_k\right)/k_{elas.i};\ \ p_j = p_0\left[L_a/\left(L_a - z_k\right)\right]^n - p_{atm}, \tag{11}$$

where $k_{elas.i}$ – coefficient of elasticity of the cavity with the working fluid; p_0 – gas charging pressure; F – working area of the pneumatic hydraulic accumulator piston; n – polytropic exponent; h – coefficient of viscous friction; c – spring stiffness; z_0 – spring pre-compression; $R^0_{fric.}$ – dry friction force; $p_{atm.}$ – atmospheric pressure.

The calculation of the recuperated power of the hydraulic cylinder of the disk implement attachment is carried out according to the following relationship:

$$N_{recup.} = P_{crit.} \cdot Q_{liq.}, \tag{12}$$

where Q_{lia} – volumetric flow rate of working fluid pumped into the pneumatic accumulator; P_{crit} – working fluid pressure.

The presented mathematical model allowed to develop a computer program simulating the operation of the tractor's recuperative mounted system. This program provides the ability to study the influence of the following factors on the change in the recuperated power of the tractor's mounted device hydraulic cylinder: tractor speed, hydraulic cylinder diameter, height of the obstacle to be overcome, obstacle density on the investigated section of the support surface.

3 Results and Discussion

When studying the influence of the diameter $D_{\text{hydr.}}$ of the hydraulic cylinder of the mounted device of the disk tool on the charging time $t_{\text{char.}}$ of the pneumatic-hydraulic accumulator and the recuperated power $N_{\text{recup.}}$, the value of the diameter $D_{\text{hydr.}}$ of the hydraulic cylinder was changed in the range from 25 mm to 70 mm with a step of 5 mm (fig. 2). It was revealed that the minimum charging time $t_{\text{char.}}$ of the pneumatic-hydraulic accumulator, equal to 49 s, is achieved using a hydraulic cylinder with a diameter $D_{\text{hydr.}}$ of 60 mm (fig. 2, *a*). The maximum value of the recuperated power $N_{\text{recup.}}$, equal to 0.55 kW, is provided by a hydraulic cylinder with a diameter $D_{\text{hydr.}}$ of 60 mm (fig. 2, *b*). At smaller values of the diameter $D_{\text{hydr.}}$, the reverse force action of the hydraulic cylinder is great, and, as a result, the intensity of pumping the working fluid into the pneumatic-hydraulic accumulator is low. At large values of diameter $D_{\text{hydr.}}$, the hydraulic cylinder has a slight reverse effect, as a result of which the intensity of pumping of the working fluid is also low.

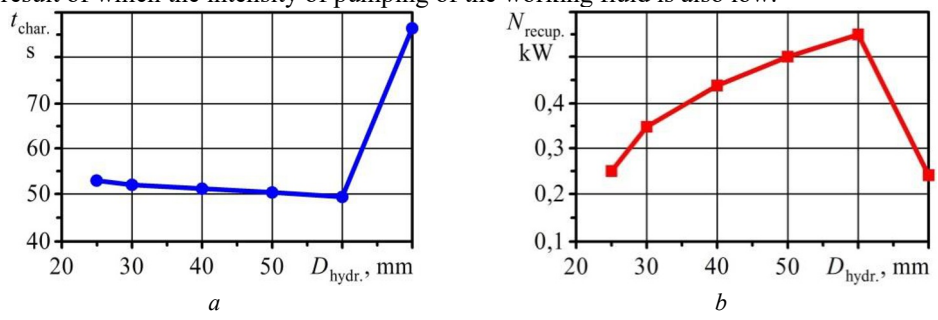
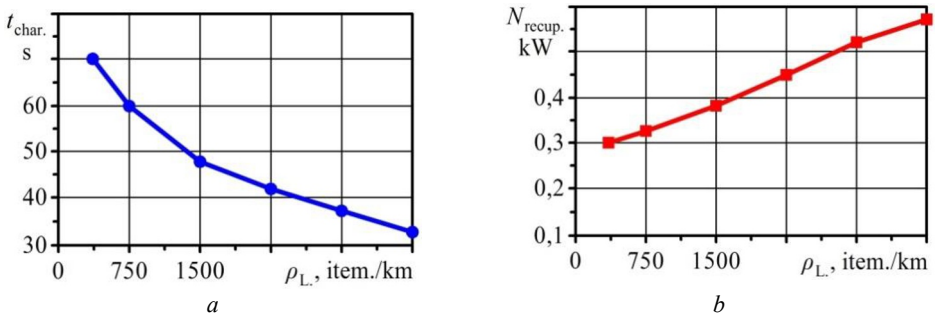


Fig. 2. Graphs of the influence of the diameter $D_{\text{hydr.}}$ of the hydraulic cylinder of the disk implement attachment on the charging time $t_{\text{char.}}$ of the pneumatic hydraulic accumulator – *a* and the recuperated power $N_{\text{recup.}}$ – *b*.

When studying the influence of the obstacle density ρ_L on the support surface when moving a tractor equipped with a mounted device with a disk implement on the charging time $t_{char.}$ of the pneumatic-hydraulic accumulator and the recuperated power $N_{recup.}$, the density value ρ_L was increased in increments of 750 pcs/km in the range from 400 to 3750 pcs/km (fig. 3). It was found that with an increase in the obstacle density ρ_L, the frequency of encounters of the disk implement with obstacles increases, and, as a consequence, the frequency of movement of the piston in the hydraulic cylinder of the mounted device of the disk implement. With an increase in the obstacle density ρ_L, the charging time $t_{char.}$ of the pneumatic-hydraulic accumulator decreases from 70 s to 32 s (fig. 3, *a*), and the recuperated power $N_{recup.}$ increases from 0.3 to 0.58 kW (fig. 3, *b*).

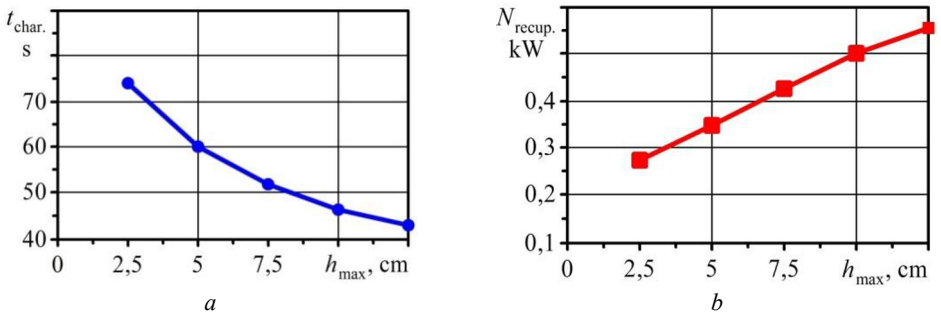
When studying the influence of the height h_{max} of obstacles overcome by a tractor equipped with a mounted device with a disk implement on the charging time $t_{char.}$ of the



a *b*

Fig. 3. Graphs of the influence of the density ρ_L of the location of obstacles on the supporting surface when a tractor equipped with a mounted device with a disk implement moves along them on the charging time $t_{char.}$ of the pneumatic-hydraulic accumulator – *a* and the recuperated power $N_{recup.}$ – *b*.

Pneumatic-hydraulic accumulator and the recuperated power $N_{recup.}$, the value of the height h_{max} of obstacles was changed in the range from 2.5 to 12.5 cm with a step of 2.5 cm (fig. 4). It was revealed that with an increase in the height h_{max} of obstacles, the charging time $t_{char.}$ of the pneumatic-hydraulic accumulator decreases from 74 s to 43 s (fig. 4, *a*), and the recuperated power $N_{recup.}$ increases from 0.27 to 0.55 kW (fig. 4, *b*).

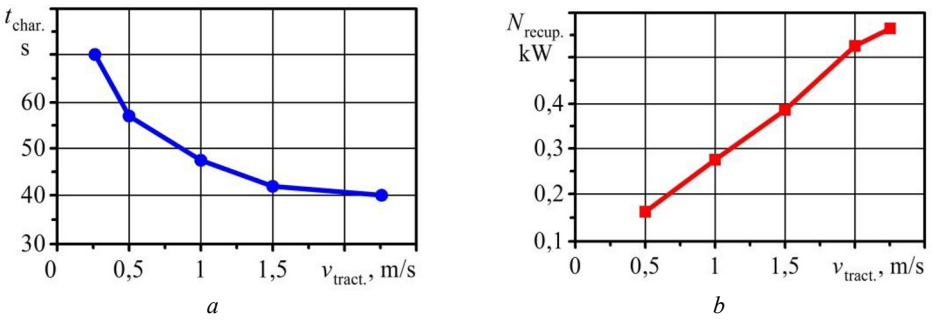


a *b*

Fig. 4. Graphs of the influence of the height h_{max} of obstacles overcome by a tractor equipped with a mounted device with a disk implement on the charging time $t_{char.}$ of the pneumatic hydroaccumulator – *a* and the recuperated power $N_{recup.}$ – *b*.

When studying the influence of the travel speed $v_{tract.}$ of a tractor equipped with a mounted device with a disk implement on the charging time $t_{char.}$ of the pneumatic-hydraulic accumulator and the recuperated power $N_{recup.}$, the travel speed $v_{tract.}$ of the tractor was changed in the range from 0 to 2.5 m/s with a step of 0.5 m/s (fig. 5). It was found that with an increase in the travel speed $v_{tract.}$ of the tractor, the charging time $t_{char.}$ of the

pneumatic-hydraulic accumulator decreases from 70 s to 40 s (fig. 5, *a*), and the recuperated power $N_{recup.}$ increases from 0.16 to 0.56 kW (fig. 5, *b*).



a *b*

Fig. 5. Graphs of the influence of the speed of movement $v_{tract.}$ of a tractor equipped with a mounted device with a disk tool on the charging time $t_{char.}$ of the pneumatic-hydraulic accumulator – *a* and the recuperated power $N_{recup.}$ – *b*.

4 Conclusion

The use of the proposed design of the recuperative mounted system of the tractor makes it possible to increase the efficiency of the tillage unit in difficult conditions of its movement on unstumped clearings and burnt areas. The obtained dependence graphs allow us to conclude that the optimal value of the diameter of the hydraulic cylinder of the mounted device when aggregating with most of the used disk tools, providing the maximum value of the recuperated power, is within 50-70 mm. With an increase in the speed of the tractor, the height and density of obstacles, the intensity of pumping the working fluid of the pneumatic hydraulic accumulator by the hydraulic cylinder increases, therefore, the recuperated power also increases. The recuperative mounted system of the tractor can also be effectively used in the implementation of preventive measures related to ensuring fire safety, due to the creation of a system of mineralized strips and plowing of monocultures of coniferous species.

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