Assessment of the effectiveness of the regenerative suspension of a timber truck based on the results of simulation

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Abstract. The relevance of using various recuperative mechanisms in vehicle suspensions is justified in order to reduce fuel consumption and improve their environmental performance. The developed hydraulic drive scheme and a mathematical model of the movement of a forest car equipped with a suspension with a recuperative mechanism are presented. An assessment of the effectiveness of the regenerative suspension of a timber truck was carried out according to the results of simulation. Analytical dependences of the influence of time, speed and diameters of recuperative suspension hydraulic cylinders on the values of recuperative power under various conditions of movement of a forest car are obtained.

1. Introduction
Timber removal by a logging truck under logging conditions is accompanied by the occurrence of a large number of longitudinal and transverse vibrations of the sprung mass in its suspension while overcoming various obstacles that arise on the logging road. This in turn leads to the appearance of significant heat losses during the conversion of vibrational energy, causing an increase in fuel consumption. Constantly increasing requirements for fuel efficiency contribute to the development of a scientific field related to the recovery of various types of energy in the suspension of a forest car [1, 2].

Gao ZP et al. Scientists conducted a study of the management strategy for energy storage of electromagnetic active suspension in various road conditions. A complex gamma correlation coefficient for changes in energy storage productivity was revealed. Using the proposed strategy will reduce the system’s energy consumption by 14.51 %, restore 2.45 % of energy, and improve the vehicle’s traffic conditions [3]. Zheng P et al. In their work investigated a regenerative hydraulic-electric suspension, which allows the vehicle to accumulate vibration energy during its movement on the road. They proposed models of road profiles, optimized battery capacity and electrical load. Modeling showed that regenerative suspension can restore 100–400 watts of power with different quality of the roadbed [4]. Jia Y et al. In the article conducted an analytical and numerical study of a magnetic spring recuperative suspension, found that the amount of energy accumulated by a car when driving on an asphalt road is 100 kW [5]. Guo ZJ and others in their work investigated the structure and principle of operation of the regenerative suspension, which allows the accumulation and reuse of electromagnetic energy. Based on the simulation, the effect of vehicle speed on the power output was established. At a vehicle speed of 60 km/h, the output current of recuperated energy is 1.53 A [6]. Lv X and others in their article examined the operation of a vehicle equipped with a recuperative hydraulic suspension that allows you to convert and accumulate energy arising from colliding with obstacles into electric, identified important factors...
that affect the shock absorbing properties, as well as the amount of energy stored by the suspension [7].

Sun Z et al. In their research cited a system for recovering and reusing energy in a vehicle’s suspension. By modeling in various road conditions, a comparison of the obtained recuperated power was performed [8]. In the materials of the article, Yu W et al. Led a comprehensive study of energy recovery technologies used simultaneously in a vehicle. A new power balance strategy has been developed that ensures the rational use and storage of extracted energy, as well as increasing the efficiency of conversion of this energy. The results also showed that the profit when applying the proposed strategy increases with increasing amount of recoverable energy [9]. The study of Taghavifar H and Rakheja S is aimed at studying the accurate assessment of the accumulated energy from the suspension of a vehicle in typical operating conditions. On the basis of mathematical modeling and data obtained in laboratory conditions, it was established that the amount of energy accumulated to a greater extent is affected by the number of roughnesses on the road, and to a lesser extent the speed of the vehicle [10]. Zou J et al. Conducted a study of energy recovery in an interlocking hydraulic suspension using recuperative shock absorbers. The results of mathematical modeling showed that regenerative shock absorbers can attenuate vibrations, improve driving conditions for the driver, and also accumulate energy to power the vehicle’s electrical equipment [11]. The work of Zhang J et al. Is devoted to the study of the energy efficiency of vibration of a car’s suspension, as well as the development of a dynamic model of energy recovery of an electromagnetic suspension system. The results obtained indicate that the proposed model makes it possible to determine the power of accumulated energy with high accuracy [12].

Zhao L et al. Conducted a study to reduce vehicle energy consumption by using a recuperative hydraulic damper in its design. Based on the developed simulation model, it was revealed that the damping characteristics of the damper meet the requirements of current standards, the accumulation of hydraulic energy is carried out during compression strokes, as well as increasing driver comfort when driving a vehicle [13]. Wen G et al. Proposed a new design of a regenerative hydroelectric suspension. Based on the developed mathematical model, an analysis of its main characteristics is performed. It was revealed that at a vehicle speed of 50 km/h the energy recovery rate was 42.3 % [14]. Wang R and other scientists in the article presented a new system for restoring vibration energy in a suspension by converting it into electric current to improve the dynamic characteristics of the entire vehicle. Based on simulation, in conditions of car movement on an asphalt road, it was revealed that this suspension has improved dynamic characteristics, as well as reduced angular and vertical accelerations of the car body [15]. Zhang H et al. Investigated the regenerative semi-active suspension of a vehicle under low-quality road conditions, as well as performed simulation and bench tests of this suspension. It was established that at the resonant frequency of the sprung mass, the amplitude of the parameters of the suspension index is ranked in decreasing order, the amount of stored energy increases with increasing number of obstacles on the road [16]. Chen L and others in their article cited the results of research and optimization based on simulation of the operation of a regenerative hydraulically interconnected suspension. The results showed that the dynamic characteristics of a car equipped with the proposed suspension are inferior to traditional interconnected suspensions, however, it can be operated in various road conditions and restore part of the vibration energy while maintaining comfortable conditions for the driver when driving [17].

Despite the significant scientific contribution of foreign researchers to the development and study of many structural designs of vehicle suspensions with the recovery of various types of energy, the results of the considered developments should not be mechanically applied to all types of vehicles due to the specific features of their use. Currently, rational circuit designs and scientific approaches have not yet been developed that are associated with the recovery of hydraulic energy in the suspensions of timber trucks. In this regard, the research carried out by the authors in this direction is relevant and timely.

The aim of the work is to evaluate the effectiveness of the regenerative suspension of a timber truck according to the results of simulation modeling, as well as to identify the dependences of the influence of time, speed and diameters of the hydraulic cylinders of the regenerative suspension on the values of the regenerative power for various conditions of movement of the timber truck.
2. Materials and methods

Based on the analysis of the results of numerous studies in studying the state of the issue, the authors proposed the design of a timber truck with a regenerative hydraulic drive, in which the suspension of the timber truck (figure 1) performs the function of the regenerative mechanism [18].

![Figure 1. The hydraulic circuit with a regenerative mechanism in suspension of a forest car: 1 – recuperative suspension mechanism; 2-4 – control valves; 5 – pump-accumulator unit; 6-8 – hydraulic cylinders of the boom, stick and slewing ring.](image)

Evaluation of the effectiveness of using a suspension with a recuperative mechanism in the design of a forest car, as well as the determination of its optimal design parameters, was carried out on the basis of a developed mathematical model for the movement of a forest car on a low-quality forest road. In the process of developing a mathematical model, the well-known methods of classical mechanics were used [19].

In the developed mathematical model, a forest car was described by a rigid body moving in three-dimensional space, perceiving force from six wheels when hitting a roughness of a forest road. The mass \(m\) of the truck and the moment of inertia \(J\) were determined at any time for the current axis of rotation. The determination of the position in space of a forest car in a mathematical model is described by the Cartesian coordinates of its gravity (\(x, y, z\)) and the deflection angles by the local coordinate system (\(\phi_x, \phi_y, \phi_z\)). To describe the movement in the mathematical model of a forest car, a system of differential equations was used, including the basic laws of dynamics of translational and rotational motion:

\[
\begin{align*}
\frac{d^2 x}{dt^2} &= \sum_{i=1}^{3} F_{\text{lef},i}^x + \sum_{i=1}^{3} F_{\text{rig},i}^x; \\
\frac{d^2 y}{dt^2} &= \sum_{i=1}^{3} F_{\text{lef},i}^y + \sum_{i=1}^{3} F_{\text{rig},i}^y; \\
\frac{d^2 z}{dt^2} &= -m_{\text{ub}} \cdot g + \sum_{i=1}^{3} F_{\text{lef},i}^z + \sum_{i=1}^{3} F_{\text{rig},i}^z; \\
J_x \frac{d^2 \phi_x}{dt^2} &= \sum_{i=1}^{3} M^x(F_{\text{lef},i}) + \sum_{i=1}^{3} M^x(F_{\text{rig},i}); \\
J_y \frac{d^2 \phi_y}{dt^2} &= \sum_{i=1}^{3} M^y(F_{\text{lef},i}) + \sum_{i=1}^{3} M^y(F_{\text{rig},i}); \\
J_z \frac{d^2 \phi_z}{dt^2} &= \sum_{i=1}^{3} M^z(F_{\text{lef},i}) + \sum_{i=1}^{3} M^z(F_{\text{rig},i});
\end{align*}
\]  

(1)

where \(t\) – time; \(F_{\text{lef},i}\) and \(F_{\text{rig},i}\) – the forces perceived by the suspension of a timber truck from the wheels of the left "lef." and right "rig." sides; \(M^i\) – moments of the considered forces relative to the axis \(i\).
To carry out the initial assessment studies, a simplified mathematical model of the wheel was used, in which the deformation of the wheel was not taken into account, and it was also taken into account that the change in height from the frame of the forest car to the supporting surface of the forest road is associated with the functioning of the suspension. The support force from the side of the wheel to the frame of the logging vehicle was determined taking into account their viscoelastic interaction according to the formula:

\[ F_i^w = c_i \left( z_{rig,i}(x_i, y_i) + R_{wh,i} - z_{wh,i} \right) - d_i \left( \frac{\partial^2 z_{wh,i}(x_i, y_i)}{\partial t^2} - \frac{\partial z_{wh,i}(x_i, y_i)}{\partial t} \right), \]  

(2)

where \( i \) – the wheel number; \( c_i \) – the stiffness coefficient of viscoelastic interaction; \( z_{rig,i}(x, y) \) – the vertical coordinate of the surface of the forest road under the wheel of the forest truck, equal to the coordinate of the lower point of the wheel; \( z_{wh,i} \) – the vertical coordinate of the point of attachment of the wheel to the frame of the forest car; \( R_{wh} \) – the radius of the wheel of the forest car; \( d_i \) – the viscous-elastic interaction damping coefficient.

The wheels of the forest car perceive the adhesion forces to the supporting surface of the forest road, in order to prevent the forest car from tipping over, the condition for the transverse component of the adhesion forces to the forest road required for this value to be met. The traction force acting on the side of its driving wheels also affects the forest car frame. These forces, acting comprehensively on a forest car, contribute to its movement in the three-dimensional space of the mathematical model.

The system of second-order differential equations describing the system of equations of motion for a forest car does not have an analytical solution in the general case, due to the impossibility of the required substitution of nonanalytic perturbing functions acting from the supporting surface of the forest road. In this regard, to solve this system of equations with the required accuracy, a second-order numerical Runge-Kutta method is used. This method consists in discretizing the time \( t \) into equal intervals, denoted by the variable \( \tau \), with a step \( \Delta t \). At each step of integration, the calculation of forces and moments acting from the wheels through the suspension onto the frame of the forest car is performed. Further, according to the known coordinates and speeds of the frame of the forest car at the current integration step, the coordinates and speeds are calculated at the next integration step. Numerical integration for the \( x \)-cartesian component is performed as follows:

\[
\begin{align*}
x_{t+1} &= x_t + v_{xt} \cdot \Delta t + F_{xt} \cdot \frac{\Delta t^2}{2}; \\
v_{xt+1} &= v_{xt} + F_{xt} \cdot \Delta t,
\end{align*}
\]  

(3)

where \( x_t, v_{xt}, x_{t+1}, v_{xt+1} \) – the coordinates and speeds of a forest car of mass \( m \) along the \( x \) axis in the previous and subsequent integration steps.

In the process of calculating the previous coordinates and speeds in the following, they find the functions of the time dependence of the angles and coordinates of the location of the forest car. Next, an analysis of these functions is carried out in order to assess the characteristics of the slope, amplitude and frequency of oscillations of the frame of the forest car.

To study the rotation of a forest car on a forest road, a horizontal supporting surface was used, described by \( f_i(t) \) equal to 0. To study the movement of a forest car in a straight line along a low quality forest road, the relief of the supporting surface consisting of overhangs extending from 2 to 5 m and obstacles with a length of 0.2 to 0.5 m.

Also, in the framework of the mathematical model, the function of the surface height from the coordinate of the contact point \( z(x_i, y_i) \) was described as a superposition of Gaussian peaks with roughness parameters on the forest road \( x_i, y_i \), the height of these roughnesses \( H_i \) and the standard deviation \( \sigma_i \) of the roughness width:
\[ z(x, y) = \sum_{i=1}^{N_{\text{prof}}+N_{\text{let}}} H_i \exp \left( -\frac{(x-x_i)^2 + (y-y_i)^2}{\sigma_i^2} \right), \] (4)

where \( N_{\text{prof}}, N_{\text{let}} \) – respectively, the number of protrusions and obstacles.

Next, at each step of numerical integration, the instantaneous value of the recuperated power in the suspension of a timber truck was determined:

\[ N_{\text{rec}}(t) = \sum_{i=1}^{6} (v_{\text{wh},i})^2 d_0 \left( \frac{D_{\text{hyd}}}{D_{\text{hyd},0}} \right)^2, \] (5)

where \( i \) – the wheel number of the forest car; \( v_{\text{wh},i} \) – component of the speed of the forest truck along the \( z \) axis of the wheel mounting point; \( d_0 \) – the damping coefficient; \( D_{\text{hyd}} \) – the diameter of the hydraulic cylinder of the regenerative suspension mechanism.

After that, the calculation of the maximum \( N_{\text{rec, max}} \) and the average \( N_{\text{rec, av}} \) of the recovered power was performed according to the function \( N_{\text{rec}}(t) \):

\[ N_{\text{rec, max}} = \max_{t_{\text{st,turn}} < t < t_{\text{en,turn}}} (N_{\text{rec}}(t)); \] (6)

\[ N_{\text{rec, av}} = \frac{1}{t_{\text{en,turn}} - t_{\text{st,turn}}} \int_{t_{\text{st,turn}}}^{t_{\text{en,turn}}} N_{\text{rec}}(t)dt, \] (7)

where \( t_{\text{st,turn}} \) and \( t_{\text{en,turn}} \) – time points at which the turn of the forest car begins and ends.

At the end of the formation of the mathematical model, according to the indicators calculated above, acting as criteria for optimizing the parameters, the diameter of the hydraulic cylinder \( D_{\text{hyd}} \) of the regenerative suspension mechanism was determined:

\[ N_{\text{rec, av}}(D_{\text{hyd}}) \rightarrow \max. \] (8)

To implement the developed mathematical model in order to assess the effectiveness of the regenerative suspension of a forest car, a computer program was developed in Object Pascal language in the Delphi 7 programming environment, which allows to reveal the dependences of the influence of time, speed and diameters of the regenerative suspension hydraulic cylinders on the value of the regenerative power in various conditions of movement of the forest car [20].

To study the effect of the diameter of the hydraulic cylinder \( D_{\text{hyd}} \) of the regenerative suspension mechanism on the intensity of energy accumulation of the working fluid, as well as on the efficiency of smoothing the vibrations of the frame of the logging truck, we performed a series of experiments in the developed computer program in which the diameter of the hydraulic cylinder \( D_{\text{hyd}} \) was changed with a step of 10 mm from 30 to 100 mm. To study the effect of the speed \( v \) of a logging car when it turns on the values of the recovered power \( N_{\text{rec, max}} \) and \( N_{\text{rec, av}} \), a series of experiments was carried out in the developed computer program in which the speed \( v \) was varied with a step of 10 km/h in the range from 30 to 90 km/h.

3. Results

It was revealed that the maximum values of recuperated power \( N_{\text{rec, max}} \) and \( N_{\text{rec, av}} \) are observed when the diameter of the hydraulic cylinder \( D_{\text{hyd}} \) is in the range from 50 to 60 mm «figure 2, a». With an increase in the diameter of the hydraulic cylinder \( D_{\text{hyd}} \), the damping of the oscillations of the frame of the logging truck «figure 2, b, 3 – \( D_{\text{hyd}} = 100 \) mm» improves, which leads to a deterioration in the effect of energy recovery in the suspension hydraulic cylinder, due to the small amplitude of its stroke. With a decrease in the diameter of the hydraulic cylinder \( D_{\text{hyd}} \) «figure 2, b, 2 – \( D_{\text{hyd}} = 60 \) mm and 1 – \( D_{\text{hyd}} = 30 \) mm»*, the amplitude of the piston stroke in the suspension hydraulic cylinder increases when the timber truck hits
an obstacle and the recovered power increases. However, in this case, the amount of accumulated working fluid decreases with each movement of the piston of the suspension hydraulic cylinder.

![Dependences of the influence of time, speed, and diameters of regenerative suspension hydraulic cylinders on the values of regenerative power in various conditions of movement of a timber truck.](image)

**Figure 2.** Dependences of the influence of time, speed, and diameters of regenerative suspension hydraulic cylinders on the values of regenerative power in various conditions of movement of a timber truck.

The results of computer experiments made it possible to determine that with an increase in the rotation speed \( v \) of the logging truck, there is a significant increase in the recuperated power \( N_{\text{rec,max}} \) and \( N_{\text{rec.av}} \) (figure 2, c). It was revealed that the maximum peak of recuperated power is affected by the largest peak of fluctuations in the suspension of the logging truck, obtained with the maximum mass transfer of the logging truck to one of its sides (figure 2, d; 1 – \( v = 30 \) km/h, 2 – \( v = 50 \) km/h, 3 – \( v = 90 \) km/h). In the process of changing the speed of the forest car when it turns from 70 to 90 km/h, an increase in regenerative power is observed from 40 to 340 kW (figure 2, c). For real rates of entry into the turn of a timber truck, the regenerative power will be 5–8 kW. It was also revealed that with an increase in the turn-through speed of the logging truck, there is an increase in the average recovered capacity (figure 2, c). At the same time, the values of the average recuperated power for the real rates of entry into the turn of the forest car are in the range from 1 to 4 kW.

4. Conclusion

Thus, the developed mathematical model, and a computer program based on it, made it possible to evaluate the effectiveness of the regenerative suspension of a timber truck in various conditions of its
movement. The use of a suspension with energy recovery of the working fluid in a forest car will enable it to increase the recuperated power in the range from 1 to 7 kW when driving along a forest road with a large number of turns. In the recuperative suspension mechanism, the most rational is the use of a hydraulic cylinder with a diameter of 50 to 60 mm, which, at the highest possible speed of the forest car, will allow reaching the maximum value of the recuperated power with effective damping of the vibrations of its frame.

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