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Movement simulation modeling of the wheeled logging machine with a vertically held tree

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Abstract

The purpose of the study is to determine the parameters of dynamics, stability and loading of a wheeled logging machine with a vertically held tree under various operating conditions taking into account the interaction of its subsystems, the influence of external factors and control forces. For this purpose, a multi-mass mathematical model of the dynamic system "Logging machine - vertical tree" was developed. The model is based on a systematic approach and takes into account the mutual influence of the main subsystems of the logging machine (such as the engine, transmission, technological equipment, and tree). The mathematical model is based on the calculation scheme of a wheeled logging machine with a vertically held tree. The logging machine is described by the kinematic scheme of the basic tractor and attachments. The analysis of the calculation scheme was carried out by constructing differential equations of motion of a logging machine, followed by checking the balance of forces and moments. The parameters of external disturbing factors and control actions necessary for calculation were determined by analogy with the dynamic loading of agricultural, machine-tractor units and road trains. As a result of differential equation numerical solution, the values of dynamic parameters were obtained and graphs of dynamic parameters of a logging machine with a vertically held tree were constructed. Movement simulation modeling of the logging machine with a vertically held tree on an uneven surface at different speeds was carried out. It showed that most dynamic parameters increase with increasing speed but the longitudinal movement of the logging machine and the angular movement of its gravity center, on the contrary, decrease. The conducted research shows that the proposed mathematical model describes the dynamic system properties taking into account the interaction of its subsystems, the effects of the external environment and control actions. Thus, it allows to solve a wide range of dynamic tasks.

Keywords: Dynamics, Oscillations, Disturbing influences, Simulation modeling, Logging, Logging machine, Tree

1. Introduction

To reduce the negative impact of logging on the forest environment some logging technologies involve the use of frontal logging machines to move a cut tree under the forest canopy in an upright position [1–4]. The retention of the tree in an upright position with this technology is mainly due to the predominant mass of the basic machine [1, 5–8]. But moving a tree in an upright position with a wheeled tractor of a small traction class has not received practical application and is implemented mainly within the framework of scientific research [2, 4, 9–11]. In our opinion this is due to the lack of theoretical research to determine the dynamic parameters of the "Logging machine - vertical tree" system under various operating conditions. Therefore, the purpose of this study is to determine the parameters of dynamics, stability and loading of a logging machine under various operating conditions, taking into account the interaction of its subsystems, the impact of external factors and control actions. The determination of the parameters is based on the dynamic system mathematical model of a logging machine movement described as wheeled tractor with a vertically held tree. Movement simulation modeling of a logging machine with a vertically held tree due to the operation of elastic elements is characterized by the interrelated action of external influences and control forces [12–16]. The following factors can be distinguished as external disturbing influences affecting the dynamic parameters of the "Logging machine – vertical tree" system: unevenness of the support surface, engine torque, resistance to movement (wind resistance or branches clinging to nearby trees) [14, 17, 18].

The actions of external disturbing influences in most cases are random. Therefore, it is advisable to use appropriate probabilistic indicators to assess the movement process of a logging machine with a vertically held tree. Also, during transients, the action time and peak values of linear and angular deviations of the dynamic system elements were taken into account which occur during acceleration and braking of the machine, hitting large obstacles and the masses movement of the gripping and cutting device.

Usually, these dynamic phenomena are accompanied by vibrations of both the machine as a whole and their working bodies. The resulting oscillations are described using basic dynamic parameters such as mass, angular and linear displacements, moments of inertia, stiffness and resistance of elastic elements [19, 20].

As a result of applying all the described modeling principles the mathematical model of a logging machine with a vertically held tree will describe the properties of a dynamic system under the influence of external disturbances, control actions and taking into account the interaction of subsystems.

2. Material and Method

2.1. Mathematical modeling

In our opinion it is reasonable to determine the dynamic parameters of elastic and dissipative elements by analyzing a multi-mass nonlinear interdependent mathematical model, which is developed on the basis of a systematic approach and takes into account the mutual influence of the logging machine main subsystems.

The main components and assemblies of a logging machine such as the engine, transmission, drive axles, wheels, gripping and cutting device (GCD), tree are assembled in the form of subsystems connected by elastic elements.

During the development of the mathematical model, a calculation scheme of the dynamic system "Logging machine – vertical tree" (Figure 1) was proposed based on the kinematic scheme of a tractor and GCD with a vertical tree.

When developing the calculation scheme of the dynamic system "Logging machine – vertical tree", a number of assumptions were made: the wheelbase of the machine is considered as a flat system which is symmetrical in the longitudinal axis; the unallocated masses of the base tractor, chassis system and tree are replaced by concentrated, connected inertia-free elastic damping links; when moving the tree in a vertical position the logging machine moves in a straight line without ascents and descents; when the machine is moving, the wheels rotate evenly, without inertia and slippage; wheels come into contact with the support surface at one point without puncturing; stiffness of transmission elements, tires, attachments and tree are constant; high-frequency vibrations of moving transmission elements are not taken into account.

The tractor idealization was carried out using two sprung solids with masses concentrated in the front axle m_{af} and in the gravity center of the tractor M_T. The tree is represented as three discrete masses connected by inertia–free rods: m_{t1} is the mass of the tree trunk lower part and the GCD, m_{t2} is the mass in the tree gravity center, m_{t3} is the tree crown mass. The scheme also takes into account the driver mass m_d the logging machine.

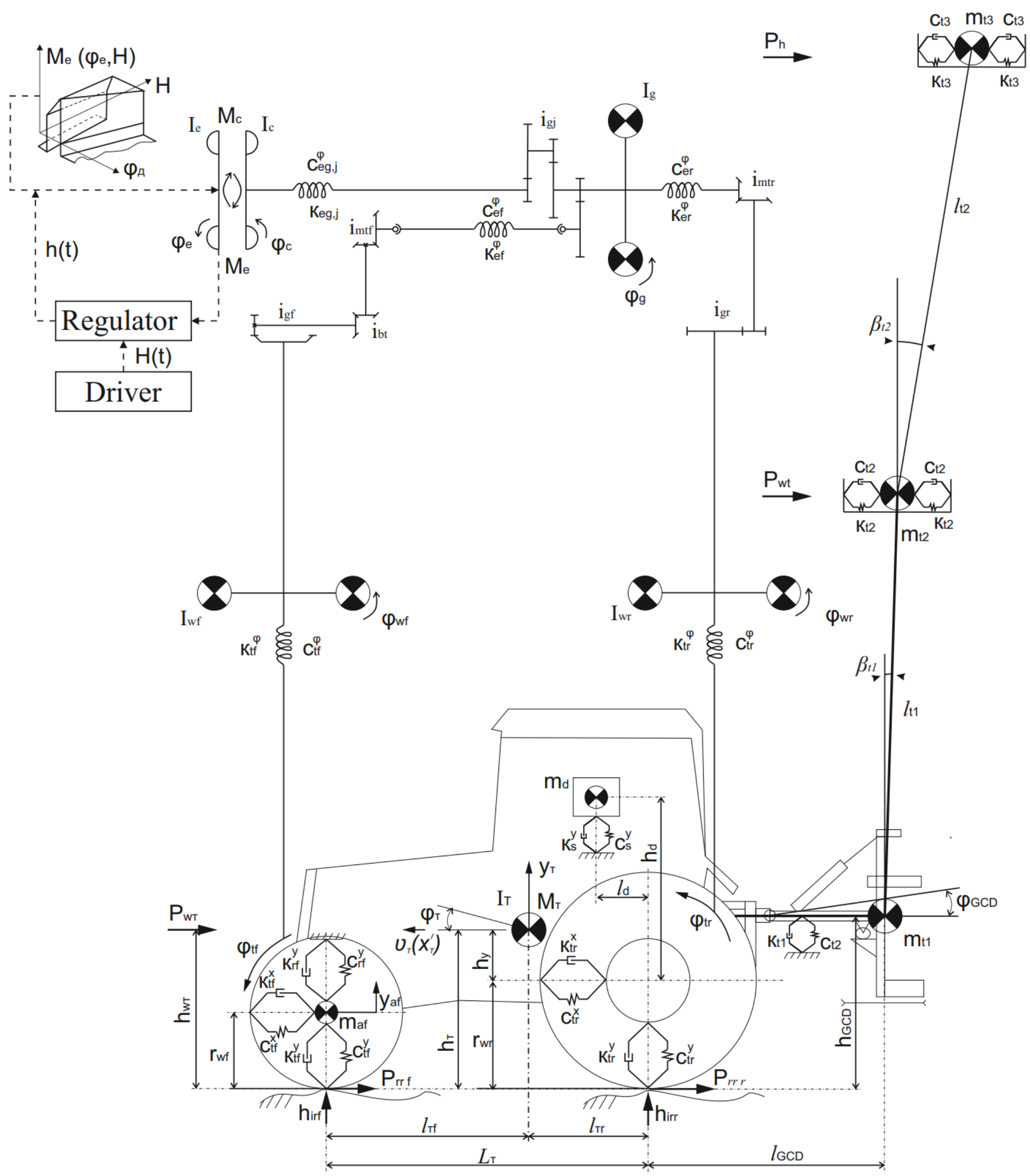

Figure 1
Calculation scheme of the logging machine movement process with a dynamically held tree in an upright position

The position of a logging machine with a vertically held tree is set by generalized coordinates such as: angular displacement of the tractor's gravity center φ_T; angular displacement of the GCD φ_{GCD}; angular displacement of the front and rear wheels φ_{wf}, φ_{wr}; angle of engine crankshaft rotation φ_e; rotation angles of transmission elements, clutch and gearbox output shaft φ_c, φ_g; gravity center vertical movements of the tractor and the front axle y_T, y_{af}; longitudinal movement of the machine x_T; rotation angle of discrete tree masses β_{t1}, β_{t2}.
The inertia of the system mass elements is determined through the corresponding inertia moments such as: the inertia moment of a logging machine with a tree J_T; the rotating masses inertia moment of the engine and the clutch leading parts J_e; the inertia moment of the driven parts and the clutch shaft J_c; the inertia moment of the secondary shaft with associated gearbox parts in the selected (j-th) gear up to the middle of the half-

axes of the front and rear axles, inclusive of J_g; the total wheels inertia moments of the front and rear drive axles with associated transmission parts $J_{wf\,(wr)}$; the inertia moment of the corresponding tree mass, J_{t1}, J_{t2}.
In places of elastic joints the connection of the system elements is set by the corresponding stiffness and resistance: C_{t1}, K_{t1} – stiffness and resistance of the GCD elements; C_{t2}, K_{t2} - stiffness and resistance to bending deformations of the tree trunk; C_s, K_s – stiffness and resistance of the driver's seat suspension; $C^{\varphi}_{ef\,(er)}$, $K^{\varphi}_{ef(er)}$– equivalent torsional stiffness and resistance of the tractor front and rear axles drive shafts ; C^{φ}_{egj}, K^{φ}_{egj}– equivalent torsional stiffness and resistance of the transmission shafts and the clutch shaft on the j-th gear (reduced to the primary shaft); $C^{\varphi}_{tf\,(tr)}$, $K^{\varphi}_{tf(tr)}$– total torsional stiffness and resistance of the machine front and rear axles tires ; $C^{y}_{tf(tr)}$, $K^{y}_{tf(tr)}$– total vertical stiffness and resistance of the tractor front and rear axles tires ; C^{y}_{rf}, K^{y}_{rr}– total vertical stiffness and suspension resistance of the tractor front axle; $C^{x}_{rf\,(rr)}$, $K^{x}_{rf\,(rr)}$– total horizontal stiffness and suspension resistance of the tractor front and rear axles; C^{y}_{s}, K^{y}_{s}– total vertical stiffness and resistance of the operator's seat.
The geometric relationship in the calculation scheme was set using the following parameters: L_T – the axial distance (tractor base); l_{Tf}, l_{Tr}, h_{T} – the coordinates of the tractor's gravity center; l_{GCD}, h_{GCD} – the coordinates of the GCD gravity center; l_{t1} , l_{t2} – the parameters of the tree; h_{irf}, h_{irr} – the height of the support surface irregularities under the front and rear wheels; h_{d}, l_{d} – coordinates of the driver's gravity center.
The kinematic parameters of the studied system are as follows: i_{gj} – gear ratio of the gearbox on the j-th gear; i_{mtf}, i_{mtr} – gear ratio of the machine front and rear axles main transmission; i_{gf}, i_{bt}, i_{gr} – gear ratio of the corresponding axles on–board transmission; r_{wf}, r_{wr} - rolling radius of the front and the rear wheels.
The calculation scheme also takes into account the torques of the system: M_e – the engine torque, set depending on the speed of its shaft rotation $\dot{\varphi}_e$ and pressing the accelerator pedal $H(t)$ depending on time; M_c – the clutch torque; M_{gj} – the torque of the gearbox on the j-th gear (reduced to the primary shaft); M_{sg} – torque on the gearbox output shaft; $M_{rf\,(rr)}$ – the drive torque of the tractor front and rear axles; $M_{tf\,(tr)}$ – the reactive torque in the tires of the front and rear wheels.
The disturbing forces acting on the studied system will be as follows: $P^{y}_{tf\,(tr)}$– the reduced force of the front and rear tires; P^{y}_{rf}, P^{y}_{s}– the suspension reduced force of the front axle and the mass of the driver in the seat; P^{ek}_{GCD}, P^{ek}_{t}– the suspension reduced force of the gripping and cutting device and the gravity center of the tree; $P_{rrf\,(rr\,r)}$ - the rolling resistance force of the front and rear wheels; P_h – the resistance force from the hook on the branches when moving the tree; P_{wT}, P_{wt} , – the wind load on the machine and the tree.
The calculation dynamic system has twelve degrees of freedom describing fluctuations in the longitudinal and vertical planes taking into account natural and production factors.
The developed calculation scheme takes into account the rotating elements operation of a logging machine with vertical and angular fluctuations in the masses of the tractor and its elastic elements.
The calculation scheme analysis was carried out using the second kind Lagrange equations followed by checking the equilibrium of forces and moments. The result is the motion differential equations of the logging machine with a vertically held tree which have the following form:

$$
\begin{aligned}
&J_e \cdot \ddot{\varphi}_e - M_e + M_c = 0;\\
&J_c \cdot \ddot{\varphi}_c - M_c + M_{gj} = 0;\\
&J_g \cdot \ddot{\varphi}_g - M_{gj} + M_{sg}/i_{gj} = 0;\\
&J_{wf} \cdot \ddot{\varphi}_{wf} - M_{rf} \cdot i_{mtf} + M_{tf} = -P_{rr\,f} \cdot r_{wf};\\
&J_{wr} \cdot \ddot{\varphi}_{w3} - M_{rr} \cdot i_{mtr} + M_{tr} = -P_{rr\,r} \cdot r_{wr};\\
&J_{\text{т}} \cdot \ddot{\varphi}_{\text{т}} - (M_{tf}/r_{wf}) \cdot (h_{\text{т}} - r_{wf}) - (M_{tr}/r_{wr})\,(h_{\text{т}} - r_{wr}) + P^{y}_{tf} \cdot l_{\text{т}f} - P^{y}_{tr} \cdot l_{\text{т}r} - P^{ek}_{\text{GCD}}\\
&\qquad\qquad \cdot l_{t1} - P^{ek}_{t} \cdot l_{t1} = -P_{w\text{т}} \cdot h_{w\text{т}} - P_{wt} \cdot l_{t1};\\
&M_{\text{т}} \cdot \ddot{y}_{\text{т}} - P^{y}_{rf} - P^{y}_{tr} = 0; \qquad\qquad (1)\\
&M_{\text{т}} \cdot \ddot{x}_{\text{т}} - M_{tf}/r_{wf} - M_{tr}/r_{wr} + P^{ek}_{\text{GCD}} + P^{ek}_{t} = -P_h - P_{w\text{т}} - P_{wt};\\
&m_{af} \cdot \ddot{y}_{af} - P^{y}_{rf} - P^{y}_{tr} = 0;\\
&m_d \cdot \ddot{y}_d - P^{y}_{s} = 0;\\
&J_{t1} \cdot \ddot{\beta}_{t1} - P^{ek}_{\text{GCD}} \cdot l_{t1} - P^{ek}_{t} \cdot l_{t1} = -P_h \cdot l_{t1} - P_{wt} \cdot l_{t1};\\
&J_{t2} \cdot \ddot{\beta}_{t2} - P^{ek}_{\text{GCD}} \cdot l_{t2} = -P_h \cdot l_{t2} - P_{wt} \cdot l_{t2}.
\end{aligned}
$$

The reduced moments and forces using in the system of equations have the following form:

$$M_{gj} = C_{egj}^{\varphi}(\varphi_{c} - \varphi_g \cdot i_{gj}) + K_{egj}^{\varphi}(\dot{\varphi}_{c} - \dot{\varphi}_g \cdot i_{gj});$$

$$M_{rf} = C_{ef}^{\varphi}(\varphi_g - \varphi_{wf} \cdot i_{gf}) + K_{ef}^{\varphi}(\dot{\varphi}_g - \dot{\varphi}_{gf} \cdot i_{gf});$$

$$M_{rr} = C_{er}^{\varphi}(\varphi_g - \varphi_{wr} \cdot i_{gr}) + K_{er}^{\varphi}(\dot{\varphi}_g - \dot{\varphi}_{gr} \cdot i_{gr});$$

$$M_{sg} = M_{rf} + M_{rr};$$

$$M_{tf} = \frac{C_{tf}^{x} \cdot r_{wf}^2 \cdot C_{tf}^{\varphi}}{C_{tf}^{\varphi} + C_{tf}^{x} \cdot r_{wf}^2}(\varphi_{wf} - \varphi_{tf}) + \frac{K_{tf}^{x} \cdot r_{wf}^2 \cdot K_{tf}^{\varphi}}{K_{tf}^{\varphi} + K_{tf}^{x} \cdot r_{wf}^2}(\dot{\varphi}_{wf} - \dot{\varphi}_{tf});$$

$$M_{tr} = \frac{C_{tr}^{x} \cdot r_{wr}^2 \cdot C_{tr}^{\varphi}}{C_{tr}^{\varphi} + C_{r}^{x} \cdot r_{wr}^2}(\varphi_{wr} - \varphi_{tr}) + \frac{K_{tr}^{x} \cdot r_{wr}^2 \cdot K_{tr}^{\varphi}}{K_{tr}^{\varphi} + K_{tr}^{x} \cdot r_{wr}^2}(\dot{\varphi}_{wr} - \dot{\varphi}_{tr});$$

$$\varphi_{tf} = (x_{т} + (h_{т} - r_{wf}) \cdot \varphi_{т})/r_{wf}; \qquad (2)$$

$$\varphi_{tr} = (x_{т} + (h_{т} - r_{wr}) \cdot \varphi_{т})/r_{wr};$$

$$P_{tf}^{y} = C_{tf}^{y}\left(y_{af} - h_{irf}(t)\right) + K_{tf}^{y}\left(\dot{y}_{af} - \dot{h}_{irf}(t)\right);$$

$$P_{tr}^{y} = C_{tr}^{y}(y_{т} - \varphi_{т} \cdot l_{Tr} - h_{irr}(t)) + K_{tr}^{y}\left(\dot{y}_{т} - \dot{\varphi}_{т} \cdot l_{Tr} - \dot{h}_{irr}(t)\right);$$

$$P_{rf}^{y} = C_{rf}^{y}(y_{т} + \varphi_{т} \cdot l_{Tf} - y_{af}) + K_{rf}^{y}(\dot{y}_{т} + \dot{\varphi}_{т} \cdot l_{Tf} - \dot{y}_{т});$$

$$P_{\text{GCD}}^{ek} = C_{t1}(x_{т} - l_{t1}(\varphi_{т} - \beta_{t1})) + K_{t1}(\dot{x}_{т} - l_{t1}(\dot{\varphi}_{т} - \dot{\beta}_{t1}));$$

$$P_{t}^{ek} = C_{t2}(x_{т} - l_{t1}(\varphi_{т} - \beta_{t1})) - \beta_{t2} \cdot l_{t2} + K_{t2}(\dot{x}_{т} - l_{t1}(\dot{\varphi}_{т} - \dot{\beta}_{t1})) - \dot{\beta}_{t2} \cdot l_{t2}.$$

To carry out the movement dynamic calculation of the logging machine with a vertically held tree, disturbing influences affecting the system were set [11].

The unevenness of the wheels support surface can be determined through the dynamic reactions of the connections on the tractor front and rear wheels using the following expressions:

$$R_{wf} = K_{tf}^{y}\left(\dot{y}_{af} - \dot{h}_{irf}(t)\right) + C_{tf}^{y}\left(y_{af} - h_{irf}(t)\right); \qquad (3)$$

$$R_{wr} = K_{tr}^{y}\left(\dot{y}_{т} - \dot{\varphi}_{т} \cdot l_{тr} - \dot{h}_{irr}(t)\right) + C_{tr}^{y}(y_{т} - \varphi_{т} \cdot l_{тr} - h_{irr}(t)). \qquad (4)$$

The transients that occur when the clutch is engaged can be determined by the following differential expressions for two cases:

1) starting from the place ($\dot{\varphi}_e \neq \dot{\varphi}_c$):

$$J_e \cdot \ddot{\varphi}_e - M_e + M_c = 0;$$
$$J_c \cdot \ddot{\varphi}_c - M_c + M_{gj} = 0; \qquad (5)$$

2) uniform movement ($\dot{\varphi}_e = \dot{\varphi}_c$):

$$(J_e + J_c) \cdot \ddot{\varphi}_e - M_e + M_{gj} = 0; \qquad (6)$$

For simplicity it is reasonable to simulate the transients of machine acceleration with a gearshift through a description of the gearshift box operation for two cases:

1) the machine acceleration with one of the gears turned on:

$$(J_{sgj}^{I} + J_{sgj}^{II} + J_w) \cdot \ddot{\varphi}_g - M_{gj} + M_{sg} = 0 \qquad (7)$$

2) alternately turning off one gear, neutral position and turning on another gear:

$$J_{sgj}^{I} \cdot \ddot{\varphi}_g - M_{gj} + M_{sg} = 0 \qquad (8)$$
$$(J_{sgj}^{II} + J_w) \cdot \ddot{\varphi}_g - M_{gj} + M_{sg} = 0$$

where J_{sgj}^{I}– the inertia moment of the gearbox leading parts on the j-th gear (reduced to the primary shaft); J_{sgj}^{II} – the inertia moment of the gearbox driven parts on the j-th gear (reduced to the primary shaft); J_w– the total inertia moments of the front and rear drive axles wheels with tires and associated transmission parts

(reduced to the primary gearbox shaft).
The disturbing effect created by single surface irregularities can be defined by describing them with the following expression:

$$h(t) = 0{,}4 \cdot h_{ir} \cdot \left(1 - cos\,\frac{2\cdot\pi\cdot\vartheta\cdot t}{l_{ir}}\right); \quad (9)$$

where h_{ir} and l_{ir} are the height and length of a single surface irregularity, υ_T is the machine speed.
The parameters of the engine (as a source of a given limited power) were set depending on the crankshaft rotation speed according to its static characteristics in the form of a linear function. The maximum torque when the engine is operating in the speed range from φ_{emin} to φ_{eo} of the rotation frequency was determined as follows:

$$M_e = M_{eo}\left(1 + \alpha_1\left(1 - \frac{\dot{\varphi}_e}{\dot{\varphi}_{eo}}\right) - \alpha_2\left(1 - \frac{\dot{\varphi}_e}{\dot{\varphi}_{eo}}\right)\right)^2; \quad (10)$$

where α_1, α_2 are the approximation coefficients depending on the engine.
The wind load parameters were determined by the following expressions:

For the tractor: $$P_{w\text{т}} = \kappa_{w\text{т}} \cdot F_{\text{т}} \cdot \dot{x}_{\text{т}}^2 \quad (11)$$

For the tree: $$P_{wt} = \beta_c \cdot c_a \cdot \frac{\beta_a \cdot \vartheta^2}{2} \cdot S_{cm} \quad (12)$$

where $F_{\text{т}}$ is the frontal area of the tractor, $\kappa_{w\text{т}}$ is the coefficient of tractor streamlining, β_c is the coefficient of crown density, c_a is the aerodynamic coefficient, β_a is the air mass density, υ_w is the wind speed, S_{cm} is the crown midsection.

An analytical solution of the differential equations system (1) describing the working process dynamics of the logging machine with a vertically held tree, in which there are random disturbing effects of a probabilistic nature, is not required for current mathematical modeling. It is more reasonable to provide the movement dynamic analysis of of the logging machine with a vertically held tree by numerical solution based on the Runge-Kutta method, which is widely used to solve dynamics problems and has sufficient accuracy and stability by selecting the integration step.

2.2 Data for modeling

Simulation modeling is performed using the natural production factors of the Republic of Mari El.
The necessary parameters for calculating the dynamic system of a logging machine with a vertically held tree are indicated in Table 1 and were determined by analogy with the dynamic loading of agricultural and machine-tractor units, which were taken from well-known studies [21, 22].

Table 1 Initial data for modeling

Name of the parameter	Value
Masses	
Tractor weight (traction class 1,4), kg	4000-4500
Weight of the front axle, kg	220
Weight of the GCD and the tree bottom, kg	100-120
Weight in the tree gravity center, kg	80-120
Weight of the tree crown, kg	20-100
Weight of the driver, kg	80
Moments of inertia	
Inertia moment of tractor with GCD and tree, reduced, $kg\cdot m^2$	5383-6410
Inertia moment of the engine, $kg\cdot^{m2}$	1,114
Inertia moment of the clutch leading parts, $kg\cdot m^2$	0,074
The inertia momentof the gearbox on the j-th gear, $kg\cdot m^2$	
I gear, $kg\cdot^{m2}$	0,1025
II gear, $kg\cdot m^2$	0,1073
III gear, $kg\cdot m^2$	0,1213
IV gear, $kg\cdot m^2$	0,1323

Name of the parameter	Value
V gear, kg·m^2	0,1452
VI gear, kg·m^2	0,1645
VII gear, kg·m^2	0,1934
VIII gear, kg·m^2	0,2310
IX gear, kg·m^2	0,5535
Inertia moment of the 1 tree mass, kg·m^2	1250-15250
Inertia moment of the 2 trees mass, kg·m^2	280-22850
Total stiffness	
Torsional stiffness of tractor front axle tires, kN·m/rad	250
Torsional stiffness of tractor rear axle tires, kN·m/rad	430
Torsional stiffness of the transmission, reduced to the j-th gear, kN·m/rad	
I gear, kN·m/rad	0,09
II gear, kN·m/rad	0,25
III gear, kN·m/rad	0,7
IV gear, kN·m/rad	1,05
V gear, kN·m/rad	1,55
VI gear, kN·m/rad	1,92
VII gear, kN·m/rad	3,1
VIII gear, kN·m/rad	4,4
Vertical stiffness of the front tires, kN/m	590
Vertical stiffness of the rear tires, kN/m	750
Vertical suspension stiffness of the front axle, kN/m	700
Vertical stiffness of the GCD and tree, kN/m	3,5-6
Vertical stiffness of tree, kN/m	1,5-6
Total vertical damping coefficients	
Resistance of tractor front tires, kN·s/m	20-60
Resistance of tractor rear tires, kN·s/m	25-200
Tractor front axle resistance, kN·s/m	20-30
Resistance of GCD and tree trunk, kN·s/m	0,3-0,8
Engine Parameters	
Rated speed of rotation, min^{-1}	2200
Rated power, kW	58
Maximum torque, N·m	274
Maximum crankshaft rotation speed, min^{-1}	1400
Geometric parameters	
Center-to-center distance (tractor base), m	2,5
The height of the tractor's gravity center from the tractor's support surface, m	0,9-1,1
Distance from the front axle to the tractor's gravity center, m	1,6-1,8
Distance from the rear axle to the tractor's gravity center, m	0,8-0,6
The distance of the GCD center from the rear axle of the tractor, m	1,2
The height of the GCD gravity center from the tractor support surface, m	0,4
Tree trunk distance from m_1 to m_2, m	2-9
Tree trunk distance from m_2 to m_3, m	4-13
Additional parameters	
Wind load on a tree, kN	1,4-2,0
The area of the tractor's frontal surface, m^2	4,6
Wind speed, m/s	9-12
Frequency of influence, 1/s	2
Gear ratios of the front and rear wheels drive i_{rf}/ i_{rr}	
I gear	150-240
II gear	90-140

Name of the parameter	Value
III gear	50-83
IV gear	40-70
V gear	35-55
VI gear	30-50
VII gear	25-40
VIII gear	20-30
IX gear	10-20

The parameters values of the forest support surface irregularities were determined by the authors earlier in a practical way [23].

3. Results

As a result of differential equations numerical solution, dynamic parameters graphs of a logging machine with a vertically held tree were constructed. Examples of graphs are shown in Figure 2-5.

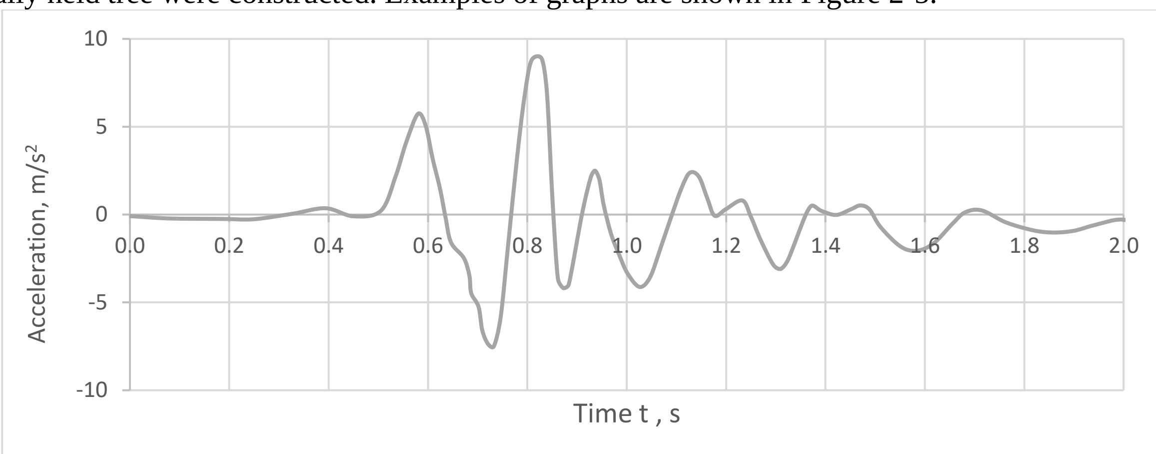

Figure 2
Example of the tractor's gravity center vertical acceleration ($\ddot{y}_т$)

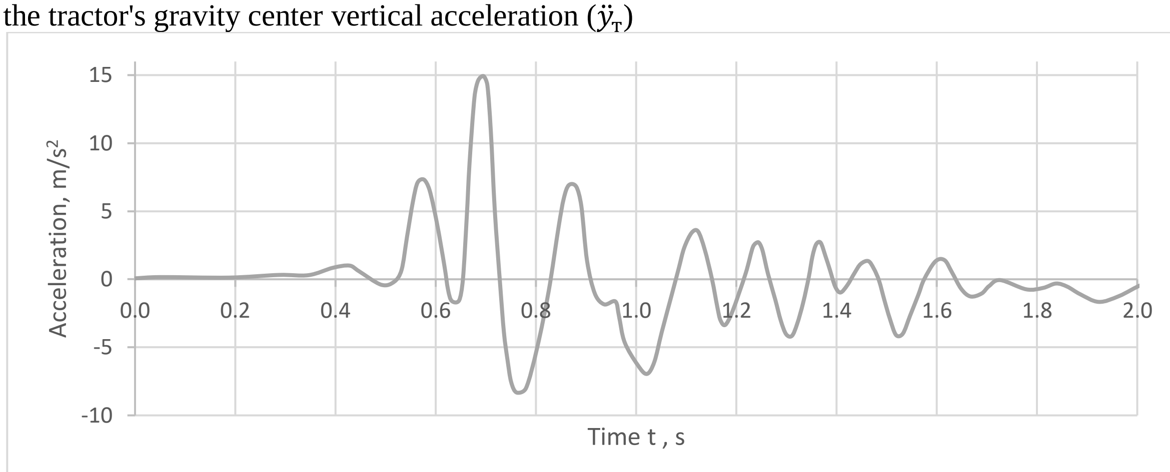

Figure 3
Example of mass vertical acceleration m_{t1} ($\ddot{y}_{mt1}$)

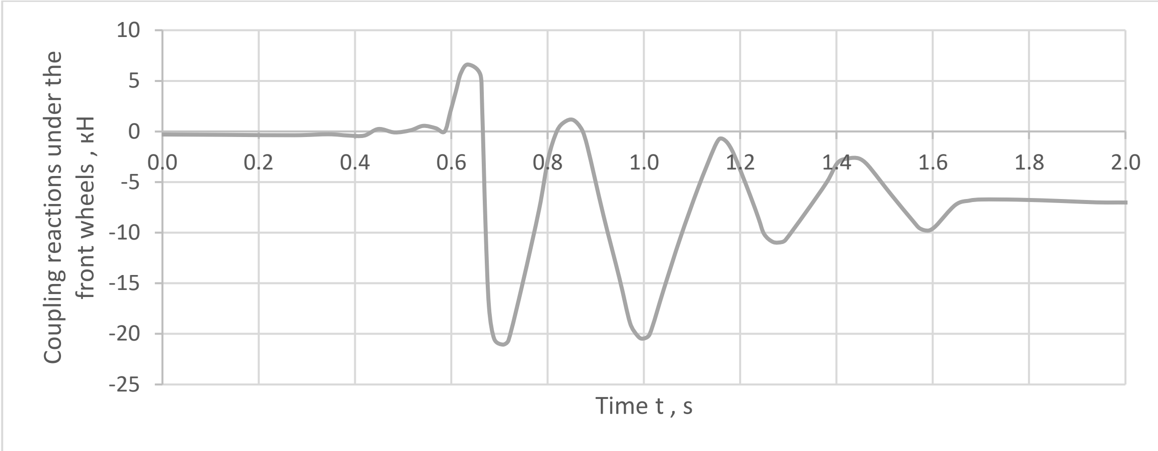

Figure 4
Coupling reactions under the front wheels (R_{wf})

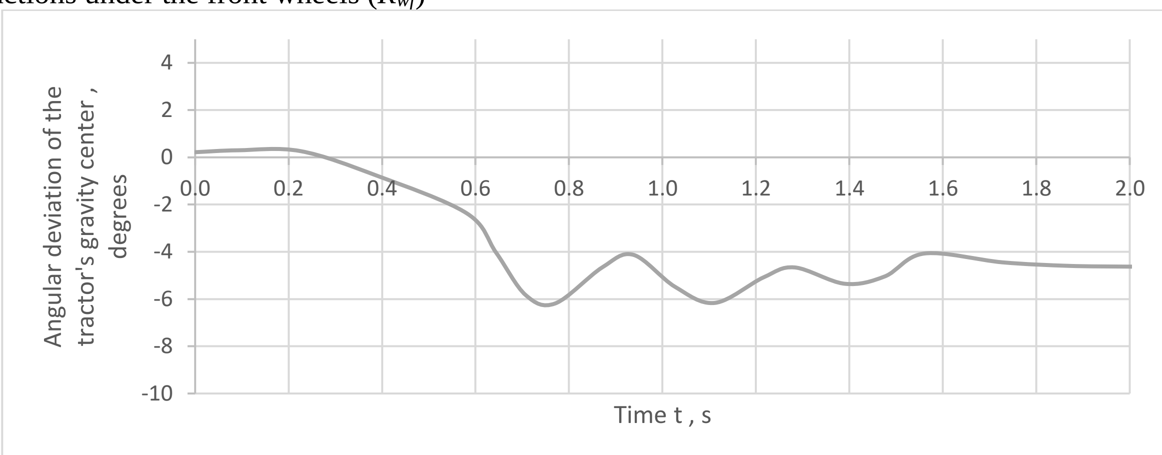

Figure 5
Angular deviation of the tractor's gravity center (φ_T)

The numerical values of the dynamic parameters obtained on the model of a logging machine with a vertically held tree weighing 150 kg when moving at different speeds and when passing through surface irregularities are presented in Table 2.

Table 2 Values of dynamic parameters (displacement and acceleration) for movement modeling of a logging machine at different speeds when passing through surface irregularities.

υ_T, km/h	y_T, m	$\ddot{y}_T$, m/s ^{2}	x_T, m	$\ddot{x}_T$, m/s^2	φ_T, rad	$\ddot{\varphi}_T$, rad/sec^2	β_{t1}, rad	β_{t2}, rad	R_{wf}+ kN	R_{wf}- kN
h_{ir}=0.05 m, l_{ir} =0.5 m										
1,5	0,0336	1,488	0,0184	0,4	0,024	0,84	0,024	0,0016	4,32	3,6
3,0	0,0336	2,56	0,016	0,608	0,0208	1,232	0,02	0,0016	6,64	3,84
4,5	0,032	3,88	0,016	0,8	0,0168	1,568	0,0176	0,0008	8,64	5,52
6,0	0,024	5,136	0,016	36477,6	0,0152	1,864	0,0136	0,0008	9,84	7,44
h_{ir} =0.1 m, l_{ir} =0.5 m										
1,5	0,068	2,984	0,024	0,8	0,04	1,68	0,0448	0,004	8,64	7,28
3,0	0,0672	5,128	0,0208	1,216	0,04	2,48	0,04	0,0032	13,36	7,68
4,5	0,0624	7,76	0,0168	1,592	0,032	3,12	0,032	0,0024	17,36	10,96
6,0	0,0544	10,24	0,016	1,768	0,024	3,72	0,028	0,00208	19,68	14,88
h_{ir} =0.15 m, l_{ir} =0.5 m										
1,5	0,096	2,856	0,04	0,816	0,0592	1,768	0,0672	0,00528	8,72	9,04
3,0	0,104	4,472	0,032	1,2	0,056	3,68	0,0608	0,0048	20	11,44
4,5	0,096	11,68	0,024	2,4	0,048	4,72	0,052	0,004	26	16,448
6,0	0,08	15,44	0,0184	2,656	0,04	5,6	0,04	0,0032	29,52	22,32

4. Discussion

Movement modeling of the logging machine with different speeds on an uneven surface showed that with increasing movement speed of the logging machine, the values of displacement decrease, but the values of accelerations increase. At the beginning of movement, the dynamic system "Logging machine – vertical tree" experiences a sharp increase in dynamic loads. With the establishment of uniform movement, the dynamic parameters decrease and tend to zero until the next disturbing effect appears.
The accuracy of the developed mathematical model and calculation methods was assessed by comparing the results of theoretical studies with experimental data conducted on a full-scale sample of a logging machine with a vertically held tree obtained by the authors in earlier works [2, 24].
In order to confirm the validity of the computational model, the spectral densities correspondence of the calculated and experimental machine oscillation processes was evaluated using the D^2 equivalence statistics of energy spectra.
From comparing the data of two spectral densities, provided that each of them (Figure 6) is obtained with the same resolution in the same frequency band, the energy spectrum equivalence test concludes that the results of the calculated and experimental data are satisfactorily convergent.

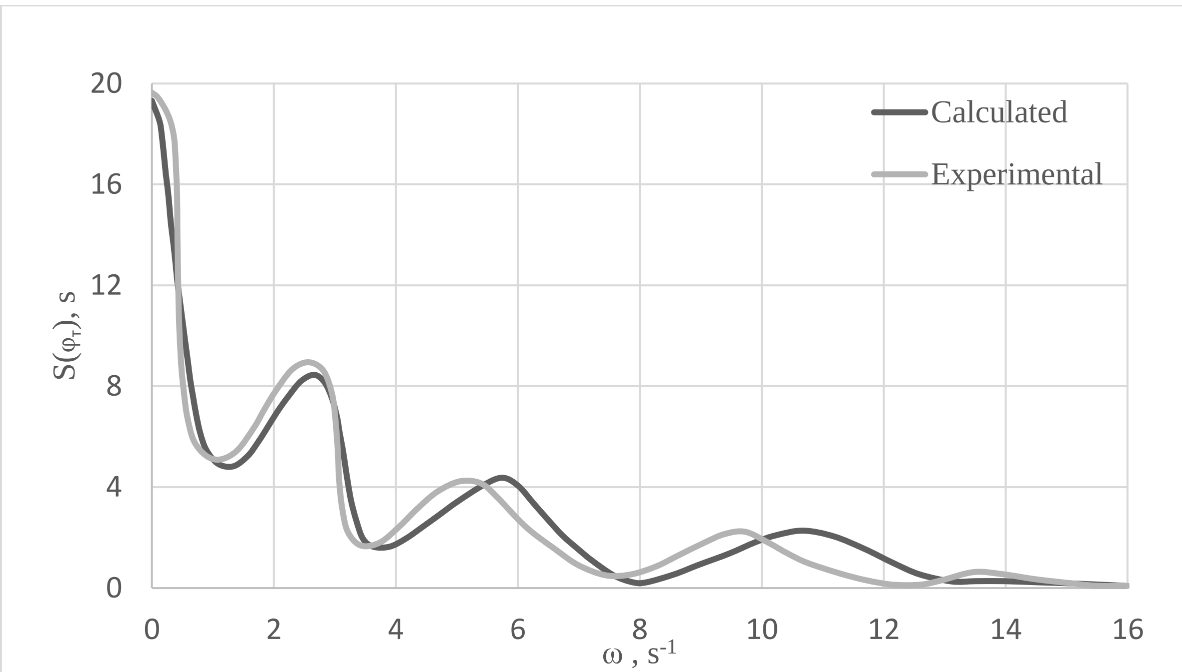

Figure 6
Normalized spectral densities of angular displacement of the machine gravity center moving at a speed of 1.3 m/s

The value of the D^2 statistic is in the range of 9.8-21.3 (with the value of the hypothesis acceptance area equal to 26.3) which indicates satisfactory convergence of the results.

5. Conclusions

The conducted research shows that the proposed mathematical model of the dynamic system "Logging machine – vertical tree" describes the properties of a dynamic system taking into account the interaction of its subsystems (engine, transmission, technological equipment, tree). The model can also simulate the operation processes, taking into account the complex disturbing effects of the support surface unevenness, wind load, resistance forces (when clinging to the branches of standing trees) and the engine torque. As a result the proposed model solves a wide range of problems related to the tasks of traction dynamics, stability, controllability and taking into account the interaction of its subsystems, environmental influences and control actions.

Based on the analysis of the results obtained, recommendations can be developed in the future aimed at improving the design and optimizing the parameters of individual elements, taking into account the conditions and operating modes.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

All authors have contributed in experiments and in preparation of the manuscript. All authors have read and approved the final manuscript.

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