Study of driving dynamics of modular forestry tillage machine-tractor units in CAE SolidWorks Motion

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Abstract. The issues of simulation studies driving dynamics of wheeled forestry machine-tractor units on the surface with obstacles are considered. The method of simulation modeling in CAD SolidWorks and CAE SolidWorks Motion is used. A simplified 3d-model of the MTZ-82.1 agricultural wheeled tractor was created, preserving all the main geometric and mass-inertia parameters of the moving elements. The tractor model was equipped with front and rear mounted modular forest tillage implements in the transport position. The research was performed on a virtual track with four different types of obstacles similar to those found in forest conditions. In a computer experiment, three different schemes of units were studied and the following parameters were obtained: wheel lift height, lateral displacement of the center of gravity, and linear speed fluctuations. Analysis of the results showed that the 0+1 scheme (rear-mounted single-row harrow) was the most stable. The heaviest scheme 1+2 (front-mounted drum chopper and rear-mounted two-row harrow) also had satisfactory stability. The least stable was a tractor equipped according to the 0+2 scheme (rear-mounted two-row harrow). The virtual experiment allowed us to study the dynamic stability of various forestry units in the transport position and establish the most stable configurations.

1. Introduction
A lot of research has been devoted to the problem of ensuring the sustainability of road transport and various machine and tractor units, but so far it remains relevant [1-3]. For example, units used in forestry, on the one hand, must have increased resistance to overturning, and on the other hand, due to the small working width, they require a multi-row arrangement of working tools for loading the tractor and reducing the number of cycles of the impact of the tractor wheels on the soil. At the same time, the multi-row arrangement of the working tools increases the dimensions of the unit, which reduces its stability [4].

The most common method for studying stability is the full-scale tests method. This is a materially costly and time-consuming method, because a full-scale sample is required. An alternative to full-scale tests are computational studies based on computer modeling [1-3]. They are able to significantly reduce time and material costs for the design and development of new equipment. Existing mathematical models, as a rule, contain many simplifications. For example, they do not take into account all the features of the design and communication of vehicles and technological equipment.

Numerical methods implemented in 3D multibody modeling (MBD) environments are capable of taking into account a wider range of factors. These are the distribution of masses in the parametric 3d model of machine-tractor units, the patterns of motion of various structural elements, the presence of elastic and damping elements, the contact interaction of various materials, etc. Similar models can be
implemented in the programs MSC.ADAMS [1-3, 5], RecurDyn [6, 7], TruckSim [8], Carsim [9, 10], SolidWorks Motion [11], etc. Let us consider the closest studies of the movement of forest machines using MBD modeling.

The study [5] researched the patterns of interaction between the wheels of the forwarder Komatsu Valmet 860.3 and forest soils (track depth under various loads) using MSC.ADAMS. Only a simplified model of a forwarder was investigated, which included one wheel moving on flat horizontal and inclined surfaces. In this study, although a full-fledged forwarder model was created, the study of its driving dynamics was not carried out.

The studies [1, 2] also examined the driving dynamics of the Komatsu Valmet 860.4 forwarder. The study was conducted on a virtual test track with obstacles of a similar shape, but different heights (150, 250, and 350 mm), located unevenly. The tire-ground interaction model simulated conditions on hard road surfaces. The experimental verification of the simulation results was carried out on a test track with a hard surface and an identical shape and location of obstacles. Comparison of the simulation results with experimental data shows their good convergence and can be used in the future to study the dynamic stability of various concepts of traction units.

Thus, at the moment, there are practically no simulation studies of the dynamics of movement of forest machine-tractor units based on wheeled tractors equipped with various combinations of front and rear implements.

The purpose of the research is to study the dynamic stability of machine and tractor units equipped with various combinations of front and rear mounted forest modular tillage implements using a virtual track.

2. Material and methods

As an object of modeling and research, a forestry machine-tractor unit based on the MTZ-82.1 tractor was selected. In the course of the research, the method of simulation in the 3d-CAD environment of the SolidWorks system was used. At the first stage, a simplified 3d model of the tractor was created, while maintaining all the basic geometric parameters [11].

At the next stage, the mass-inertial characteristics of the main moving elements were set by applying to them the properties of materials from standard libraries. These are wheels, suspension elements and attachment mechanisms for working equipment.

Also, additionally, a spherical element was installed to compensate for the mass-inertial characteristics of the non-simulated stationary elements of the tractor. He has the ability to change the spatial position and mass. By adjusting these parameters, the mass-inertial characteristics of the tractor model were brought to the parameters of a real tractor.

The tractor model was equipped with front and rear mounted forestry modular tillage implements [4] (figure 1). The following implements were used in the modeling: front-mounted drum chopper (figure 1a), rear-mounted single-row harrow (figure 1b); rear-mounted two-row harrow (figure 1c).

Figure 1. Forestry modular tillage implements: (a) front-mounted drum chopper; (b) rear-mounted single-row harrow; (c) rear-mounted two-row harrow.

Figure 2a shows three typical unit layout options: unit with a single-row rear-mounted implement (scheme
0 + 1), two-row rear-mounted implement (scheme 0 + 2), and with front-mounted and two-row rear-mounted implements (scheme 1 + 2).

Depending on the applied reforestation technology and operating conditions, the implements can be equipped with sets of various working tools. The overall dimensions of the working tools and their mass-inertial characteristics are maximally unified. As a result, the mass-inertial characteristics of modular implements for various purposes are also very similar. In the study, a front-mounted drum chopper, a rear-mounted one and two-row harrow was used to complete the unit.

Four test sites were created with semi-cylindrical immovable obstacles located on them, oriented perpendicularly to the direction of movement of the tractor, which simulates movement in forest areas (figure 2b), these are: single linear (1); single sequential (2); group linear (3); and group sequential (4).

![Figure 2. Virtual test stand: (a) – different schemes of a machine-tractor unit; (b) – various types of obstacles.](image)

The height of single obstacles 1 and 2 was 200 mm, group obstacles 3 and 4 was 150 mm. To speed up the modeling process, all four types of obstacles are combined into a single test track 40 meters long and 6 meters wide. The interaction between the contact pairs “support surface – tractor wheels” had the parameters of the standard “steel – rubber” interaction taken from the SolidWorks Motion library, but the coefficients of dynamic and static friction were modified. They were increased from 0.3 to 0.7. This is necessary to reduce wheel slippage, since the support surfaces are not deformed and do not have roughnesses for adhesion to the tread. The speed of the tractor in all series of experiments was 3.22 km/h (0.9 m/s), which corresponds to the second lower gear of the tractor MTZ-82.1. It was set by applying independent virtual engines to each wheel. The engine speed was 10.9 for the rear wheels and 24.4 rpm for the front wheels. During the simulation, the following parameters were recorded: lifting height of the geometric center of the wheels (four parameters); displacement of the center of gravity of the forestry machine-tractor unit in the transverse direction; linear speed of the machine-tractor unit.
Figure 3 shows a screenshot of the simulation process showing the parameters in real time.

Figure 3. The process of modeling the dynamic stability of forestry machine-tractor unit on a virtual stand with tracking parameters.

3. Results and discussion
Figure 4 presents graphs demonstrating the lifting height of the front (a) and rear wheels (b) of various schemes of the machine-tractor unit above the supporting surface.

Figure 4. Wheel lift height of various schemes of a machine-tractor unit: (a) – front pair; (b) – back pair.
Let us analyze in more detail the lift height of the wheels various schemes of the machine-tractor unit when overcoming obstacles.

In figure 5-7a solid lines show the lift heights for each wheel when overcoming single obstacles (obstacles 1, 2) and the average lift heights values when overcoming group obstacles (obstacles 3, 4). Additionally, dashed lines show the maximum lift heights when overcoming group obstacles, as they are critical values that determine the stability of the tractor.

For convenience of data analysis, figure 5-7b shows the average values of wheels oscillations on one axis. Solid lines show the average lift heights values of the front and rear wheels. The dashed lines show the average maximum wheel lift heights values on one axis.

Figure 5a compares the wheel lift heights when the unit of the 0+1 scheme is overcoming obstacles. The lifting heights of the right and left wheels of one axis on obstacle 1 differ slightly, amounting to 213.61 and 221.70 mm for the front pair, 196.27 and 199.86 mm for the rear pair. For obstacle 2, the lifting heights are 203.17 and 211.41 mm for the front pair, 209.95 and 204.66 mm for the rear pair. The average values calculated for group obstacles 3 and 4 are also similar. For the obstacle 3, lifting heights are 158.00 and 160.62 mm for the front pair, 154.93 and 157.95 mm for the rear pair. For obstacle 4, the lifting heights are 159.44 and 161.60 mm for the front pair, 173.84 and 182.65 mm for the rear pair. The maximum front wheel lift values for obstacles 3 and 4 are also very similar (obstacle 3 172.80 and 174.66 mm; obstacle 4 166.90 and 174.85 mm), the lift heights of the left and right rear axis wheels when overcoming obstacle 4 have minor differences (obstacle 3 165.48 and 163.81 mm; obstacle 4 193.94 and 208.42 mm).

Figure 5b shows the average lift heights of the front and rear pair of wheels of a 0+1 scheme unit. On obstacle 1, the lift heights of the front wheels are noticeably higher than those of the rear ones and are 217.66 and 198.07 mm. On obstacle 2 there are practically no differences for the front and rear wheels, amounting to 207.35 and 207.14 mm. When overcoming obstacle 3, the front wheels lift by 159.31 mm, and the rear wheels by 156.44 mm. When overcoming obstacle 4, the trend changes, the front wheels have a lift of 160.52 mm, and the rear wheels 178.24 mm.

Figure 6a compares the wheel lift heights when the unit of the 0+2 scheme is crossing obstacles. The lifting heights of the right and left wheels of one axis on obstacle 1 differ slightly, amounting to 331.02 and 352.65 mm for the front pair, 195.55 and 193.64 mm for the rear pair. For obstacle 2, the lifting heights are 216.50 and 269.60 mm for the front pair, 203.12 and 194.52 mm for the rear pair. The average values calculated for group obstacles 3 and 4 are also similar. For obstacle 3, the differences are 261.41 and 277.28 mm for the front pair, 166.27 and 163.23 mm for the rear pair. For obstacle 4, the lifting heights are 231.38 and 204.40 mm for the front pair, 177.70 and 181.07 mm for the rear pair. The maximum front wheel lift values for obstacles 3 and 4 are also very similar (obstacle 3 350.36 and 330.64 mm; obstacle 4 277.57 and 291.05 mm), the lift heights of the left and right rear axis wheels when overcoming obstacle 4 have minor differences (obstacle 3 186.29 and 178.97 mm; obstacle 4 203.65 and 203.79 mm).
Figure 6b shows the average lift heights of the front and rear pair of wheels of a 0+2 scheme unit. On obstacle 1, the lift heights of the front wheels are much higher than the rear ones and are 341.84 and 194.60 mm. On obstacle 2, the differences for the front and rear wheels are less pronounced, amounting to 243.05 and 198.82 mm. When overcoming obstacle 3, the front wheels are lift by 269.35 mm, and the rear wheels by 164.75 mm. When overcoming obstacle 4, the discrepancies again decrease, the front wheels have a lift of 217.89 mm, and the rear wheels 179.39 mm.

![Figure 6](image)

**Figure 6.** Wheel lift height of a machine-tractor unit 0+2 scheme: (a) – for each wheel; (b) – average for the front and rear wheels.

Figure 7a compares the wheel lift heights when the unit of the 0+2 scheme is crossing obstacles. The lifting heights of the right and left wheels of one axis on obstacle 1 differ slightly, amounting to 237.64 and 228.93 mm for the front pair, 200.80 and 205.24 mm for the rear pair. For obstacle 2, the lifting heights are 215.95 and 201.27 mm for the front pair, 207.71 and 201.37 mm for the rear pair. The average values calculated for group obstacles 3 and 4 are also similar. For obstacle 3, the differences are 195.79 and 198.96 mm for the front pair, 161.39 and 168.48 mm for the rear pair. For obstacle 4, the lifting heights are 167.14 and 163.30 mm for the front pair, and 190.26 and 179.94 mm for the rear pair. The maximum front wheel lift values for obstacles 3 and 4 are also very similar (obstacle 3 243.15 and 247.54 mm; obstacle 4 177.15 and 181.98 mm), however, the lift heights of the left and right rear axis wheels when overcoming an obstacle 4 have noticeable differences (obstacle 3 180.77 and 181.74 mm; obstacle 4 269.55 and 208.56 mm).

Figure 7b shows the average lift heights of the front and rear pair of wheels of a 1+2 scheme unit. On obstacle 1, the lift heights of the front wheels are noticeably higher than the rear ones and are 233.29 and 203.02 mm. On obstacle 2, there are practically no differences for the front and rear wheels, amounting to 204.54 and 212.11 mm. When overcoming obstacle 3, the front wheels are lift by 197.37, and the rear wheels by 164.93 mm. When overcoming obstacle 4, the trend changes, the front wheels have a lift of 163.3 mm, and the rear wheels have 185.102 mm.

![Figure 7](image)
Figure 7. Wheel lift height of a machine-tractor unit 1+2 scheme: (a) – for each wheel; (b) – average for the front and rear wheels.

Figure 8 presents graphs demonstrating the lifting height of the front (a) and rear wheels (b) of various schemes of the machine-tractor unit above the supporting surface.

Analysis of the data showed that the smallest oscillations of the front wheels (figure 8, a) of the machine-tractor unit scheme 0+1. Somewhat large oscillations in the scheme 1+2. Significantly large oscillations were observed in the 0+2 scheme. This trend continued for the maximum values of oscillations. Moreover, in all cases, significantly more oscillations were observed for linear obstacles.

The average values of the rear wheel oscillations (figure 8b) of various schemes do not have pronounced differences. In contrast to the front wheels, the greatest oscillations were observed when overcoming sequential obstacles. This is clearly seen by the maximum values when moving a group sequential obstacle 4.

Figure 9 shows the lateral displacement of the center gravity of various schemes machine-tractor unit that occurs when overcoming obstacles. In the process of modeling, additional correction of the trajectory was not performed. A comparative analysis of the graphs showed that the smallest deviations from the course are experienced by a unit equipped with a rear mounted light implement (0+1 scheme). Units equipped with a rear-mounted massive implement (scheme 0+2), as well as a front-mounted and
rear-mounted massive implement (scheme 1+2) have more significant deviations from the course. After overcoming the most difficult obstacle 4, both units either experience significant displacement with a turn, or lose stability with a rollover.

Figure 9. Lateral displacement of the center gravity of various machine-tractor units.

Figure 10 shows the linear velocity oscillations of the three investigated unit circuits during the passage of the track. The greatest amplitude of velocity oscillations is observed for the unit scheme 1+2, the minimum for the scheme 0+1. For the scheme 0+2, the maximum oscillation values are less than for the scheme 1+2, but the oscillations do not damp even in the intermediate sections without obstacles.

Figure 10. Oscillations in linear speed of various schemes of a machine-tractor unit.

Figure 11a presents an analysis of the linear velocity oscillations of various machine-tractor units. At a nominal speed of 0.9 m/s, the actual speed value for scheme 0+1 is 0.863 m/s, scheme 0+2 is 0.870 m/s and scheme 1+2 is 0.850 m/s. This difference is associated with wheel slippage when overcoming obstacles. The standard deviation of velocity (figure 11b) for scheme 0+1 is 0.098 m/s, scheme 0+2 is 0.109 m/s and scheme 1+2 is 0.12 m/s.
Figure 11. Analysis of oscillations in the linear speed of various schemes of machine-tractor units: (a) average speed; (b) standard deviation.

4. Conclusion
An analysis of the stages of movement of the forestry machine-tractor unit on a virtual stand made it possible to study the dynamics of overcoming various types of obstacles, similar to usual in forest conditions. Three different schemes of forest modular units based on the MTZ-82.1 wheeled tractor were compared. The results obtained are in good agreement with the data of similar studies.

Using virtual stand makes it possible to significantly reduce the time and material costs for the design and development of new equipment. All modeling steps were performed in the most widely used CAD and CAE SolidWorks. This significantly reduced the complexity of the study by eliminating the need to export data between the 3d modeling software and the engineering calculation environment, which provided a two-way communication between the geometry and the calculation environment. The advantage of the simulation method used is the ability to quickly rebuild the geometry of tractors, implements, the shape and location of obstacles, as well as modeling conditions in accordance with various forest conditions.

In the future, the presented model can be used to study the transport stability of various forest wheeled tractor units equipped with various implements, including those that are only at the development stage. It will also be necessary to validate the model by experimental studies when the unit moves on a hard and deformable base.

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