Study driving dynamics of the machine-tractor unit on a virtual stand with obstacles

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Abstract. The problems of studying the dynamic stability of machine-tractor units by the methods of multi-body dynamics (MBD) are considered. To create a simulation model, the virtual modeling method in CAD SolidWorks and CAE SolidWorks Motion was used. A 3d model of the MTZ-82.1 tractor was created, equipped with front and rear mounted three-point linkage. The tractor was aggregated with modular implements. To test the machine-tractor unit, a test track was simulated, consisting of four sections with various non-movable obstacles: single linear; single sequential; group linear; group sequential. In the process of modeling, the following parameters were recorded: lifting height of the geometric center of the wheels; displacement of the machine-tractor unit center of gravity in the transverse direction; linear speed. An analysis stages movement of the machine-tractor unit showed that overcoming a single linear, single sequential and group linear obstacles at a speed of 0.9 m/s occurs without loss of stability. Only when overcoming a group sequential obstacle, significant oscillations in the tractor frame are observed, however, due to the balancing suspension of the front wheels, they do not always lead to the rollover of the tractor. In the future, using the developed virtual stand, it is possible to carry out studies of the dynamic stability of various configurations of a machine-tractor unit. It is also possible to change the geometry of obstacles, the angles of inclination of the support surface, the speeds of motion, the contact parameters of the wheels, etc.

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.

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 [1-4]. An alternative to full-scale tests are computational studies based on computer modeling. 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. In contrast to these models, modern computer methods of multibody modeling (MBD) implemented by the programs MSC.ADAMS, SolidWorks Motion, LMS Virtual.lab, SimPack, TruckSim, etc. allow taking into account many factors, for example: distribution of masses, moments of inertia elements in the spatial model, kinematics of moving parts, the presence of elastic elements, etc. [5-15].
2. Material and methods
As an object of modeling and research, a machine-tractor unit based on the MTZ-82.1 tractor was selected. It was equipped with mounted modular implements [16]. Modeling was performed in CAD SolidWorks and CAE SolidWorks Motion by the method of multi-body dynamics (MBD).

At the first stage of the study, a model of a tractor equipped with front and rear three-point linkage was created (figure 1). All the basic structural elements and their geometric and mass-inertial parameters were preserved. All stationary elements of the tractor were excluded from the model (shown in the figure in wireframe). To replace them, we used an equal mass ball of custom high density material. By adjusting the position of the ball, the center of mass of the simplified model is combined with the real operational center of mass of the tractor. This simplification allows to perform simulation with minimal computer load.

Figure 1. Simplified simulation model of the tractor MTZ-82.1.

Four test sites were created with semi-cylindrical immovable obstacles located on them, oriented perpendicularly to the direction of movement of the tractor (figure 2), these are:
- single linear (a);
- single sequential (b);
- group linear (c);
- group sequential (d).

Figure 2. Types of obstacles: (a) – single linear, (b) – single sequential, (c) – group linear, (d) – group sequential.
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 (figure 3).

![Test Track Image](image)

**Figure 3.** Stand for dynamic testing of machine-tractor unit in the presence of various types of obstacles.

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. More detailed simulation parameters are presented in table 1.

| Parameter                             | Value          |
|---------------------------------------|----------------|
| Movement speed (m/s)                  | 0.90           |
| Wheel diameter:                       |                |
| front (m)                             | 0.70           |
| rear (m)                              | 1.57           |
| Speed of rotation wheels:             |                |
| front (rpm)                           | 24.40          |
| rear (rpm)                            | 10.90          |
| Contact options “support surface – wheels” |               |
| contact pair materials                 | steel-rubber   |
| dynamic friction velocity, $\nu_k$ (mm/s) | 10.16         |
| dynamic friction coefficient, $\mu_k$ | 0.70           |
| static friction velocity, $\nu_s$ (mm/s) | 0.10          |
| static friction coefficient, $\mu_s$  | 0.70           |
| stiffness, $k$ (N/mm)                 | 2856           |
| max. damping, $c_{\text{max}}$ (N/(mm/s)) | 0.49          |

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 machine-tractor unit in the transverse direction;
- linear speed of the machine-tractor unit.

Figure 4 shows the simulation process with real-time display of parameters.

![Figure 4](image)

**Figure 4.** The process of modeling the dynamic stability of machine-tractor unit on a virtual stand with tracking parameters.

3. Results and discussion

Figure 5 shows the process of overcoming various obstacles with a machine-tractor unit. Overcoming a single linear obstacle in all series of experiments occurred without dangerous rolls and oscillations of the tractor.

Overcoming a single sequential obstacle caused insignificant tractor oscillations. At the time of moving the obstacles with the front wheels, the balanced suspension of the front axle was actively working, reducing lateral vibrations. When overcoming obstacles with the rear wheels, the oscillations were more significant, due to their rigid attachment.

The group linear obstacle in all series of experiments was overcome without rollover the tractor, but noticeable tractor oscillations arose in the process. They reached maximum amplitude on the front wheels at a time when the front and rear wheels simultaneously overcome obstacles.

When overcoming a group sequential obstacle, significant fluctuations in both the front and rear wheels were observed. At the moment of descent from the obstacle, the fact of the tractor rollover was recorded in three out of five cases. Moreover, even in those experiments where there was no rollover, a significant turn and lateral displacement of the tractor was observed.
Let us analyze in more detail the numerical data of virtual modeling. To do this, we use a parameter such as the lift height of the geometric center of the wheels above the supporting surface. Figure 6 presents graphs showing the lift height of the front (a) and rear wheels (b) above the supporting surface.

Figure 5. The process of overcoming obstacles: (a) – phase of entry, (b) – phase of descent.

Figure 6. The lift height of the wheels of the machine-tractor unit: (a) – front pair; (b) – back pair.
Figure 6, a compares the lift heights of the wheels when overcoming various obstacles. The solid lines show the lift heights when overcoming single obstacles (obstacles 1, 2) and the average lift heights values when overcoming group obstacles (obstacles 2, 3). Additionally, dashed lines show the maximum lift heights when overcoming group obstacles, as they are critical values that determine the stability of the tractor. Let us consider how the values of the lift heights of the wheels located on the same axis (front and rear pairs) differ. The lifting heights of the left and right wheels of one axis on obstacles 1 and 2 differ insignificantly. The average values for the wheels of one axle calculated for group obstacles 3 and 4 are also similar. The maximum values lift of the front wheels for obstacles 3 and 4 are also similar, however, the lift heights of the left and right wheels of the rear axle when overcoming obstacles 4 have significant differences. This is due to a significant jump in one of the rear wheels at the time of its descent from the obstacle, which in some experiments led to the rollover of the tractor.

For convenience of data analysis, figure 6, b 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.

Let us consider the trends in the lift heights of the wheels when overcoming various obstacles (figure 7).

Figure 7. Machine-tractor unit wheel lift height: (a) – for each wheel, (b) – average for the front and rear wheels.

On the obstacle 1, the lifting heights of the front wheels are significant higher than the rear wheels and are 233.29 and 203.02 mm, respectively. On obstacle 2, differences for the front and rear wheels are practically absent, amounting to 204.54 and 212.11 mm, respectively. When overcoming an obstacle 3, the front wheels lift heights by 197.37, and the rear wheels by 164.93 mm. When overcoming obstacles 4, the trend changes, the front wheels have a lift heights of 163.3, and the rear 185.102 mm.

Figure 8. Simulation results: (a) – lateral displacement of the center of gravity, (b) – linear velocity.
Figure 8 (a) presented data showing the directional stability of the tractor, that is, lateral displacement relative to the longitudinal axis of the track. It can be seen that after overcoming the last obstacle, the tractor loses directional stability. This is due to significant oscillations causing its reversal.

Also, figure 8 (b) shows the linear velocity oscillations during the passing of the track. The actual speed of the tractor was 0.85 m/s at a nominal speed of 0.9 m/s. This difference of 5.6% is associated with wheel slip when overcoming obstacles. The standard deviation of the velocity was 0.12 m/s.

An analysis of the stages of movement of the machine-tractor unit showed that overcoming a single linear (1), single sequential (2) and group linear (3) obstacles at a speed of 0.9 m/s occurs without loss of stability. Only when overcoming a group sequential obstacle (4), significant oscillations in the tractor frame are observed, however, due to the balancing suspension of the front wheels, they do not always lead to the rollover of the unit.

4. Conclusions

The developed virtual stand allows you to quickly conduct a study of the dynamic characteristics of the machine-tractor unit, equipped with various combinations of tools. This makes it possible to significantly reduce the time and material costs for the design and development of new equipment. All simulation steps were performed in CAD and CAE SolidWorks. This significantly reduced the laboriousness of the study due to the lack of the need to export data between 3D-modeling and engineering calculations software. The advantage of the simulation method used is the ability to quickly changes the geometry of the equipment, the shape and location of obstacles, as well as the modeling conditions.

In the future, using the developed virtual stand, it is possible to carry out studies of the dynamic stability of various configurations of a machine-tractor unit (a different combination of equipment on the rear and front three-point linkage, the use of a counterweight, etc.).

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References

[1] Bietresato M and Mazzetto F 2018 Increasing the safety of agricultural machinery operating on sloping grounds by performing static and dynamic tests of stability on a new-concept facility Int. J. Saf. Secur. Eng. 8 77-89
[2] Choi K, Kim S and Hong S 2017 Analysis of static stability by modified mathematical model for asymmetric tractor-harvester system: changes in lateral overturning angle by movement of center of gravity coordinates J. Biosyst. Eng. 3 127-35
[3] Gravalos I et al 2011 An experimental study on the impact of the rear track width on the stability of agricultural tractors using a test bench J. Terramechanics 4 319-23
[4] Kireev I M and Koval Z M 2019 Experimental-theoretical method for determining the longitudinal and transverse static stability of agricultural units AgroForum 6 58-62
[5] Azad N L, McPhee J and Khajepour A 2005 Off-road lateral stability analysis of an articulated steer vehicle with a rear-mounted load Int. J. Veh. Syst. Model. Test 1 106-130
[6] Butin D A, Kostin S Yu, Vasiliev A A and Sereda P V 2017 Studies of the stability of a light commercial vehicle depending on the rigidity of the supporting system Fundamental Research 1 21-6
[7] Duan Z H 2018 Tilting stability analysis and experiment of the 3-DOF lifting platform for hilly orchards Int. J. Agric. Biol. Eng. 6 73-80
[8] Kolesnikovich A N, Algin V B and Kharitonchik S V 2004 Virtual tests of vehicles for static stability Improving the competitiveness of vehicles 229-33
[9] Li S and Cao S 2017 Simulation on the rollover system of corn harvester based on the ADAMS Adv. Intell. Syst. Res. 141 32-5
[10] Li S and Cao S 2017 Research and simulation of anti-rollover technology of harvester 2017 IOP Conf. Ser. Mater. Sci. Eng. 231 1-7
[11] Lysych M N 2019 Three-dimensional virtual dynamometer to measure the process of overcoming obstacles by disc cultivator *IOP Conf. Ser. Earth Environ. Sci.* **392** 12054

[12] Tumasov A V, Kostin S Y, Butin D A, Vasiliev A A and Sereda P V 2019 Influence of LCV bearing stiffness on its static and dynamic characteristics of stability and steerability *Mater. Phys. Mech.* **41** 111-5

[13] Vygonny A G, Kolesnikovich A N and Kharitonchik S 2012 Technologies for virtual testing of automotive vehicles: a comprehensive assessment of the indicators of controllability and stability *Materials of the 79th International Scientific and Technical Conference AAI 79* 9-15

[14] Yao Z, Wang G, Li X, Qu J, Zhang Y and Yang Y 2014 Dynamic simulation for the rollover stability performances of articulated vehicles *Proc. Inst. Mech. Eng.* **7** 771-83

[15] Zhou S and Zhang S Study on tractor semi-trailer roll stability control *Open Mech. Eng. J.* **8** 238-42

[16] Bartenev I M, Lysych M N 2019 The general concept of block-modular construction of forest tillage tools *Tractors and agricultural machinery* **1** 18-26