Three-dimensional virtual dynamometer to measure the process of overcoming obstacles by disc cultivator

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Abstract. The process of interaction between elastically fastened tillage tools and obstacles is investigated by means of computer applications that simulate the dynamics of the movement of 3d-models (MDB) created in the CAD. Design of the virtual stand and dynamometer block, implemented in the SolidWorks CAD system and the application for modeling the movement dynamics of SolidWorks Motion are described. The virtual stand enables to simultaneously capture all the components of traction resistance vector (RX, RY, RZ). Measured volumetric power characteristics of the process of stump overcoming by a section of a modular disk cultivator and the forces arising on the spring of a safety mechanism are given as an example of the virtual stand use. The discrepancy between experimental data and modeling data at the entrance to the stump is 8 ... 10%. In the future, virtual test data can be used to optimize the structures of tillage tools and safety mechanisms, as well as to reliably simulate disturbances in modeling the working process of the machine-tractor unit as a whole.

1. Introduction

To create efficient tillage tools of forest tillage implements, it is necessary to investigate their ability to overcome various obstacles. These studies should be carried out with maximum use of computer simulation. At present, simulation of interaction of soil-cultivating tillage tools with obstacles is considered only in a two-dimensional coordinate system [1, 2] or three-dimensional one, but with measurement of only traction resistance [3]. This leads to a significant simplification of the geometry of tillage tools and reduces the reliability and informativeness of research. Existing studies of volumetric interaction of soil-cultivating tillage tools relate to the study of their interaction with homogeneous soil. In this case, either the finite element method (FEM) [4-6] or the discrete element method (DEM) [6-9] is used. However, these methods are not applicable for modeling the dynamics of multi-link mechanisms. The method of multibody dynamics (MBD), is the most suitable for this problem, and widely used, for example, to simulate the movement of vehicle suspension [10, 11].

Thus, the purpose of the study is to create a virtual stand for volumetric force testing of the process of overcoming obstacles by the tillage tools and experimental verification of the reliability of the obtained data.
2. Material and methods

2.1. Tillage tool model
The initial stage of the research was the creation of a parametric 3D model of a cultivating tool and a cultivator section (figure 1). The model completely reproduces the geometry of a real experimental sample. For this, SolidWorks CAD was used.

![Cultivator section](image1.png)

Figure 1. Cultivator section: (a) – real life, (b) – 3D-model.

2.2. Virtual test stand
A virtual stand in the SolidWorks CAD system and the application for modeling the movement dynamics SolidWorks Motion was created for a volumetric dynamometer test of the process of overcoming obstacles by the tillage tools (figure 2).

The stand consists of a base 1, a guide 2, a carrier 3 and a conditionally marked soil 4. A virtual dynamometer unit 5 (to which the section of the modular tool 6 is attached) is mounted on the carrier, having the possibility of straight-line movement without friction. A stump 7 with different lateral displacement is set at the base.

![Virtual stand](image2.png)

Figure 2. Virtual stand: (a) – general view, (b) – variants of lateral displacement.
The virtual dynamometric unit (figure 3) consists of guide 1 and carriage 2 of R_\text{Y} direction, guide 3 and carriage 4 of R_\text{Z} direction, guide 5 and carriage 6 of R_\text{X} direction. Virtual load springs 7 without preload are installed between each carriage and the guide. The stiffness of the springs is chosen to be either equal to the stiffness of the steel, which excludes its deformation under the loads that occur during modeling, or equal to the rigidity of the tractor mounted devices to simulate their vibrations.

For testing, the dynamometer unit is rigidly connected with the guide 1 to the carrier on one side, and the carriage 6 with the test instrument on the other. Also, the carriage 2 and the guide 3, the carriage 4 and the guide 5 are rigidly interconnected. Thus, the final link 6 can mix in three directions R_\text{X}, R_\text{Y}, R_\text{Z} relative to the initial fixed link 1, while its mobility is limited by virtual springs with given rigidity.

![Virtual dynamometer unit](image)

**Figure 3.** Virtual dynamometer unit.

The data obtained using the virtual stand can be analyzed directly in the application in real time, or can be output to third-party programs where their final processing takes place.

The simulation parameters are presented in table 1.

| Parameter                    | Value             |
|------------------------------|-------------------|
| Movement speed (m/s)         | 1                 |
| Spring stiffness:            |                   |
| dynamometer block (N/mm)    | 1\cdot10^5        |
| safety mechanism (N/mm)     | 100               |
| Linear damper (N/mm)        | 10                |
| Stump parameter:            |                   |
| lateral displacement (cm)   | 0, 15, 30         |
| height +10 (cm)             | 0, 10, 20, 30     |
| diameter (cm)               | 40                |
| material (cm)               | aluminum          |
| Tillage tool parameter      |                   |
| diameter (cm)               | 51                |
| installation angle (°)      | 30                |
| material                    | steel             |
2.3. Laboratory test bench
Strain gauge installation was used (figure 4) to verify the data obtained in the multibody simulation of the process dynamics of obstacle overcoming. It includes two frames located one under the other and connected by oscillating leads 1. The frames have the ability to move relative to each other only in the longitudinal direction. This degree of freedom is limited by tensile link 2, which connects the frames for moving forward and stops 3 with screw adjustment, which perceive the loads in the transport position of the tool. The square tube 4 of the upper frame fastens the fixture allowing the separate module 5 to be mounted. The cylindrical pins and lugs of the lower frame connect to the rods 6 and 7 of the carriage 8 of the ground channel 9. Cable 10 connecting the load link 2 with the recording equipment is displayed outside the soil channel with the help of an external rod 11 in order to avoid its ingress under the moving parts of the unit. In the working position of the instrument, as the unit moves forward, the lower frame, shifting on the swinging leads 1 relative to the upper frame, stretches the tensile link, registering this force. The adjustment of the stretching moment, as well as the prestressing of the load link, is carried out by the nut 12. When the tool is lifted by the hydraulic cylinder 13 to the transport position, the upper frame, with the tool attached to it, under the weight, moves forward and the load is removed from the load link. Further relative movement of the framework is limited by the stops 3.

![Figure 4](image)

**Figure 4.** Strain gauge unit: (a) – general form, (b) – kinematic diagram of the unit.

3. Results and discussion

3.1. Virtual dynamometer test
Figure 5 presents the data of a virtual study of the stump overcoming process by a cultivating tool. Frontal interaction option. The text presents the values of the forces in increasing order of the height of the obstacle above the soil surface + the depth of tillage (0+10, 10+10, 20+10, 30+10 cm).
Figure 5. Modeling of the process of overcoming the stump in the frontal interaction.

The traction resistance component $R_X$ increases with increasing stump height (3394, 5570, 9051, 11910 N). The maximum force is reached at the moment of collision with an obstacle. Then there is a rapid decrease in load for 0.5-0.6 s. When moving on a horizontal surface of the stump, the average force decreases with increasing stump height (452, 397, 278, 193 N).

Component $R_Y$ also increases (negative values) with increasing stump height (-93, -4068, -11299, -17850 N). The maximum force is reached at the moment of collision with an obstacle. When moving on the surface of the stump, the direction of the force changes (818, 745, 560, 322 N).

Component $R_Z$, when colliding with stumps with a height of 20+10 and 30+10 cm, briefly takes negative values of -6362 and -7235 N, after which it rises to 3343 and 3080 N. When colliding with stumps with a height of 0+10 and 10+10 cm, the force increases to 3414 and 4156 N. During the movement on the horizontal surface of the stump, the average values of the force decrease with increasing stump height (3318, 3161, 2878, 1571 N). The impact force at the exit from the stump is -2674, -7974, -8295, -8491 N.

The force on the spring increases with increasing stump height and reaches its maximum when moving along its horizontal surface (10890, 14958, 17581, 18995 N).

Figure 6 shows a variant of interaction with a lateral displacement of 15 cm.
Figure 6. Simulation of the process of overcoming the stump at a lateral displacement of 15 cm.

The traction resistance component $R_X$ increases with increasing stump height. The maximum force is reached at the moment of collision with an obstacle (4059, 6790, 9793, 13637 N). Then there is a rapid decrease in load for 0.4-0.5 seconds. When moving on a horizontal surface of the stump, the average force decreases with increasing stump height (490, 457, 335, 164 N).

Component $R_Y$ when meeting with stumps with a height of 20 + 10 and 30 + 10 cm briefly takes negative values -1668 and -2942 N, after which it increases to 1502 and 1226 N. When colliding with stumps with a height of 0 + 10 and 10 + 10 cm, the force increases to 1501 and 2002 N. During the movement on the horizontal surface of the stump, the average values of the force decrease with increasing stump height (809, 787, 676, 415 N).

The $R_Z$ component when colliding with stumps with a height of 200 + 100 and 300 + 100 cm briefly takes negative values -3712 and -4941 N, after which it rises to 2860 and 2148 N. When colliding with stumps with a height of 0 + 100 and 100 + 100 cm, the force increases to 4302 and 3912 N. During the movement on the horizontal surface of the stump, the average force decreases with increasing stump height (4112, 3768, 2765, 1254 N). The impact force at the exit from the stump is -4238, -2470, -2696 N.

The force on the spring increases with increasing stump height and reaches its maximum when moving along a horizontal surface (11687, 15236, 17619, 18994 N).

Figure 7 shows a variant of interaction with a lateral displacement of 30 cm.

The traction resistance component $R_X$ also increases with the height of the stump. However, with a maximum height of an obstacle of 30 + 10 cm, anchoring of the tillage tool occurs. This causes critical loads. Therefore, this option is excluded from the study. The maximum force is reached at the moment of collision with an obstacle (4603, 6329, 6976 N). Then there is a rapid decline in the time of 0.2-0.3 s. When moving along the horizontal surface of the stump, the average value of the $R_X$ component decreases with increasing obstacle height (512, 454, 310 N).
Figure 7. Simulation of the process of overcoming the stump at a lateral displacement of 30 cm.

The $R_Y$ component also increases with increasing stump height (5092, 9228, 9392 N). When moving on the horizontal surface of the stump, the average force decreases with increasing stump height (913, 891, 698 N).

Component $R_Z$ decreases with increasing stump height (4313, 3855, 3209 N). When moving on a horizontal surface of the stump, the average values of the force decrease with increasing height of the obstacle (4153, 3792, 2748 N). The impact force at the exit from the stump is -3728, -1982, -4220 N.

Compare the resulting forces at different lateral displacements and equal to the height of the stump (figure 8). Stump height choose 20+10 cm as this is the maximum recommended working height. The maximum values of the components $R_X$ and the nature of their changes differ slightly. So at the moment of collision with an obstacle, a sharp fluctuation of force (6976-11910 N) is observed, rapidly decreasing in 0.5-0.7 seconds to 287-310 N. This interval corresponds to the movement along the horizontal surface of the stump. At the descent from the stump there are observed shock loads of no more than -3933 N.

The maximum values of the $R_Y$ component and the nature of their changes have significant differences. So when the frontal interaction occurs, a significant negative force (-11299 N) arises due to the contact of the back side of the disk with a stump. At a displacement of 30 cm, a fluctuations of force similar in character is observed, but with the opposite sign (9392 N). At a displacement of 15 cm, significantly smaller fluctuations in the negative and positive sides are observed. Further, when moving along the horizontal surface of the stump, the forces are aligned, being in the range of 560-698 N.

The maximum values of the $R_Z$ component and the nature of their changes do not have significant differences having maximum values in the range of 2748-2878 N. Differences are observed only in the maximum values upon contact with the stump and exit from it. The greatest oscillations are observed during frontal interaction (-6362 and -8295 N).

The change of forces on the spring also has a similar character, differing only in the duration of the process. The maximum values are observed when moving along the horizontal surface of the stump 17581-17619 N.
3.2. Experimental verification

The verification of the reliability of the power parameters was carried out by comparing the traction resistance and the longitudinal component of the force $R_X$ on the virtual dynamometric unit with frontal interaction with a stump and a lateral displacement of 30 cm (figure 9). This is due to the fact that the design of the laboratory strain gauge does not allow fixing other components of the traction resistance vector.

Analysis of the graphs shows that with frontal interaction, the maximum value (average over 0.2 s) at the time of the meeting with the stump obtained during modeling is 10% more (7145, 7938 N). Upon further movement, the force obtained in the simulation has a more intense decline. When moving on a horizontal surface of the stump, the values obtained by theoretical and experimental methods are practically compared. However, further forces obtained experimentally begins to increase.
This is due to the lateral removal of the disc due to cutting into the surface of the stump. At the time of descending from an obstacle during the simulation, shock loads are recorded. In the experimental data, these fluctuations of force are absent. This is probably due to the design of the measurement setup, which does not allow fixing rapidly changing forces.

An analysis of the graphs obtained during lateral interaction showed that the maximum experimental value at the time of encountering a stump is 8% more than that obtained in modeling (7191, 6587 N). Upon further movement, the force obtained in the simulation also has a more intense decline. The increase in force when moving on a horizontal surface of a stump experimentally obtained is less significant. This is due to the smaller disc drive due to the smaller distance traveled on the horizontal surface of the stump. At the time of exit from the obstacle in the experimental data, the force fluctuations are also absent.

4. Conclusions

Experimental and theoretical data allow us to conclude that the theoretical forces of impact and shock loads can be due to a sufficient degree of accuracy. This is important because the designs of most dynamometric systems and the characteristics of recording equipment do not allow fixing shock loads and all components of traction resistance.

The discrepancies between the experimental and theoretical data arose from the fact that the strain gauge recorded not only the longitudinal component of the resistance force, but also partly lateral and vertical. In this case, the comparison was carried out only with the longitudinal component obtained in a virtual experiment. Another reason for the discrepancies is probably that the model used a hard stump, which excluded significant cutting of the cutting edges of the tillage tools into its surface and their lateral withdrawal.

Virtual test data can be used to optimize the structures of tillage tools and safety mechanisms, as well as to reliably simulate disturbances when modeling the working process of the machine-tractor unit as a whole. For more reliable confirmation of simulation data, it is desirable to conduct an experimental test using test bench for volumetric dynamometer.

Acknowledgments

The reported study was funded by RFBR according to the research project No. 18-38-00920.

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