INVESTIGATION OF AGRICULTURAL UNIT LOADS IN NON-ESTABLISHED MODE OF MOTION WHEN PERFORMING TECHNOLOGICAL OPERATIONS

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Abstract. Modern agriculture requires introduction of rational, energy-saving and environmentally friendly agricultural technologies. Methods and tools that allow studying machines and units when they move, without stopping the implementation of agricultural operations, are of particular interest to scientists in recent years. Performing technological operations, agricultural units are exposed to various forces. The action of forces on the unit is both stochastic and different in nature. The study of the processes of motion of agricultural units under the action of forces is one the most important tasks when studying the dynamics of the unit of various purposes. The dynamics of the unit must be considered in the process of simultaneous interaction of all its components. The mobile agricultural unit in its dynamic aspect is represented by a mechanical system, the parts of which are connected by rigid and elastic connections between them. This entire mechanical system during technological operations performs both translational and rotational motion in the plane of the field. To study the dynamics of agricultural units, the university staff developed a registration and measurement system based on accelerometers. The system enables experimental measurement of accelerations in three planes. The sensors are attached to the unit, do not disturb its structure and show the dynamics of acceleration in real time. Based on the results of the experiment, a special program processes the signal and shows the dynamics of the agricultural unit operating parameters. In the process of rectilinear motion, the unit and all components have the same kinematic parameters. Angular displacements occur when turning, skidding or diverting an agricultural unit, and then its different points will have different values of linear and angular velocities and accelerations.

Keywords: agricultural unit, dynamic tests, forces, technological operation, acceleration, speed.

Introduction

In recent years, the intensification of scientific and technological progress in agricultural production has been especially felt, and we see this in the examples of mechanized processes that are inextricably linked with the qualitative development of agricultural mechanics.

Realization of technological operations by a mobile agricultural unit is associated with energy costs. This energy is spent on the performance of the technological operation and the dynamic processes that occur in the “tractor – agricultural implement – soil” system [1].

When determining the traction and energy assessment of agricultural units (traction force, traction power, movement resistance force) according to the static traction characteristic, which is based on dynamometers and strain gauges, it is notable for its highly laborious, and for some agricultural units its application is difficult to implement [2].

The traction characteristics of tractors in farms engaged in crop production have decisive importance in the process of acquisition and use of a machine-tractor unit (MTU). The stochastic influence of external factors during the interaction of the working bodies of machines with the processed medium (soil, plants) and movers with the field surface determines the nature of the movement of the unit’s individual points. This movement characterizes to a large extent the quality of many tillage operations (ploughing, inter-row cultivation, etc.). Many scientists, who are dealing with the dynamics of agricultural units, increase the time of the technological operation and disturb the design of agricultural units [3; 4]. Computer modelling of the process operations is now a common practice, as are the trajectories of machines and units [5; 6].

We propose a measuring and recording system that allows to study and monitor the parameters of agricultural machinery and units online.

Materials and methods

The study of the characteristics of the agricultural unit’s movement under the action of forces is one of the most important tasks in the study of the dynamics of units designed for carrying out various agrotechnical operations. A mobile agricultural unit in a dynamic sense is a dynamic system, the parts of which are interconnected by rigid and elastic links. The dynamics of the aggregate must be considered as a system in which all its constituent parts interact simultaneously. This entire dynamic system, when carrying out technological operations, realizes both translational and rotational motion on the field plane [7].

Agricultural units operate in conditions of constantly changing numerous external factors. For mobile agricultural units, such factors are the physical and mechanical properties of the soil (moisture, density, mechanical composition, etc.), field surface roughness, plant properties (yield, pollution, etc.), changes in the mass of the unit during the technological process, as well as energy costs required for tillage and movement of the unit [8]. The method for assessing the dynamic (traction, energy) characteristics of tractors and cars, which determines the possible speed of tractors and cars on roads with different rolling resistance, is comprehensively considered in the work “Fundamentals of the theory and calculation of a tractor and a car” by D.A. Chudakov [9]. The problem of such research is the need to intervene in the design of the unit and increase the time to perform the agro-technological operation.

When considering the movement of a unit, it is necessary to take into account the action of forces and how these forces affect the dynamics of the machine. One of the ways to determine the loads acting on an agricultural unit is the method of partial accelerations [10]. This method allows to measure parameters in real time and reduce the cost of research.

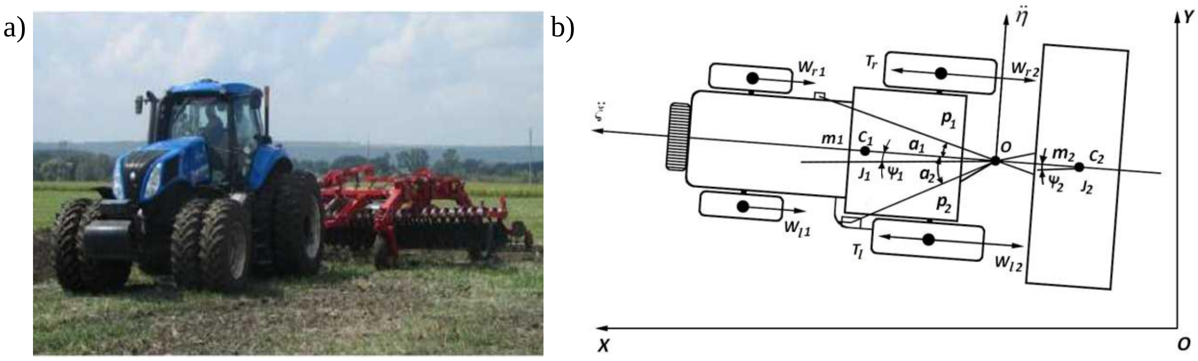

Fig. 1. **Agricultural tillage unit New Holland T 8. 390 + DHM-8.0 (modernized disc harrow):** a – general view of the unit; b – design scheme

Results and discussion

To further determine the dynamic indicators, it is necessary to draw up an equation for the power balance of the unit, taking into account the majority of energy costs in the process of carrying out agrotechnical operations

$$N_P^D = N_e^n - N_\eta - N_\delta - N_f - N_j \pm N_\alpha . \quad (1)$$

where N_e^n – effective engine power, kW;

N_η – mechanical losses in transmission, $N_\eta = N_e^n (1 - \eta_M)$, kW;

N_δ – for skidding of driving wheels, $N_\delta = N_e^n \eta_M \frac{\delta}{100}$, kW;

N_f – to overcome swing resistance, $N_f = \frac{GV}{3.6} f$, kW;

N_α – to overcome lifting, $N_\alpha = \pm \frac{GV}{3.6} \frac{i}{100}$, kW;

N_j – to change the speed of the machine-tractor unit, kW;

We will calculate the traction and energy indicators of the selected tillage unit New Holland T 8.390 + DHM-8.0 using known static data.

We will determine the engine power that it can realize when carrying out an agrotechnical operation, based on the technical characteristics [11; 12]. The dependence of acceleration on the force action is straightforward. As a result of this dependence, we conclude that the greater the force, the greater the acceleration with which the agricultural unit begins to move during the transition process (acceleration or deceleration) [13].

After substituting all the components in (1) and transformations, we determine the dynamic power

$$N_P^D = N_e^n \eta_M \left(1 - \frac{\delta}{100}\right) - \frac{GV\left(f \pm \frac{i}{100}\right)}{3.6}, \tag{2}$$

where η_M – mechanical efficiency of power transmission, (for wheeled tractors η_M = 0.91…0.92);
δ – skid of tractor movers, % (for wheeled tractors 4K2 permissible skid δ_D = 18%, 4K4 δ_D = 15%;
G – tractor operating weight, kN;
f – coefficient of rolling resistance of tractor movers;
V – speed of the agricultural unit, km·h^{-1};
i – field slope, %.

At the beginning of the technological operation by the unit, during acceleration, the maximum engine power is realized. After carrying out the transformations, we proceed to determination of dynamic indicators by measuring accelerations. The initial increase in power provides the appearance of linear acceleration

$$\dot{V}_a = \frac{dV}{dt},$$

which becomes an indicator of the unit's dynamics,

$$\frac{dV}{dt} = -\frac{1}{3.6G}\left[3.6T\ \delta + fG\cos\alpha + G\sin\alpha + T - (T_f + T_\alpha) + \frac{T}{\eta_{tt}\eta_\delta}(1-\eta_{tt})(3-\eta_{PTO})\right], \tag{3}$$

where η_{PTO} – tractor PTO efficiency;
α – field slope angle, degree;
η_{tt} – tractor transmission efficiency.

When analyzing the resulting equation, we conclude that the acceleration is directly proportional to the traction force T that is transmitted to the driving wheels from the engine, and it is inversely proportional to the weight of the mobile agricultural unit.

To determine the traction force by static parameters, we use the well-known formula [13]

$$T = \frac{N_e \eta}{V_1}. \tag{4}$$

where N_e – effective engine power, kW;
η – tractor transmission efficiency;
V_1 – tractor speed.

The determination of the static resistance force of a disk agricultural implement will be carried out according to the formula proposed in [14]

$$R = fG + 2an\sin\alpha\cos\beta\sqrt{a(D\cos\beta - \alpha)}\left(k + \varepsilon v^2\right). \tag{5}$$

The proposed methodology makes it possible to conduct dynamic tests of agricultural units at lower cost, without interfering with the design of the unit, in on-line mode, to more effectively providing the configuration and operation of agricultural machinery [10].

At the same time, $\zeta(t)$, $\eta(t)$ – are coordinates of the attachment point of the agricultural implement to the tractor, $\psi_1(t)$ and $\psi_2(t)$ – accordingly, the rotation angles of the tractor and the implement relative to the OX axis of the fixed coordinate system. The plane-parallel motion of a rigid body can be represented as such that it consists of a translational motion defined by a certain point (in our case, the connection point of the implement and the tractor with coordinates $\zeta(t)$ and $\eta(t)$), as well as rotational motion around this point [10], which is described by a change in the angle of rotation of the tractor $\psi_1(t)$ relative to the axis OX (see Fig. 1, b). Acceleration components are measured using a measuring and registration complex relative to a fixed coordinate system in which the movement of an agricultural unit is considered.

For such a case, the acceleration of any point of the aggregate can be represented as a geometric sum of three accelerations [5]

$$\vec{a}_{м} = \vec{a}_{o} + \vec{a}_{b} + \vec{a}_{c}, \quad (6)$$

where $\vec{a}_{o}$ – translational acceleration at a point O;
$\vec{a}_{b}$ – rotational acceleration;
$\vec{a}_{c}$ – centrifugal acceleration.

From the formulated equation and the dynamic scheme of the unit, we see that the acceleration $\vec{a}_{o}$ is represented by the components, $a_x^o = \ddot{\xi}$, $a_y^o = \ddot{\eta}$.

Centrifugal acceleration is directed along a straight line that connects the points of installation of sensors and fixation of the unit, and its value

$$a_c = \rho \dot{\psi}_1^2 , \quad (7)$$

where ρ – distance between the installation points of the sensors and fixing of the unit.

Rotational acceleration $\vec{a}_{b}$ is directed along a straight line perpendicular to the straight line, which connects the points of installation of the sensors and the attachment of the unit

$$a_{\mathrm{b}} = \rho \ddot{\psi}_1 . \quad (8)$$

For the dynamic model (Fig. 1, b), we will compose a system of equations that describes the movement of the unit under the action of various forces

$$\begin{cases} m\ddot{\xi} = T - W_1 - W_2 - R_X + R_Y\psi_2 \\ m\ddot{\eta} + m_1 b_1\ddot{\psi}_1 + m_2 b_2\ddot{\psi}_2 = (T - W_1 - W_2)\psi_1 - R_X\psi_2 - R_Y \\ m_1 b_1\ddot{\eta} + 2J_1\ddot{\psi}_1 + C(\psi_1 - \psi_2) = 0 \\ m_2 b_2\ddot{\eta} + 2J_2\ddot{\psi}_2 - C(\psi_1 - \psi_2) = R_Y l - R_X l\psi_2 , \end{cases} \quad (9)$$

where $T_r = T_l = 0.5T$ – tractor traction force;
$W_{r1} = W_{l1} = W_1$, $W_{r2} = W_{l2} = W_2$ – rolling resistance force;
$R = R_x$, $R_Y = \alpha R$ – agricultural implement resistance force;
$m = m_1 + m_2$ – weight of the agricultural unit.

For this system of equations, the moments of inertia $J_1 = b_1^2 m_1$ were determined for the tractor and the agricultural tillage tool – $J_2 = b_2^2 m_2$ $J_2 = b_2^2 m_2$.

To apply the method of partial accelerations, it is necessary to linearize the system of equations (9). Let us make the assumption that the traction forces on the driving wheels of the tractor are equal to each other and the rolling resistance forces of the wheels are also equal.

Thus, the first equation (9) has a standard form for using the partial acceleration method. Indeed, the value $\ddot{\xi}$ is a component of the acceleration vector of the unit in the longitudinal direction, and m is its total mass. Then it is possible to write

$$\ddot{\xi} = \frac{T}{m} - \frac{W}{m} - \frac{R(1 - \alpha\psi_2)}{m} . \quad (10)$$

For this equation

$$\ddot{\xi}_T = \frac{T}{m}$$

will be the partial acceleration that occurs during the acceleration of the agricultural unit in the case of absence of any forces other than the traction force T.

The value

$$\ddot{\xi}_K = -\frac{W}{m}$$

represents the partial acceleration of the tractor under the action of only the rolling resistance force on the tractor wheels.

For the case when there is no traction force on the drive wheels, the rolling resistance force

$$\ddot{\xi}_R = -\frac{R\left(1-\alpha\psi_2\right)}{m}$$

will be as the partial acceleration of the unit under the action of the resistance forces of the agricultural implement.

After the assumptions made, using partial accelerations, we write the equation of motion of the aggregate in the form

$$\ddot{\xi} = \ddot{\xi}_T + \ddot{\xi}_K + \ddot{\xi}_R \ . \tag{10}$$

The presence of a measuring and registration complex [11], which provides the measurement and processing of longitudinal linear accelerations (Fig. 2), allows us using the developed methodology [5] and determining the forces acting on the agricultural unit as a function of time.

The calculation of the dynamics of the tractor traction force, taking into account the forces of rolling resistance of the wheels, was carried out according to the presented formula

$$\begin{gathered} T = \left(m_1+m_2\right)\ddot{\xi}_{x1} + \frac{m_1\left(b_2^2+\rho_2^2\right)+m_2\rho_2^2}{\gamma\left(b_2^2+\rho_2^2-b_2 l\right)}\ddot{\eta}_y + \Delta\ddot{\xi}_x\left[\left(m_1+m_2\right)D_1 + \frac{m_1\left(b_2^2+\rho_2^2\right)+m_2\rho_2^2}{\gamma\left(b_2^2+\rho_2^2-b_2 l\right)}D_2\right] + \\ + \Delta\ddot{\eta}_y\left[\frac{m_1\left(b_2^2+\rho_2^2\right)+m_2\rho_2^2\left(D_1-b_1D_3\right)+\rho_2^2 m_2 D_1}{\gamma\left(b_2^2+\rho_2^2-b_2 l\right)} - \left(m_1+m_2\right)D_2\right] + \left(\psi_1-\psi_2\right)\frac{b_2 D}{\gamma\left(b_2^2+\rho_2^2-b_2 l\right)} . \end{gathered} \tag{11}$$

Change of the traction force in the course of work is of an oscillating nature, which is confirmed by the graphs (Fig.3) based on the experimental measurements and theoretical calculations.

The resistance forces of an agricultural tool are determined taking into account the experimental data on the dynamics of accelerations.

$$\begin{gathered} R = \sqrt{R_x^2+R_y^2} = \left|R_x\right|\sqrt{1+\gamma^2} = \frac{\sqrt{1+\gamma^2\left(b_2^2+\rho_2^2\right)}}{\gamma\left(b_2^2+\rho_2^2-b_2 l\right)}\left|\left(\psi_1-\psi_2\right)\frac{Db_2}{b_2^2+\rho_2^2} + \ddot{\eta}_{y1}\left(m_1 + \frac{\rho_2^2}{b_2^2+\rho_2^2}m_2\right) + \right. \\ \left. + \Delta\ddot{\xi}_x\left(m_1\left(D_2-b_1D_3\right)+m_2\frac{\rho_2^2 D_2}{b_2^2+\rho_2^2}\right) + \Delta\ddot{\eta}_y\left(m_1\left(D_1-b_1D_4\right)+m_2D_1\right)\right|, \end{gathered} \tag{12}$$

where γ – proportionality factor of the acceleration components;
R_x and R_y – components of the resistance force of an agricultural implement.

Graphs of the values of static calculations and experimental measurements are shown in Fig. 3.

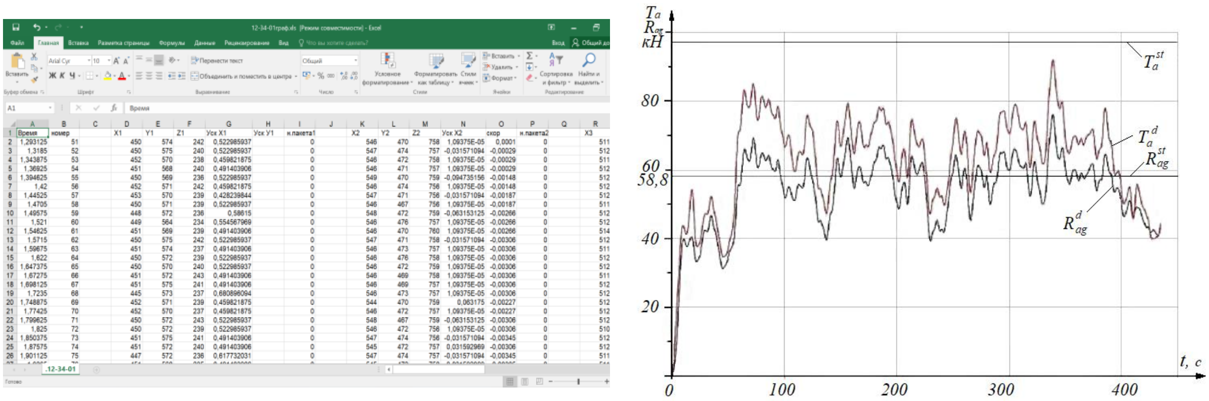

Fig. 2. **Array of experimental data of the measuring and registration complex obtained during the agrotechnical operation**

Fig. 3. **Dynamics of the tractor traction force and resistance force of the tillage implement New Holland T 8.390 + DHM-8.0**

As a result of the analysis of the calculations and the graphs, the following conclusions can be made: using the obtained formulas, it is possible to determine the traction force of the tractor, as well as the drag force of the agricultural implement as a function of time. At the same time, the graph shows calculated according to static data T_a^{st} and calculated T_a^d using the proposed method of partial accelerations. The graphs which were made confirm the fluctuations in the resistance force of the soil-cultivating tool over the entire length of the rut, theoretically substantiated by previous researchers.

Conclusions

Tracking changes in the acceleration of an agricultural unit allows to control changes in the dynamics of its work and stability during agrotechnical operations.

Experimentally measured components of acceleration are an effective tool of solving the modified challenge of dynamics – determining the rower characteristics in the process of flat-parallel movement of the agricultural unit.

The obtained characteristics of the unsteady process of the work of tillage units can be used by modeling loads during agrotechnical operations for various purposes. The static maximum theoretically calculated thrust force is T_a^{st} = 97.61 kN, and the thrust force variations calculated using the new methodology are within T_a^d = 87...92 kN, which is about 92% of the maximum static force.

Author contributions

Research methodology, theoretical substantiation, Nikolay Artiomov; preparation and conduction of the experiment, Aleksandr Kaluzhnij, Kiril Sirovitskiy, Ivan Kolodiazhnyi; writing: drafting, Nikolay Artiomov, Aleksandr Anikeev; writing: review and edit, Nikolay Artiomov, Aleksandr Anikeev, Kiril Sirovitskiy; visualization, Aleksandr Kaluzhnij, Ivan Kolodiazhnyi; funding acquisition, Nikolay Artiomov, Aleksandr Anikeev, Aleksandr Kaluzhnij, Kiril Sirovitskiy, Ivan Kolodiazhnyi. All authors have read and agreed to the published version of the manuscript.

References

[1] Василенко П.М. Введение в земледельческую механику. П.М. Василенко – Киев.: Сільгоспосвіта, 1996. – 251 с. (An introduction to agricultural mechanics.) (In Ukrainian).

[2] Погорілий Л.В. Мобільна сільськогосподарська енергетика: історія, тенденції розвитку, прогноз/Л.В. Погорілий, В.Г. Євтенко. – К.: Фенікс. 2005. – 184 с.(Mobile agriculture energy: History, development trends, forecast.) (In Ukrainian).

[3] Kabir M. S. N., Ryu M.-J., Chung S.-O., Kim Y.-J., Choi C.-H., Hong S.-J., Sung J.-H. Research Trends for Performance, Safety, and Comfort Evaluation of Agricultural Tractors: A Review. Journal of Biosystems Engineering, 39 (1), 2014¸pp. 21-33. DOI: 10.5307/jbe.2014.39.1.021 (In Korean)

[4] Serrano J.M., Peca J.O. da Silva M.J., Pinheiro A., Carvalho M. Tractor energy requirements in disc harrow systems Journal of Biosystems Engineering, 98(3), pp. 286-296. DOI: 10.1016/j.biosystemseng.2007.08.002 (In Portuguese)

[5] Werner R., Kormann G., Mueller S. Dynamic modeling and path tracking control for a farm tractor towing an implement with steerable wheels and steerable drawbar. 2nd Commercial Vehicle Technology Symposium. Kaiserslautern, 2012, pp. 241-250. (In Germany)

[6] Blundell M., Harty D. The Multibody Systems Approach to Vehicle Dynamics. Butterworth-Heinemann, 288, 2004. DOI: 10.1016/b978-0-7506-5112-7.x5000-3. (In German)

[7] Артьомов М.П. Визначення кількості ступенів рухливості машинно-тракторних агрегатів та їх вплив на керованість/М.П. Артьомов // сільськогосподарські машини: Збірник наукових праць. – Луцьк: ЛНТУ, 2013. – Вип. 24, Т.1. – С. 9-18. (Determination of the number of degrees of rupture of machine and tractor units and their impact on the controllability.) (In Ukrainian).

[8] Лебедев А. Тракторна енергетика: проблеми та їх розв’язання/А. Лебедев, В. Кравчук, С. Лебедев // Техніка і технології АПК. - 2011. - № 2 (17) – С. 4-8. (Tractor energy: problems and solutions) (In Ukrainian).

[9] Чудаков Е.А. Теория автомобиля/Е.А. Чудаков. – М.-Л.: Машгиз, 1940. – 396 с. (Vehicle theory) (In Russian).

[10] Метод парциальных ускорений и его приложения в динамике мобильных машин/[Н.П. Артемов, А.Т. Лебедев, М.А. Подригало, А.С. Полянский, Д.М. Клец, А.И. Коробко, В.В. Задорожняя] – Харьков: изд-во «Міськдрук», 2012. – 220 с. (The partial acceleration method and its applications in mobile machine dynamics) (In Ukrainian).

[11] Traktor book. [online] [11.03.2022] Available at: https://traktorbook.com/traktor-nyu-xolland-t-8-390/ Free access.

[12] Hydromarket [online] [11.03.2022] Available at: https://hydromarket.com.ua/p688653657-diskovyj-luschilnik-dukat.html

[13] Зангиев А.А. Практикум по эксплуатации машинно-тракторного парка/А.А. Зангиев, А.Н. Скороходов. – М.: «КолосС», 2006. – 317с. (Workshop on the operation of machine and tractor fleets) (In Russian).

[14] Припоров Е.В. Анализ факторов, влияющих на коэффициент полезного действия дисковой бороны // Известия Оренбургского государственного аграрного университета. Оренбург. ОГАУ, 2020, - № 4(84) – С.142 – 145. (Analysis of factors influencing disc harrow efficiency) (In Russian).

[15] Ляпунов А.М. Лекции по теоретической механике/А.М. Ляпунов. – К.: - Наукова думка, 1982. – 632с. (Lectures in theoretical mechanics) (In Ukrainian).

[16] Artiomov N., Antoshchenkov R., Antoshchenkov V., Ayubov A. Innovative approach to agricultural machinery testing, Latvia University of Life Sciences and Technologies, 20th International Scientific Conference Engineering for rural development Proceedings, Volume 20 May 26-28, 2021. pp. 451-456.