# EXPERIMENTAL AND THEORETICAL STUDY ON STRAIGHTNESS IMPROVEMENT IN AGRICULTURAL MACHINERY MOVEMENT
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# *EKSPERIMENTĀLS UN TEORĒTISKS PĒTĪJUMS PAR LINEARITĀTES UZLABOŠANU LAUKSAIMNIECĪBAS MAŠĪNU KUSTĪBĀ*

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## ABSTRACT
*This research was conducted for enhancing the linearity (or straightness) of the movement of a seeding machine-tractor system (SMTS), encompassing both theoretical and experimental studies. The experimental studies were conducted using a SMTS as part of a classic all-wheel drive tractor and a pneumatic trailed seeder. Theoretical research of the SMTS was carried out for three versions of the initial parameters of the mathematical model. In the first version the speed of movement was $v$ = 2.5 m·s$^{-1}$, the distance from the point of the seeder trailer to the centre of mass of the seeder was $l_5$ = 2 m, and the pressure in the pneumatic tires of the tractor wheels was $P_w$ = 0.10 MPa. In the second one, the speed of the unit is increased to $v$ = 2.8 m·s$^{-1}$, the distance from the point of the seeder trailer to the centre of mass of the seeder is increased to $l_5$ = 3 m, and the pressure in the tractor's tires is $P_w$ = 0.10 MPa. In the third versions, the pressure in the tractor tires is increased to 0.12 MPa. The difference between values $O_{(1)(T)}$, $O_{(2)(T)}$ of the trajectory of the movement of the centres of mass of the tractor and the seeder, determined during the theoretical research, and determined during the experimental research is 11%, and the discrepancy between the values of the rotation angles of the centres of mass is 9%; therefore, the mathematical model of the dynamics of the SMTS may be considered adequate.*

## *Kopsavilkums*
*Šajā darbā tika pārbaudīta metode sēšanas mašīnas–traktora vienības (SMTV) kustības linearitātes uzlabošanai, izstrādājot kustības dinamisko vienādojumu, piemērojot otrā veida Lagranža vienādojumus un veicot teorētiskus un eksperimentālus pētījumus. Eksperimentālie pētījumi tika veikti, izmantojot SMTV, kā traktora un piekabināmas pneimatiskās sējmašīnas kombināciju, bet teorētiskie pētījumi tika veikti trīs matemātiskā modeļa sākotnējo parametru variantiem. Pirmajā variantā kustības ātrums bija $v$ = 2.5 m·s$^{-1}$, attālums no sējmašīnas piekabes punkta līdz sējmašīnas masas centram bija $l_5$ = 2 m, un spiediens traktora riteņu pneimatiskajās riepās bija Pw = 0.10 MPa. Otrajā variantā vienības ātrums palielināts līdz $v$ = 2.8 m·s$^{-1}$, attālums no sējmašīnas piekabes punkta līdz sējmašīnas masas centram palielināts līdz $l_5$ = 3 m, un spiediens traktora riepās ir $P_w$ = 0.10 MPa. Trešajā variantā spiediens traktora riepās palielināts līdz 0.12 MPa. Teorētiskajos pētījumos noteiktās traktora un sējmašīnas masu centru kustības trajektorijas vērtības $O_{(1)(T)}$, $O_{(2)(T)}$ un eksperimentālos pētījumos noteiktās vērtības atšķiras par 11 %, bet masu centru rotācijas leņķu vērtības atšķiras par 9 %; tādēļ SMTS dinamikas matemātiskais modelis var tikt uzskatīts par atbilstošu.*

## INTRODUCTION

In modern agriculture, the efficiency of agronomic processes largely depends on the use of modern equipment, seeding machine-tractor units in particular. Therefore, the relevance of the conducted research is determined by the need to improve the accuracy and stability of the movement of the SMTS, which directly affects the efficiency of technological operations in the conditions of precision farming and changing climate.

The plane-parallel movement of the SMTS is crucial to ensure seeding accuracy and quality, as well as to optimize the resource costs. The research presented in this work aimed to develop a mathematical model describing the movement of a classic all-wheel drive tractor in combination with a seeder. This model will allow a deeper understanding of the mechanics of interaction between the elements of the unit, as well as the influence of various parameters on the stability of movement and productivity. The relevance of this study is determined by the need to improve the efficiency of agricultural operations, which is especially important in the context of growing competition and changing climatic conditions.

Analysis of the latest research and publications shows that in agricultural production, especially in precision farming, there is a growing need to improve the efficiency and productivity of the seeding operations. An important aspect is to ensure stability and precision of movement of the SMTSs that perform these operations (*Adamchuk et.al., 2023*). In particular, the research of the plane-parallel movement of the SMTS, consisting of all-wheel drive tractors of classical design and seeders, is an urgent task since it allows optimizing the sowing process, reducing the resource costs and increasing the yields *(Parihar et.al., 2024*).

Instability of movement may lead to uneven seed distribution, increased skips and double sowings, which negatively affects the quality of sowing and the yield (*Sun et.al., 2022*).

Contemporary research in the field of the SMTS dynamics is focused on the development of mathematical models that consider various factors influencing the motion of the unit (*Ivanovs et.al., 2020; Startcev et.al., 2021*). Mathematical modelling allows analysis of the stability of movement, determining the optimal design parameters and operating modes of the SMTS, and develop automatic control systems that ensure high accuracy and stability of movement (*Adamchuk et.al., 2023*).

This paper presents the results of research of the plane-parallel movement of a SMTS, consisting of a classic-configuration all-wheel drive tractor and a seeder. The purpose of this research is to develop a mathematical model, describing the movement dynamics of the unit in a horizontal plane, taking into account the design parameters of the tractor and the seeder, as well as external forces, acting upon the SMTS. The developed mathematical model allows evaluation of the impact of various factors upon the movement stability of the unit and determination of the optimal parameters that ensure high precision and stability of the sowing operations (*Babaei et.al., 2024*).

All-wheel drive tractors remain essential in modern agriculture due to their adaptability to diverse soil conditions. Their integration into smart mobile systems (SMTS) requires careful analysis of movement stability to ensure precise and efficient field operations (*Li et.al., 2024*). In this regard, the development of a mathematical model that takes into account the design features of such tractors and their interaction with the seeder is a pressing task (*Prasanna Kumar et.al., 2009*).

In some previous investigations there was considered the improvement of the dynamic properties of the machine-tractor *system*, achieved through theoretical studies of their dynamics, assessment of the linearity (straightness) of the movement, stability and controllability (*Wang et.al., 2024a; Antoshchenkov et.al., 2023; Antoshchenkov et.al., 2022; Bulgakov et.al., 2017, 2022*).

In the above investigations an analysis of the movement of the SMTS was made, the dynamic models of which were presented in the form of spatial and plane-parallel models with two or more elements (masses).

Other studies have confirmed the topicality of this task; for example, a model of a mouldboard-less seeder with a semi-active shock absorber, based on magnetorheological fluid, has been developed, which allows the movement of the unit to be adapted to the uneven soil surfaces and vibrations, which increases the accuracy of sowing and the stability of movement (*Sharipov, 2019*).

An energy analysis of a wide-cut seeder was also performed, showing that up to 90.8% of the tractor power is spent on overcoming the traction resistance, which emphasizes the importance to optimize the design of the unit in order to increase its efficiency (*Tulegenov et.al., 2020*).

In another investigation, the effect of vibration upon the accuracy of a pneumatic seeder at different speeds of travel is examined. A CFD–DEM model was used, confirming that the vibrations significantly affect the accuracy of the seed sowing and the stability of the movement of the seeding unit (*Wang et.al., 2024b*). *Findura and Ruman (2024*) have studied the manoeuvrability of a three-module seeding unit, based on a reversible tractor. The theoretical and experimental investigations have shown that increasing the length of the drawbar of the side seeders and the width of the tractor track allows for a reduction in the turning radius of the seeding unit and an increase in the stability of its movement on the headland.

The improvement of the dynamic properties of the SMTS needs theoretical studies of the plane-parallel movement of a two-mass unit with four degrees of freedom.

Seeders are an integral part of the SMTS, playing an important role in ensuring uniform seed distribution. Their design features and parameters also affect the dynamics of the movement of the unit. Therefore, when developing a mathematical model, it is necessary to take these factors into account to obtain accurate results (*Wang et.al., 2024a*).

The purpose of the research is to increase the linearity (straightness) of the movement of the SMTS as part of an all-wheel drive tractor and a seeder by theoretically substantiation pf the design parameters and operating modes.

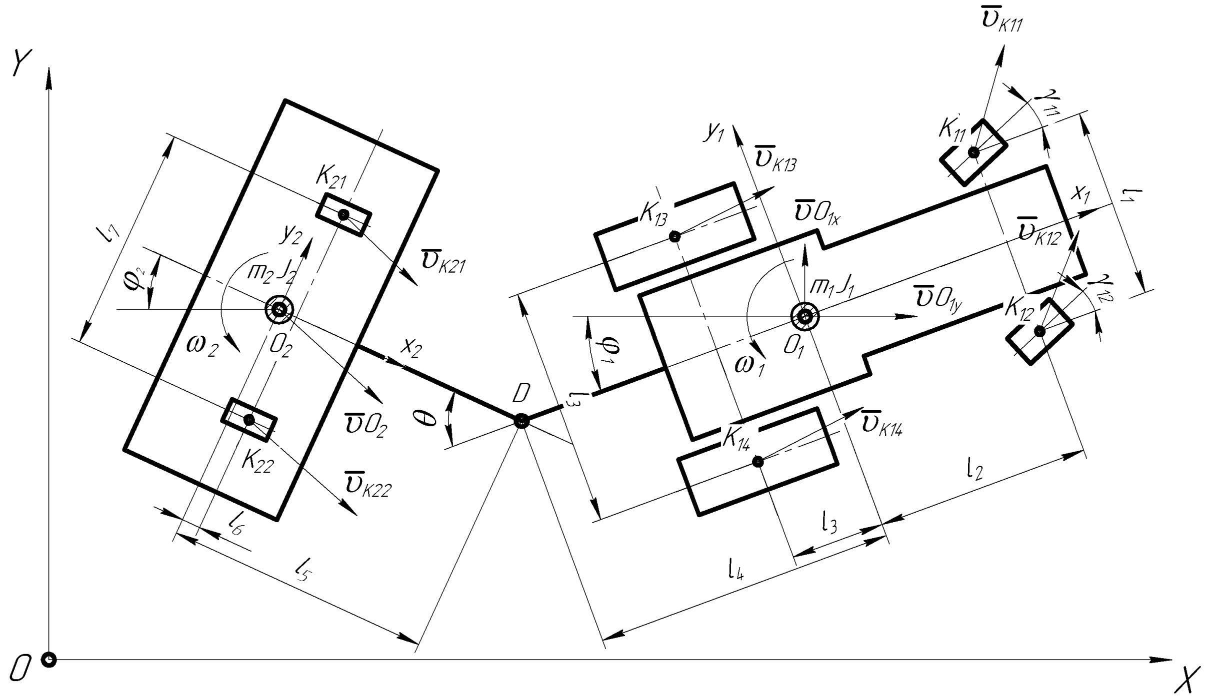
## MATERIALS AND METHODS

Theoretical investigations have been conducted using a SMTS as part of an all-wheel drive tractor and a *pneumatic* trailed seeder. Classic-design tractor, all-wheel drive 79 kW, trailed pneumatic seeder, which is designed for the simultaneous sowing of two crops.

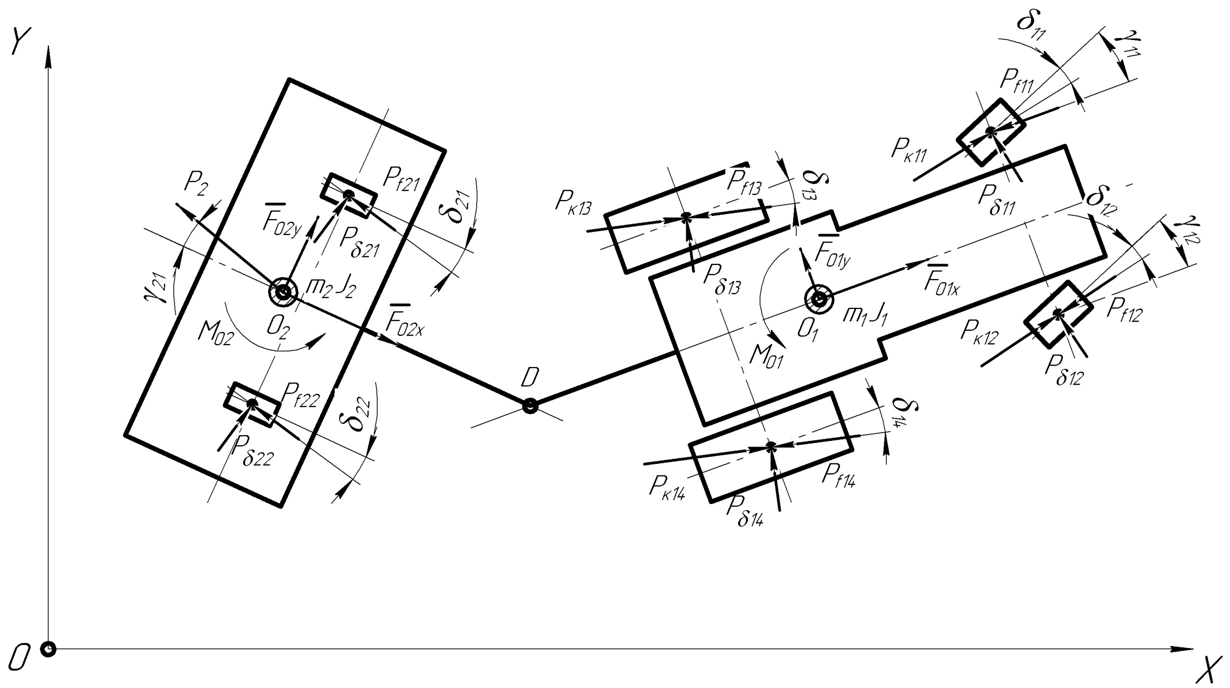
Formation of the equations of the movement of the unit requires making assumptions that will simplify the solution of the problem, as well as discarding factors that complicate mathematical modelling and do not affect the calculation. The following assumptions were introduced: plane-parallel movement of the unit was considered; in the process of compiling the mathematical model, the deferent (plane-parallel movement of the unit in the *XOZ* plane) and the roll (plane-parallel movement of the unit in the *YOZ* plane) were not taken into account; the processes that occur in the hydraulic steering drive were not taken into account; the processes that occur in the transmission were not taken into account; the dynamic characteristics of the engine during acceleration and braking of the unit were not taken into account; the frames of the sections are absolutely rigid bodies, and the entire unit is symmetrical relative to the longitudinal plane; the rolling resistance forces are considered constant; the lateral forces onto the tires are limited by the adhesion of the wheels to the road. The rolling resistance of the tractor and the seeder wheels is calculated depending on the vertical load on the corresponding wheel (*Damme et.al., 2021*).

The accepted assumptions allow representation of the SMTS as a flat dynamic system in the horizontal plane *XOY*, since in this plane there are projections of forces that form loads upon the elements of the unit, the coupling device, the resistance force of the seeder, the resistance force to rolling of the machine, lateral forces and driving forces.

The equivalent scheme (Fig. 1) is a dynamic model of the plane-parallel movement of a two-element (two-mass) SMTS, consisting of two parts: a tractor and a seeder.




a)




b)

**Fig. 1 – A kinematic (a) and a dynamic (b) model of plane-parallel movement of a two-element (two-mass) SMTS**

When compiling a mathematical model, the case of movement along a curvilinear trajectory is used, which corresponds to the actual trajectory of movement of the seeding units across the field (*Antoshchenkov et.al., 2024*). During movement, the leading wheels are the front and the rear wheels of the tractor. The loads that the unit experiences in this case are not critical and are typical for the technological process of sowing. A distinctive feature of the developed mathematical model is that it allows analysis of the trajectories of the movement of the unit elements, deviations and frequencies depending on the control action and design parameters.

The following designations are used in the diagram of the kinematic and the dynamic model of plane-parallel movement of a two-element (two-mass) SMTS (Fig. 1): *XOY* – the global (fixed) coordinate system; $O_1$ – the centre of mass of the tractor; $O_2$ – the centre of mass of the seeder; $x_1O_1y_1$ – the connected (moving) coordinate system of the tractor, passing through the centre of mass, point $O_1$; $x_2O_2y_2$ – the connected (moving) coordinate system of the seeder, passing through the centre of mass, point $O_2$; point *D* – the coupling device (the connection point of the tractor and the seeder); $\varphi_1$ – the turning angle of the tractor frame around the vertical axis; $\varphi_2$ – the turning angle of the seeder frame around the vertical axis; $\omega_1$ – the angular velocity of turning of the tractor frame around the vertical axis z; $\omega_2$ – the angular velocity of turning of the seeder frame around the vertical axis z; $\gamma_{11}$ – the turning angle of the steered front left wheel of the tractor; $\gamma_{12}$ – the turning angle of the steered front right wheel of the tractor; $\delta_{11}$, $\delta_{12}$, $\delta_{13}$, $\delta_{14}$ – l lateral slip angle of the front left, front right, rear left and rear right wheels of the tractor; the lateral slip angle of the front left, front right, rear left and rear right wheels of the tractor; $\delta_{21}$, $\delta_{22}$ – the lateral slip angle of the left and the right wheels of the seeder; $\theta$ – the bend angle (the angle between the longitudinal axes of the tractor and the seeder); $l_1$ – the track of the front wheels of the tractor; $l_2$ – the distance from the front wheels to the centre of mass of the tractor; $l_3$ – the distance from the centre of mass to the axis of the rear wheels of the tractor; $l_4$ – the distance from the centre of mass of the tractor to the attachment point of the seeder; $l_5$ – the distance from the attachment point of the seeder to the centre of mass; $l_6$ – the distance from the centre of mass of the seeder to the axis of the wheel; $l_7$ – the track of the seeder wheel; $m_1$ – mass of the tractor; $J_1$ – the moment of inertia of the tractor; $m_2$ – mass of the seeder; $J_2$ – the moment of inertia of the seeder; $P_{\kappa 11}$, $P_{\kappa 12}$, $P_{\kappa 13}$, $P_{\kappa 14}$ – the tangential traction force of the front left, front right, rear left and rear right wheels of the tractor; $P_{f11}$, $P_{f12}$, $P_{f13}$, $P_{f14}$ – the rolling resistance force of the front left, front right, rear left and rear right wheels of the tractor; $P_{\delta 11}$, $P_{\delta 12}$, $P_{\delta 13}$, $P_{\delta 14}$ – the lateral slip force of the front left, front right, rear left and rear right wheels of the tractor; $P_2$ – the vector of the traction resistance forces of the seeder; $\gamma_{21}$ – rotation angle of the vector of the seeder's traction resistance forces; $P_{f21}$, $P_{f22}$ – the rolling resistance force of the left and right wheels of the seeder; $P_{\delta 21}$, $P_{\delta 22}$ – the lateral slip force of the left and the right wheels of the seeder; $F_{O1x}$, $F_{O1y}$, $F_{O2x}$, $F_{O2y}$ – the projections of the main vector of forces from the side of the support surface for the tractor and seeder; $M_{O1}$, $M_{O2}$ – the main point of disturbing effects from the side of the supporting surface for the tractor and seeder.

The position of the dynamic system "tractor-seeder" will be determined by four generalized coordinates: $O_{1x}$ – the projection of the speed of the center of mass of the tractor onto axle *x*; $O_{1y}$ – the projection of the speed of the center of mass of the tractor onto axle *y*; $\varphi_1$ – the turning angle of the tractor frame around the vertical axis *z*; $\varphi_2$ – the turning angle of the seeder frame around the vertical axis *z*.

As a mathematical apparatus for the compilation of differential equations of movement of a two-element (two-mass) seeding unit, consisting of a tractor and a seeder, the Lagrange dynamics equations of the second kind were adopted (*Antoshchenkov et.al., 2024*):

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_k}\right) - \frac{\partial T}{\partial q_k} = Q_k, k = 1,2,3,4 \tag{1}$$

where: $T$ – the kinetic energy of the system; $Q$ – the generalized forces of the system; $q_k$ – the generalized coordinates of the system.

The Lagrange equations of the second order, describing the dynamics of the seeding unit, are formed relative to the following generalized coordinates: $O_{1x}$ and $O_{1y}$ – the centre of mass of the tractor (point $O_1$); the turning angles of the tractor frame $\varphi_1$ and the seeder $\varphi_2$ around axle *z*. The equations of the dynamics of the unit in the general case have the following form:

$$\begin{cases} \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_{O_1}}\right) - \frac{\partial T}{\partial x_{O_1}} = Q_{O1x} \\ \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{y}_{O_1}}\right) - \frac{\partial T}{\partial y_{O_1}} = Q_{Oy1} \\ \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\varphi}_1}\right) - \frac{\partial T}{\partial \varphi_1} = Q_{\varphi_1} \\ \frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\varphi}_2}\right) - \frac{\partial T}{\partial \varphi_2} = Q_{\varphi_2} \end{cases} \tag{2}$$

where:

$Q_{O1x}$, $Q_{O1y}$, $Q_{\varphi 1}$, $Q_{\varphi 2}$ – generalized forces of the corresponding generalized coordinates.

The kinetic energy of the SMTS consists of the kinetic energy of the tractor and the seeder and is determined from the expression:

$$T = \frac{m_1 v_{O_1}^2}{2} + \frac{J_{O_1}\omega_1^2}{2} + \frac{m_2 v_{O_2}^2}{2} + \frac{J_{O_2}\omega_2^2}{2}, \tag{3}$$

where: $v_{O1}$, $v_{O2}$ – the velocities of the centres of mass of the tractor and the seeder; $\omega_1$, $\omega_2$ – the angular velocities of the tractor and the seeder relative to the corresponding vertical axes *z*; $J_{O1}$, $J_{O2}$ – the moments of inertia of the tractor and the seeder relative to the corresponding vertical axes *z*.

To use the numerical method for solving a system of differential equations (a modified Runge-Kutta method of 4-5 order), it is necessary to reduce system (2) to the Cauchy form.

To reduce equations (1) – (3) to the Cauchy form and numerically solve the system of linear algebraic equations (SLAE) using Cramer's method, the MatLab 2021a mathematical software package (*Shior et.al., 2024*) was used and the following variables were introduced:

$$\begin{cases} a_{11} = m_1 + m_2; a_{12} = 0; a_{13} = m_2 l_4 \sin\varphi_1; a_{14} = m_2 l_5 \sin\varphi_2; \\ a_{21} = 0; a_{22} = m_1 + m_2; a_{23} = -m_2 l_4 \cos\varphi_1; a_{24} = -m_2 l_5 \cos\varphi_2; \\ a_{31} = m_2 l_4 \sin\varphi_1; a_{32} = -m_2 l_4 \cos\varphi_1; a_{33} = J_1 + m_2 l_4^2; a_{34} = m_2 l_4 l_5; \\ a_{41} = m_2 l_5 \sin\varphi_2; a_{42} = -m_2 l_5 \cos\varphi_2; a_{43} = m_2 l_5 l_4 \cos(\varphi_1 - \varphi_2); a_{44} = J_2 + m_2 l_5^2. \end{cases} \tag{4}$$

Considering equations (1 )– (3), after performing the necessary groupings and transformations, the Lagrange equations are obtained, with the form:

$$\begin{cases} a_{11}\ddot{x}_{O_1} + a_{12} y_{O_1} + a_{13}\ddot{\varphi}_1 + a_{14}\ddot{\varphi}_2 = Q_{x_{O_1}}; \\ a_{21}\ddot{x}_{O_1} + a_{22} y_{O_1} + a_{23}\ddot{\varphi}_1 + a_{24}\ddot{\varphi}_2 = Q_{y_{O_1}}; \\ a_{31}\ddot{x}_{O_1} + a_{32} y_{O_1} + a_{33}\ddot{\varphi}_1 + a_{34}\ddot{\varphi}_2 = Q_{\varphi_1}; \\ a_{41}\ddot{x}_{O_1} + a_{42} y_{O_1} + a_{43}\ddot{\varphi}_1 + a_{44}\ddot{\varphi}_2 = Q_{\varphi_2}. \end{cases} \tag{5}$$

The coefficients of the second derivative systems (5) and generalized forces are functions of the mass, geometric, operational parameters of the tractor and the unit, generalized coordinates and speeds. The equation of the motion of the SMTS is a system of four inhomogeneous second-order differential equations.

Generalized forces contain such characteristics of the unit as tangential traction forces of the tractor wheels; rolling resistance forces of the tractor wheels; lateral input forces of the tractor wheels; vector traction resistance force of the seeder; rolling resistance forces of the seeder wheels; lateral input forces of the seeder wheels; projections of the main vector of forces from the support surface for the tractor and seeder; the main moment of the disturbing effects from the supporting surface for the tractor and the seeder. The type and conditions of the soil affect the rolling resistance forces of the tractor wheels; the lateral input forces of the tractor wheels; traction force of the seeder; the forces of the seeder's traction resistance; the rolling resistance forces of the seeder wheels; lateral wheel slip of forces of the seeder.

The developed mathematical model allows studying the dynamics (movement) of the SMTS elements in a longitudinally parallel plane and determining the impact of the geometric parameters of the unit upon its dynamics, the oscillations of the elements around a straight trajectory and the stability of movement.

The experimental research of the SMTS is aimed to confirm the adequacy of the developed mathematical model of the dynamics of the seeding unit. During the experimental investigations of the SMTS a measuring system for the dynamics and energy of mobile machines was used (*Antoshchenkov et.al., 2023*). The measuring system for the dynamics and energy of mobile machines (MSDEMM) is a technical means of measurement for testing, diagnostics and operational control. The measuring system (MS) is designed to determine the kinematic, dynamic, power and energy characteristics of mobile machines and their elements during road, field and bench tests (*Antoshchenkov et.al., 2022*).

When conducting experimental investigations of the SMTS, the following sensors are used as part of the measuring system:

– an inertial measurement device (IMD), consisting of a microcontroller, accelerometer, gyroscope and magnetometer, being designed to determine accelerations, angular velocities, the strength of the Earth's magnetic field, the orientation angles, vibration, and the actual trajectory of movement in three planes (*Bulgakov et.al., 2022*);

– the wheel dynamics sensor (WDS), consisting of a microcontroller, accelerometer, gyroscope and magnetometer and being designed to determine accelerations, the angular velocities, the orientation angles, vibration, and the wheel rotation speed;

– the GPS receiver, determining the actual speed of the unit, its geographic location, and the angle of the direction of movement.

During the experimental investigations, the impact of the design parameters of the unit upon the dynamics and vibrations of the elements was determined, as well as to confirm the adequacy of the developed mathematical model of the unit dynamics. The location of the sensors on the SMTS during the experimental research is shown in Fig. 2. The placement of sensors on the SMTS during experimental investigations is shown in Fig. 2.

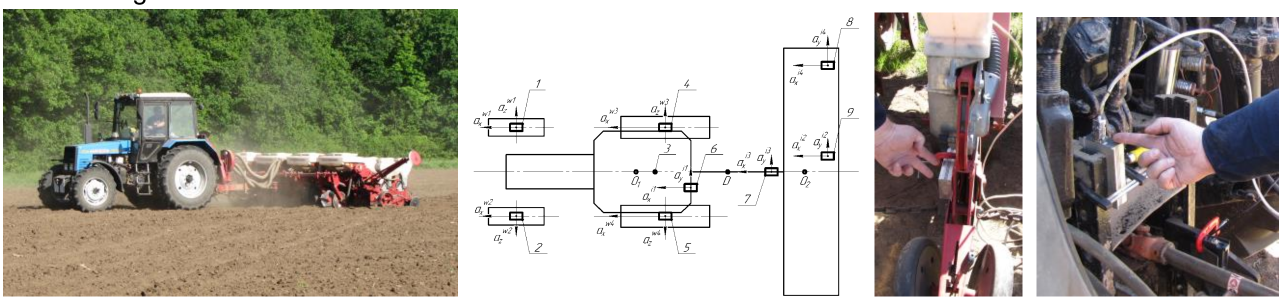


**Fig. 2 – The placement of sensors on the SMTS during experimental investigations**

*1 – the wheel dynamics sensor 1 (the front right wheel of the tractor); 2 – the wheel dynamics sensor 2 (the front left wheel of the tractor); 3 – the GPS receiver antenna; 4 – the wheel dynamics sensor 3 (the rear right wheel of the tractor); 5 – the wheel dynamics sensor 4 (the rear left wheel of the tractor); 6 – the inertial measuring device 1; 7 – the inertial measuring device 3; 8 – the inertial measuring device 4; 9 – the inertial measuring device 2*

The wheel dynamics sensor 1 was located on the front right wheel of the tractor. The wheel dynamics sensor 2 was located on the front left wheel of the tractor. The GPS receiver antenna was located on the roof of the tractor (in the longitudinal-horizontal plane in the centre of mass of the tractor). The wheel dynamics sensor 3 was located on the rear right wheel of the tractor. The wheel dynamics sensor 4 – on the rear left wheel of the tractor. The inertial measuring device 1 – on the tractor frame; the inertial IMD-3 – on the rear of the seeder; the IMD - on the extreme (eighth) section of the seeder; the IMD-2– on the fourth section of the seeder.

A methodology for conducting experimental studies, using modelling and simulation of dynamic experimental measurement method (MSDEMM) is described in detail in the works by *Antoshchenkov et.al., (2022); Antoshchenkov et.al., (2023.*)

The methodology of experimental research includes three stages. In the first stage, the measuring equipment is located on the elements of the unit. The second stage allows to exclude the influence of extraneous factors. The elimination of random factors is achieved by repeating each experiment three times. To eliminate the influence of the technical condition, it is necessary to carry out routine maintenance at the beginning of the shift. To eliminate the influence of the field relief, experiments are carried out in one and the opposite direction (this is considered a separate experiment). When conducting experiments, two fields with the most characteristic soil structure are selected, which differ sharply in their physical and mechanical properties. The same type of experiments are carried out in two fields during one shift. At the third stage, after the completion of operations to prepare the unit for research, information is collected. The soil properties (physical and mechanical properties and moisture) and environmental parameters are determined. The computing module is turned on to collect information. The required number of experiments is conducted, and after each experiment the obtained data is stored on the hard drive for further processing. After completion of the research, the measuring system is switched off and dismantled from the unit.

Experimental studies are conducted in the fields of the experimental farm (50.041266, 36.485128) with an area of 54 hectares. The sowing of combined crops of corn, soybeans and sorghum was performed, using highly productive varieties: corn "Solominskaya 298 SR", soybeans – "Khutoryanochka", which had high laboratory seed germination: 98% and 94%. The sorghum variety, sown together with soybeans, is called "Samurai", the seeds of which also had a high laboratory germination rate – 98%.

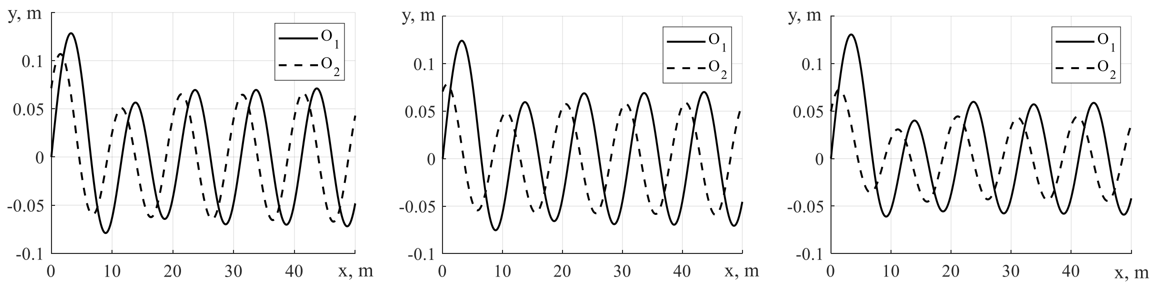
The soil condition indicators meet the conditions for sowing grain crops. The soil hardness in spherical layers 0-5 cm – 1.1 MPa; 5-10 cm – 1.4 MPa; 10-15 cm – 1.7 MPa. The soil moisture in the 0-5 cm layers was 21.4%; 5-10 cm – 23.9%, 10-15 cm – 22.9%. Sowing was carried out after pre-sowing soil cultivation, using a 240 HP tractor and a John Deere 10 m cultivator, the cultivation depth 7-11 cm.

By experimental research the trajectories of the centres of mass of the unit elements and the turning angles were determined.

## RESULTS

The theoretical investigations of the SMTS were conducted for three versions of the initial parameters of the mathematical model. In the first version, the speed of movement was $v$ = 2.5 m·s$^{-1}$; the distance from the point of the seeder trailer to the centre of mass of the seeder was $l_5$ = 2 m; the pressure in the tires of the tractor wheels was $P_w$ = 0.10 MPa. In the second version, the speed of the unit is increased to $v$ = 2.8 m·s$^{-1}$; the distance from the seeder trailer point to the seeder's center of mass is increased to $l_5$ = 3 m; the pressure in the tractor wheels – $P_w$ = 0.10 MPa. In the third variant, the pressure in the tractor tires is increased to $P_w$ = 0.12 MPa.

The trajectories of the centres of mass of the tractor $O_1$ and the seeder $O_2$ (Fig. 3), the dependences of the turning angles of the centres of mass of the tractor $\gamma_1$ and the seeder $\gamma_2$ around the vertical axis on the distance traveled (Fig. 4), and the spectral densities of the trajectories of the centres of mass of the tractor $S(O_1)$ and the seeder $S(O_2)$ (Fig. 5) were determined and compared.




a b c

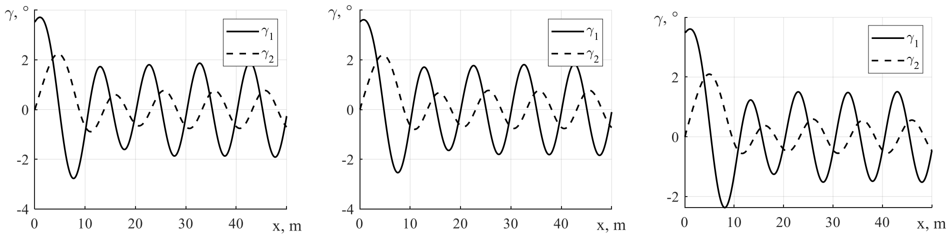
**Fig. 3 – Trajectories of the centres of mass of the tractor**

*$O_1$ and the seeder $O_2$ (a – $v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa; b – $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.10 MPa; c – $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.12 MPa)*

The maximum deviation of the centre of mass of the tractor from a straight-line trajectory is 0.125 m (Fig. 3, a), and for other design parameters of the SMTS – 0.12 m. The range of oscillations of the centre of mass of the tractor is 0.12 m (at $v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa). An increase in the travel speed to 2.8 m·s$^{-1}$ and an increase in the pressure in the tractor tires to 0.12 MPa lead to a decrease in the amplitude of the tractor frame oscillations to 0.11 m (Fig. 3, c).

The range of oscillations of the centre of mass of the seeder decreases from 0.11 m (at $v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa, Fig. 3, a) to 0.08 m (at $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.12 MPa, Fig. 3, c).

Increasing the travel speed to 2.8 m·s$^{-1}$, increasing the distance from the seeder trailer point to the center of mass of the seeder $l_5$ to 3 m, and increasing the tire pressure of the tractor wheels to 0.12 MPa have a positive effect on the linearity (straightness) of the movement of the elements of this seeding unit.



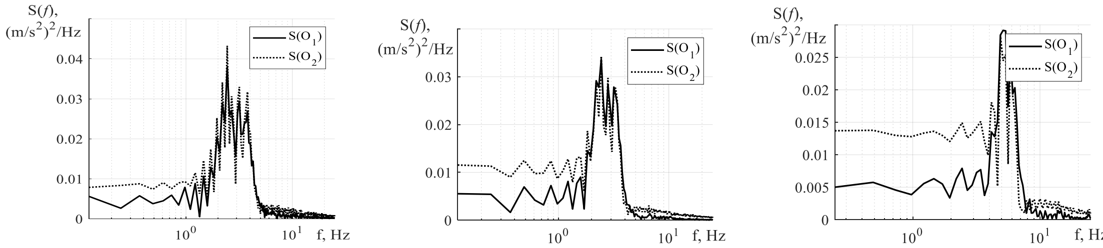

a b c

**Fig. 4 – Dependences of the turning angles of the centres of mass of the tractor $\gamma_1$ and the seeder $\gamma_2$ around the vertical axis on the distance travelled**

*a – $v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa P; b – $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, Pw = 0.10 MPa; c – $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, Pw = 0.12 MPa*

The maximum range of values of the turning angle of the tractor frame around the vertical axis is 5.8 degrees (at $v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa, Fig. 4, a). The range of oscillations of the seeder frame angle for this case is 2.2 deg. An increase in the speed of the SMTS and an increase in the length of the seeder linkage leads to a decrease in the angle of the tractor and seeder to 2.8 degrees and 1.8 degrees, respectively (at $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.12 MPa, Fig. 4, c).

A complex indicator for the assessment of the dynamics of the elements of this seeding unit is the spectral densities of the trajectories of the centres of mass of the tractor and the seeder (*Antoshchenkov, et.al., 2022; Bulgakov, et.al., 2022*). The spectral densities of the trajectories of the centres of mass of the tractor $S(O_1)$ and the seeder $S(O_2)$ were calculated for three variants of the design parameters of the SMTS (Fig. 5).




a b c

**Fig. 5 – Spectral densities of trajectories of the centres of mass of the tractor $S(O_1)$ and the seeder $S(O_2)$**

*a – $v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa; b – $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.10 MPa; c – $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.12 MPa*

The spectral density of the trajectory of the centre of mass of the tractor has the highest amplitude: 0.045 (m·s$^{-2}$)$^2$·Hz$^{-1}$ at a frequency of 3.1 Hz; the spectral density of the trajectory of the seeder's centre of mass is 0.032 (m·s$^{-2}$)$^2$·Hz$^{-1}$ at frequencies of 2.5–4 Hz (Fig. 5, a). Increasing the speed of the SMTS to 2.8 m·s$^{-1}$ leads to a decrease in the amplitude of the spectral density of the trajectory of the centre of mass of the tractor and the seeder to 0.032 (m·s$^{-2}$)$^2$·Hz$^{-1}$·at frequencies of 2.5–5 Hz (at $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.10 MPa, Fig. 5, b). The decrease in amplitudes to 0.028 (m·s$^{-2}$)$^2$·Hz$^{-1}$ at frequencies of 5–7 Hz occurs at $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.12 MPa (Fig. 5, c).

To test the adequacy of the mathematical model of the dynamics of the SMTS, experimental investigations were conducted in which the trajectories of the movement of the centres of mass of the tractor and the seeder were determined and compared with the theoretical ones for two movement speeds of 2.5 and 2.8 m·s$^{-1}$ (Fig. 6). The trajectories of the movement of the centres of mass of the investigated SMTS are a complex parameter for assessing the adequacy of the mathematical model of movement (*Bulgakov et.al., 2022*).

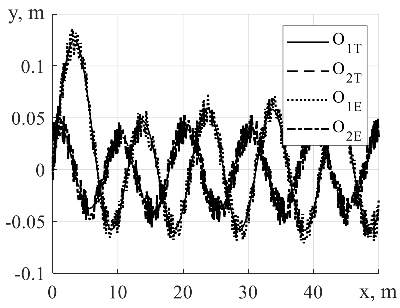



**Fig. 6 – The trajectories of the centres of mass of the tractor and the seeder were determined during the theoretical investigations $O_{1T}$, $O_{2T}$ and were verified during the experimental studies $O_{1E}$, $O_{2E}$**
*a – v = 2.8 m·s⁻¹; b – v = 2.8 m·s⁻¹*

Additionally, a comparison between the turning angles of the centres of mass of the tractor and the seeder around the vertical axes was made, being determined during the theoretical research $\gamma_{1T}$, $\gamma_{2T}$ and during the experimental studies (Fig. 7), using the methodology that has shown efficiency in the previous works (*Antoshchenkov et.al., 2022; Bulgakov et.al., 2022; Antoshchenkov et.al., 2024*).

The discrepancies between the values of the trajectory of the movement of the centres of mass of the tractor and the seeder, determined during the theoretical research $O_{1T}$, $O_{2T}$ and determined during the experimental studies is 11%, and the discrepancy between the values of the turning angles of the centres of mass is 9%; therefore, the mathematical model of the dynamics of the SMTS can be considered adequate.

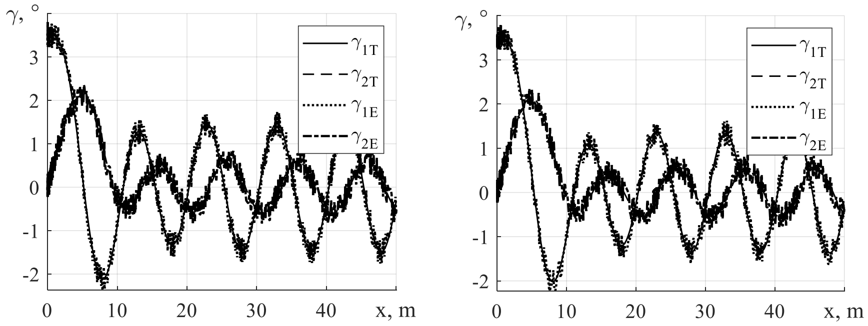



**Fig. 7 – The turning angles of the centres of mass of the tractor and the seeder around the vertical axes, determined during theoretical research $\gamma_{1T}$, $\gamma_{2T}$ and verified during experimental studies $\gamma_{1E}$, $\gamma_{2E}$**
*a – v = 2.5 m·s⁻¹; b – v = 2.8 m·s⁻¹*

The results of the research of the movement of the SMTS for three different sets of parameters showed that an increase in the speed of the movement and the pressure in the pneumatic tires of the running wheels has a positive impact upon the linearity (straightness) of the movement of this seeding unit. The maximum deviation of the centre of mass of the tractor from the preset trajectory of movement decreased from 0.125 m to 0.11 m, and the amplitude of oscillations of the centre of mass of the seeder decreased from 0.11 m to 0.08 m. This indicates an increase in the stability and accuracy of sowing.

For a comprehensive assessment of stability, spectral analysis of the trajectories of the centres of mass was used. The spectral density of the movement centre of mass of the tractor decreased from 0.045 $(m·s^{-2})^2·Hz^{-1}$ at a frequency of 3.1 Hz to 0.028 $(m·s^{-2})^2·Hz^{-1}$ at a frequency of 5–7 Hz. Similar changes were recorded for the seeder. This means that the system exhibits reduced dynamic instability under optimal driving conditions.

Comparison of the theoretical and the experimental data made it possible to evaluate the adequacy of the developed model. The average deviation in trajectories was 11%, and in the turning angles – 9%, which is within the acceptable limits of engineering modelling.

In other studies, it was pointed out to similar trends, for example, a research conducted in Germany, showed that the introduction of magnetorheological shock absorbers reduces vibrations and improves the controllability of the SMTS when sowing on uneven soil surfaces (*Sharipov, 2019*).

During a research in China CFD–DEM modelling was applied to analyse vibrations for seed dosing accuracy in pneumatic seed drills. It was found that increasing the travel speed with proper design settings reduces the negative impact of vibrations upon sowing (*Wang et.al., 2024b*).

The authors of another study analysed the energy distribution in a wide-cut SMTS and determined that up to 90.8% of the power of the tractor is spent on overcoming resistance, emphasizing the importance of optimizing the design of the unit (*Tulegenov et.al., 2020*).

The authors of theoretical and experimental investigations of three-module sowing machine-tractor system studied the impact of the length of the drawbar of the side seeder and the track width upon the stability of the unit when it is turned. The results confirmed that changing the geometry of the SMTS increases its stability (*Findura et.al., 2024*).

The results of modelling, presented in the work of *Marcinkiewicz et.al., (2019*), demonstrate high accuracy of the analysis of the seeder elements using the discrete element method (DEM), which made it possible to evaluate in detail the interaction of components during the sowing process. These approaches are well compatible with the results of our study, where the use of Lagrange equations of the second kind provided a reliable description of the plane-parallel movement of an aggregating wheeled tractor and a trailed seeder. Both approaches confirm that digital modelling – whether DEM or classical mechanics – allows optimizing the design parameters of the seeding unit, reducing dynamic vibrations and increasing the accuracy of the seeding process in real field conditions.

Thus, the obtained results confirm the efficiency of the proposed mathematical model and show its applicability for optimizing the movement of a sowing machine-tractor system. The conducted comparison with the studies by foreign authors confirms that, considering the geometric parameters, pressure in the pneumatic tires of the running wheels, the speed of movement and spectral characteristics, is an important condition for increasing the accuracy and reliability of the technological process of sowing various agricultural crops.

## CONCLUSIONS

It was determined that the maximum value of deviation of the tractor's centre of mass from a straight-line trajectory is 0.125 m ($v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa; $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.10 MPa) and 0.12 m ($v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa). The length of the range of oscillations of the tractor's centre of mass is 0.12 m (at $v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa).

Increasing the travel speed to 2.8 m·s$^{-1}$ and increasing the pressure in the tractor tires to 0.12 MPa lead to a decrease in the amplitude of the oscillations of the tractor's centre of mass to 0.11 m.

The range of oscillations of the centre of mass of the seeder decreases from 0.11 m (at $v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa, to 0.08 m (at $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.12 MPa). The maximum turning angle of the tractor frame around the vertical axis is 5.8 degrees (at $v$ = 2.5 m·s$^{-1}$, $l_5$ = 2 m, $P_w$ = 0.10 MPa). The turning angle of the seeder frame for this case is 2.2 deg.

Increasing the speed of the SMTS and increasing the length of the seeder hitch leads to a decrease in the angle $\varphi_1$ of the tractor and seeder to 2.8 degrees and 1.8 degrees, respectively (at $v$ = 2.8 m·s$^{-1}$, $l_5$ = 3 m, $P_w$ = 0.12 MPa).

Increasing the speed of movement to 2.8 m·s$^{-1}$, increasing the distance from the seeder trailer point to the centre of mass of the seeder $l_5$ to 3 m, and increasing the pressure in the tractor wheels to 0.12 MPa have a positive effect on the linearity (straightness) of the movement of the SMTS elements.

It has been established that the discrepancy between the values of the trajectory of the movement of the centres of mass of the tractor and the seeder, determined during the theoretical research $O_{1T}$, $O_{2T}$ and determined during the experimental studies is 11%, and the discrepancy between the values of the rotation angles of the centres of mass is 9%; therefore, the mathematical model of the dynamics of the SMTS can be considered adequate.

## REFERENCES


[1] Adamchuk V., Bulgakov V., Nadykto V., Trohaniak O., & Chorna T. (2023). Theoretical study of the stability of asymmetric movement sowing machine-tractor aggregate. *Bulletin of Agricultural Science*, 101(5), 57–64. https://doi.org/10.31073/agrovisnyk202305-08

[2] Antoshchenkov R., Halych I., Nikiforov A., Cherevatenko H., Chyzhykov I., Sushko S., Ponomarenko N., Diundi S., Tsebriuk I. (2022). Determining the influence of geometric parameters of the traction-transportation vehicle's frame on its tractive capacity and energy indicators. *Eastern-European Journal of Enterprise Technologies*, 2, (7-116), 60-61. DOI: 10.15587/1729-4061.2022.254688

[3] Antoshchenko R.V., Cherevatenko G.I., Zadorozhny V.P., Svitlychny O.V., Kuskov M.A. (2023). Research on the dynamics of an all-wheel drive traction and transport machine. *Ukrainian Journal of Applied Economics and Technology*, 7(3). 125–135.

[4] Antoshchenkov R., Halych I., Antoshchenkov V., Nykyforov A., Kis-Korkishchenko L., Cherevatenko H., Smitskov D. (2024). Measuring system of dynamics and energy of mobile machines: monograph. – Katowice: *Wydawnictwo Uniwersytetu Śląskiego*. 150 p.

[5] Babaei Robat A., Arezoo K., Alipour K., & Tarvirdizadeh B. (2024). Dynamics modelling and path following controller of tractor-trailer-wheeled robots considering wheels slip. *ISA Transactions*, 148, 45–63. https://doi.org/10.1016/j.isatra.2024.03.004

[6] Bulgakov V., Adamchuk V., Ivanovs S., Ihnatiev Y. (2017). Theoretical investigation of aggregation of top removal machine frontally mounted on wheeled tractor. *Engineering for Rural Development*, 16, 273–280. https://www.iitf.lbtu.lv/conference/proceedings2017/Papers/N054.pdf

[7] Bulgakov V., Antoshchenkov R., Adamchuk V., Halych I., Ihnatiev Y., Beloev I., Ivanovs S. (2022). Investigation ofwhats the tractor performance when ballasting its rear half-frame. *INMATEH – Agricultural Engineering*, 68(3), 533–542. http://dx.doi.org/10.35633/inmateh-68-52

[8] Dammeten L., Schjonning P., J. Munkholm L., Green O., K. Nielsen S., & Lamandé M. (2021). Traction and repeated wheeling – effects on contact area characteristics and stresses in the upper subsoil. *Soil and Tillage Research*. 211, Article 105020. https://doi.org/10.1016/j.still.2021.105020

[9] Ivanovs S., Bulgakov V., Nadykto V., Ihnatiev Ye., Smolinskyi S., Kiernicki Z. (2020). Experimental study of the movement control-lability of a machine-and-tractor aggregate of the modular type. *INMATEH – Agricultural Engineering,* 61(2), 9–16. https://doi.org/10.35633/inmateh-61-01

[10] Findura P., Kollárová K., Nadykto V., Kyurchev V., Zhokin I. (2024). Turning Research of a Sowing Unit Based on Reversible Tractor. *Acta Technologica Agriculturae*. 27. 194-202. http://dx.doi.org/10.2478/ata-2024-0026

[11] Li X., Xu L., Liu M., Yan X., & Zhang M. (2024). Research on torque cooperative control of distributed drive system for fuel cell electric tractor. *Computers and Electronics in Agriculture*, 219, 108811. https://doi.org/10.1016/j.compag.2024.108811

[12] Marcinkiewicz J., Selech J., Staszak Ż., Gierz Ł., Ulbrich D., & Romek D. (2019). DEM simulation research of selected sowing unit elements used in a mechanical seeding drill. *MATEC Web of Conferences*, 254, 02021. https://doi.org/10.1051/matecconf/201925402021

[13] Parihar N.S., Sharma S., & Khar S. (2024). Factors Affecting the Performance of a Potato Digger – A Review. *Potato Research*, 67(4), 1563–1580. https://doi.org/10.1007/s11540-024-09704-5.

[14] Prasanna Kumar G.V., Srivastava B., & Nagesh D.S. (2009). Modelling and optimization of parameters of flow rate of paddy rice grains through the horizontal rotating cylindrical drum of drum seeder. *Computers and Electronics in Agriculture*, 65(1), 26–35. https://doi.org/10.1016/j.compag.2008.07.006

[15] Sharipov M.G. (2019). *Modelling and Optimization of No-Till Seeder Dynamics*. [Dissertation Submitted in fulfilment of the regulations to acquire the degree "Doktor der Agrarwissenschaften"], https://scispace.com/pdf/modelling-and-optimisation-of-no-till-seeder-dynamics-for-gfa7s97zi9.pdf

[16] Shior M.M., Agbata B.C., Gbor G.D., Ezugorie I.U., & Topman N.N. (2024). Solution of First Order Ordinary Differential Equations Using Fourth Order Runge-Kutta Method with MATLAB. *International Journal of Mathematics and Statistics Studies*, 12(1), 54–63. https://doi.org/10.37745/ijmss.13/vol12n15463

[17] Startcev A., Romanov S., & Vagina O. (2021). Research into the Course Stability of a Four-Wheel Drive Wheeled Machine–Tractor Unit. In *Lecture Notes in Mechanical Engineering*, Springer International Publishing. 607–614. https://doi.org/10.1007/978-3-030-54814-8_70

[18] Sun J., Zhang Y., Zhang Y., Li P., & Teng G. (2022). Precision Seeding Compensation and Positioning Based on Multisensors. *Sensors*, 22(19), 7228. https://doi.org/10.3390/s22197228

[19] Wang L., Zhu J., Liu F., He Z., Lai Q., Zhu Z., Song Z., & Li Z. (2024a). Algorithm and scale experiment of gyro-based tractor rollover control towards hilly farmland application. *Computers and Electronics in Agriculture*, 220, 108925. https://doi.org/10.1016/j.compag.2024.108925

[20] Wang Y., Zhang W., Luo, X., Zang Y., Ma L., Zhang W., Liu, J., & Zeng S. (2024b). Effect of Vibration Conditions on the Seed Suction Performance of an Air-Suction Precision Seeder for Small Seeds. *Agriculture*, 14(4), 559. https://doi.org/10.3390/agriculture14040559