UDC 621.01:[631.372+631.331]
DOI: 10.15587/1729-4061.2023.270988

DETERMINATION OF DYNAMIC AND TRACTION-ENERGY INDICATORS OF ALL-WHEEL-DRIVE TRACTION-TRANSPORT MACHINE

Roman Antoshchenkov
Corresponding author
Doctor of Technical Sciences, Professor, Head of Department*
E-mail: roman.antoshchenkov@gmail.com
Serhii Bogdanovich
PhD, Senior Lecturer
Department of Mechatronics and Machine Parts**
Ivan Halych
PhD, Senior Lecturer*
Halyna Cherevatenko
Postgraduate Student*
*Department of Mechatronics, Life Safety and Quality Management**
**State Biotechnological University
Alchevskikh str., 44, Kharkiv, Ukraine, 61002

The results of a study of dynamic and traction-energy indicators of an all-wheel drive wheeled traction-transport machine are presented. A diagram of a dynamic transmission model for an all-wheel drive wheeled traction and transport machine and a system of equations for the transmission dynamics in the Cauchy form have been compiled. This made it possible to determine the dependences of the angular speeds of rotation of the transmission elements of the traction-transport machine, the dependences of the torques and the dependences of the contacting traction forces on the wheels on time. The method allows to determine the optimal transmission parameters, differential designs and gear ratios to improve the traction and coupling and fuel-economic performance of the machine. It has been established that the angular speeds of rotation of the front wheels of the traction-transport machine 1.29 rad/s, 1.27 rad/s are higher than the angular speeds of rotation of the rear wheels 1.24 rad/s, 1.25 rad/s, which leads to the appearance of a kinematic discrepancies and additional energy losses. The torques of the front drive wheels are 6972 Nm, the rear drive wheels are 4622 Nm. The contacting traction forces on the front wheels of the machine are 5478 N after the end of the acceleration of the machine, on the rear wheels – 3473 N. Experimental studies were carried out on the example of an all-wheel drive wheeled tractor with an articulated frame to validate the method for assessing the dynamics of the traction-transport transmission. The difference between the values of the angular speeds of rotation of the wheels and the tangential traction forces on the wheels, determined theoretically and obtained during experimental studies, is 2 %. The developed method for assessing the transmission dynamics of an all-wheel drive traction and transport machine should be considered valid. The method proposed in the paper can be used to assess the dynamics of wheeled machines

Keywords: angular velocity of rotation, torque, tangential traction force, all-wheel drive wheeled traction and transport machine

Received date 03.10.2022
Accepted date 08.12.2022
Published date 30.12.2022

***How to Cite:** Antoshchenkov, R., Bogdanovich, S., Halych, I., Cherevatenko, H. (2023). Determination of dynamic and traction-energy indicators of all-wheel-drive traction-transport machine. Eastern-European Journal of Enterprise Technologies, 1 (7 (121)), 40–47. doi: https://doi.org/10.15587/1729-4061.2023.270988*

1. Introduction

The modern stage of development of technology is characterized by an extremely rapid change in models of products. There is a growing number of developments based on new, previously unknown principles that provide products with higher consumer qualities and create fierce competition in the market for their sale.

The new technical object must, of course, surpass the existing ones. This is achieved by an appropriate design strategy aimed at achieving high technical level and efficiency of the created product.

The stage of functional design is especially important, at which the optimal structures and parameters of a technical object are determined. Solving problems of functional design requires the development of methods for constructing mathematical models, numerous methods for solving systems of equations that describe the functioning of a technical object, optimization methods and structure.

In agro-industrial production, multi-operational combined units with high productivity are increasingly used. One of the main components of the combined units is all-wheel drive wheeled traction and transport machines (TTM) [1].

Wheeled all-wheel drive TTMs have a high cross-country ability and can be attributed to a separate group of machines due to the specifics of their design and application conditions. All-wheel drive high-flotation machines are preferably used on soils with low bearing capacity, when operating on off-road or poor quality dirt roads, where they can move at high average speeds. Wheeled TTMs are aggregated with agricultural machines and mass trailers [2].

The improvement of designs and the creation of new TTMs of increased energy efficiency and energy saturation require in-depth studies of the transmission dynamics of especially all-wheel drive wheeled machines. The problem of assessing the influence of TTM operating conditions on traction and dynamic indicators, which depend on the parameters of the machine's transmission, remains insufficiently studied. Therefore, studies devoted to the determination of the dynamic and traction and energy performance of an all-wheel drive traction and transport machine are relevant and promising.

2. Literature review and problem statement

In order to improve the efficiency of the operation of the machine, the change in the mass of the machine was studied in [3]. When driving, a change in the mass of the machine has a significant impact on the traction and energy performance, which accordingly leads to a change in the loads on the transmission elements. Thus, the problem of assessing the effect of mass change on the traction and energy performance of the machine and transmission elements remains unexplored.

The authors of [4] note that TTMs with a hybrid or exclusively electric power plant are promising. Hybrid or electric powertrains are more energy efficient than internal combustion engines. All-wheel drive transmissions with a hybrid or electric power plant have certain design features. Researchers ignored the issues of studying the traction and energy performance of a machine with all-wheel drive and the features of the operation of an all-wheel drive transmission.

The two-mass system considered in [5] is the object of the automatic control system for the machine transmission. Automatic transmission control systems for all-wheel drive machines must take into account the peculiarities of the redistribution of traction power between the front and rear axles. It should be noted that in most cases the transmission of the machine is a multi-element (multi-mass) system, the issue of studying the control system of a multi-element (multi-mass) transmission remains unresolved.

In works [6, 7], the elements of the hydromechanical transmission of a traction-transport machine are studied, dynamic and energy indicators are determined. The authors conducted a study for a rear-wheel drive traction and transport machine. Preferably, the hydromechanical transmission of a four-wheel drive machine has two hydraulic motors (one for each axle) or four (one hydraulic motor for each wheel). In the studies, the authors did not take into account the features of the operation of the elements of the hydromechanical transmission of all-wheel drive wheeled machines.

In [8], the case of plane-parallel movement of a combined sowing machine was studied. The power tool of the combined seeding unit is an all-wheel drive traction and transport machine. The problem of the influence of the transmission dynamics on the straightness of movement and the energy costs of the traction and transport machine as part of the unit has not been studied.

Rear-wheel drive mechanical boxes were studied by the authors in [9, 10]. The transfer of torque from the engine to one axle has the significant advantage of not circulating parasitic power. The authors accepted the restriction to apply the proposed mathematical models to assess the dynamics and energy performance of wheeled machines with a drive on one axle with one differential.

The authors studied the interaction of the engine and electromechanical transmission in [11]. The internal combustion engine and electromechanical transmission lead to a reduction in energy costs for the operation of the machine and the fulfillment of the technological task. The authors did not pay attention to the question of the influence of the assessment of the dynamics of the all-wheel drive of the machine on the energy performance of the operation.

The studied limited slip differentials have a significant impact on the dynamics and controllability of the machine [12]. Such differentials are used on special-purpose machines, but they have not received distribution on traction and transport machines used in agriculture. The authors of the work paid insufficient attention to determining the energy performance of a machine with limited slip differentials.

The dynamics of a traction-transport machine with technological modules was studied in [13, 14]. Considering that TTMs with technological modules are most often used in agricultural production, such machines are mainly all-wheel drive. The study of the influence of the kinematic parameters of technological modules on the dynamic loads of the transmission elements and the energy performance of the power tool remained without the attention of researchers.

From the analysis of information sources [3–14], it was found that the influence of dynamic and traction and energy indicators of an all-wheel drive wheeled traction and transport machine with front and rear differentials, limited slip differentials remains unexplored.

3. The aim and objectives of research

The aim of research is to determine the dynamic and traction and energy performance of an all-wheel drive wheeled traction and transport machine. This will provide designers and manufacturers of traction and transport all-wheel drive machines with recommendations on the creation and improvement of machine designs in order to improve traction and coupling properties.

To achieve the aim, the following objectives must be completed:

– evaluate the influence of the design parameters of the all-wheel drive wheeled TTM on the dynamic and traction-energy performance;

– carry out experimental studies of the machine to validate the method for determining the dynamic and traction and energy performance of an all-wheel drive wheeled traction and transport machine.

4. Materials and methods of research

4. 1. The object of research

The study of the dynamics of an all-wheel drive traction and transport machine requires the preparation of appropriate kinematic and dynamic schemes and a mathematical model of the machine's transmission.

The object of the study is the relationship between the transmission parameters of the TTM and the traction and energy performance of the machine.

When compiling a mathematical model of the transmission of a wheeled all-wheel drive TTM, the following assumptions were made:

1. TTM transmission elements are studied as absolutely rigid bodies symmetrical around the axis of rotation.

2. Dissipative energy costs are constant and do not depend on the transmission temperature.

3. Shafts have linear torsional stiffness.

The accepted assumptions can be considered valid, since the transmission elements (shafts, gears) are symmetrical bodies of rotation. When studying the transmission of machines, the authors of [6, 7, 11, 12] also did not take into account the temperature of the transmission elements.

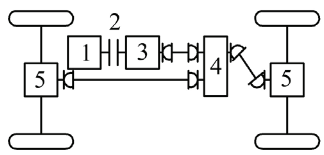
4. 2. Method for assessing the influence of transmission parameters on the traction and energy performance of an all-wheel drive wheeled traction transport machine

Designing a new and improving an existing mechanical transmission requires the definition of a kinematic scheme, i.e. ways and means of supplying power from the engine to the wheels. There are on-board and bridge transmission schemes, which can be with a blocked, differential or mixed drive.

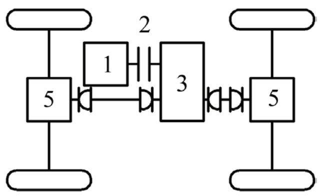
Fig. 1 shows the most common transmission schemes for all-wheel drive wheeled traction and transport machines with a 4×4 wheel arrangement [15, 16].

Transfer case 4 is usually a mandatory unit in the transmission of an all-wheel drive wheeled machine with axle drive 5, except for the case when gearbox 3 performs the transfer case function.

A diagram of a dynamic model of the transmission of an all-wheel drive traction and transport machine (Fig. 2) is drawn up, based on the diagram (Fig. 1, *b*) in which the functions of the transfer case 4 are performed by the gearbox 3.



a



b

Fig. 1. Transmission diagrams for all-wheel drive traction and transport machines: *a* — transmission diagram with a bridge drive and a transfer case; *b* — without transfer case; 1 — engine; 2 — clutch; 3 — gearbox; 4 — transfer case; 5 — main gear and differential

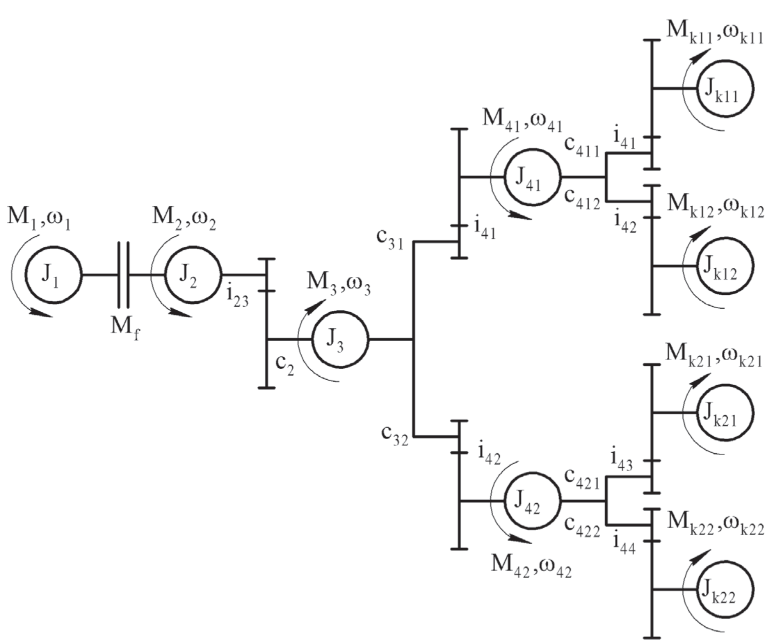


Fig. 2. Scheme of the dynamic model of the transmission of an all-wheel drive traction and transport machine

The following designations are given in Fig. 2: J_1 – reduced moment of inertia of the rotating masses of the masses of the internal combustion engine; M_1 – the effective torque of the internal combustion engine; ω_1 is the angular speed of rotation of the ICE crankshaft; M_1 – the clutch moment; J_2, M_2, ω_2, c_2, – reduced moment of inertia, torque, angular velocity of rotation and reduced angular rigidity of the gearbox input shaft; η_{23}, i_{23} – efficiency and gear ratio of the box; J_3, M_3, ω_3 – reduced moment of inertia, torque, angular velocity of rotation of the secondary shaft of the box; c_{31}, c_{32} – the angular stiffness of the front and rear propeller shafts is given; η_{23}, i_{41}, i_{42} – efficiency and gear ratio of the main gear of the front and rear axles; J_{41}, M_{41}, ω_{41} – reduced moment of inertia, torque and angular speed of rotation of the main gear of the front axle; J_{42}, M_{42}, ω_{42} – reduced moment of inertia, torque and angular speed of rotation of the main gear of the rear axle; c_{411}, c_{412}, c_{421}, c_{422} –reduced angular rigidities of the front left, front right, rear left and rear right axle shafts; η_{23}, i_{411}, i_{412}, i_{421}, i_{422} – efficiency and gear ratio of the front left, front right, rear left and rear right final drives; J_{kij}, M_{kij}, ω_{kij} – reduced moment of inertia, torque and angular speed of rotation of the TTM drive wheel (*ij*=11 – front left, *ij*=12 – front right, *ij*=21 – rear left, *ij*=22 – rear right).

The torque from the internal combustion engine M_1 is transmitted through the clutch M_f to the input shaft of the box and the transmission i_{23}. Further, the torque of the output shaft of the box is transmitted to the front and rear differentials of the TTM through shafts c_{31} and c_{32}. The front differential appears with elements J_{41}, c_{411}, c_{412}, and the rear differential with J_{41}, c_{411}, c_{412}.

For an all-wheel drive wheeled TTM, a system of equations for the transmission dynamics in the Cauchy form has been compiled, which has the form:

$$\begin{cases} \dot{\omega}_1 = J_1^{-1}\left(M_1 - M_f\right); \\ \dot{\omega}_2 = J_2^{-1}\left(M_f - M_2\right); \\ \dot{M}_{23} = c_2^{-1}\left(\omega_2 - i_{23}\omega_3\right); \\ \dot{\omega}_3 = J_3^{-1}\left(M_3 - i_{23}^{-1}\eta_{23}\left(M_{31}+M_{32}\right)\right); \\ \dot{M}_{31} = c_{31}^{-1}\left(\omega_3 - i_{41}\omega_{41}\right); \\ \dot{M}_{32} = c_{32}^{-1}\left(\omega_3 - i_{42}\omega_{42}\right); \\ \dot{\omega}_{41} = J_{41}^{-1}\left(M_{31} - i_{41}^{-1}\eta_{41}\left(M_{411}+M_{412}\right)\right); \\ \dot{\omega}_{42} = J_{42}^{-1}\left(M_{32} - i_{42}^{-1}\eta_{42}\left(M_{421}+M_{422}\right)\right); \\ \dot{M}_{411} = c_{411}^{-1}\left(\omega_{41} - i_{411}\omega_{k11}\right); \\ \dot{M}_{412} = c_{412}^{-1}\left(\omega_{41} - i_{412}\omega_{k12}\right); \\ \dot{\omega}_{k11} = J_{k11}^{-1}\left(M_{411} - i_{411}^{-1}\eta_{411}M_{k11}\right); \\ \dot{\omega}_{k12} = J_{k12}^{-1}\left(M_{412} - i_{412}^{-1}\eta_{412}M_{k12}\right); \\ \dot{M}_{421} = c_{421}^{-1}\left(\omega_{42} - i_{421}\omega_{k21}\right); \\ \dot{M}_{422} = c_{422}^{-1}\left(\omega_{42} - i_{422}\omega_{k22}\right); \\ \dot{\omega}_{k21} = J_{k21}^{-1}\left(M_{421} - i_{421}^{-1}\eta_{421}M_{k21}\right); \\ \dot{\omega}_{k22} = J_{k22}^{-1}\left(M_{422} - i_{422}^{-1}\eta_{422}M_{k22}\right). \end{cases} \tag{1}$$

The system of equations for the transmission dynamics of a wheeled all-wheel drive TTM in the Cauchy form (1) is solved using the MatLab software package. The initial data for calculating the mathematical model are given in [17].

The developed mathematical model of the transmission of an all-wheel drive wheeled TTM can be used to study the dynamics of transmissions of wheeled machines, agricultural tractors both in the warehouse of machine and tractor units and separately.

4. 3. Measuring system of dynamics and energy of mobile machines

The proposed method for assessing the influence of the geometric parameters of the frame of a traction and transport machine on its traction and energy performance requires validation through experimental studies. In the course of experimental studies, a measuring system for the dynamics and energy of mobile machines was used, the block diagram of which is shown in Fig. 3.

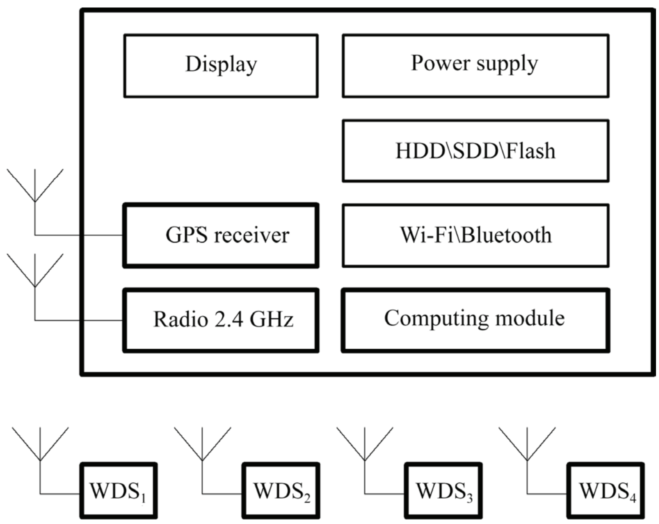


Fig. 3. Structural diagram of the measuring system of dynamics and energy of mobile machines: WDS_i – wheel dynamics sensor (i=1...4)

The measuring system used in experimental studies belongs to the technical means of diagnostics and operational control. It can be used in agriculture and engineering industry. The system is designed to determine the kinematic, dynamic, powerful and energy characteristics of mobile machines and their elements during road, field and bench tests [18].

The measuring system includes inertial measuring devices (IMS), consisting of gyroscopes (G) and acceleration sensors (A), navigation receiver (GPS), wheel dynamics sensors (WDS), electronic dynamometer (ED) and fuel consumption sensor (Q) . For the measuring system, the DASys PC Suite software was developed, which is responsible for storing information from sensors on an internal or external storage medium. Communication between the sensors and the computing module occurs via the CAN bus and radio channel in the 2.4 GHz band [19].

Wheel dynamics sensors (WDS) are installed on the final drives of the machine under study in such a way that the axes of rotation of the sensors around the vertical axis coincide with the axes of rotation of the wheel.

The algorithm for processing data from the sensors by the measuring system makes it possible to exclude the influence of indicators of the location of the sensors, free fall acceleration, field irregularities and inclination. A Kalman filter was used to combat random errors that occur during research. The mathematical apparatus of data processing by the measuring system is described in detail in [20].

5. The results of the study of the influence of the geometric parameters of the frame of the traction and transport machine on the traction and energy performance

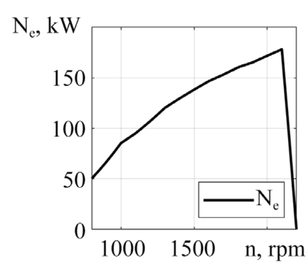
5. 1. The effect of the geometric parameters of the frame of the traction-transport machine on the normal reactions of the wheels on the supporting surface

Diesel engines are mainly installed on TTM. The dynamics of a wheeled all-wheel drive TTM with a diesel engine with a maximum power of N_{emax}=176 kW (240 hp) has been studied. The dependence of the power and effective torque of the internal combustion engine of the traction-transport machine on the rotation speed is shown in Fig. 4.

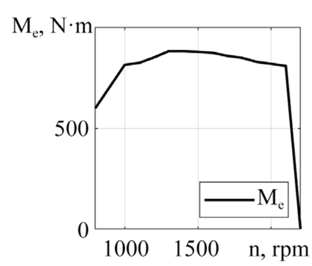
The maximum torque of the internal combustion engine is M M_{emax}=883 Nm (90 kgf) at a rotation speed of $n_{M\text{nom}}$=1250–1450 rpm (Fig. 4).

The initial data for calculating the mathematical model (1) are the following: ICE power – N_{emax}=176 kW; moments of inertia are given J_1=0.618 kg·m^2, J_2=0.0081 kg·m^2, J_3=0.618 kg·m^2, J_{41}=0.002098 kg·m^2, J_{42}=0.00404 kg·m^2, J_{k11}=J_{k12}=J_{k21}=J_{k22}=31.1 kg·m^2. Angular stiffnesses c_2= =10,023 N rad, c_{31}=2,750 N rad, c_{32}=23,032 N rad, c_{411}=c_{412}= =c_{421}=c_{422}=8,523 N rad are given. Gear ratios i_{23}=2.4, i_{41}=2.9, i_{411}=i_{412}=i_{421}=i_{422}=4.1. Efficiency – η_{23}=0.921, η_{41}=η_{42}=0.922, η_{411}=η_{412}=η_{421}=η_{422}=0.945.

For an all-wheel drive wheeled TTM, the dependences of the angular velocities of rotation of the transmission elements of the traction-transport machine on time are determined (Fig. 5).

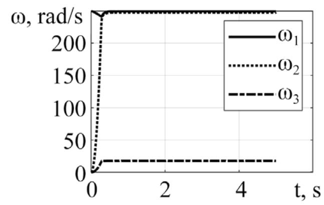


a

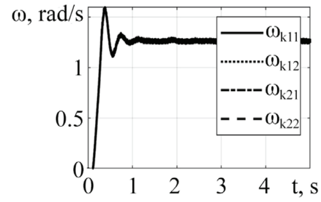


b

Fig. 4. Dependence of the power and effective torque of the internal combustion engine of the traction-transport machine on the rotation speed: *a* – power dependence; *b* – effective torque dependence



a

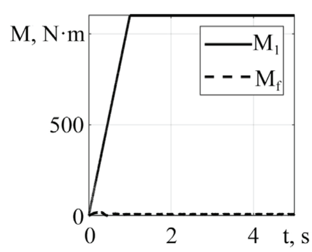


b

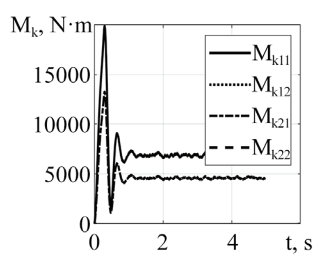
Fig. 5. Dependences of the angular speeds of rotation of the transmission elements of the traction-transport machine on time: *a* – dependences of the angular speeds of rotation of the transmission elements; *b* – dependences of the angular speeds of rotation of the wheels

The process of TTM acceleration was studied, during which the angular velocity of the internal combustion engine decreases from the nominal value n_{nom}=250 rad/s to 241 rad/s and returns to the nominal value again at t>1 s (Fig. 5). At 0 <t<1 s, the clutch is engaged and the speed of the input shaft of the box is aligned with the angular velocity of the internal combustion engine of 250 rad/s. The angular speeds of rotation of the TTM wheels are stabilized at the level ω_{k11}=1.29 rad/s, ω_{k12}=1.27 rad/s, ω_{k21}=1.24 rad/s, ω_{k22}=1.25 rad/s at t>1 s.

The dependences of the torques of the elements of the transmission of the traction-transport machine on time have been established (Fig. 6).



a



b

Fig. 6. Dependences of the torques of the transmission elements of the traction-transport machine on time: *a* – dependences of the torques of the transmission elements; *b* – dependences of the torques of the driving wheels

The torque of the internal combustion engine increases linearly up to the nominal value M_{enom}=1,100 Nm during the acceleration of the TTM (Fig. 6). The moment of friction of the clutch at the beginning of acceleration has an oscillatory process with a range of ΔM_f=50 N·m. The torques of the front driving wheels briefly increase to M_{k11}=M_{k12}=20,012 N·m and at t>1 s they take the value M_{k11}=M_{k12}=6,972 N·m. Similar processes occur on the rear driving wheels, however, the torques increase to M_{k21}=M_{k22}=13,209 N·m at 0 <t<1 s, and then take the value M_{k21}=M_{k22}=4,622 N·m.

The dependences of the contacting traction forces on the wheels of the traction-transport machine on time are calculated (Fig. 7).

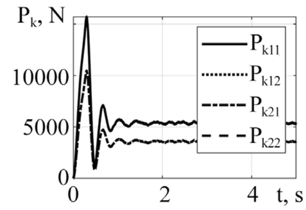


Fig. 7. Dependences of the contacting traction forces on the wheels of the traction-transport machine on time

The contacting traction forces on the front wheels of the TTM increase to P_{k11}=P_{k12}=15,667 N at 0<t<1 s and stabilize at the value P_{k11}=P_{k12}=5,478 N after the end of acceleration. Also, at t>1 s, the contacting traction forces on the rear wheels of the TTM stabilize with the values P_{k21}=P_{k22}=3,473 N, and during acceleration they take on the largest values P_{k21}=P_{k22}=10,442 N.

5. 2. Results of experimental studies of an all-wheel drive wheeled traction and transport machine for validating the proposed method

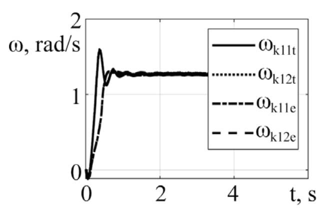
Experimental studies of the all-wheel drive wheeled TTM were carried out on the example of an all-wheel drive tractor with a hinged frame. The measurement of TTM functioning parameters was carried out by the measuring system of the dynamics and energy of mobile machines.

The methodology for conducting experimental studies using a measuring system for the dynamics and energy of mobile machines is based on GOST 30745-2001 (ISO 789-9-90), GOST 7057-2001 and GOST 24055-88 and is described in [20, 21].

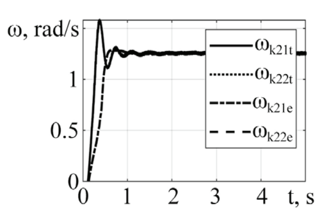
The methodology includes three stages. At the first stage, the measuring equipment was placed on the elements of the unit. Inertial measuring devices were installed, fixed on the frames of each of the elements. The navigation device antenna is located above the tractor cab. Fuel consumption sensors are integrated into the engine power supply. The electronic dynamometer is located at the junction of the traction machine and the technological module. Wheel speaker sensors are mounted at the center of the wheels or drive sprockets of the traction machine. The second stage eliminates the influence of extraneous factors. The exclusion of random factors is carried out by repeating each experiment three times. The exclusion of the influence of the technical condition requires at the beginning of the shift to carry out routine maintenance. To exclude the influence of the field relief, the experiments are carried out in one and the opposite direction (this is considered a separate experiment). When conducting experiments, two fields are selected with the most characteristic soil structure, which differ sharply in physical and mechanical properties. Experiments of the same type are carried out on two fields during one shift. At the third stage, after the completion of operations to prepare the unit for research, information is collected. Soil properties (physico-mechanical properties and humidity) and environmental parameters are determined. The computing module for collecting information is turned on. The required number of experiments is carried out, and after each experiment, the data obtained are stored on a hard disk for further processing. After the end of the research, the measuring system is turned off and dismantled from the unit.

The developed technique allows to determine the energy and dynamic indicators of the functioning of agricultural machines and units in the shortest possible time. When working with the system, one operator is enough.

Usually, the verification of the adequacy of mathematical models is based on the verification of a statistical hypothesis regarding the equality of the variances of inadequacy and experimental errors (Fisher's criterion). In theoretical studies of the TTM dynamics, in particular, studies of the dynamics of the transmission of a machine, it is impossible to verify the adequacy of the developed mathematical model due to the use of the Fisher criterion [22]. Validation of the method for assessing the transmission dynamics of an all-wheel drive wheeled TTM was carried out by comparing the angular speeds of rotation of the wheels and the contiguous traction forces, which were determined experimentally and calculated theoretically (Fig. 8, 9). The validation method is described in [22] and tested by researchers [19, 20], where its effectiveness was confirmed.



a

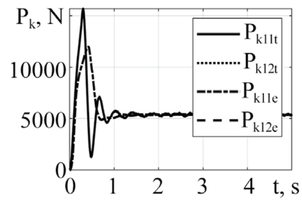


b

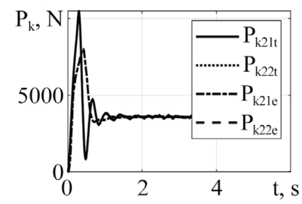
Fig. 8. Dependences of the angular speeds of rotation of the front and rear wheels of the traction-transport machine on time, obtained during theoretical and experimental studies: *a* — angular speeds of rotation of the front wheels; *b* — angular speeds of rotation of the rear wheels; ω_{k11t}, ω_{k12t}, ω_{k21t}, ω_{k22t} — the angular speeds of rotation of the wheels (front left, front right, rear left and rear right) of the traction-transport machine, determined theoretically and experimentally ω_{k11e}, ω_{k12e}, ω_{k21e}, ω_{k22e}

The angular speeds of rotation are determined by the operation of the tractor in the 2nd gear of the III range during the acceleration of the tractor to a speed of υ=10.2 km/h. The angular speeds of rotation of the wheels of the machine, determined during experimental studies, are ω_{k11e}=1.27 rad/s, ω_{k12e}=1.29 rad/s, ω_{k21e}=1.23 rad/s, ω_{k22e}=1.24 rad/s at t>1 s (Fig. 8). The difference between the results obtained theoretically ω_{k11t}, ω_{k12t}, ω_{k21t}, ω_{k22t} and experimentally ω_{k11e}, ω_{k12e}, ω_{k21e}, ω_{k22e} is 2 %, i.e. corresponds to the relative error in measuring the angular velocities by the wheel dynamics sensors.

In the course of experimental studies, the tangential traction forces on the wheels of the machine were determined and compared with theoretical results (Fig. 9).



a



b

Fig. 9. Dependences of the tangential traction force on the wheels of the front and rear wheels of the traction and transport machine on time, obtained during theoretical and experimental studies: *a* — tangential traction force on the front wheels; *b* — tangential traction forces on the rear wheels; P_{k11t}, P_{k12t}, P_{k21t}, P_{k22t} — relating to the traction force on the wheels of the machine (front left, front right, rear left and rear right), determined theoretically and experimentally P_{k11e}, P_{k12e}, P_{k21e}, P_{k22e}

The traction forces on the front wheels of the machine under study, determined during experimental studies (at t>1 s), are P_{k11e}=P_{k12e}=5,406 N, on the rear wheels of the TTM - P_{k21e}=P_{k22e}=3,403 N (Fig. 9). The difference between the values of the contact forces on the wheels of the machine obtained theoretically P_{k12t}, P_{k21t}, P_{k22t} and experimentally P_{k11e}, P_{k12e}, P_{k21e}, P_{k22e} does not exceed 2 %. Therefore, the method for studying the evaluation of the transmission dynamics of an all-wheel drive TTM should be considered valid. It should be noted that the transient processes occurring in the investigated tractor and the mathematical model have differences at the beginning of the movement (at t<1 s).

6. Discussion of the results of the study of the influence of the geometric parameters of the frame of the traction and transport machine on the traction and energy performance

The method for assessing the influence of transmission parameters on the traction and energy performance of an all-wheel drive wheeled traction and transport machine uses methods of mathematical modeling and formation and calculation of differential equations in the Cauchy form. This method makes it possible to determine the dependences of the angular speeds of rotation of the elements of the transmission of a traction-transport machine on time (Fig. 5), the dependence of torques on time (Fig. 6) and the dependence of the adjoining traction forces on the wheels (Fig. 7).

The method makes it possible to determine the optimal transmission parameters, differential designs and gear ratios to improve the traction-coupling and fuel-economic indicators of the TTM.

It was determined that the torques on the front and rear wheels of the TTM differ by 2,350 Nm during steady motion and by 6,809 Nm during acceleration (Fig. 6), which negatively affects the overall traction performance of the machine. It has been established that the front and rear wheels of the TTM rotate at different angular speeds (Fig. 5), which leads to a kinematic mismatch and additional energy losses.

An increase in traction and energy performance can be achieved by reducing the speed of rotation of the front wheels of the TTM w_{k11}, w_{k12}, or by increasing the angular speed of rotation of the rear wheels – w_{k11}, w_{k22}.

The developed method for assessing the influence of transmission parameters on the traction and energy performance of an all-wheel drive wheeled TTM makes it possible to study both all-wheel drive mechanical transmissions of machines and rear-wheel drive ones, studied in [9, 10]. The method takes into account the dynamics of both ordinary differentials and limited slip differentials studied by the authors of [12].

The developed method makes it possible to evaluate the effect of technological modules that create different thrust forces along the sides of the TTM, which were studied in [13, 14].

In contrast to the studies given in [6, 9], where attention is paid to the study of individual elements of the transmission, the study of the transmission of a wheeled machine makes it possible to determine the influence of the parameters of individual elements on the dynamic and traction-energy parameters of the machine. This becomes possible thanks to the developed mathematical model (1).

In contrast to the known methods for evaluating the influence of TTM transmission parameters on traction and energy indicators, the proposed method allows determining the traction and energy parameters of TTM functioning for all driving wheels.

As a limitation in assessing the effect of transmission parameters on the traction and energy performance of the TTM, it is assumed that the transmission elements are studied as absolutely rigid bodies symmetrical around the axis of rotation. Such a restriction is legitimate, because the elements of the transmission are acquired bodies.

The method proposed in the work can be used to assess the dynamics of wheeled machines, agricultural tractors both in the warehouse of machine and tractor units and separately.

The method for assessing the dynamics of an all-wheel drive wheeled TTM cannot be used for four tracked machines of a high traction class.

Future studies will focus on taking into account the types of differentials under study (regular, locked or limited slip) and assessing the impact on the traction and energy performance of the TTM.

7. Conclusions

1. It has been established that the angular speeds of rotation of the front wheels of the TTM ω_{k11}=1.29 rad/s, ω_{k12}=1.27 rad/s are higher than the angular velocities of the rear wheels ω_{k12}=1.24 rad/s, ω_{k22}=1.25 rad/s /with. The difference between the angular speeds of the front and rear wheels leads to a kinematic mismatch and additional energy losses. The torques of the front driving wheels briefly increase to M_{k11}=M_{k12}=20,012 N m and at t>1 s they take the value M_{k11}=M_{k12}=6,972 N m. Similar processes occur on the rear driving wheels, however, the torques increase to M_{k21}=M_{k22}=13,209 N m at 0<t<1 s, and then take the value M_{k21}=M_{k22}=4,622 N m. The contacting traction forces on the front wheels of the TTM increase to P_{k11}=P_{k12}=15,667 N at 0<t<1 s and stabilize at the value P_{k11}=P_{k12}=5,478 N after the end of acceleration. Also, at t>1 s, the contacting traction forces on the rear wheels of the TTM stabilize with the values P_{k21}=P_{k22}=3,473 N, and during acceleration they take on the largest values P_{k21}=P_{k22}=10,442 N.

2. The method for assessing the transmission dynamics of the all-wheel drive TTM has been validated by comparing the results of theoretical and experimental studies. Experimental studies of the TTM were carried out on the example of an all-wheel drive wheeled tractor with an articulated frame. The angular speeds of rotation were determined when the tractor was operating in the 2nd gear of the III range when the tractor was accelerating to a speed of υ=10.2 km/h. The angular speeds of rotation of the wheels of the machine, determined during experimental studies are ω_{k11e}=1.27 rad/s, ω_{k12e}=1.29 rad/s, ω_{k21e}=1.23 rad/s, ω_{k22e}=1.24 rad/s at t>1 s, and the contacting traction forces on the front wheels of the machine under study are P_{k11e}==P_{k12e}=5,406 N, P_{k21e}=P_{k22e}=3,403 N. The difference between the values of the contact forces on the wheels of the machine obtained theoretically is P_{k11t}, P_{k12t}, P_{k21t}, P_{k22t}, and experimentally ω_{k11e}, ω_{k12e}, ω_{k21e}, ω_{k22e} does not exceed 2 %. The developed method for assessing the transmission dynamics of an all-wheel drive TTM should be considered valid. The transient processes occurring in the investigated tractor and the mathematical model have differences at the beginning of the movement (at t<1 s).

Conflict of interests

The authors declare that there is no conflict of interest regarding this study, including financial, personal nature, authorship or other nature that could affect the research and its results presented in this article.

Financing

The study was carried out within the framework of the state budget scientific and technical (experimental) development of young scientists "Innovative beginnings of creating a measuring system for the dynamics of mobile machines by taking into account operating modes, dynamic loads and structures" (DR No. 0122U000747).

Data availability

The manuscript has no associated data.

References

1. Bulgakov, V., Ivanovs, S., Adamchuk, V., Antoshchenkov, R. (2019). Investigations of the Dynamics of a Four-Element Machine-and-Tractor Aggregate. Acta Technologica Agriculturae, 22 (4), 146–151. doi: https://doi.org/10.2478/ata-2019-0026

2. Antoshchenkov, R., Halych, I., Nykyforov, A., Cherevatenko, H., Chyzhykov, I., Sushko, S. et al. (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: https://doi.org/10.15587/1729-4061.2022.254688
3. Kondratiev, A. (2019). Improving the mass efficiency of a composite launch vehicle head fairing with a sandwich structure. Eastern-European Journal of Enterprise Technologies, 6 (7 (102)), 6–18. doi: https://doi.org/10.15587/1729-4061.2019.184551
4. Osadchyy, V., Nazarova, O., Brylystyi, V. (2021). Laboratory Stand for Research of Energy Characteristics of Electric Vehicle Drives. 2021 IEEE International Conference on Modern Electrical and Energy Systems (MEES). doi: https://doi.org/10.1109/mees52427.2021.9598661
5. Osadchyy, V., Nazarova, O., Olieinikov, M. (2021). The Research of a Two-Mass System with a PID Controller, Considering the Control Object Identification. 2021 IEEE International Conference on Modern Electrical and Energy Systems (MEES). doi: https://doi.org/10.1109/mees52427.2021.9598542
6. Voloshina, A., Panchenko, A., Titova, O., Milaeva, I., Pastushenko, A. (2021). Prediction of Changes in the Output Characteristics of the Planetary Hydraulic Motor. Advanced Manufacturing Processes II, 744–754. doi: https://doi.org/10.1007/978-3-030-68014-5_72
7. Panchenko, A., Voloshina, A., Luzan, P., Panchenko, I., Volkov, S. (2021). Kinematics of motion of rotors of an orbital hydraulic machine. IOP Conference Series: Materials Science and Engineering, 1021 (1), 012045. doi: https://doi.org/10.1088/1757-899x/1021/1/012045
8. Adamchuk, V., Petrychenko, I., Korenko, M., Beloev, H., Borisov, B. (2018). Study plane-parallel motion movement combined seeding unit. Mechanization in agriculture & Conserving of the resources, 64 (6), 184–187. Available at: https://stumejournals.com/journals/am/2018/6/184
9. Awadallah, M., Tawadros, P., Walker, P., Zhang, N. (2017). Dynamic modelling and simulation of a manual transmission based mild hybrid vehicle. Mechanism and Machine Theory, 112, 218–239. doi: https://doi.org/10.1016/j.mechmachtheory.2017.02.011
10. Tian, Y., Ruan, J., Zhang, N., Wu, J., Walker, P. (2018). Modelling and control of a novel two-speed transmission for electric vehicles. Mechanism and Machine Theory, 127, 13–32. doi: https://doi.org/10.1016/j.mechmachtheory.2018.04.023
11. Dong, H., Zhuang, W., Chen, B., Wang, Y., Lu, Y., Liu, Y. et al. (2022). A comparative study of energy-efficient driving strategy for connected internal combustion engine and electric vehicles at signalized intersections. Applied Energy, 310, 118524. doi: https://doi.org/10.1016/j.apenergy.2022.118524
12. Morselli, R., Zanasi, R., Sandoni, G. (2006). Detailed and reduced dynamic models of passive and active limited-slip car differentials. Mathematical and Computer Modelling of Dynamical Systems, 12 (4), 347–362. doi: https://doi.org/10.1080/13873950500066959
13. Tajanowskij, G., Tanaś, W. (2012). Analysis of movement kinematics at turn of wheel tractor with semi-trailer with articulated operated draught bar. Journal of Research and Applications in Agricultural Engineering, 57 (2), 190–196. Available at: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BAR8-0019-0058/c/httpwww_pimr_poznan_plbiul2012237tt.pdf
14. Padureanu, V., Lupu, M. I., Canja, C. M. (2013). Theoretical research to improve traction performance of wheeled tractors by using a suplementary driven axle. Computational Mechanics and Virtual Engineering. Brasov, 410–415. Available at: http://aspeckt.unitbv.ro/jspui/bitstream/123456789/415/1/410%20-%20415%2c%20Padureanu%201.pdf
15. Suhane, A., Rana, R. S., Purohit, R. (2018). Prospects of Torsen Differential in Four Wheel Drive Automobile Transmission System. Materials Today: Proceedings, 5 (2), 4036–4045. https://doi.org/10.1016/j.matpr.2017.11.664
16. Efimov, A., Polushkin, O., Kireev, S., Korchagina, M. (2021). A Mathematical Model of a Differential Drive with a Limited Gear Ratio. Transportation Research Procedia, 54, 699–711. doi: https://doi.org/10.1016/j.trpro.2021.02.123
17. Yin, Z., Dai, Q., Guo, H., Chen, H., Chao, L. (2018). Estimation Road Slope and Longitudinal Velocity for Four-wheel Drive Vehicle. IFAC-PapersOnLine, 51 (31), 572–577. doi: https://doi.org/10.1016/j.ifacol.2018.10.139
18. Galych, I., Antoshchenkov, R., Antoshchenkov, V., Lukjanov, I., Diundik, S., Kis, O. (2021). Estimating the dynamics of a machine-tractor assembly considering the effect of the supporting surface profile. Eastern-European Journal of Enterprise Technologies, 1 (7 (109)), 51–62. doi: https://doi.org/10.15587/1729-4061.2021.225117
19. Artiomov, N., Antoshchenkov, R., Antoshchenkov, V., Ayubov, A. (2021). Innovative approach to agricultural machinery testing. Engineering for Rural Development. Jelgava, 692–698. doi: https://doi.org/10.22616/ERDev.2021.20.TF150
20. Antoshchenkov R. (2017). Dynamika ta enerhetyka rukhu bahatoelementnykh mashynno-traktornykh ahrehativ. Kharkiv: KhNTUSH, 244. Available at: https://www.academia.edu/43129375/ДИНАМІКА_ТА_ЕНЕРГЕТИКА_РУХУ_БАГАТОЕЛЕМЕНТНИХ_МАШИННО_ТРАКТОРНИХ_АГРЕГАТІВ
21. Dzyuba, O., Dzyuba, A., Polyakov, A., Volokh, V., Antoshchenkov, R., Mykhailov, A. (2019). Studying the influence of structural-mode parameters on energy efficiency of the plough PLN-3-35. Eastern-European Journal of Enterprise Technologies, 3 (1 (99)), 55–65. doi: https://doi.org/10.15587/1729-4061.2019.169903
22. Mittal, A., Misra, A. (2021). A novel mathematical model to estimate the ride frequency of an off road vehicle with experimental validation. Materials Today: Proceedings, 46, 9683–9689. doi: https://doi.org/10.1016/j.matpr.2020.08.022