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DETERMINATION OF RATIONAL CONDITIONS FOR THE MOVEMENT OF TRANSPORT AND TECHNOLOGICAL UNITS WHEN USING TECHNOLOGICAL MACHINES WITH DRIVING WHEELS

The object of research is the operation process of a transport and technological unit with the driving wheels of a technological machine.

One of the most problematic areas of the effective operation of an energy-intensive tractor as part of a transport and technological unit is the incomplete use of the potential capabilities of the tractor engine. This is due to the fact that at the beginning and at the end of the technological operation the mass of the load of the technological machine will be different. A possible solution to this problem is the use of additional driving axles of the technological machine, which allows to increase the relative share of the coupling weight in the unit. This allows part of the engine power to be realized through the tractor's running system, and part to be transferred to the technological machine.

During the study, it was found that when transferring part of the power to the technological machine, three modes of movement are possible: $P_{kT}>P_{xm}$; $P_{kT}=P_{xm}$; $P_{kT}<P_{xm}$. For their analysis, taking into account the dynamic components of the movement, an equivalent dynamic model of the transport and technological unit was used. The oscillations of longitudinal forces acting on the unit characteristic of each mode of movement were obtained. It was found that the movement of the unit with the transmission of part of the power to the drive wheels of the technological machine must be implemented under the movement condition $P_{kT}>P_{xm}$, i. e. under partial underload. This is due to the fact that the proposed movement mode allows stabilizing the oscillations of longitudinal forces and increasing the part of the engine power that can be realized in the traction mode. In particular, for this movement condition, the potential traction force P_{ka} increases to 45.92 kN with a decrease in the mean square deviation $\sigma_{ka}=1.74$ kN. Also, this movement mode is characterized by the absence of the technological machine running into the tractor, as a result, there are the smallest dynamic oscillations and a stabilizing effect for longitudinal forces.

Due to this, the possibility of activating the wheels of the technological machine with compensation for the negative factors inherent in the movement of all-wheel drive vehicles is ensured. Compared with similar known methods of using full engine power for transport and technological units with variable mass, ensuring a certain movement condition will increase the efficiency of their work.

Keywords: *transport and technological unit, driving wheels, variable mass, dynamics, vibrations, engine load.*

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1. Introduction

In recent years, there has been a clear trend in the world to increase the energy density of tractors, for the most part, manufacturers are focused on the possibility of using complex tillage and wide-grip machine-tractor units. They allow to minimize the number of passes through the field and provide better fuel efficiency. The use of such units prevents soil destruction and compaction. When such a combined unit includes a module with a variable mass (hopper, trailer-loader, container, etc.). It is impossible to achieve a constant tractor engine load, since the mass of the load will be different at the beginning and end of the technological operation. Many studies have been devoted to the problem of increasing the efficiency of energy-intensive tractors [1, 2]. The main condition for increasing the energy saving of such tractors is the full use of the potential capabilities of their engines [3]. When performing a technological operation, a large amount of energy is consumed, including on the dynamic components of the tractor movement [2]. Researchers draw attention to the feasibility of increasing the number of drive wheels and switching to all-wheel drive, as this allows for maximum use of the tractor's coupling weight and improves a number of operational characteristics [4, 5]. It is well known that the characteristics of the supporting surface affect the efficiency of off-road vehicles and ensure the required coefficient of adhesion [6, 7]. Research results show that optimal performance, regardless of the vertical load distribution, is achieved when the torque is shifted to the rear axle. In [8], the issues of wheel-supporting surface interaction are considered and the influence of rolling radius fluctuations on changes in the coefficient of slippage of tractors with MFWD is established.

Studies have shown that improper drive of the front wheels of a tractor leads to power circulation in the transmission system, excessive tire wear, reduced efficiency and increased fuel consumption. The studies were conducted for a tractor with mechanical front-wheel drive (MFWD) during straight-line movement [9, 10].

The use of additional drive axles of the unit (activation of the trailer or agricultural machine drives) allows to increase the relative share of the coupling weight in the unit by redistributing the torque to the technological part of the unit with the driving wheels. With this approach, only part of the engine power will be realized through the tractor running system, and its specific material consumption can be reduced. When switching to the use of an active drive on the wheels of a technological machine (hopper, trailer-loader, container), problems similar to four-wheel drive tractors or vehicles will arise. With the peculiarity that multi-mass models must be used to simulate the dynamics of movement. The movement of combined variable-mass units, such as sowing complexes or complexes for applying mineral fertilizers and plant protection products to the soil, looks especially complex from the research perspective. In works [11, 12], the issues of motion dynamics and energy saving of combined sowing units are considered, but the problem of changing the mass of the cargo in the bunker of an agricultural machine is not given enough attention. In works [13, 14], a model of the unit is created, which allows studying the effects of fluctuations in the mass of liquid cargo on the dynamics of the unit's motion, but the issues of energy saving and energy-efficient modes of motion are not considered. In work [15], a method for calculating the load on the wheel during rectilinear motion of a road train containing two articulated vehicles is substantiated. It allows predicting the loads on the axles, wheels or hinges to assess the maximum achievable characteristics in longitudinal dynamics (acceleration, braking, lifting, lowering). Dynamic models that take into account the specifics of the operation of multi-wheeled vehicles are presented in the following works and focus on taking into account the transverse and longitudinal slip of the wheels [16] and the dynamic load on the axle of a semi-trailer with air suspension [17].

In [18], the advantages of using modular traction vehicles with variable traction force, which expands the scope of their use, are considered. In [19], the redistribution of load during the movement of multi-wheeled vehicles is considered. However, insufficient attention is paid to the issues of motion dynamics.

In [20], a dynamic model of the transmission is substantiated and the results of the study of the dynamic and traction-energy characteristics of an all-wheel drive traction vehicle are presented. In [21], a vehicle design is proposed to improve off-road characteristics, which includes a tractor with a wheeled chassis of increased cross-country ability and a trailer with a driving axle.

Among the variety of simulation studies of the movement of agricultural machinery during transport and technological work, the PowerMix test procedures are popular [22].

The balance of power distribution of the traction and drive unit is significantly influenced by the "pushing force" P_{xm} from the active working bodies or wheels of the agricultural machine [23]. Depending on the ratio of P_{xm} and the traction force on the tractor hook P_{kT}, three cases of movement of the unit are possible: when $P_{kT} > P_{xm}$, a torque (driving) moment M_k and a tangential force acting in the direction of movement of the MTA are applied to the tractor drives. In this case, skidding of the tractor drives is possible ($\delta > 0$). When $P_{kT} = P_{xm}$, the MTA movement is carried out without skidding of the tractor drives ($\delta = 0$). When $P_{kT} > P_{xm}$, the tractor drives are loaded with a negative moment M_k, in which the traction force P_k is directed against the tractor's movement, which leads to negative skidding ($\delta < 0$) [23]. It follows that the optimal traction-energy parameters are achieved when the traction force of the tractor and the pushing agricultural machine and the sum of the rolling resistances of the tractor and machines are equal. However, this statement is relevant for a stable mode of movement or for a dynamic equilibrium mode, which are almost impossible to achieve in operation.

Therefore, it is relevant to conduct an analysis of the three specified cases, which allows formulating the condition for the effective operation of the traction and drive unit taking into account the dynamics of movement. When distributing power between the driving wheels of the transport and technological unit, it is necessary to take into account that the resistance to movement and vertical loads on the wheels, i. e. the weight distribution of the unit, change continuously and are oscillatory processes. An additional factor is the change in the mass of the technological part of the unit, which affects the weight distribution between the driving axles of the tractor. That is, the movement of the transport and technological unit in real operation is quasi-static with a constant average speed and fluctuations in the instantaneous speed. Thus, *the aim of research* is to determine the rational modes of movement of the transport and technological unit under the condition of using the active drive of the wheels of the technological machine, taking into account the dynamics of movement.

2. Materials and Methods

The object of research is the operation process of the transport and technological unit with the driving wheels of the technological machine.

The research was conducted on the example of the transport and technological unit ХТЗ-240К when aggregated with the technological machine МЖТ-16. The technological speed of movement was taken as 10 km/h, with the traction resistance of the technological machine $R_{xm} = 12.5$ kN. When studying the dynamics of the movement of the transport and technological unit with a variable mass, dynamic models of all-wheel drive tractors [2] were analyzed as part of multi-element machine-tractor units (complexes for sowing, fertilizing, harvesting, etc.) [11–14]. In general, the specified models are used for the mathematical description of the plane-parallel movement of the unit with the tractor in the tractor mode. The analyzed models are quite complex when switching to an all-wheel drive unit using active wheels of the technological machine. Therefore, in this study, it is proposed to use an equivalent dynamic model, which will simplify the modeling of motion dynamics and focus on the study of the motion conditions when using active wheels of a technological machine.

Research objectives:

- to substantiate the dynamic model of a transport and technological unit with active wheels and to analyze the dynamics of the unit's motion, with different ratios of traction and pushing forces;
- to determine the rational conditions for the movement of a transport and technological unit, taking into account the dynamic components and the redistribution of part of the engine power to the active wheels of the technological machine at different speed modes.

The following scientific methods were used in the study: Mathematical modeling of a transport and technological unit in the process of performing a technological operation in crop production when studying the features of its motion. Mathematical modeling allows to conduct a calculation experiment and obtain theoretical foundations for substantiating the conditions for the movement of a transport and technological unit with active wheels of a technological machine. This method allows to obtain dynamic characteristics of the unit and to investigate the change in oscillation of longitudinal forces without conducting a field experiment. In further studies, the use of the method of partial accelerations [24] and the corresponding diagnostic equipment is planned when conducting the experiment. The obtained data after processing and filtering represent a stochastic random signal of the acceleration of the unit, which is advisable to analyze using mathematical statistics methods. Therefore, for the adequacy of the compared parameters when studying the conditions of movement of the transport and technological unit taking into account dynamic components based on modeling, the use of the method of statistical analysis is proposed.

The main task of using the active wheel drive of the transport and technological unit is to create additional traction power by fully using the potential capabilities of the tractor engine. This approach opens up much wider possibilities for completing units due to the ability of the tractor to work equivalently to tractors of higher traction classes. This is especially true for variable mass machines, since to ensure the greatest efficiency, the traction class must be changed during the performance of the technological operation. When analyzing the dynamics of the movement of the unit, special attention should be paid to the statement regarding the equality of traction and pushing forces. Since this statement is true from the point of view of energy conservation and functional stability, it is relevant only for a uniform mode of movement, which cannot be achieved in operation. To simplify the mathematical description of the model, an equivalent model of a transport and technological unit (Fig. 1) for steady (quasi-static) movement with flywheel masses, the kinetic energy of which corresponds to the total energy of the masses being replaced, will be used.

The equivalent dynamic model is described by the following parameters:

I_e, I_{cl} – respectively, the moments of inertia of the flywheel masses of the engine, the driving and driven parts of the clutch. I_{tr} – moments of inertia of the common part of the transmission brought to the output shaft;

I_{aT1}, I_{aT2}, I_{am1}, I_{am2} – moments of inertia, respectively, of the tractor and technological machine axles;

m_T – operating mass of the tractor, kg. m_m – mass of the technological machine (trailer), calculated $m_m = m_c + m_l$, m_c – constructive mass of the trailer, m_l – mass of the cargo being transported. Depending on the type of machine and the nature of the technological operation, the movement of the center of gravity can be described by a linear or parabolic dependence and presented as a function of time or path;

I_{wT1}, I_{wT2}, I_{wm1}, I_{wm2} – moments of inertia, respectively, of the driving wheels (disks) of the tractor and the technological machine;

I_{tT1}, I_{tT2}, I_{tm1}, I_{tm2} – moments of inertia, respectively, of the tires of the driving wheels of the tractor and the technological machine;

c_{tr}, k_{tr} – the angular stiffness and damping coefficient of the common part of the transmission are given. c_{aT1}, c_{aT2}, c_{am1}, c_{am2}, k_{aT1}, k_{aT2}, k_{am1}, k_{am2} – the angular stiffness and damping coefficients, respectively, of the drive parts of the front and rear axles of the tractor and the technological machine are given;

c_{wT1}, c_{wT2}, c_{wm1}, c_{wm2}, k_{wT1}, k_{wT2}, k_{wm1}, k_{wm2} – the angular stiffness and damping coefficients, respectively, of the driving wheels of the tractor and the technological machine are given;

c_{tT1}, c_{tT2}, c_{tm1}, c_{tm2}, k_{tT1}, k_{tT2}, k_{tm1}, k_{tm2} – given angular stiffness and damping coefficients of the tractor and technological machine tires. c_{xT1}, c_{xT1}, c_{xm1}, c_{xm1}, k_{xT1}, k_{xT2}, k_{xm1}, k_{xm2} – coefficient of longitudinal stiffness and damping coefficients of the tire-soil pair, respectively, of the tractor and technological machine tires;

M_e – engine torque. M_r – moment of resistance at the engine inputs. M_{fT1}, M_{fT2}, M_{fm1}, M_{fm2} – moments of tangential forces of the tractor and technological machine wheels when interacting with the soil; φ_e, φ_{cl}, φ_{tr}, φ_{aT1}, φ_{aT2}, φ_{am1}, φ_{am2}, φ_{wT1}, φ_{wT2}, φ_{wm1}, φ_{wm2}, φ_{tT1}, φ_{tT2}, φ_{tm1}, φ_{tm2} – angles of rotation and angular displacements of the unit elements, the angular velocity is denoted by ω with the corresponding index.

In this case, P_{kT} – traction force on the tractor hook, which is spent on overcoming the traction resistance R_{xm} of the technological machine (barrel, trailer, bunker). $P_{kT} = R_{xm}$; P_{xm} – pushing force created by the driving wheels of the technological machine in this study will vary depending on the drive power transmitted to the driving wheels. To study three cases of movement of the unit: $P_{kT} > P_{xm}$; $P_{kT} = P_{xm}$; $P_{kT} < P_{xm}$. P_{ka} – potential tractive force of the unit (tractor + technological machine), which can be used to overcome the traction resistance of agricultural implements R_{xa} in a combined unit (soil-tillage implements). This indicator is used as an estimate for comparing the efficiency of the unit with all-wheel drive and the classic one.

The differential equation of motion of the engine crankshaft is represented using the D'Alembert principle

$$I_e \cdot \ddot{\varphi} = M_e - M_r. \tag{1}$$

Since for tractors with mechanical transmission in a steady state mode of movement $\varphi_e = \varphi_{cl}$, and the reduced moment of inertia of the engine can be taken as the sum of the moments of the engine and clutch, equation (1) will take the form

$$\left(I_e + I_{cl}\right)\ddot{\varphi}_{cl} = M_e - k_{tr}\left(\dot{\varphi}_{cl} - \dot{\varphi}_{tr}\right) - c_{tr}\left(\varphi_{cl} - \varphi_{tr}\right). \tag{2}$$

Let's represent the moments of tangential forces of the wheels of the tractor and the technological machine when interacting with the soil, through the moments determined by the elasticity and damping in the tires

$$\begin{cases} M_{fT1} = \left(c_{xT1} \cdot \lambda_{tT1} + k_{T1} \cdot \dot{\lambda}_{tT1} + \left(a_{T1}/r_{dT1}\right) R_{zT1}\right) r_{dT1}; \\ M_{fT2} = \left(c_{xT2} \cdot \lambda_{tT2} + k_{T2} \cdot \dot{\lambda}_{tT2} + \left(a_{T2}/r_{dT2}\right) R_{zT2}\right) r_{dT2}; \\ M_{fm1} = \left(c_{xm1} \cdot \lambda_{tm1} + k_{m1} \cdot \dot{\lambda}_{tm1} + \left(a_{m1}/r_{dm1}\right) R_{zm1}\right) r_{dm1}; \\ M_{fm2} = \left(c_{xm2} \cdot \lambda_{tm2} + k_{m2} \cdot \dot{\lambda}_{tm2} + \left(a_{m2}/r_{dm2}\right) R_{zm2}\right) r_{dm2}, \end{cases} \tag{3}$$

where λ_{tT1}, λ_{tT2}, λ_{tm1}, λ_{tm2} – the longitudinal deformations of the tires of the corresponding wheels; R_{zT1}, R_{zT2}, R_{zm1}, R_{zm2} – the vertical reactions in the contact spot of the wheel with the supporting surface; a_{T1}, a_{T2}, a_{m1}, a_{m2} – the displacements of the vertical reactions relative to the wheel axis, which can be represented taking into account the coefficient of rolling resistance and longitudinal deformation: $a_{T1(m)} = f_{T(m)} \cdot r_{dT(m)} + \lambda_{tT(m)}$; r_{dT1}, r_{dT2}, r_{dm1}, r_{dm2} – dynamic radii, respectively, of the wheels of the tractor and the technological machine.

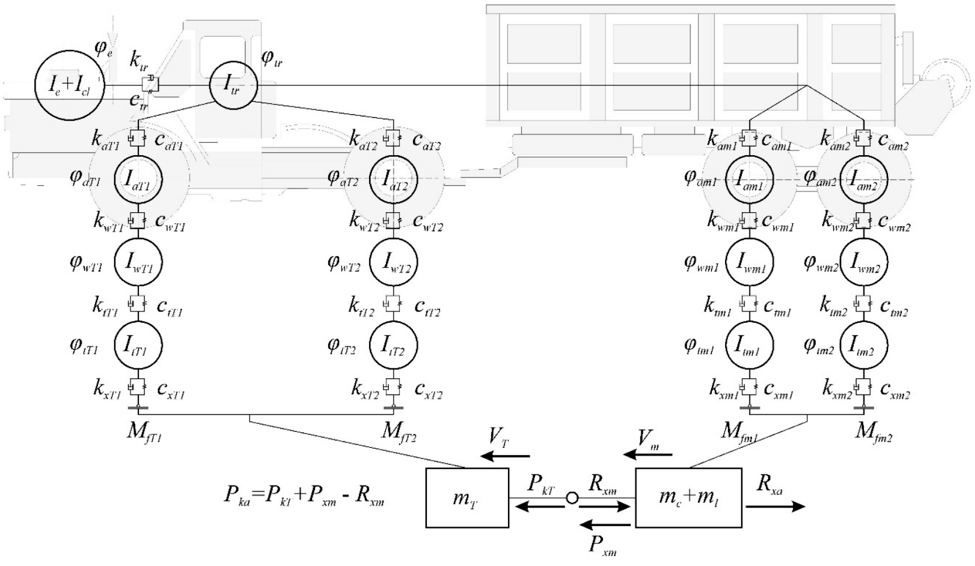


Fig. 1. Equivalent dynamic model of a transport and technological unit with active wheels

The equation of motion of the tractor as part of a classical unit can be represented as follows

$$m_T \cdot \dot{x}_T = \frac{M_{fT1}}{r_{dT1}} + \frac{M_{fT2}}{r_{dT2}} - \left(R_{xm} + R_{xa}\right). \tag{4}$$

The equation of motion of the technological machine in a unit with all-wheel drive

$$m_m \cdot \dot{x}_m = \frac{M_{fm1}}{r_{dm1}} + \frac{M_{fm2}}{r_{dm2}} + R_{xm} - R_{xa}. \tag{5}$$

When using all-wheel drive, equations are added to the system of equations of the classical unit that describe the operation of the driving wheels of the technological machine, then the system of equations will take the form

$$\begin{cases}
\left(I_e + I_{cl}\right) \cdot \ddot{\varphi}_{cl} = M_e - k_{tr}\left(\dot{\varphi}_{cl} - \dot{\varphi}_{tr}\right) - c_{tr}\left(\varphi_{cl} - \varphi_{tr}\right); \\
I_{tr} \cdot \ddot{\varphi}_{tr} = c_{tr}\left(\varphi_{cl} - \varphi_{tr}\right) + k_{tr}\left(\dot{\varphi}_{cl} - \dot{\varphi}_{tr}\right) - c_{aT1}\left(\varphi_{tr} - \varphi_{aT1}\right) - k_{aT1}\left(\dot{\varphi}_{tr} - \dot{\varphi}_{aT1}\right) - c_{aT2}\left(\varphi_{tr} - \varphi_{aT2}\right) - \\
- k_{aT2}\left(\dot{\varphi}_{tr} - \dot{\varphi}_{aT2}\right) - c_{am1}\left(\varphi_{tr} - \varphi_{am1}\right) - k_{am1}\left(\dot{\varphi}_{tr} - \dot{\varphi}_{am1}\right) - c_{am2}\left(\varphi_{tr} - \varphi_{am2}\right) - k_{am2}\left(\dot{\varphi}_{tr} - \dot{\varphi}_{am2}\right); \\
I_{aT1} \cdot \ddot{\varphi}_{aT1} = c_{aT1}\left(\varphi_{tr} - \varphi_{aT1}\right) + k_{aT1}\left(\dot{\varphi}_{tr} - \dot{\varphi}_{aT1}\right) - c_{wT1}\left(\varphi_{aT1} - \varphi_{wT1}\right) - k_{wT1}\left(\dot{\varphi}_{aT1} - \dot{\varphi}_{wT1}\right); \\
I_{aT2} \cdot \ddot{\varphi}_{aT2} = c_{aT2}\left(\varphi_{tr} - \varphi_{aT2}\right) + k_{aT2}\left(\dot{\varphi}_{tr} - \dot{\varphi}_{aT2}\right) - c_{wT2}\left(\varphi_{aT2} - \varphi_{wT2}\right) - k_{wT2}\left(\dot{\varphi}_{aT2} - \dot{\varphi}_{wT2}\right); \\
I_{am1} \cdot \ddot{\varphi}_{am1} = c_{am1}\left(\varphi_{tr} - \varphi_{am1}\right) + k_{am1}\left(\dot{\varphi}_{tr} - \dot{\varphi}_{am1}\right) - c_{wm1}\left(\varphi_{am1} - \varphi_{wm1}\right) - k_{wm1}\left(\dot{\varphi}_{am1} - \dot{\varphi}_{wm1}\right); \\
I_{am2} \cdot \ddot{\varphi}_{am2} = c_{am2}\left(\varphi_{tr} - \varphi_{am2}\right) + k_{am2}\left(\dot{\varphi}_{tr} - \dot{\varphi}_{am2}\right) - c_{wm2}\left(\varphi_{am2} - \varphi_{wm2}\right) - k_{wm2}\left(\dot{\varphi}_{am2} - \dot{\varphi}_{wm2}\right); \\
I_{wT1} \cdot \ddot{\varphi}_{wT1} = c_{wT1}\left(\varphi_{aT1} - \varphi_{wT1}\right) + k_{wT1}\left(\dot{\varphi}_{aT1} - \dot{\varphi}_{wT1}\right) - c_{tT1}\left(\varphi_{wT1} - \varphi_{tT1}\right) - k_{tT1}\left(\dot{\varphi}_{wT1} - \dot{\varphi}_{tT1}\right); \\
I_{wT2} \cdot \ddot{\varphi}_{wT2} = c_{wT2}\left(\varphi_{aT2} - \varphi_{wT2}\right) + k_{wT2}\left(\dot{\varphi}_{aT2} - \dot{\varphi}_{wT2}\right) - c_{tT2}\left(\varphi_{wT2} - \varphi_{tT2}\right) + k_{tT2}\left(\dot{\varphi}_{wT2} - \dot{\varphi}_{tT2}\right); \\
I_{wm1} \cdot \ddot{\varphi}_{wm1} = c_{wm1}\left(\varphi_{am1} - \varphi_{wm1}\right) + k_{wm1}\left(\dot{\varphi}_{am1} - \dot{\varphi}_{wm1}\right) - c_{tm1}\left(\varphi_{wm1} - \varphi_{tm1}\right) + k_{tm1}\left(\dot{\varphi}_{wm1} - \dot{\varphi}_{tm1}\right); \\
I_{wm2} \cdot \ddot{\varphi}_{wm2} = c_{wm2}\left(\varphi_{am2} - \varphi_{wm2}\right) + k_{wm1}\left(\dot{\varphi}_{am2} - \dot{\varphi}_{wm2}\right) - c_{tm2}\left(\varphi_{wm2} - \varphi_{tm2}\right) + k_{tm2}\left(\dot{\varphi}_{wm2} - \dot{\varphi}_{tm2}\right); \\
I_{tT1} \cdot \ddot{\varphi}_{tT1} = c_{tT1}\left(\varphi_{wT1} - \varphi_{tT1}\right) + k_{tT1}\left(\dot{\varphi}_{wT1} - \dot{\varphi}_{tT1}\right) - \left(c_{xT1} \cdot \lambda_{tT1} + k_{xT1} \cdot \dot{\lambda}_{tT1} + \frac{a_{T1}}{r_{dT1}} R_{zT1}\right) r_{dT1}; \\
I_{tT2} \cdot \ddot{\varphi}_{tT2} = c_{tT2}\left(\varphi_{wT2} - \varphi_{tT2}\right) + k_{tT2}\left(\dot{\varphi}_{wT2} - \dot{\varphi}_{tT2}\right) - \left(c_{xT2} \cdot \lambda_{tT2} + k_{xT2} \cdot \dot{\lambda}_{tT2} + \frac{a_{T2}}{r_{dT2}} R_{zT2}\right) r_{dT2}; \\
I_{tm1} \cdot \ddot{\varphi}_{tm1} = c_{tm1}\left(\varphi_{wm1} - \varphi_{tm1}\right) + k_{tm1}\left(\dot{\varphi}_{wm1} - \dot{\varphi}_{tm1}\right) - c\left(c_{xm1} \cdot \lambda_{tm1} + k_{xm1} \cdot \dot{\lambda}_{tm1} + \frac{a_{m1}}{r_{dm1}} R_{zm1}\right) r_{dm1}; \\
I_{tm2} \cdot \ddot{\varphi}_{tm2} = c_{tm2}\left(\varphi_{wm2} - \varphi_{tm2}\right) + k_{tm2}\left(\dot{\varphi}_{wm2} - \dot{\varphi}_{tm2}\right) - \left(c_{xm2} \cdot \lambda_{tm2} + k_{xm2} \cdot \dot{\lambda}_{tm2} + \frac{a_{m2}}{r_{dm2}} R_{zm2}\right) r_{dm2}; \\
m_T \cdot \ddot{x}_T = \frac{M_{fT1}}{r_{dT1}} + \frac{M_{fT2}}{r_{dT2}} - \left(R_{xm} + R_{xa}\right); \\
m_m \cdot \ddot{x}_m = \frac{M_{fm1}}{r_{dm1}} + \frac{M_{fm2}}{r_{dm2}} + R_{xm} - R_{xa}; \\
\dot{x}_T = \dot{\varphi}_{tT1} \cdot r_{dT1} - \dot{\lambda}_{tT1} - \delta_{T1} \cdot \lambda_{tT1}; \\
\dot{x}_T = \dot{\varphi}_{tT2} \cdot r_{dT2} - \dot{\lambda}_{tT2} - \delta_{T2} \cdot \lambda_{tT2}; \\
\dot{x}_m = \dot{\varphi}_{tm1} \cdot r_{dm1} - \dot{\lambda}_{tm1} - \delta_{m1} \cdot \lambda_{tm1}; \\
\dot{x}_m = \dot{\varphi}_{tm2} \cdot r_{dm2} - \dot{\lambda}_{tm2} - \delta_{m2} \cdot \lambda_{tm2},
\end{cases}$$

where δ_{T1}, δ_{T2} – coefficients that take into account the slippage of the front and rear driving wheels of the tractor, respectively; δ_{m1}, δ_{m2} – coefficients that take into account the slippage of the front and rear driving wheels of the technological machine, respectively.

Solving the above equations allows to obtain the dynamic components of the operation of the transport and technological unit. The unit was presented as a system consisting of functional subsystems: engine, transmission, bridges, wheels, etc.

Since the main task of the modeling was to clarify the conditions of movement of the transport and technological unit regarding the distribution of pushing P_{xm} and traction P_{kT} forces, taking into account the dynamic component of movement.

The methodology for conducting research using the above equivalent dynamic model is as follows.

For the transport and technological unit of the ХТЗ-240К tractor when aggregated with the МЖТ-16 technological machine at a technological speed of 10 km/h and the traction resistance of the technological machine $R_{xm} = 12.5$ kN. The basic, estimated performance characteristics when using the tractor in the tractor mode with a 4×4 wheel formula were obtained. The model included the performance characteristics in 3 gears of 2 ranges with a maximum power on the hook for this gear of 90 kW and the tractor engines slipping within 10–12%. The values of P_{tT}, P_{ka} and the acceleration of the basic unit a were obtained as estimated indicators.

The relationships of the specified parameters are determined from the equation of the traction balance of the unit (tractor)

$$P_{ka} = P_{tT} - P_{fT} - R_{xm}, \tag{6}$$

where P_{tT} – the tangential traction force of the tractor; P_{fT} – the rolling resistance force of the tractor wheels; P_{ka} – the potential traction force (estimated indicator), which can be used to overcome the traction resistance of agricultural implements R_{xm} in a combined unit (soil-tillage implements); R_{xm} – the resistance force of the technological machine (trailer, barrels, bunker).

Using the basic indicators, the transfer of part of the tractor engine power to the active wheels of the technological machine is simulated. Since the main purpose is always to study three cases of movement of the unit: $P_{kT} > P_{xm}$; $P_{kT} = P_{xm}$; $P_{kT} < P_{xm}$, for these cases the trends of changes in the oscillations of the longitudinal forces acting on the unit are determined. The pushing force P_{xm} is calculated based on the power required to overcome the costs of self-propulsion of the technological machine. The power is determined as follows $N_{km} = R_x V \cdot k$, where $k = 0.85$; 1; 1.15. That is, 85%, 100% and 115% of the power spent on moving the technological machine, taking into account fluctuations in engine power. When modeling, let's take R_{xm} as the average value from the calculations of the base unit $R_{xm} = 12.5$ kN.

For an all-wheel drive unit, an increase in P_{ka} is characteristic, since the realization of the potential power of the tractor engine increases. So, in the case of using active wheels, the potential traction force of the unit is equal to

$$P_{ka} = P_{tT} + P_{xm} - P_{fT} - R_{xm}, \tag{7}$$

where P_{xm} – the traction force of the technological machine (pushing force), kN.

To compare the fluctuations of longitudinal forces in different cases of movement ($P_{kT} > P_{xm}$; $P_{kT} = P_{xm}$; $P_{kT} < P_{xm}$) using a dynamic model, let's obtain P_{tT}, P_{ka} and acceleration a of the unit with active wheels of the technological machine for each of the values $k = 0.85$; 1; 1.15. Using statistical analysis methods, it is possible to determine the best case of movement.

Since the transport and technological unit, depending on the characteristics of the operation and equipment, can operate at different technological speeds. Further analysis of the cases of movement ($P_{kT} > P_{xm}$; $P_{kT} = P_{xm}$; $P_{kT} < P_{xm}$) according to the above method is carried out for different speed modes of movement.

3. Results and Discussion

3.1. Results of modeling of dynamic components of the operation of the transport and technological unit

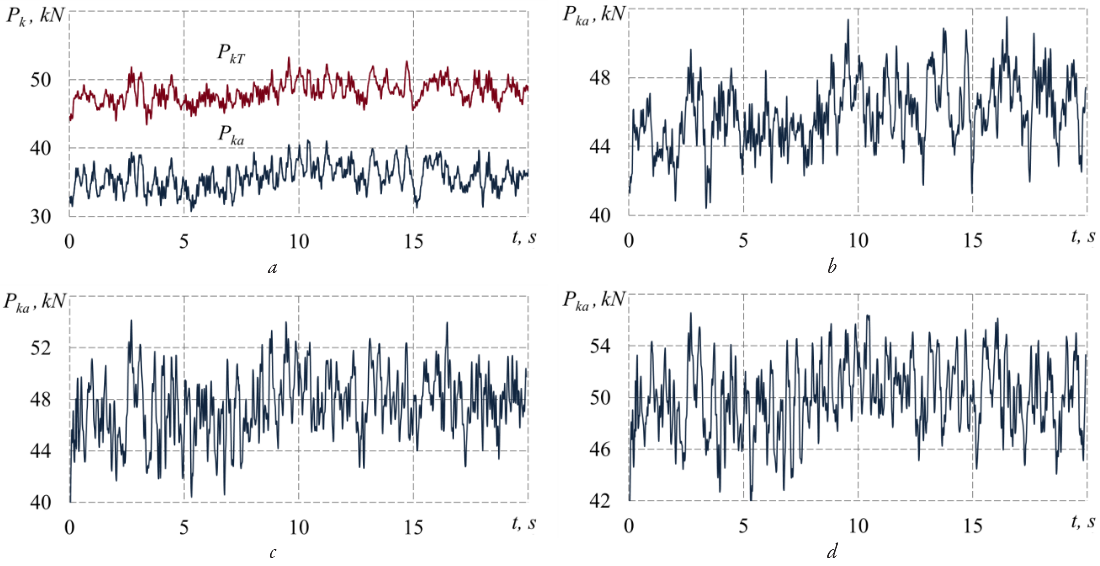
The maximum traction force on the hook $P_{kT\max}$ is presented in the modeling as the maximum traction force at a certain gear, limited by the parameters of the interaction of the wheel with the supporting surface (coefficients of adhesion φ and slippage δ). When using the tractor in the tractor mode, P_{ka} will be equal to the maximum traction force on the hook $P_{kT\max}$ at a certain transmission gear, minus R_{xm}.

Simulation results for the base unit and the unit with the driving wheels of the technological machine under the condition of movement $k = 0.85$; $k = 1$; $k = 1.15$: potential traction force P_{ka} (Fig. 2); resistance force of the technological machine R_{xm} (Fig. 3).

The average value of the maximum traction force on the hook is $P_{kT\max} = 48.21$ kN, the standard deviation $\sigma_{T\max} = 1.63$ kN. In this and subsequent calculations, the obtained value $P_{kT\max}$ will be used as a base for determining the potential traction force P_{ka}, which can be additionally used to overcome the traction resistance of agricultural implements. Its value is determined taking into account the resistance force R_{xm} and is $P_{ka} = 33.74$ kN at $\sigma_{ka} = 1.93$ kN. In this case, the standard deviation R_{xm} is $\sigma_{xm} = 1.03$ kN.

As basic indicators, the values of speed and acceleration fluctuations of the unit were obtained without using the drive wheels of the technological machine (Fig. 4, *a*).

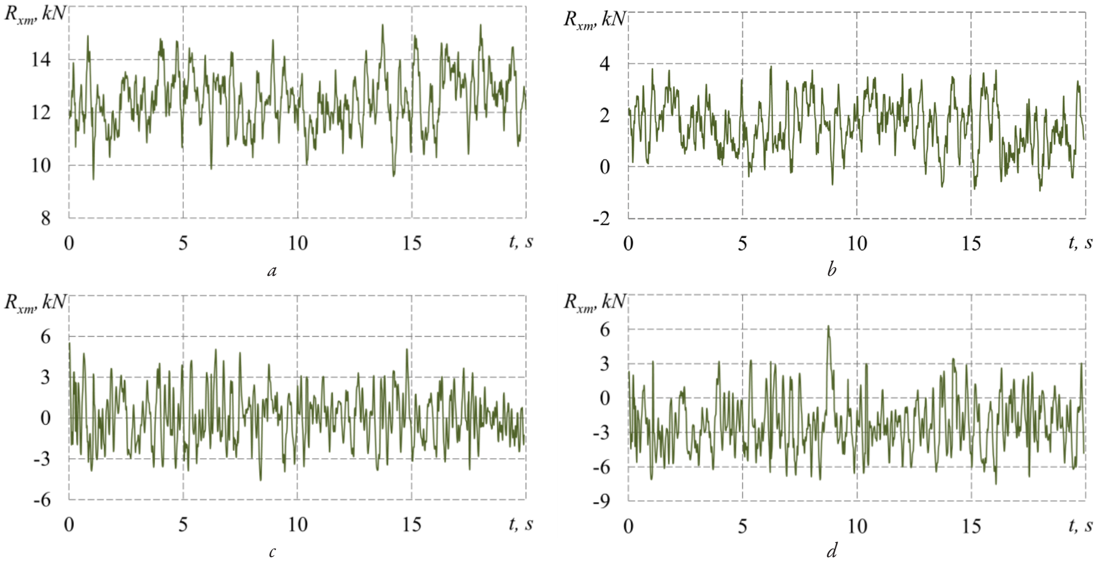
The average speed value is 10.32 km/h with a deviation $\sigma_v = 0.22$ km/h, since a steady motion is considered, the average acceleration value is zero. Its oscillation in the longitudinal plane under the action of forces applied to the unit is an estimated parameter and can be used in the future when conducting experimental studies $\sigma_a = 0.26$ m/s^2. According to the results of the calculations, let's obtain a_x for different conditions of movement: $k = 0.85$ (Fig. 4, *b*), $k = 1$ (Fig. 4, *c*), $k = 1.15$ (Fig. 4, *d*).



a *b*

c *d*

Fig. 2. Force P_{ka} (potential traction force) of the base unit and the unit with active wheels of the technological machine: *a* – base unit; *b* – $k = 0.85$; *c* – $k = 1$; *d* – $k = 1.15$



a *b*

c *d*

Fig. 3. Traction resistance R_{xm} of the technological machine for the base unit and the unit with active wheels of the technological machine: *a* – base unit; *b* – $k = 0.85$; *c* – $k = 1$; *d* – $k = 1.15$

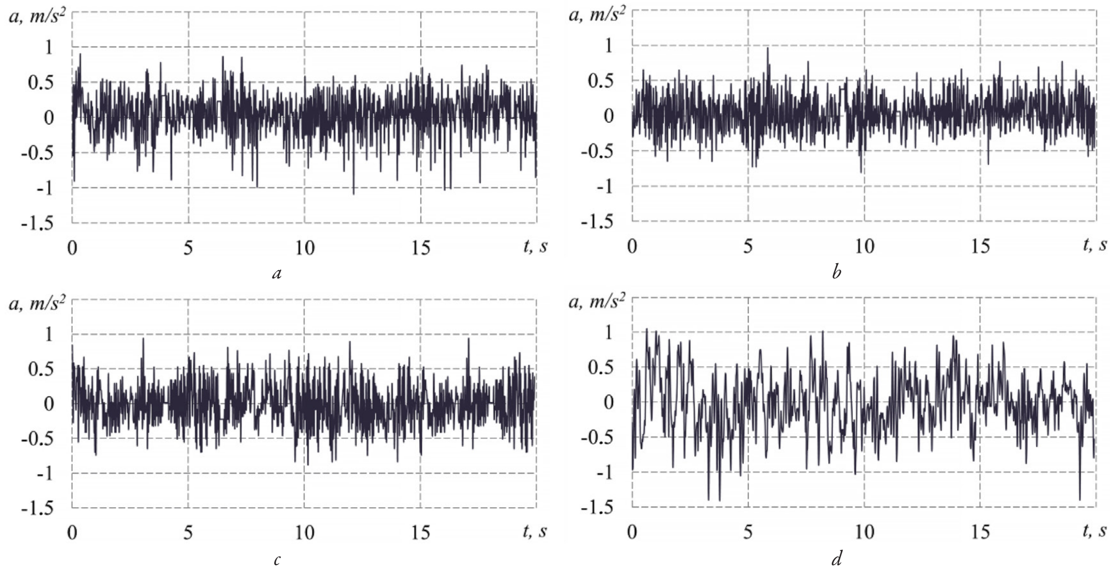


Fig. 4. Acceleration of the base unit and the unit with active wheels of the technological machine: *a* – base unit; *b* – $k=0.85$; *c* – $k=1$; *d* – $k=1.15$

3.2. Determining the influence of speed on changes in longitudinal force oscillations

For further analysis, it is advisable to determine the dependence of the change in σ_{ka}, k_N on the speed of movement of the unit, since transport and technological units can operate in a wide range of technological speeds (Fig. 5).

Analysis of the obtained results allows to state that the tendency to increase the oscillations of P_{ka} when transmitting power to the driving wheels of the technological machine at $k=1$–1.15 persists regardless of the change in the speed of movement. It is also possible to pay attention to the general decrease in oscillations at a speed of 12 km/h.

Dependences of the change in the oscillations of acceleration σ_a, kN on the speed of the transport and technological unit are presented in Fig. 6.

A general problem of analyzing the oscillations of the forces applied to the transport and technological unit when moving across the field is the complexity of the experimental determination of the corresponding forces. Since the installation of additional strain gauge links affects the dynamics, the use of strain gauges on structural elements is complicated by the problem of calibration, the determination of forces is possible only as a function of the traction force, etc. Therefore, to compare theoretical and experimental results, the acceleration of the unit can be used, which will allow using the method of partial accelerations [24] to determine the necessary values of forces and their characteristic oscillations.

Since the force P_{ka} was considered as a potential force that the unit can realize in a certain gear, the power transfer to the driving wheels was limited precisely by the value R_{xm}.

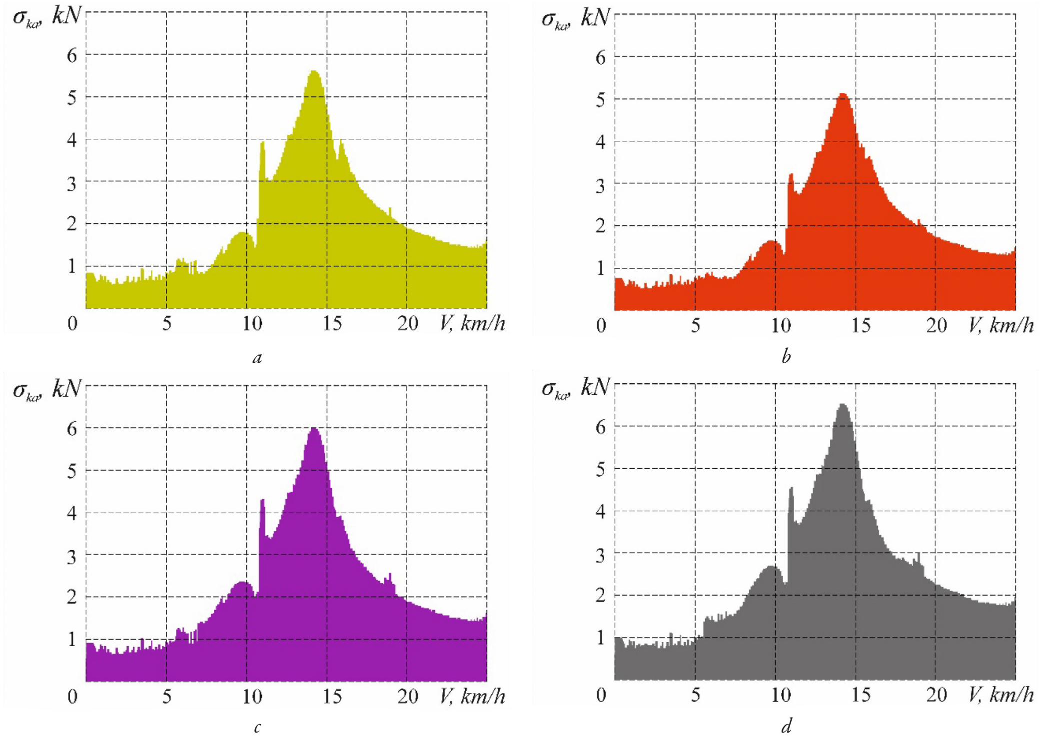
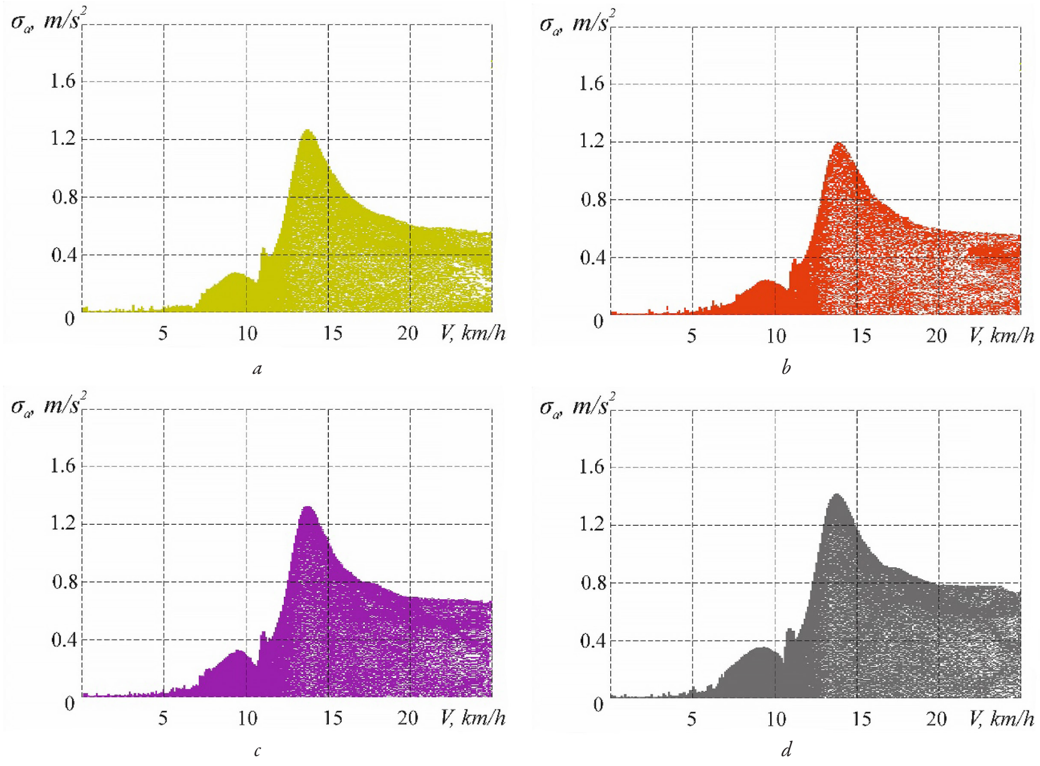


Fig. 5. Dependences of the change in σ_{ka}, kN on the speed of movement of the base unit and the unit with active wheels of the technological machine: *a* – base unit; *b* – $k=0.85$; *c* – $k=1$; *d* – $k=1.15$



a *b* *c* *d*

Fig. 6. Dependences of the change in σ_a, kN on the speed of movement of the base unit and the unit with active wheels of the technological machine: *a* – base unit; *b* – $k=0.85$; *c* – $k=1$; *d* – $k=1.15$

To realize the potential capabilities of the tractor engine as part of the all-wheel drive unit, it is advisable to transfer the greatest possible power to the active wheels of the technological machine, that is, to use its coupling weight to the maximum.

If the aggregate includes an agricultural implement, the power transmitted to the drive wheels of the technological machine will increase in proportion to the increase in the resistance of the agricultural implement $N_{km}=(R_{xm}+R_{xa})\cdot V\cdot k$ (potentially up to the clutch limit), while the condition of movement at $k=0.85$–0.9 must be maintained.

3.3. Research limitations and prospects for its development

The limitations of this research are the use of an equivalent dynamic model, which was used to simplify the modeling of the dynamics of the movement of a multi-mass semi-mounted transport and technological unit. This study did not consider the types of power transmission to the wheels of the technological machine, which will additionally affect the dynamics of movement and is necessary for further practical implementation. The practical value of the results obtained is to obtain theoretical foundations for the development of methods for rational power transmission to the active wheels of the technological machine, which are obtained taking into account the dynamic components of movement. Their use will allow to substantiate the designs of active wheel drives, which will be able to flexibly adapt to the transmission of the required part of the power. Given the conducted research, it can be clearly determined that these designs should be based on combined hydromechanical or electromechanical transmissions with electronic control. The use of adaptive control will allow to level the kinematic mismatch and reduce or completely eliminate the circulation of power in the wire.

Further development of the research, taking into account the practical use of the results, is to conduct field experiments with in-depth statistical and spectral analysis of the oscillation of longitudinal forces.

4. Conclusions

Using the equivalent dynamic module of the transport and technological unit, the dynamic component of the movement was analyzed in three cases of movement of the unit: $P_{kT}>P_{xm}$; $P_{kT}=P_{xm}$; $P_{kT}<P_{xm}$. It was determined that the movement of the unit with the transmission of part of the power to the drive wheels of the technological machine must be implemented with partial underloading $P_{kT}>P_{xm}$. This is due to the fact that for the movement condition at $k=0.85$, the potential traction force P_{ka} increases to 45.92 kN with a decrease in the mean square deviation $\sigma_{ka}=1.74$ kN. In this movement mode, the technological machine does not run into the tractor, as a result, there are the smallest dynamic oscillations and a stabilizing effect for longitudinal forces.

When analyzing different speed modes of movement of the transport and technological unit. It was found that the tendency towards movement with partial underloading $P_{kT}>P_{xm}$ is preserved at all working and transport speeds for the considered unit. It should be noted that if there is an agricultural implement in the unit, the power transmitted to the drive wheels of the technological machine will increase in proportion to the increase in resistance. Potentially, such an increase is possible up to the clutch limit, which will characterize such a mode as rational from the point of view of energy saving and stability of operation. In this case, the condition of movement at $k=0.85$–0.9 must be maintained. A further increase in k is possible only when the wheel is operating in a free mode, for which it is necessary to implement the power transmission in such a way that the power necessary to overcome the moment of tangential forces of its interaction with the soil is transmitted to a specific wheel. That is, to ensure the dynamic balance of the elements of the unit in the absence of moments of running of the technological machine on the tractor.

Conflict of interest

The authors declare that they have no conflicts of interest, in relation to the current research, including financial, personal, authorship, or any other, that could affect the research and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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