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ANALYSIS OF CURVILINEAR MOTION OF TRACKED VEHICLES WITH ELECTROMECHANICAL DUAL-FLUX TURNING MECHANISMS

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Методами чисельного моделювання проаналізовані можливості встановлення електроприводу в двопотокові механізми повороту гусеничних машин. Це дозволяє одержати плавну керовану зміну радіусу повороту від вільного до фіксованого з частковою рекуперацією енергії уповільнення. Обрані кінематичні схеми і параметри електроприводу, які найбільш раціональні для проведення неглибокої модернізації трансмісії на прикладі гусеничного тягача МТЛБ

Ключові слова: гусенична машина, двопотоковий механізм повороту, електромеханічний механізм повороту, радіус повороту

Методами численного моделирования проанализированы возможности установки электропривода в двухпоточные механизмы поворота гусеничных машин. Это позволяет получить плавное управляемое изменение радиуса поворота от свободного до фиксированного с частичной рекуперацией энергии замедления. Выбраны кинематические схемы и параметры электропривода, наиболее рациональные для проведения неглубокой модернизации трансмиссии на примере гусеничного тягача МТЛБ

Ключевые слова: гусеничная машина, двухпоточный механизм поворота, электромеханический механизм поворота, радиус поворота

1. Introduction

There were from 40 to 50 thousand tractors of the MTLB type and vehicles on their chassis in the world at the turn of the millennium by the calculations of the analysts of the Central Scientific Research Institute of armament and military equipment of Ukraine and the state concern “Ukroboronprom”. On the one hand, these vehicles display good results of reliability and passability until now, but on the other hand, they dramatically lose to contemporary vehicles in specific power, protection and ergonomic parameters.

According to the operating instructions for the military tracked vehicles, it is accepted, when undergoing capital repairs, to simultaneously perform more or less considerable modernization, which allows, if not bringing them into full compliance, then at least drawing the old vehicles closer to the new requirements and standards.

Thus, with a sharp increase in the volumes of the operation of military tracked vehicles in connection with ATO campaing in Ukraine, a number of emergencies and road accidents with their involvement grew, provoked by the combination of low qualification of drivers and by complexity and inconvenience of the system of the turning control in the old tracked vehicles.

Therefore, the solution of the problem, connected with the facilitation of the steering process of the old military tracked vehicles after repair with simple upgrade and relatively inexpensive modernization, is actual.

2. Analysis of scientific literature and the problem statement

The theory of motion and, in particular, of the turning of tracked vehicles is explored quite fully and fundamentally. Classical approach to the description of the turning of tracked vehicles is presented in [1–3].

When designing contemporary tracked vehicles, the organization of the turning is solved by the following main methods:

– by the application of full-flux drive or dual-flux central hydrovolumetric-mechanical transmissions;

– by the application of automatic systems of control of the motion for mechanical step transmission, which make it possible to automatically control the process of slipping of the friction clutches.

Over the past 15–20 years, in parallel with automobiles and wheel military machines, an electric drive has been more actively applied in the transmission of tracked vehicles.

The described methods make it possible to implement the process of the turning control with the aid of a steering wheel, in contrast to the old vehicles, in which this was done by levers. Accordingly, it is possible to find a large number of publications in the scientific literature, devoted to the improvement of hydrovolumetric transmissions and the turning mechanisms (TM) [4–6]; to the improvement of systems of the turning control and motion as a whole [7, 11, 13, 14]; to the improvement of electrical and hybrid drive for the tracked vehicles [9–13]. Even the topic of the deceleration energy recovery for the hydrovolumetric-mechanical transmission is examined [8]. However, none of the indicated directions suits simple modernization of old tracked vehicles. Thus, the installation of hydrovolumetric TM requires radical treatment of transmission, installation of the cooling system for the working fluid and allows only instantaneous energy regeneration without the possibility of its accumulation. The installation of the contemporary control systems, which manage the process of the slipping of friction clutches, does not solve the problem of permanent losses of energy to the friction, connected with deceleration of the lagging edge, while the installation of a full-scale electrical transmission requires powerful and expensive electric motors, powerful generator and capacious accumulator.

And we have not seen in the scientific publications any materials on the study of the possibility of applying electric drive for the organization of the turning in the dual-flux mechanical step transmissions of the tracked vehicles. More to the point, the variants of the application of electric motors, predominantly in the generator and brake modes were not examined either.

Thus, the following conclusion can be made. In contemporary scientific periodicals, the questions, connected to the proposals of scientifically substantiated technical solutions, which make it possible to attain smooth controlled change in the turning radius of the old military tracked vehicles, were not properly developed. In particular, the study directed towards obtaining the solutions, which ensure the possibility of energy regeneration at braking of the trailing edge in the turning, would be of much interest.

The authors of this article published materials earlier [15–19], in which they explored the topic of using an electric drive in the dual-flux mechanisms of the turning and gears (MTG) based on the example of the tracked tractor MTLB. We arrived at a conclusion on the basis of the conducted research that it was inexpedient to install and use in the traction mode electric motors in TM when performing simple modernization of the tractor transmission, at that stage of development of electric drive. This is linked to the need for the installation of electric motors with the power of not less than 40 kW onboard, in order to abandon mechanical branch in TM and to keep the speed indicators of the turning on heavy soils. Installation of such motors will require considerably more powerful generator and more capacious storage batteries. As a result, a required increase in the mobility and controllability of a machine without a considerable increase of engine power, fuel consumption, of machine weight and its price will be impossible.

3. The purpose and objectives of the study

The purpose of the work is to explore a possibility of increasing steerability of tracked vehicles with dual-flux mechanical step TM by a smooth controlled change in the turning radius with the energy recuperation of the trailing edge braking by installing additional electric drive in TM.

The problem, the solution to which implies achieving this goal, is conducting comparative analysis of steerability and energy efficiency of the chosen technical solutions on different soils.

4. Formulation of the problem of numerical simulation of the curvilinear motion of a tracked vehicle with mechanical and electromechanical dual-flux turning mechanisms and the methods applied in the study

To solve the set problem, in this paper we applied a method of mathematical simulation of the curvilinear motion of a tracked vehicle using mathematical apparatus of numerical integration of the system of differential equations of second order by the Runge-Kutta method with constant lead.

In the article [19] the authors described an algorithm for numerical simulation of the curvilinear motion of the tracked tractor MTLB, equipped with a regular mechanical and two variants of the proposed electromechanical TM.

In accordance with the materials presented in [19], three schemes were selected for the analysis:

– regular mechanical dual-flux TM of the tractor MTLB (Fig. 1);

– a dual-flux TM with one electromotor and counter-rotation of the sun gears of the summing planetary gear sets of the opposite drives (Fig. 2);

– a dual-flux TM with two electromotors that work predominantly in the brake mode, while maintaining the mechanical branch of a regular transmission of the tractor MTLB (Fig. 3).

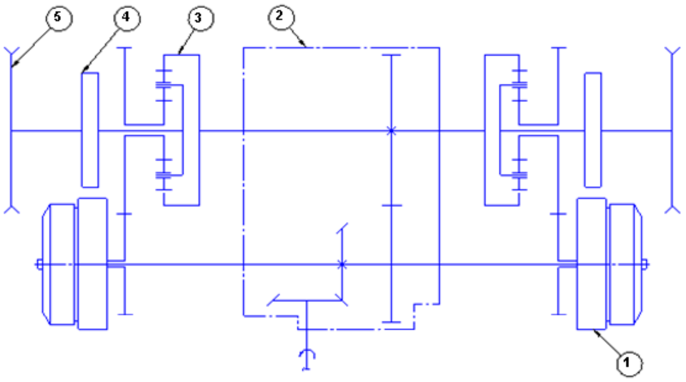


Fig. 1. Kinematic diagram of MTLB regular transmission: 1 – TM; 2 – gearbox; 3 – summing planetary gear sets; 5 – final drives; 6 – driving wheels

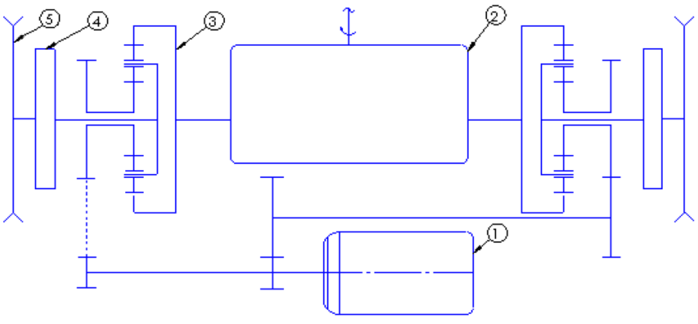


Fig. 2. Kinematic diagram of transmission with one electric motor and counter–rotation of the sun gears of the summing planetary gear sets: 1 – electric motor; 2 – gearbox; 3 – summing planetary gear sets; 4 – final drives; 5 – driving wheels

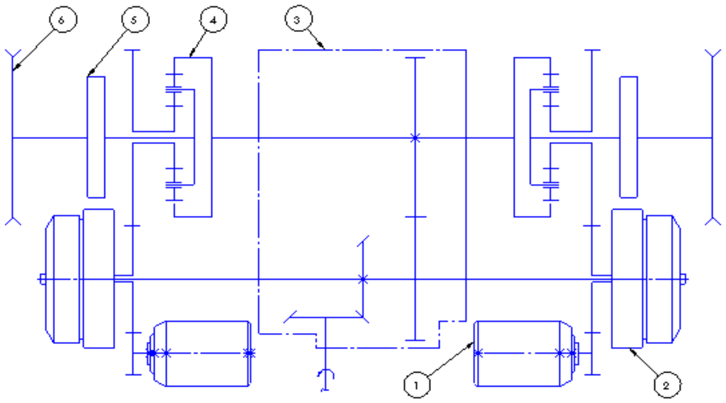


Fig. 3. Kinematic diagram of transmission with two motors operating in braking mode, while maintaining the mechanical branch in TM: 1 — electric motors; 2 — regular TM; 3 — gearbox; 4 — summing planetary gear sets; 5 — final drives; 6 — driving wheels

Initial data on the tractor and the soils, on which the turning was explored, are given in Tables 1, 2 [19].

Table 1

Vehicle parameters

No	Parameter	Value
1	Weight of vehicle, t	12,5
2	Type of engine	YaMZ–238B
3	Power of engine, kW (hp)	176 (240)
4	Rotation frequency of crankshaft at maximum power, r/min	2100
5	Maximum torque, N·m (kG·m)	883 (90)
6	Rotation frequency of crankshaft at maximum torque, r/min	1250–1450
7	Transmission ratio of input bevel reducer	0,905
8	Transmission ratios of gearbox: I II III IV V VI	 ∞ 3,125 1,500 0,833 0,585 0,435
9	Internal transmission ratio of the summing planetary gear sets	–2,41
10	Transmission ratio of final drives	6
11	Radius of drive wheel, m	0,265
12	Width of the vehicle on the track, m	2,5
13	Length of support surface of tracks, m	3,7
14	Height of the center of mass location, m	1,1
15	Moment of inertia of the engine with a flywheel, kgm^2	4,61
16	Moment of inertia of the vehicle when rotating relative to the vertical axis through the center of mass, kgm^2	50000

The work of regular TM of the tractor MTLB is performed as follows. At the rectilinear motion on the normal number of transmission, both locking friction clutches in TM are switched on, while the TM brakes are switched off. The power from the input shaft of the transmission passes by three flows: first – through the selected pair of gears in the gearbox, second and third – through the left and right TM. As a result, the epicycles of the summing planetary gear sets revolve at the speed corresponding to the selected gear and the sun gears of the summing planetary gear sets revolve in the same direction with the constant velocity that does not depend on the selected gear.

Table 2

Parameters of terrain

№	Type of terrain (road)	f	φ	μ_{max}
1	Dry turfy loamy soil (humidity< 8 %)	0,08	0.9	0,9
2	Dry earth road on the loam	0,07	0,8	0,8
3	Tillage on the loam	0,1	0,7	0,7
4	Wet road on the loam	0,125	0,6	0,35
5	Friable snow	0,25	0,3	0,3

The turning with a free radius implies disconnection of locking friction clutch on the trailing edge. As a result, power from the engine is not supplied to the drive wheel on the trailing edge and it revolves in a free mode as a result of the motion of the vehicle.

The turning with a fixed radius involves disconnection of locking friction clutch and the start of stopping brake on the trailing edge. As a result, the sun gear of the summing planetary gear sets on the trailing edge stops, and this drive wheel revolves at the velocity corresponding to the motion of the vehicle in the selected gear, but in the slow row of transmission. In this case the surplus of kinetic energy, linked to the slowing motion speed of the vehicle on the trailing edge, is transferred into heat on the stopping brake.

For a dual-flux TM with one electromotor and counter-rotation of the sun gears of the summing planetary gear sets of the opposite edges, the turning is performed due to an increase in the speed of rotation of the drive wheel on the leading edge and corresponding decrease in the rotation velocity of the drive wheel in the trailing edge.

The turning with a free radius for this TM is impossible since the disconnection of driving electromotor will lead to the unpredictable turning of the vehicle to the side of the board with a larger resistance to the motion. To keep the machine in the mode of rectilinear motion, it will be necessary in this case by constant mechanical or electromagnetic method to keep the anchor of electromotor from cranking under the influence of the difference in the moments of resistance to the motion under the boards.

For a dual-flux TM with two electromotors while maintaining the mechanical branch of the regular transmission of the tractor MTLB, different modes of the organization of the turning are possible.

Thus, the first variant implies, with the installation of sufficiently powerful electromotors (larger than 40 kW per drive), the organization of the turning with maintaining the speed of rectilinear motion similar to the previous scheme. Then for the leading board, the electromotor switches on in the traction mode and ensures the speed of rotation of the sun gear of its summing planetary gear sets that is larger than while switching on a corresponding locking friction clutch. For the lagging edge, depending on the speed of the vehicle motion of and the type of terrain, the electromotor works in the traction or generator (brake) mode, ensuring that the speed of rotation of the sun gear of its summing planetary gear set is slower than while switching on a corresponding locking friction clutch.

The second variant implies the installation of two electromotors with the power of up to 15–20 kW in parallel to the existing mechanical dual-flux TM. In this case, the work of TM is possible according to the first variant on 4–6 gears only, or on the soils with a low value of the coefficient of resistance to the turning. On heavy soils and lower gears, the use of electromotors in TM is meant only as the electrodynamic brakes (generator mode) until the full stop of the sun gear of the corresponding summing planetary gear set. After that, the sun gear is fixed by a stopping brake. The exit of the turning, depending on the value of the coefficient of resistance to the turning, can be fulfilled due to the acceleration of the corresponding electromotor or by the start of a locking friction clutch, similar to a regular transmission.

The turning with a free radius for this scheme implies the disconnection of a locking friction clutch and corresponding electromotor on the lagging edge. As a result, power from the diesel engine and the electromotor is not fed to the drive wheel on the lagging edge, and it revolves in a free mode as a result of the movement of a vehicle.

5. Results of the comparative analysis of the steerability of tracked vehicles with mechanical and electromechanical dual-flux mechanisms of the turning

With the use of the described algorithm [19] and the software program, developed for its realization, we carried out comparative numerical simulation of the performance of a tracked tractor on different soils.

The results of the simulation of the process of the turning of a tractor with a regular transmission by the time of the turning at 45° and 90° are presented in Fig. 4. These are the values of the turning time at 45° and 90° with free and fixed radii for all gears, in which stable motion of a vehicle is feasible, on three soils (*a* – dry turfy loamy soil at humidity lower 8 %; *b* – tillage on the loam; *c* – wet road on the loam).

During the simulation of electromechanical TM, it was assumed that the traction and braking characteristics of electromotors corresponded to Fig. 5 [19]. And the electromotor power varied in steps while keeping speed characteristics only due to the torque and for a dual-engine scheme it amounted to 0,125N_{nom}, 0,2N_{nom}, 0,25N_{nom} and 0,3N_{nom}, and for a single-engine scheme 0,5N_{nom}, 0,75N_{nom} and N_{nom}. The power of N_{nom}=46 kW was accepted as the nominal power.

The results of the simulation of the process of the turning of the tractor with two variants of electromechanical transmission by the time of the turning at 45° and 90° are represented in Fig. 6, 7.

Fig. 8–11 present combined dependencies of the turning radii and the speed of the vehicle motion for each type of terrain. For each diagram the numbers designate:

1 – boundary between the areas of the turning with complete and partial skid (analytical calculation);

2 – boundary between the areas of the turning without skid and with partial skid (analytical calculation);

3 – theoretical characteristic of the turning of a standard tractor MTLB with fixed radii in a normal number of transmission (analytical calculation);

4 – characteristic of the turning of a tractor with a regular transmission (numerical simulation);

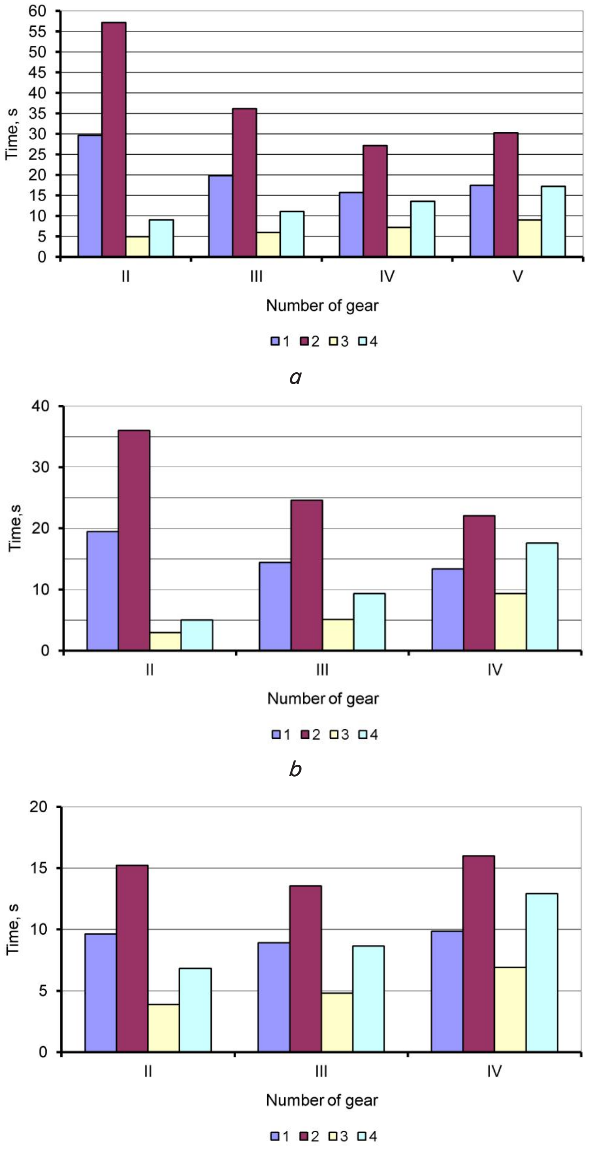
5 – characteristic of the turning of a tractor with electromechanical TM with one electromotor at N_{em}=0,5N_{nom}=23 kW (numerical simulation);

6 – characteristic of the turning of a tractor with electromechanical TM with one electromotor at N_{em}=0,75N_{nom}=34,5 kW (numerical simulation);

7 – characteristic of the turning of a tractor with electromechanical TM with one electromotor at N_{em}=N_{nom}=46 kW (numerical simulation);

8 – characteristic of the turning of a tractor with a regular transmission at a reduced value of gear ratio TM from 2,61 to 2 with fixed radii (numerical simulation);

9 – characteristic of the turning of a tractor with free turning radius.



a

b

c

Fig. 4. Dependence of the time of the turning on the type of terrain and a gear number for a regular transmission: row 1 is the turning at 45° with a free radius; row 2 is the turning at 45° with a fixed radius; row 3 is the turning at 90° with a free radius; row 4 is the turning at 90° with a fixed radius; *a* is the dry turfy loam; *b* is the tillage on the loam; *c* is the wet earth road on the loam

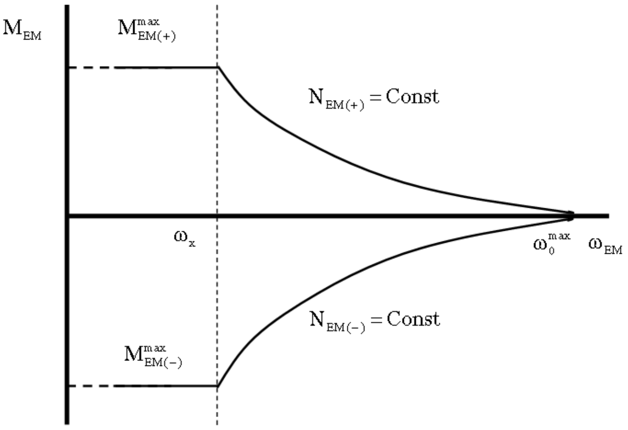
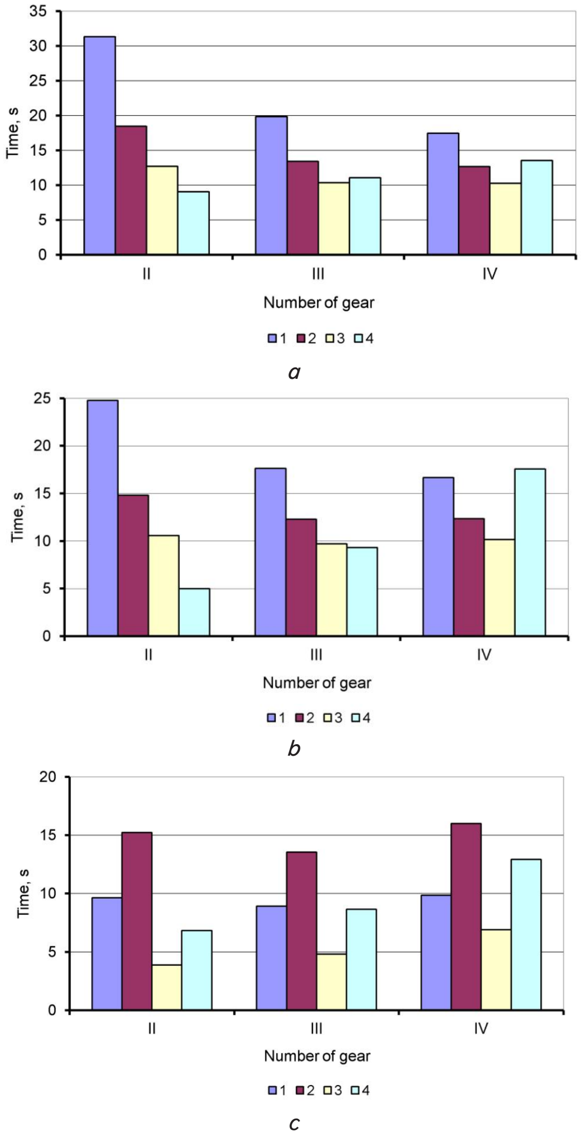


Fig. 5. Dependence of the traction (braking) torque of TM electric motor on the rotation speed of its anchor taking into account the work of control system

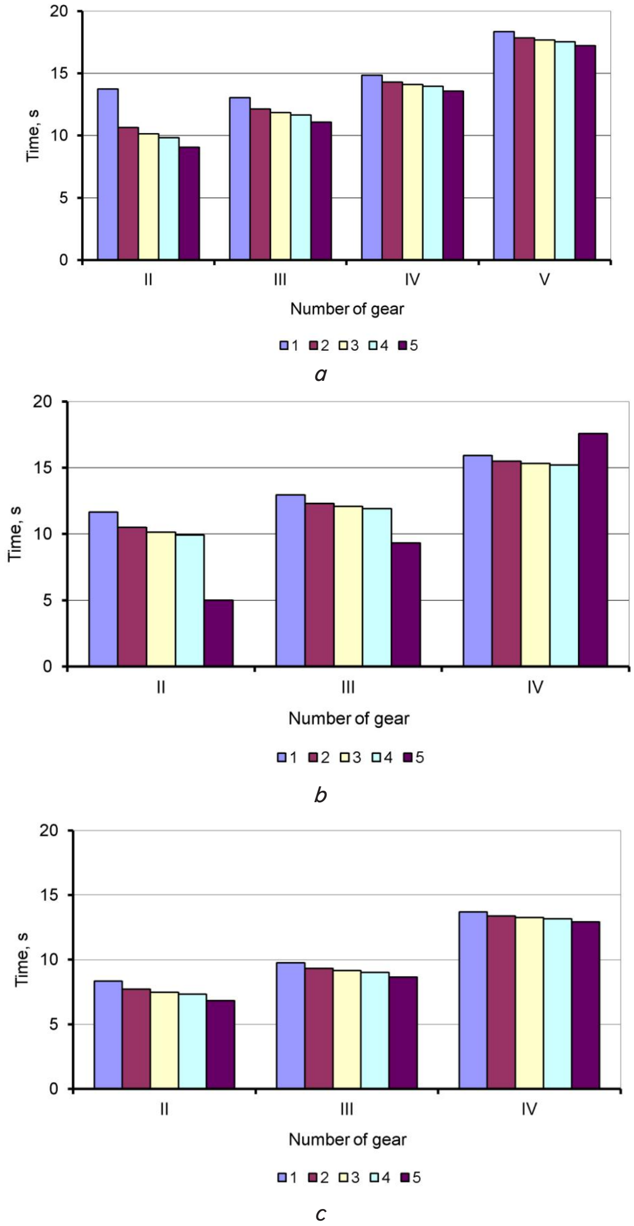


a

b

c

Fig. 6. Dependence of the time of the turning at 90° on the type of terrain and a gear number for electromechanical TM with one electromotor: row 1 is $N_{em}=0{,}5N_{nom}$; row 2 is $N_{em}=0{,}75N_{nom}$; row 3 is $N_{em}=N_{nom}$; row 4 is the regular transmission; *a* is the dry turfy loam; *b* is the tillage on the loam; *c* is the wet earth road on the loam



a

b

c

Fig. 7. Dependence of the time of the turning at 90° on the type of terrain and a gear number for electromechanical TM with two electromotors: row 1 is $N_{em}=0{,}125N_{nom}$; row 2 is $N_{em}=0{,}2N_{nom}$; row 3 is $N_{em}=0{,}25N_{nom}$; row 4 is $N_{em}=0{,}3N_{nom}$; row 5 is the regular transmission; *a* is the dry turfy loam; *b* is the tillage on the loam; *c* is the wet earth road on the loam

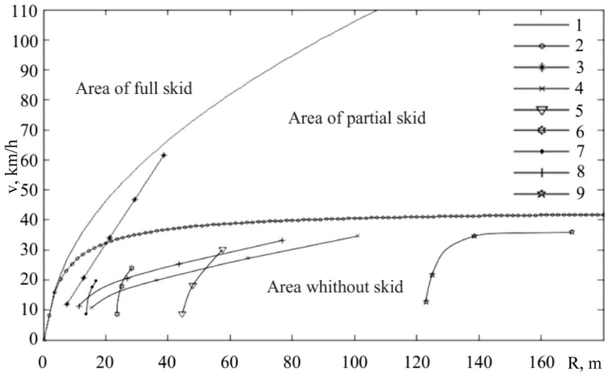


Fig. 8. Dependence of speed on the turning radius for the dry turfy loam

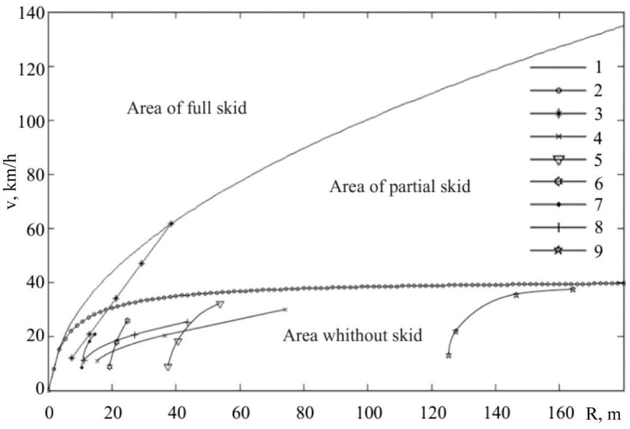


Fig. 9. Dependence of speed on the turning radius for the dry earth road on the loam

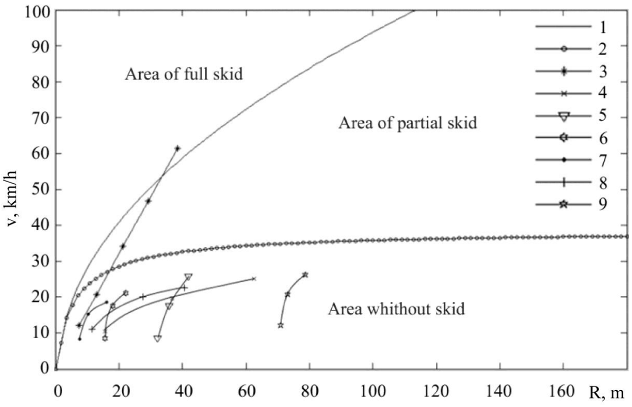


Fig. 10. Dependence of speed on the turning radius for the tillage on the loam

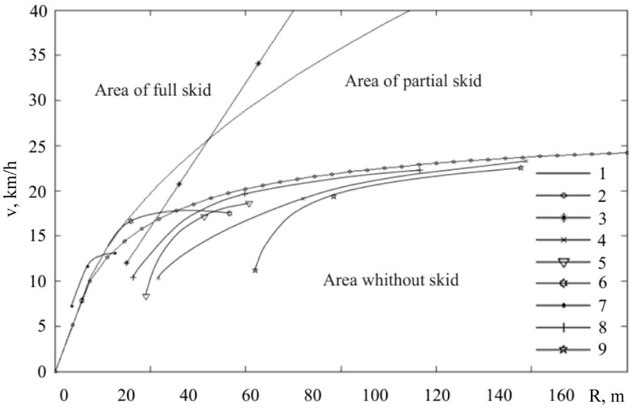


Fig. 11. Dependence of speed on the turning radius for the wet earth road on the loam

When applying a scheme of electromechanical TM with two electromotors that work only or predominantly in the brake mode, the turning radii are similar to the regular mechanical TM, which is why they are not separately represented in the diagrams.

Fig. 12 presents dependencies of the amount of mechanical energy of the lagging edge, which the scheme with electromechanical TM with two electromotors that work only or predominantly in the brake mode can return in one entry of the vehicle into the turning to the board network taking into account the converter efficiency.

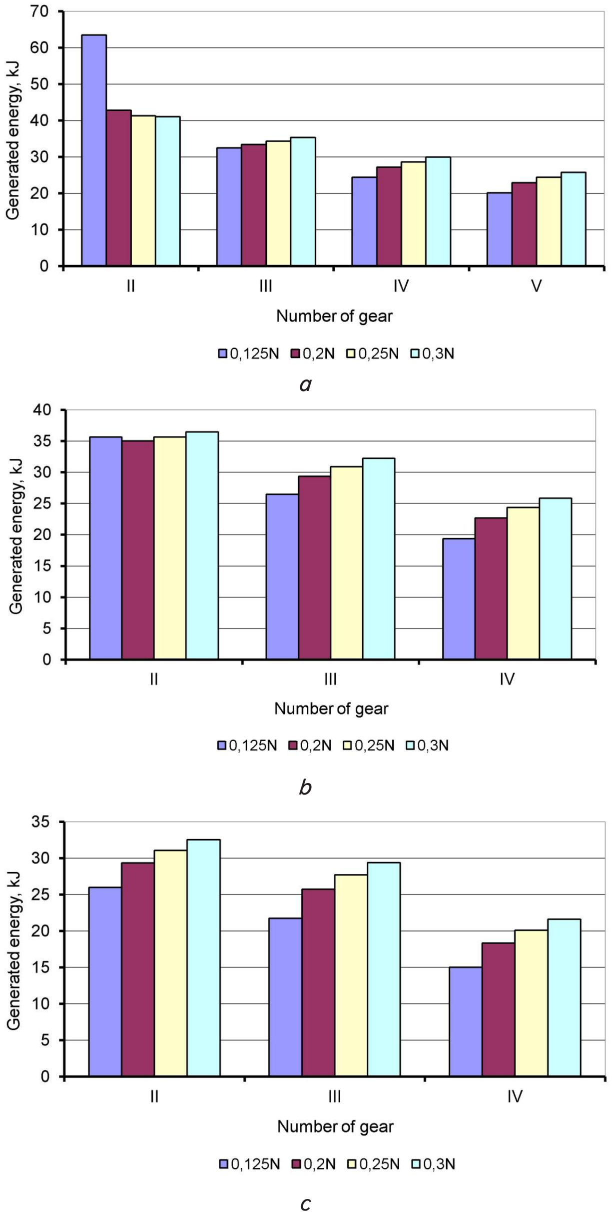


Fig. 12. Dependence of the energy, returned to board network at the entry into the turning with a fixed radius, on the type of terrain and a gear number for electromechanical TM with two electromotors: *a* is the dry turfy loam; *b* is the tillage on the loam; *c* is the wet earth road on the loam

For the identification of the developed mathematical model, we carried out a comparison of the results of the tested tractor MTLB in 1984 with the results of calculations according to the proposed model. With this aim, the initial data were entered into the mathematical model, which correspond to the vehicle and conditions of conducting the tests. The magnitude of divergence in the real turning radii on the sod loam amounted to 3,3 % in higher gears to 9,6 % in second gear.

6. Discussion of the results of comparative analysis of the steerability of tracked vehicles with mechanical and electromechanical dual-flux mechanisms of the turning

It follows from the analysis of the obtained results that although for a regular transmission, the theoretical dependencies of speed on the turning radius exceed on all soils the boundary of partial skid and on some soils – the boundary of full skid, the real turning radii, given skidding and slipping of tracks for a regular TM, are located in the zone of full steerability.

There is also noticeable reserve for many soils between the real turning radii for a regular TM and the boundary of partial skid, which indicates a capacity for realization of more intensive turning by this vehicle by the criterion of skid. An increase in the intensity of the turning in mechanical TM is possible to attain by the decrease of gear ratios of mechanical branch or by the installation of electromechanical TM with the counter-rotation of the sun gears of the summing planetary gear sets of the opposite drives.

However, the represented results show that for a modernized tractor with the weight of 12,5 tons, the power of a standard engine is not sufficient for the turning retaining the speed, which the scheme with electromechanical TM with one electromotor must provide. This scheme not only requires to use the electromotor with power exceeding 40 kW, but also to increase the power of the main diesel engine. An increase in the power of the main diesel engine is necessary to provide a larger power of the mechanical branch in MTG to keep the balance with the more intensive turning and feeding more powerful generator to maintain the operation of powerful electromotor. The calculations showed that the power of the main diesel engine for the studied vehicle must be in this case exceed 220 kW (300 hp).

The variant of installation an electromechanical TM with two electromotors to the tractor is possible in two designs:

– electromotors work in both the traction and the brake modes, in this case mechanical branches of regular MP with their friction clutches do not preserve;

– electromotors work in the brake mode while maintaining mechanical branches of regular TM.

The first design, in comparison to a single-engine scheme, requires two electromotors with their power exceeding 30–35 kW each, but in this case there appears a possibility to move briefly, including rectilinearly by electric drive and to accelerated at any gear due to the addition of the powers of the main diesel engine and two electromotors. However, this will require a considerable increase in the storage capacity. The use of the same electromotors in the mode of the motion at low speeds is possible in this case as a generator.

The second design requires minimum changes in the regular transmission of a tractor and it actually substitutes stopping brakes in TM by electrodynamic brakes. In this case mechanical branches in TM remain completely and help to ensure the turning under extra heavy conditions or on case of failure of the electric system of control of electromechanical TM. The required power of electromotors, installed in this case, is within the range of 10…15 kW. The returned mechanical power without taking into account the efficiency of conversion at the entry point in the turning with a fixed radius depending on the soil and the mode of motion, is from 8 % to 52 % of the power, necessary for maintaining the rectilinear motion in this mode. Lower values correspond to high speeds and heavier soils, and larger values – to the lower speeds and lighter soils of those examined in this work.

7. Conclusions

Numerical simulation and comparative analysis of the curvilinear motion of the tracked vehicles with the dual-flux mechanical and electromechanical mechanisms of the turning displayed the following.

The magnitude of divergence in the real turning radii on the sod loam for the results, obtained at the numerical simulation and in the field testing, reached from 3,3 % in high gears to 9,6 % in second gear.

The use of a scheme with one electric motor and counter-rotation of the sun gears of the summing planetary gear sets makes it possible to obtain relatively lower values of the required power of electromotor; however, it does not give the possibility to use an electromotor in the generator mode and it will require installing more powerful generator and accumulator to the vehicle during modernization. Furthermore, the turning, ensured by this scheme and retaining the speed of the motion, overloads the main diesel engine and it can be recommended only with an increase in power up to 220 kW (300 hp), which corresponds to an increase in the specific power up to 17,6 kW/t (24 hp/t).

When conducting simple modernization, it is expedient to use the scheme with two electromotors whose work includes a traction mode. This is due to the fact that in this case, for retaining turnability at a regular level, it will be required to install electromotors with the power of 30–35 kW per one drive.

The application of the scheme with two electromotors that work predominantly in the generator mode will require retention of the mechanical branches of the mechanisms of the turning. This will make it possible to obtain easily controlled smooth change in the turning radii from free to fixed, retaining the turning dynamics with the use of two electromotors with power of up to 15 kW each. In this case, a required increase in the storage capacity will not be needed and the installed electromotors will completely replace regular generator with power of 4,2 kW, having freed this power to add to the transmission.

With an increase in the specific power up to 17,6 kW/t (24 hp/t), the decrease of gear ratios in the branches of the turning mechanism from 2,6 to 2 will make it possible to increase the turnability of a vehicle by 11–15 % even without introduction of an electric drive to the turning mechanisms.

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