STUDY OF THE TURNING PROCESS OF THE BRIDGE TYPE MACHINES / *ДОСЛІДЖЕННЯ ПРОЦЕСУ СИЛОВОГО (БОРТОВОГО) ПОВОРОТУ МОСТОВИХ МАШИН*

Volodymyr BULGAKOV[1)], **Semjons IVANOVS**[2)], **Volodymyr KUVACHOV**[3)],
Valerii ADAMCHUK[4)], **Viktor KAMINSKIY**[5)]

[1)] Department of Mechanics, Faculty of Construction and Design, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine
[2)]Faculty of Engineering, Latvia University of Life Sciences and Technologies, Jelgava / Latvia
[3)]Department of Machine-Using in Agriculture, Dmytro Motornyi Tavria State Agrotechnological University, Melitopol / Ukraine
[4)]Institute of Mechanics and Automation of Agricultural Production of the National Academy of Agrarian Sciences of Ukraine, Kyiv / Ukraine
[5)]National Scientific Centre, Institute of Agriculture of NAAS of Ukraine, Kyiv Region / Ukraine

E-mail: semjons@apollo.lv
DOI: https://doi.org/10.35633/inmateh-70-23

Keywords: *agricultural wide span vehicle (gantry), controlled traffic farming, side turn, power, research.*

ABSTRACT

One of the ways to improve the manoeuvrability of wheeled axle machines when they move along the tracks of a constant technological track is the use of onboard turning. This simplifies the layout, increases the useful volume of the machine due to the release of niches in the machine body, necessary for placing the steering wheels when turning. However, the question of the efficiency of onboard turning of axle machines by the criterion of power input remains insufficiently studied. The aim of the research is to substantiate the criterion of the power required to implement on-board turns of an overhead machine. Theoretical research, synthesis of design schemes, parameters and modes of operation of bridge machines have been carried out by simulating on a personal computer the conditions of their functioning. The basics of theoretical mechanics and tractor theory were the basis of the research methods. As a result of the research, it has been established that power (onboard) turning is widely used for wheeled machines and has a prospect of application on bridge machines used in the track farming system. Approbation of the developed methodology of determining power inputs for power (onboard) turning of wheeled axle machines has shown that under the accepted conditions of turning the power required for turning of the axle machine is 28% of the engine power at a speed of 5 km·h^{-1}. As the gauge of the bridge machine increases, the total power required for the power (onboard) turn increases exponentially.

АНОТАЦІЯ

Одним із шляхів підвищення маневреності колісних мостових машин при їх русі по слідах постійної технологічної колії є використання бортового повороту. Це спрощує компоновку, збільшує корисний об'єм машини за рахунок звільнення в корпусі машини ніш, необхідних для розміщення рульових коліс при поворотах. Проте залишається недостатньо вивченим питання ефективності бортового повороту мостових машин за критерієм енергоспоживання. Метою дослідження є обґрунтування критерію потужності, необхідної для здійснення бортових поворотів мостової машини. Теоретичні дослідження, синтез розрахункових схем, параметрів і режимів роботи мостових машин здійснено шляхом моделювання на персональному комп'ютері умов їх функціонування. В основу методів дослідження покладені основи теоретичної механіки та теорії трактора. В результаті проведених досліджень встановлено, що силовий (бортовий) поворот широко використовується для колісних машин і має перспективу застосування на мостових машинах, які використовуються в системі колійного землеробства. Апробація розробленої методики визначення енергозатрат на силовий (бортовий) поворот колісних буксових машин показала, що за прийнятих умов повороту потужність, необхідна для повороту мостової машини, становить 28% потужності її двигуна на швидкості 5 км·год$^{-1}$. Зі збільшенням ширини колії мостової машини загальна потужність, необхідна для силового (бортового) повороту, зростає експоненціально.

INTRODUCTION

A perspective direction of further development of agriculture in the world is the introduction of innovative technologies, which should include the tracked farming system (*Pedersen H.H. et al., 2016*; *Chamen W.C.T. 2013; Onal I. 2012; Thomsen M. et al., 2018*). The effectiveness of the practical implementation of this farming strategy is determined by the use of a new power tool in the form of the so-called «wide span vehicle» (gantry) (*Pedersen H.H. et al., 2016*; *Chamen W.C.T. 2013; Onal I. 2012*).

Bridge machines for Controlled traffic farming (CTF) should be equipped with a wheeled propeller, which should be considered the most acceptable. The use of tracked or other type of propulsion for driving on the tracks of a permanent technological track is not appropriate.

The theory of movement and controllability of wheeled traction-transport machines is sufficiently studied (*Nadykto V. et al., 2015; Bulgakov V. et al., 2022; Bulgakov V. et al., 2020; Ivanovs S. et al., 2020; Bulgakov V. et al., 2018; Ivanovs S. et al., 2018; Bulgakov V. et al., 2016; Szakács T., 2010; Bulgakov V. et al., 2021; Fashutdinov M. et al., 2020; Panchenko, A., 2015*). The operation of any wheeled machine takes place under conditions of a large number of disturbing factors (forces and their moments) that change the position of the machine in space and deviate its movement from the specified trajectory. Constant monitoring and intervention by the operator is required to keep the axle-wheeled machine within the trace of a constant tramline.

The steering of most modern wheeled machines is adapted to manual steering and is based on the kinematic or power steering principle (*Nadykto V. et al., 2015; Bulgakov V. et al., 2022*; *Demšar I. et al., 2012; Bulgakov V. et al., 2020; Ivanovs S. et al., 2020; Bulgakov V. et al., 2018; Ivanovs S. et al., 2018; Bulgakov V. et al., 2016; Bulgakov V. et al., 2021*). Kinematic steering involves turning the steered wheels (front, rear or both front and rear) relative to the carcass or changing the position of one part of the mobile machine relative to the other in the horizontal plane (articulated frame). Power (onboard) turning is realized by rotation of wheels of different sides of the machine with different speed.

The use of onboard (power) turning on an axle machine is the simplest solution technically in terms of simplicity of the chassis and steering drive (*Zhao D. et al., 2020; Bulgakov V. et al., 2015; Bulgakov V. et al., 2017)*. With this method of turning the bridge machine, its motor wheels are mounted on two unguided axles, and its turning in the horizontal plane is performed by different rotation frequency of front and rear wheels of the right and left side.

It is also known that the use of onboard turning on a wheeled vehicle, is one of the ways to improve its manoeuvrability. This simplifies the layout, increases the useful volume of the machine due to the release of niches in the body of the machine required to place the steerable wheels when turning. However, the disadvantage of this turning method is increased tire wear and increased power required to turn the wheeled machine.

Many scientists have considered the issues of controlling vehicles with non-swivel wheels and power (onboard) steering (*Bulgakov V. et al., 2015; Bulgakov V. et al., 2017; Kazachenko G., 1982; Kolesnikovich A., 2019; Gurudatta M. et al., 2018; Zhuravel D. et al., 2022).* Today, onboard steering is widely used in military vehicles, such as armoured vehicles and armoured personnel carriers (Fig. 1a), amphibious all-terrain vehicles (figures 1b and 1c), as well as various small loaders (Fig. 1d) and overhead vehicles (Fig. 1e) (*Kazachenko G., 1982; Kolesnikovich A., 2019; https://www.army-technology; http://www.atv-quad.org; https://pmto-agrosoyuz.com.ua)*.

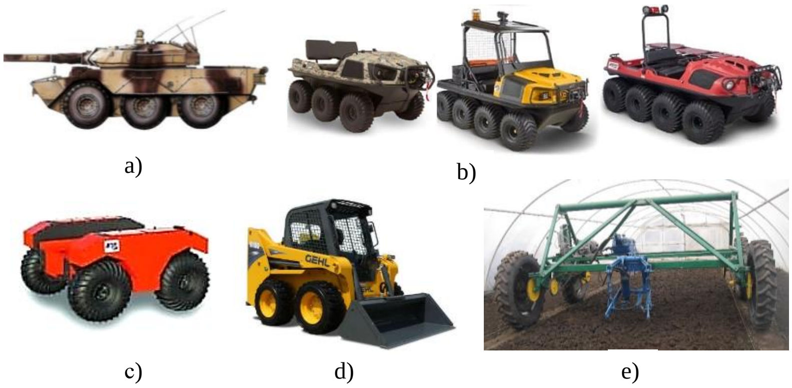

Fig. 1 – Wheeled machines with non-swivel wheels and power steering
a – armoured vehicles and armoured personnel carriers; b – amphibious all-terrain vehicles ARGO; c – amphibious all-terrain vehicle; d – small loader; e – overhead vehicles

Scientists' studies of power (onboard) turning of traction vehicles have shown that the manoeuvrability of a wheeled machine depends on the ratio of its base and track dimensions $L \cdot B^{-1}$, where L – machine base, B – machine track, the number and location of axles on the base, specific power, and other factors (*Bulgakov V. et al., 2015; Bulgakov V. et al., 2017; Kazachenko G., 1982; Kolesnikovich A., 2019; Song P. et al., 2014)*.

However, the issue of the efficiency of on-board turning of bridge machines by the criterion of power input remains insufficiently studied.

The purpose of the research is to determine the variation of forces and power required for turning with constructive and operating parameters of the running system, for machines equipped with non-pivotal wheels.

MATERIALS AND METHODS

The objects of the study are vehicles with onboard turning: AMX-10RC armoured vehicle (*https://www.army-technology*), ARGO amphibious all-terrain vehicle (*http://www.atv-quad.org*), GEHL R150 small loader (*https://pmto-agrosoyuz.com.ua*), vehicles with onboard turning (*Kazachenko G., 1982; Kolesnikovich A., 2019)*, an overhead vehicle of our design (*Bulgakov V. et al., 2018*).

As a physical model to analyse the power consumption for turning, a prototype of an overhead vehicle was used (Fig. 1e) (*Bulgakov V. et al., 2018*). This problem was solved using a PC and Mathcad software.

Theoretical studies, synthesis of design schemes, parameters and modes of operation of bridge machines were carried out by modeling on a personal computer the conditions of their functioning. The basics of theoretical mechanics and tractor theory were the basis of the research methods.

Based on the technical characteristics of the wheeled vehicles with onboard turning, taken as objects of research, the dependence of their estimated parameters obtained experimentally was plotted (Fig. 2).

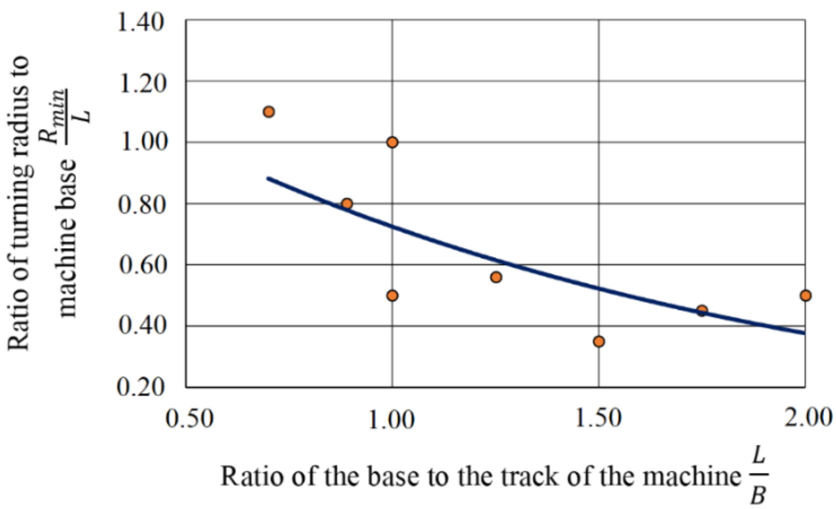

Fig. 2 – Estimation of the relationship between the constructive parameters of the running system and those of turning for wheeled machines

R_{min} – minimum turning radius of a wheeled vehicle; L – wheelbase of the machine; B – machine track

Analysing the curve shown in Fig. 2, it follows that for the considered wheeled machines with a sideways turn their minimum turning radius R_{min} depends considerably on the base *L* and the track width B.

This is especially relevant for overhead machines in the tracked farming system. Since it is known that increasing the track width of axle machines improves land use, i.e. increases the ratio of the area of the agricultural zone of the field to the total area of the land plot.

However, increasing the turning radius will require a proportional increase in the engineering area of the field on the turning lane, which reduces the productive part of the field. At the same time, the power consumption for turning the bridge machine will also increase.

To analyse the power consumption for turning the bridge machine, let's make a computational scheme of forces acting on it (Fig. 3).

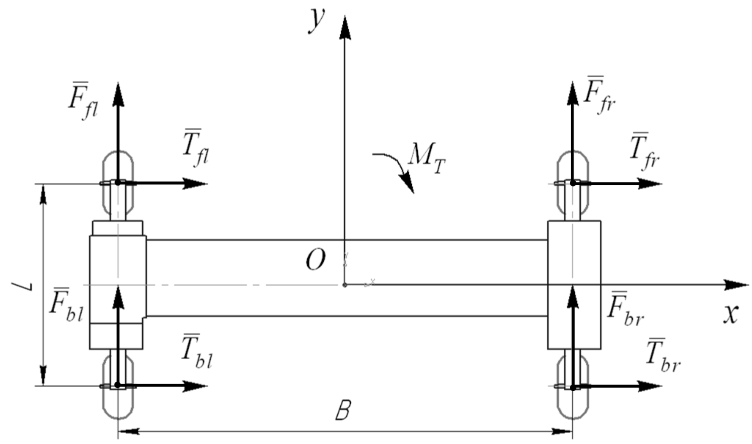

Fig. 3 – Forces acting on a machine when making a turn

xOy – is the system of fixed coordinates; F_{fr}, F_{br} – tangential forces applied to the front and rear wheels of the left side of the bridge machine; F_{fl}, F_{bl} – tangential forces applied to the front and rear wheels of the left side of the bridge machine; B – bridge track gauge; L – wheelbase of the machine; M_T – turning moment of the bridge machine

Power N_T, spent to make an overhead machine turn can be calculated as the product of multiplying the known turning moment M_T at the rate of turn ($d\varphi/dt$):

$$N_T = M_T \cdot \frac{d\varphi}{dt} \tag{1}$$

where:

M_T – moment of rotation of an overhead machine (N·m);

$d\varphi/dt$ – turning speed of the overhead machine (s^{-1}).

The rectilinear motion of the bridge machine along the traces of the constant tramline is preserved when:

– there is absence of disturbing forces and moments acting on the bridge machine;

– there is equality of the sum of the leading moments wheels of the overhead machine right and left sides;

– there is identity of the dimensions and elastic characteristics of the wheels of the bridge machine and the supporting surface of the traces of a permanent technological track in the area of its interaction with the wheel.

Violation of any of these conditions leads to the appearance of the moment of forces in the horizontal plane:

$$M_T = \frac{B}{2} \cdot \left(F_{fr} + F_{br} - F_{fl} - F_{bl}\right) \neq 0 \tag{2}$$

where:

B – track width of the overhead machine;

F_{fr}, F_{br} – tangential forces applied to the front and rear wheels of the right side of the overhead machine;

F_{fl}, F_{bl} – tangential forces applied to the front and rear wheels of the left side of the overhead machine.

Resistance to rotation of the bridge machine is caused by the moment of lateral forces T of interaction of the wheels with the supporting surface M_S, which can be considered the stabilizing moment and the moment of inertial forces M_J:

$$M_T = M_S + M_J = \frac{L}{2} \cdot \left(T_{fr} + T_{fl} - T_{br} - T_{bl}\right) + J_M \cdot \frac{d_2\varphi}{dt^2} \tag{3}$$

where:

T_{fr}, T_{br} – side forces applied to the front and rear wheels of the right side of the overhead machine;

T_{fl}, T_{bl} – side forces applied to the front and rear wheels of the left side of the overhead machine.

J_M – moment of inertia of the machine in the horizontal plane;

$d^2\varphi/dt^2$ – angular acceleration of the machine in the horizontal plane, which takes place at the entrance to the turn and exit from the turn and is equal to zero at the steady-state turn, i.e. at the turn with a constant radius.

For mathematical description of side interaction of the wheeled machine with the supporting soil surface, the "side input" hypothesis in linear interpretation is most often used (*Bulgakov V. et al., 2018; Ivanovs S. et al., 2018; Bulgakov V. et al., 2016*). In this case, to determine side horizontal forces at the points of contact between the wheels and the ground, the resistance coefficients to side departure of tires are used:

$$T_{fr} = k_{fr} \cdot \delta_{fr}$$

$$T_{fl} = k_{fl} \cdot \delta_{fl} \tag{4}$$

$$T_{br} = k_{br} \cdot \delta_{br}$$

$$T_{bl} = k_{bl} \cdot \delta_{bl}$$

where:

k_{fr}, k_{fl}, k_{br} and k_{bl} – coefficients of resistance to wheel entry of the left and right sides of the overhead machine, respectively;

δ_{fr}, δ_{fl}, δ_{br} and δ_{bl} – left and right wheel angles of the overhead machine.

RESULTS

It is known that the coefficients of k_{fr}, k_{fl} and k_{br}, k_{bl} of the resistance to wheel escape of machines depend on the ratio of the following parameters (*Bulgakov V. et al., 2018*):

$$\frac{h}{D_0} = 0.42 \cdot \frac{Q}{p_w \cdot D_0^2} \cdot \sqrt{\frac{D_0}{b_0}} \tag{5}$$

where:

h – is the depth of the footprint formed by the machine wheel in the soil;

D_0 – static tire diameter of the machine wheel;

b_0 – tire width of the machine wheel;

p_w – air pressure in the tire of the machine wheel;

Q – vertical load on the tire of the machine wheel.

At the physical object of research under consideration, which is an overhead machine, tires of size 9.5R32 were used, for which D_0 = 1.245 m and b_0 = 0.241 m. Taking into account the parameters of the indicated tires, the ratio h/D_0 < 0.0885, so, the coefficients of resistance to tire deflection in the process of mathematical modeling, k_i, were calculated according to this dependence:

$$k_i = 60 \cdot \rho_w \cdot {b_0}^2 \left[1.75 \cdot \left(\frac{h}{D_0}\right) - 12.27 \cdot \left(\frac{h}{D_0}\right)^2\right] \tag{6}$$

Taking into account values of air pressure in tires of the overhead machine p_w within 0.14...0.16 kPa, the value of its tire deflection coefficients by expression (6) became 25.6…27.0 kN·rad^{-1}.

When calculating the power required to turn the bridge machine coefficient of traction of its wheels with the bearing surface of the tracks of a constant technological track was taken equal to 0.6, and the speed of movement 5 km·h^{-1}.

The result of calculating the power consumption for the implementation of onboard turning of the bridge machine from the width of its track is shown in Fig. 4.

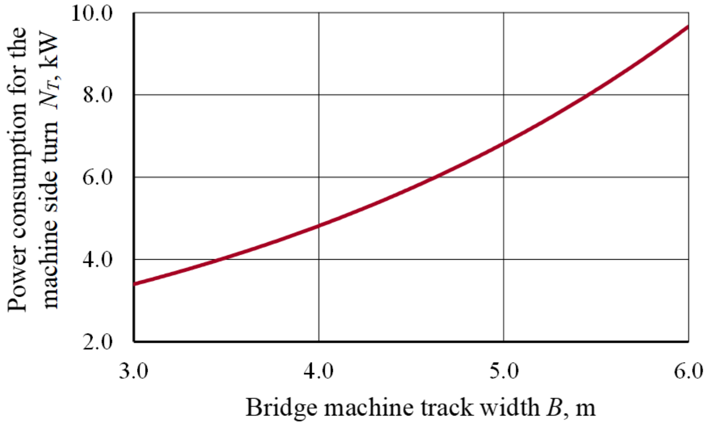

Fig. 4 – The influence of the track width of a vehicle on the traction power during the turn
N_T – power expended on the implementation of the turn of the bridge machine; B – machine track

Analysis of Fig. 4 shows that with increasing the track width of the bridge machine by 2 times, the total power, spent on the power (onboard) turn at the specified parameters, increases exponentially. It can be explained by the fact that with increasing the track width of the bridge machine its mass increases, which increases the moment of inertia JM according to expression (3), the parameters of its wheels also increase, resulting in an increase in the drag coefficients according to (6). Specific power consumption for turning of the bridge machine is at least 28% of the total power of its power plants and essentially depends on the speed of its turning.

CONCLUSIONS

Power (onboard) turning is widely used in wheeled machines and has a prospect of application on bridge machines used in the track system of farming.

Testing of the developed methodology of determining power consumption for power (onboard) turning of wheeled axle machines has shown that under the accepted turning conditions the power required for turning of the axle machine is 28% of the engine power at speed 5 $km \cdot h^{-1}$.

As the track width of an overhead machine increases, the total power spent on the power (onboard) turn increases exponentially. Therefore, from the point of view of reducing energy costs for operation of bridge machines, only their optimal parameters (track width, base, weight, wheel tire parameters, as well as driving mode on the turn) will allow to have minimum power consumption, spent by them for making power (onboard) turn.

REFERENCES

[1] AMX 10RC *Wheeled Armoured Reconnaisance Vehicle* (2008). France. https://www.army-technology.com/projects/amx/.

[2] Bulgakov V., Aboltins A., Beloev H., Ruzhylo Z., Ivanovs S. (2022). Theoretical Investigation of Selection (Calculation) of Design Parameters of Modular Draft Device in Aggregation of Semitrailers. *Applied Sciences*, Switzerland, 12(20), 10267.

[3] Bulgakov V., Aboltins A., Ivanovs S., Nadykto V., Beloev H. (2020). A mathematical model of plane-parallel movement of the tractor aggregate modular type. *Agriculture, Switzerland*, 10(10). 1–22, 454.

[4] Bulgakov V., Adamchuk V., Kuvachov V., Ivanovs S. (2017). Theoretical justification of the turn of a wide span tractor (vehicle) for controlled traffic farming. *INMATEH – Agricultural Engineering*, 53(3), 1–9.

[5] Bulgakov V., Holovach I., Kuvachov V. et al. (2018). Theoretical investigation of a rear-mounted linkage for wide-span tractors. *Mechanization in agriculture & Conserving of the resources*, 1, pp. 11–14.

[6] Bulgakov V., Ivanovs S., Adamchuk V., Nadykto V. (2016). Theoretical investigation of turning ability of machine and tractor aggregate on basis of ploughing and intertilling wheeled tractor. *Engineering for Rural Development*, 2016-January, 1077–1084.

[7] Bulgakov V., Ivanovs S., Kuvachov V., Prysiazhniuk D. (2021). Investigation of the Influence of Permanent Traffic Lane Properties on Rolling of Bridge Agricultural Equipment Wheels. *Acta Technologica Agriculturae*, 24(2), 97–102.

[8] Bulgakov V., Ivanovs S., Nadykto V., Kuvachov V., Masalabov V. (2018) Research on the turning ability of a two-machine aggregate. *INMATEH – Agricultural Engineering*, 54(1), 139–146.
[9] Bulgakov V., Kuvachov V., Nozdrovický L., Smolinskyi S., Ihnatiev Y. (2018). The study of movement of the wide span tractor-based field machine unit with power method of its control. *Acta Technologica Agriculturae*, 21(4), 160–165.
[10] Bulgakov V., Pascuzzi S., Nadykto V., Ivanovs S. (2018). A mathematical model of the plane-parallel movement of an asymmetric machine-and-tractor aggregate. *Agriculture*, Switzerland, 8(10), 151.
[11] Chamen W.C.T. Wide Span CTF. (2013). http://ctfeurope.co.uk/ WhatIs /Wide–Span–CTF.aspx.
[12] Demšar I., Bernik R., Duhovnik J. (2012). A mathematical model and numerical simulation of the static stability of a tractor. *Agriculturae Conspectus Scientificus*, 77 (3). 143–150.
[13] Fashutdinov Marat, Khafizov Kamil, Galiev Ilgiz, Gabdrafikov Fanil and Khaliullin Farit (2020). Research of dynamics of turning of machine-tractor aggregate with tractor on wheeled-crawler mover. *International Scientific-Practical Conference «Agriculture and Food Security: Technology, Innovation*, Markets, Human Resources» (FIES 2019). 17. 00056.
[14] Gurudatta M. Anche, Velmurugan M.A., Arun Kumar S., Shankar C. (2018). Subramanian Model Based Compensator Design for Pitch Plane Stability of a Farm Tractor with Implement. *IFAC-PapersOnLine*. Vol. 51. Issue 1. 208–213.
[15] Ivanovs S., Bulgakov V., Nadykto V., Kuvachov V. (2018). Theoretical investigation of turning ability of two-machine sowing aggregate. *Engineering for Rural Development*, 17, 314–322.
[16] Ivanovs S., Bulgakov V., Nadykto V., Smolinskyi S., Kiernicki Z. (2020). Experimental study of the movement controllability of a machine-and-tractor aggregate of the modular type. *INMATEH – Agricultural Engineering*, 61(2), 9–16.
[17] Nadykto V., Arak M., Olt J. (2015). Theoretical research into the frictional slipping of wheel-type undercarriage taking into account the limitation of their impact on the soil. *Agronomy Research*, 13(1), 148–157.
[18] Onal I. (2012). Controlled traffic farming and wide span tractors. *Agricultural Machinery Science*, 8(4), 353–364.
[19] Panchenko, A.; Voloshina, A.; Milaeva, I.; Luzan, P. (2019). Operating conditions' influence on the change of functional characteristics for mechatronic systems with orbital hydraulic motors. Modern Development Paths of Agricultural Production: *Trends and Innovations*. 169-176. DOI: 10.1007/978-3-030-14918-5_18.
[20] Pedersen H.H., Oudshoorn F.W., McPhee J.E. (2016) Wide span–re-mechanising vegetable production. *XXIX International horticultural congress on horticulture: sustaining lives, livelihoods and landscapes: international symposia on the physiology of perennial fruit crops and production systems and mechanisation, precision horticulture and robotics Book Series: Acta Horticulturae*, 1130, 551–557.
[21] Song P., Zong C.-F., Tomizuka M. (2014). A terminal sliding mode based torque distribution control for an individual-wheel-drive vehicle. *Journal of Zhejiang University*: Science A. 15 (9), 681-693.
[22] Szakács T. (2010). Developing stability control theories for agricultural transport systems. *Acta Polytechnica Hungarica*, 7 (2), 25–37.
[23] Thomsen Maria Nygård, Tamirat Tseganesh, Pedersen Søren Marcus et al. (2018) Farmers perception of Controlled Traffic Farming (CTF) and associated technologies. *IFRO working paper*. 2018/12.
[24] Zhao Ding, Yaoming Li, Zhong Tang (2020). Theoretical Model for Prediction of Turning Resistance of Tracked Vehicle on Soft Terrain. *Mathematical Problems in Engineering*. 1–9.
[25] Zhuravel D., Samoichuk K., Petrychenko S. et al. (2022). Modeling of Diesel Engine Fuel Systems Reliability When Operating on Biofuels. *Energies*. 15(5). 1795. DOI: 10.3390/en15051795.
[26] Kazachenko G.V. (1982). *The study of the rotation of wheeled vehicles with an onboard control scheme: abstract of the dissertation of a candidate of technical sciences*. Belarus, 21 p.
[27] Kolesnikovich A. N., Vygonny A. G., Goncharko A. A. (2019). Analysis of the use of skid steer of wheeled vehicles, Belarus, Working Paper. https://rep.bntu.by/bitstream/handle/data/60329/64-69.pdf?sequence=1&isAllowed=y.
[28] ***http://www.atv-quad.org/de/fahrzeuge/argo_amphibienfahrzeuge/.
[29] ***https://pmto-agrosoyuz.com.ua/ua/p679231165-mini-pogruzchik-bortovym.html