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A THEORETICAL AND EXPERIMENTAL STUDY OF THE TRACTION PROPERTIES OF AGRICULTURAL GANTRY SYSTEMS

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ABSTRACT. The movement conditions experienced by an agricultural gantry system along the solid and level ground surface of permanent artificial tracks must make it possible to generate most of its maximum tractive force. Concurrently, the adhesive ability of the agricultural gantry system on the ground surface of such permanent artificial tracks must be sufficient to generate nominal drawbar pull when working at a certain level of slip. This means that there exists the need to seek out the following compromise: the maximum slippage experienced by the wheeled chassis of an agricultural gantry system must be such that, in a situation in which the level of adhesion with the surface of permanent artificial tracks is suitable, it will be able to generate the maximum possible tractive force. The effect of the parameters that involve an agricultural gantry system's wheels – and the physical and mechanical properties of the ground surface along which they move – on potential slippage has not yet been sufficiently studied. This effect cannot be taken into consideration without taking into account the dynamics of any rolling resistance being offered by the agricultural gantry system's chassis. The purpose of this particular study is to research the traction properties of an agricultural gantry system's wheeled chassis in terms of its movement along compacted and level ground upon which have been mounted permanent artificial tracks. The research determines that the wheels of such an agricultural gantry system that are rolling along permanent artificial tracks suffer less slippage and therefore generate a higher level of tractive force. As a result, the agricultural gantry system loses less of its speed of movement and, therefore, uses less energy in that movement. When an agricultural gantry system moves across an agricultural field that has been prepared for sowing, the research also determines the maximum tractive force that its wheels can develop when the adhesion coefficient is set at a figure that is between 0.22–0.24. Once such movement begins along permanent artificial tracks, this coefficient decreases to between 0.15–0.17. An agricultural gantry system's wheels are able to generate a higher level of tractive force when moving along on permanent artificial tracks. This figure is at least 30% higher when its movement has to be considered across an agricultural field that has been prepared for sowing.

Introduction

The modern agricultural production industry is being characterised by a qualitatively new stage of technological rearming. International scientific publications are providing more and more information about the outlook regarding, and the effectiveness of using, gantry tractors (or agricultural gantry systems) (Webb *et al.*, 2004; Önal, 2012; Pedersen *et al.*, 2013; Antille *et al.*, 2015; Chamen, 2015; Bulgakov *et al.*, 2017; Bulgakov *et al.*, 2018).

The nominal drawbar pull that is generated by a gantry tractor in a situation in which its chassis has sufficient adhesion with a ground surface that is formed by permanent artificial tracks must naturally be higher than that of a traditional tractor even with equal technical parameters being available. In that context, the adhesion ability of the chassis of a gantry tractor to the surface of permanent artificial tracks must be sufficient to generate nominal drawbar pull when working at a certain level of slippage. At the same time, it is already known that a smaller slip coefficient correlates with a lower value for the tractive force that is generated by a tractor.

The conditions under which a gantry tractor that is moving on a compacted level ground surface as formed by permanent artificial tracks must provide for a higher value of maximum tractive force, while for a traditional tractor the maximum tractive force goes into slippage, which significantly increases the level at which it is possible to cause unacceptable damage to the soil environment (Grosch, 1996; Nadykto *et al.*, 2015; Battiato, Diserens, 2017; Czarnecki *et al.*, 2019). This leads to a need to seek out the following compromise: the maximum permitted slippage values for the wheeled chassis of a gantry tractor must be such that it will generate the maximum levels of tractive force under conditions of sufficient adhesive ability with a ground surface that is formed by permanent artificial tracks (Gil-Sierra *et al.*, 2007).

The relevance of the study at hand stems also from the fact that the tractor theory includes no separate discussion of the effect of the wheel's parameters and the ground surface's physical and mechanical properties on any slippage. This effect cannot be considered without accounting for changes in the rolling resistance of the chassis. Such rolling resistance naturally has to be smaller for a gantry tractor that moves along on permanent artificial tracks than it would be for a moving tractor on the soil of an area that has been set aside for crops.

When discussing problems that are related to the development of a scientific basis for using gantry tractors, some researchers have reached the conclusion (Chen *et al.*, 2010; Bulgakov *et al.*, 2019a) that their theory and the relevant technological properties require further development.

The well-known theory regarding the traditional wheeled tractor states that its traction properties largely depend upon the adhesion properties of its driven wheels (Lebedev, 2012; Nadykto, Velychko, 2015; Battiato, Diserens, 2017). The adhesive ability of driven wheels in regards to soil is considered to be the result of two forces: the friction forces between the tyre's support surface and the ground surface (as a rule, this means soil), and the adhesive forces of the tyre's tread lugs (its 'ground-hooking' elements) in the soil (Zoz, Grisso, 2003; Bulgakov *et al.*, 2020). On tracks which have a solid surface, the friction forces have a more prominent role. On soft ground (typical for tractor work), the adhesive forces are more significant. On ground under the wheels which is of intermediate density, the forces of friction and adhesion have nearly equal significance (Bulgakov *et al.*, 2019b).

Multi-year studies (Lebedev, 2012; Nadykto, Velychko, 2014; Nadykto *et al.*, 2015; Adamchuk *et al.*, 2016; Bulgakov *et al.*, 2019b) have shown that, in terms of tractor work on soft ground of the type that is characteristic of almost all agricultural operations, the tread lugs on the wheels tend to penetrate deeply into the soil layer. While they are dug into the soil the tread lugs compress that soil horizontally, in a direction that is opposite to that of the tractor's direction of movement. As a result, the tractor's speed of movement decreases. The relative loss of speed for the tractor is estimated as the slip coefficient (Zoz, Grisso, 2003; Ekinci *et al.*, 2015; Nadykto *et al.*, 2015). The aforementioned horizontal deformation of the soil depends upon the individual pressure that is applied to the soil's elements by the tread lugs of the tyres and on the soil's ability to resist deformation, the latter being closely estimated as the individual deformation coefficient (Guskov, 1996). The value of the individual horizontal pressure is determined by the value and the nature of any change in the tractive force (Wulfsohn, Way, 2009).

In that direction, scientists have not yet carried out sufficient levels of research that could be applied to the conditions under which gantry tractors move on permanent artificial tracks.

The purpose of this research is to study the traction properties of the wheeled chassis of an agricultural gantry system when it moves along on the levelled and compacted ground surface of permanent artificial tracks.

Material and Methods

The theoretical research methods that were used were a determination of the tractive force in various positions. On the one hand, the maximum tractive force P_{kmax} which the wheel of an agricultural gantry system generates is determined by the conditions of its sufficient adhesive ability on a ground surface that is formed by permanent artificial tracks:

$$P_{kmax} = f(\varphi), \tag{1}$$

where φ is the adhesive coefficient, realised by the agricultural gantry system's chassis under the conditions of it interacting with the ground surface.

According to condition Eq. 1, a wheel's adhesive ability must be sufficient for the agricultural gantry system to generate a nominal drawbar pull when working on crop soil with a determined slippage coefficient.

On the other hand, the value of the tractive force P_{kmax}, which is what a wheel of the agricultural gantry system generates, depends upon the normal load being applied to it, as well as on the parameters of the wheel itself, the physical and mechanical properties of the ground surface where that is formed by permanent artificial tracks, and the mode of its movement (the slippage coefficient):

$$P_{kmax} = f(\delta_{max}, f_k, N_{ek}, k_0, r_0, b_0, ...), \quad (2)$$

where δ_{max} is the slip coefficient (that maximum) of the agricultural gantry system's chassis; f_k is the rolling resistance coefficient of the agricultural gantry system's wheel; k_0 is the coefficient of the physical and mechanical properties of the ground surface as formed by permanent artificial tracks; N_{ek} is the vertical operational load applied to the agricultural gantry system's wheel; r_0, b_0 are the static diameter and the static width of the agricultural gantry system's wheel.

Figure 1. An agricultural gantry system with a design that had been developed by us, during the experimental studying of its traction properties

In the course of the experimental studies, the tractive force P_k which was generated by a wheel of the agricultural gantry system (Fig. 1) was assessed as a sum of its two constituent forces – the drawbar pull and the rolling resistance (Macmillan, 2002):

$$P_k = P_h + P_f, \quad (3)$$

where P_h is the drawbar pull force that is generated by a wheel of the agricultural gantry system; and P_f is the rolling resistance that the wheel of the agricultural gantry system must overcome.

The slip coefficient δ of the agricultural gantry system's chassis was determined experimentally from the following expression:

$$\delta = 1 - \frac{n_{k0}}{n_{km}} \cdot \frac{V_m}{V_0}, \quad (4)$$

where n_{k0} and n_{km} are the number of revolutions of the agricultural gantry system's wheel over one and the same track distance whilst proceeding without a load and then whilst in work mode, respectively; V_0 and V_m are the movement speeds for the agricultural gantry system when travelling without a load and when in work mode, respectively.

The research programme proposed a study of the dependence of the traction properties of an agricultural gantry system in regard to the normal load applied to its wheel, and on the wheel's parameters, on the physical and mechanical properties of the ground surface that is formed by the permanent artificial tracks, and on the agricultural gantry system's movement mode (the slip coefficient).

The accuracy of the research results was assessed on the basis of experimental results which were drawn from testing the agricultural gantry system.

Results and Discussion

For the purpose of theoretical studies we shall present as an equivalent diagram the agricultural gantry system as it moves along on the ground surface that is formed by permanent artificial tracks (Fig. 2), showing the forces that are generated by its chassis.

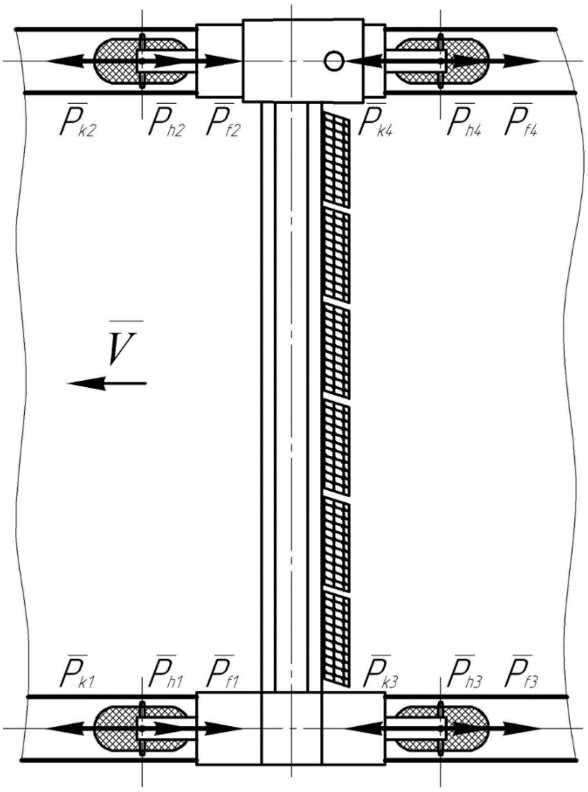

Figure 2. The equivalent diagram showing the agricultural gantry system, moving on permanent artificial tracks

The maximum tractive force that is generated by the gantry tractor's wheel in condition Eq. 2 is expressed as follows:

$$P_{kmax} = \delta_{max} \cdot S_k \cdot k_0 \cdot L, \quad (5)$$

where S_k is the sum of vertical projections of the tread lug surfaces on the agricultural gantry system's wheel that have been plunged into the ground, in m^2; k_o is the coefficient of volume compression of the ground surface (on permanent artificial tracks) (Guskov, 2007), in $N \cdot m^{-3}$; L is the length of the ground surface adhesive arch for the tread lugs on the agricultural gantry system's wheel (on permanent artificial tracks), in metres.

The expression for determining the dimension L is as follows:

$$L = r_k \left(arctan \frac{f_k \cdot (1 - f_k^2)^{\frac{1}{2}}}{0.5 - f_k^2} + 2 \cdot f_k^2 \right), \quad (6)$$

where r_k is the wheel's rolling radius, in metres.

The wheel's rolling radius r_k can be expressed through its static radius r_0 and its tyre's normal sag h_z:

$$r_k = r_0 + h_z \quad (7)$$

The tyre's normal sag is determined from the following expression:

$$h_z = \frac{N_{ek}}{\pi \cdot \rho_w \cdot \sqrt{2r_0 \cdot b_0}}, \quad (8)$$

where ρ_w is the air pressure inside the tyre, in Pa.

The sum S_k of vertical projections of the tread lug surfaces plunged into the ground on the agricultural gantry system's wheel is determined from the following equation (Guskov, 1996):

$$S_k = \pi \cdot h_z \cdot [(2r_0 - h_z) \cdot (b_0 - h_z)]^{\frac{1}{2}} \quad (9)$$

At the same time, the agricultural gantry system's realisation of the tractive power is determined by its adhesive properties. From this it follows that the adhesive ability must be sufficient for the agricultural gantry system's wheel in condition Eq. 1 to generate the maximum tractive force (Guskov, 1996):

$$P_{kmax} = \varphi \cdot N_{ek} \quad (10)$$

Putting the values of S_k, L, r_k from expressions Eqs. 6–9 into expression Eq. 5 and equalising Eqs. 5 and 10, we get:

$$\delta_{max} \cdot \pi \cdot h_z \cdot [(2r_0 - h_z) \cdot (b_0 - h_z)]^{\frac{1}{2}} \cdot k_0 \cdot (r_0 + h_z) \times \left(arctan \frac{f_k \cdot (1 - f_k^2)^{\frac{1}{2}}}{0.5 - f_k^2} + 2 \cdot f_k^2 \right) = \varphi \cdot N_{ek} \quad (11)$$

An analysis of the resulting Eq. 11 indicates that, with an increase of the tractive coefficient φ which is generated by the agricultural gantry system's chassis in its interaction with the ground surface as formed by permanent artificial tracks, the maximum slip coefficient δ_{max} will also increase. With an increase of the wheel's radius r_0, tyre width b_0, and internal air pressure ρ_w, as well as the vertical load N_{ek} applied to it, the tractive coefficient φ of the agricultural gantry system's wheel on the ground surface as formed by permanent artificial tracks will also increase. This leads to the conclusion that the higher the adhesive ability of an agricultural gantry system's wheel on the ground surface as formed by permanent artificial tracks, the higher the levels of slippage that can be achieved in that situation. The nature of that interaction is determined by the agricultural gantry system's parameters, its movement mode, and the properties of the ground surface as formed by permanent artificial tracks.

The resulting mathematical model 11 makes it possible for us to study the dependence of the driving and adhesive properties of an agricultural gantry system on the vertical load that is applied to its wheel, and on the wheel's parameters, and also on the physical and mechanical properties of the ground surface that is formed by permanent artificial tracks, and even on the agricultural gantry system's mode of movement (its slippage coefficient). For this end, we will present the Eq. 11 that resulted from our studies as the dependence of the maximum slip coefficient δ_{max} of the agricultural gantry system's wheel on the indicated parameters:

$$\delta_{max} = \frac{\varphi \cdot N_{ek}}{\pi \cdot h_z \cdot [(2r_0 - h_z) \cdot (b_0 - h_z)]^{\frac{1}{2}} \cdot k_0 \cdot (r_0 + h_z) \times \left(arctan \frac{f_k \cdot (1 - f_k^2)^{\frac{1}{2}}}{0.5 - f_k^2} + 2 \cdot f_k^2 \right)} \quad (12)$$

We will now study the character of the dependence of the slip coefficient δ_{max} of the wheel of an agricultural gantry system, with the design having been developed by u, based upon the value of its tractive coefficient φ when moving on two variants of the ground's surface. According to the first variant, the agricultural gantry system moves on crop soil that corresponds in terms of its condition to those of soil that has been prepared for sowing. In that context, the crop soil's coefficient of resistance to the rolling of the agricultural gantry system is $f_k = 0.15$. According to the second variant, the agricultural gantry system moves on levelled, compacted ground that is formed by permanent artificial tracks. The coefficient of resistance to the rolling of the agricultural gantry system on its permanent artificial tracks is $f_k = 0.05$. The results of the study are presented in Fig. 3.

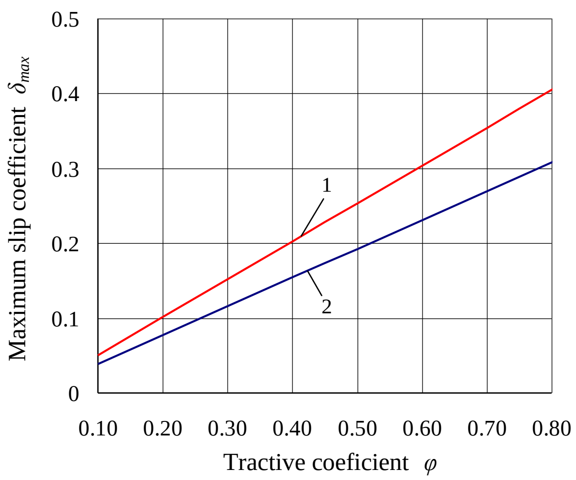

Figure 3. The dependence of the maximum slip coefficient δ_{max} for an agricultural gantry system's wheel on its tractive coefficient φ on the ground's surface: 1) soil that has been prepared for sowing of crop ($f_k = 0.15$); 2) permanent artificial tracks ($f_k = 0.05$)

The analysis of the diagrams shown in Fig. 3 indicates that a decrease of the coefficient f_k of resistance to the rolling of the agricultural gantry system makes it possible to increase the maximum slip coefficient δ_{max} of its wheels. An increase of the latter means a higher maximum tractive force being generated by the gantry tractor under conditions in which sufficient adhesive ability can be applied to the ground's surface, as would result from dependency Eq. 12. For example, with the slip coefficient of an agricultural gantry system's chassis being the same, ie. $\delta_{max} = 0.22$, at which level it applies the maximum tractive force to the crop soil, its tractive coefficient is $\varphi = 0.43$. On permanent artificial tracks this coefficient increases to $\varphi = 0.55$. This means that the movement of an agricultural gantry system on permanent artificial tracks is characterised by better traction properties when compared with its movement on crop soil that has been prepared for sowing.

This result can be explained by the following: the traction properties of an agricultural gantry system when working on porous soil are determined mainly by the soil's ability to resist the horizontal deformation (shift) that is caused by the wheel's tread lugs. Therefore the slippage coefficient of its wheels is determined on the basis of the horizontal deformation (shift) of the soil as caused by the tread lugs. This horizontal deformation of the soil depends upon the individual pressure being applied to the soil's elements by the tread lugs of the tyres and on the soil's ability to resist the resultant deformation, the latter being estimated as the individual deformation coefficient. The phenomenon of slippage itself appears as a result of the tread lugs shifting the soil until contact forces of sufficient strength appear in the soil to resist it. The higher the strength of the soil's ground surface on which the agricultural gantry system's wheel is running, the lower the effect that the slippage has on the connections between the soil's particles. As a result, the depth at which the wheels sink into the ground decreases, correspondingly reducing the energy spent on forming the tracks.

The experimentally-derived dependence of the tractive force on the rolling mode of the agricultural gantry system's wheel provided a rather complex result (Fig. 4).

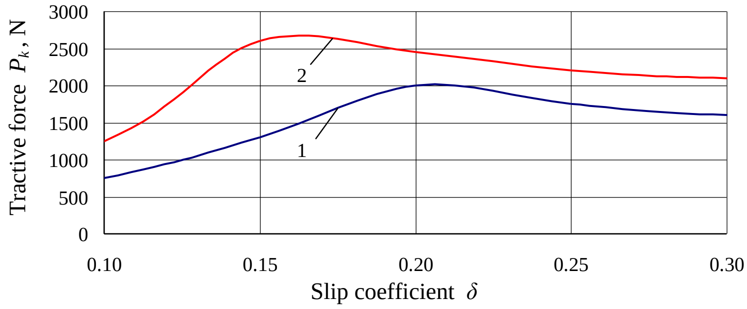

Figure 4. The dependence of the tractive force P_k of an agricultural gantry system's wheel on the slippage coefficient δ_{max} when moving over soil that has been prepared for sowing of crop (1) and on permanent artificial tracks (2)

The graphs in Fig. 4 indicate that, in both variants, the driving force increases until the slippage coefficient reaches a certain value. Thereafter it starts decreasing. The decrease of the driving force upon high slippage values is explained by the process of soil chunks being cut loose, thrust between the tread lugs, and rotating as part of the wheel. As the values for the soil's resistance forces at the time of shifting are less than those for the maximum force when it is at rest, the wheel's driving force is also lower.

The slip coefficient δ_{max} at which a wheel on an agricultural gantry system that has been designed and developed by us applies the maximum tractive force to soil that has been prepared for sowing of crop falls within the range of between 0.22–0.24. Within that context, the value for this force for the agricultural gantry system at hand is 2 kN. When moving along on permanent artificial tracks, the value for the maximum slip coefficient δ_{max} decreases to between 0.15–0.17, while the maximum driving force being generated by the wheel increases to 2.65 kN, i.e. more than 30%.

Conclusions

1. The theoretical and experimental studies that have been carried out indicate that the rolling of the agricultural gantry system's wheel on permanent artificial tracks is accompanied by a lower slippage value, while at the same time the wheel generates a higher tractive force. As a result, the agricultural gantry system loses less of its intended movement speed and uses less energy to reach that speed. It has been determined that, when the agricultural gantry system moves on soil that has been prepared for sowing of crop, the maximum tractive force is generated at the slip coefficient of between 0.22–0.24. When moving on permanent artificial tracks, this value decreases to between 0.15–0.17.
2. The studies that have been carried out indicate that the maximum tractive force being generated by the wheel of an agricultural gantry system is higher when that system is moving on permanent artificial tracks. When compared to moving on soil that has been prepared for sowing of crop, this value is at least 30% higher.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author contributions

VB – study conception and design;
JO – drafting of the manuscript, critical revision and approval of the final manuscript;
VK – analysis and interpretation of data;
SS – acquisition of data.

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