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A THEORETICAL AND EXPERIMENTAL STUDY OF COMBINED AGRICULTURAL GANTRY UNIT WITH A MINERAL FERTILISER SPREADER

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ABSTRACT. Operations to apply mineral fertilisers to the soil are an important part of practically every form of agricultural technology. The current global trend of transitioning to bridge and gantry-type agricultural systems leaves the unanswered relevant question of the effectiveness of the technological process of applying mineral fertilisers to the soil. This is relevant because, in gantry agriculture, a section of the arable soil is separated as an engineering area. This is why the main difference in gantry agriculture from traditional methods of the bulk spreading of fertiliser onto a field is that, with gantry systems, the amount of fertiliser that lands within the engineering zone are limited. This significantly affects the manufacturing costs involved in the entire area of agricultural technology and, as a result, the production costs of the end product. This study aimed to research the patterns that are apparent in affecting the parameters involved in the use of gantry-type equipment when applying fertiliser with the parameters and operational modes of a specially-developed electric spreader of mineral fertilisers. The physical object of the study was the agricultural gantry equipment that had been developed by the authors. This equipment, which is used for spreading fertiliser, was in the form of a tractor-mounted, suspended, single-disc spreader which was known as JarMet, and which had especially been modified to run from an electrical supply. The study indicated that the biggest influence on the speed of rotation of the centrifugal disc in the mineral fertiliser spreader stems from its height above the ground, the distance of track of the agricultural gantry itself, and the aerodynamic coefficient of the fertiliser. It was determined that, for the agricultural gantry with a distance of tracks of 3.5 m, a sufficient angular speed of the single-disc centrifugal tool is 15.5 rad·s^{-1}, with a power demand for driving this at 0.35 kW·h. When using agricultural gantries of this type with an extended track width of up to 6 m, the necessary angular speed of the centrifugal tool for spreading fertiliser increases exponentially, to 318.2 rad·s^{-1}, with the power demand for driving it increasing to the third power.

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Introduction

Operations to apply mineral fertilisers to the soil are an important part of practically every form of agricultural technology. The current global trend of transitioning to gantry-type agricultural systems (Nadykto *et al.*, 1997; Blackwell *et al.*, 2004; Gil-Sierra *et al.*, 2007; Jørgensen, 2012; Bindi *et al.*, 2013; Pedersen *et al.*, 2013; 2016; Chamen, 2015; Bulgakov *et al.*, 2019) leaves unanswered the relevant question of the effectiveness of the technological process involved in applying mineral fertilisers to the soil. This is relevant because, when it comes to gantry agriculture, a section of the arable soil is separated as an engineering area (Webb *et al.*, 2004; Uleksin, 2008; Bochtis *et al.*, 2010[a,b]; Önal, 2012; Antille *et al.*, 2015; Bulgakov *et al.*, 2017; 2018[a,b]; 2020). This area includes the transportation system for moving all items of mechanisation, energy, and water supply, plus communications and navigation equipment. This is why the main difference between gantry agriculture and traditional methods of bulk spreading fertiliser onto a field is that, with gantry systems, the amount of fertiliser that lands within the engineering zone are limited. This advance significantly affects the manufacturing costs involved in the entire area of agricultural technology and, as a result, the production costs of the end product.

Theoretical and experimental studies of centrifugal spreaders have been conducted by many of the world's scientists (Scheufle, Bolwin, 1991; Rainer, 2001; Villette *et al.*, 2005; Adamchuk, 2006; Olt, Heinloo, 2009; Van Liedekerke *et al.*, 2009; Villette *et al.*, 2010). They have studied the effect of the structural design of the discs, their vanes, and other elements of their construction, as well as their parameter and modes of operation, the physical and mechanical properties of the mineral fertiliser and other bulk materials, and the operating conditions for the equipment in terms of working width – in particular the spreading distance – along with the heterogeneity of applying the fertiliser, *etc.* The studies indicated that the biggest influence on the maximum flight distance of mineral fertiliser comes from the speed of rotation of the mineral fertiliser spreader's centrifugal disc, as well as from its height above the ground and the aerodynamic coefficient of the fertiliser (Villette *et al.*, 2008).

It is known that the effectiveness of using mineral fertilisers not only depends upon the fertilisers themselves but also on their manner of application (Adamchuk, 2002). Researchers are currently proposing various ways in which the effectiveness of that technological process can be improved. The world's most popular mechanical fertiliser spreaders are of a type that moves mineral fertilisers from a centralised technological bunker to spread it across the working width of the machine using the mechanical action of its operating elements on the fertiliser itself. More than 90% of the world's mineral fertiliser and chemical application-to-plant machines have disc-based spreader tools. In particular, machines of this type are made by Amazone, Bogballe, Bredal, Kuhn, Maschio, Rauch, Sulky, Titan, Vicon *etc.*

Also, disc-based centrifugal tools are widely used when applying granulated and bowdlerised fertilisers by sowing and planting machines, as well as by cultivators and plant nutrition machines. The latter's design incorporates a disc with vanes (Yasenetsky, Sheychenko, 2002; Dintwa *et al.*, 2004; Villette *et al.*, 2005) on its top surface. The disc itself is attached to a vertical shaft that is installed with the option of rotating it on the horizontal plane and which is connected to the driving mechanism. The operating process for the tool attachment of such a fertiliser spreader involves the fertiliser coming from the technological bunker, having first been grabbed by the vane and then pulled into rotating motion, and being moved along the vanes under centrifugal force towards the disc's edge. When reaching the ends of the vanes, the fertiliser slides off the tool at a certain pre-set speed. Thanks to its acquired kinetic energy reserve, the fertiliser particles overwhelm the aerodynamic resistance of the atmosphere. Thanks to this the fertiliser moves away from the centrifugal tool in a fan formation, along the equipment's working width. Under gravity, the fertiliser reaches the soil's surface, forming a continuous screen.

In the initial stages of the process of creating the machines for spreading mineral fertilisers, their designs incorporated tools with flat disks. The choice of the proper parameters and work modes for their centrifugal tools had an important role in ensuring the effectiveness of such machines.

Recently global manufacturers of machines for applying fertilisers and plant chemicals increased the diameter of the discs in their centrifugal spreader tools to 800 mm and their rotational speed to 1 000 min^{-1}. But any further increase of the tool disc's diameter has certain limits. In particular, the machine's design itself becomes a limitation for the diameter and strength of the mineral fertiliser's granules becomes a limitation for the rotational speed (Adamchuk, 2006). Correspondingly, to increase the machine's working width and to improve the quality of applying the fertiliser, a fertiliser spreader's working tool was created that had a cone-shaped disc with the cone's tip pointed towards the ground. Thanks to such a design in terms of the disc, the machine's working width was increased without increasing the disc's diameter or its rotational speed.

At one point in time, a fertiliser spreader with a centrifugal tool was created in Ukraine, which incorporated the good qualities both of a flat disc and a cone-shaped disc (Adamchuk, 2006). With that tool, the angle of the vanes was adjustable both on the plane of the horizontal disc in a vertical plane and along the radius of the disc on the horizontal plane. This design for the tool ensures an increase of the working width when it comes to applying mineral fertilisers, to 33 m, when compared with its analogues.

But this paper will not be discussing the advantages of these or other methods and technical means when it comes to applying mineral fertiliser by way of spreading. The authors discuss the problem of fertiliser spread in an agricultural gantry, which states that the possibility of mineral fertilisers landing within the engineering zone of the field is something that must be prevented, *i.e.* a particle of mineral fertiliser which has been distributed using the centrifugal disc tool at the required speed must perform free flight through the atmosphere and land on the surface of the arable (crop-bearing) area of the field without reaching the transport tracks within the field's engineering area.

The study aimed to research patterns when it comes to affecting the parameters of the tractor equipment in terms of applying fertiliser, and proper functioning using the principles of gantry-type equipment, with the parameters and operation modes of a specially-developed electric spreader of mineral fertilisers being taken into account.

Materials and methods

This theoretical study and the synthesis of design diagrams and parameters for an agricultural gantry system which will successfully apply mineral fertilisers to the soil were carried out using software-based modelling on a PC of its functioning conditions.

The physical object of the study was the agricultural gantry unit that had been developed by the authors Bulgakov *et al.* (2017).

For the experimental studies, a tractor-mounted, hanging, single-disc spreader of the Jar Met type was specially reconstructed to be driven by an electric motor, *i.e.* it was remodelled into being an electric spreader of mineral fertilisers, fully modelling the power take-off shaft from the tractor's front axle (Fig. 1a). For that end, an electric motor with a gearbox was placed under the disc-type fertiliser spreader. The rotational speed for the electric motor's shaft was electronically regulated (a frequency modulator) (Fig. 2). The parameters for the electrical current were documented using a measuring set of the K-505 type, which consisted of a portable unit that had been intended for measuring the current's strength, direction, and power in single-phase and three-phase AC circuits with three and four conductors during equal and unequal loading of the phases.

To prevent the mineral fertiliser from landing within the engineering area's track zone, the agricultural gantry unit was supplied with special screens on its left-hand and right-hand sides (Fig. 1b). The suspended technical system for the agricultural gantry unit is a serial-produced suspended mechanism that comes from a traditional tractor with a main hydraulic cylinder, and bottom and top rigidity elements. With its suspended system, the indicated mineral fertiliser spreader was connected to the elements of the agricultural gantry's suspended mechanism.

When conducting the experimental studies using the combined tractor and the mineral fertiliser spreader in an agricultural gantry system, Nitroamofoska mineral fertiliser was used as the bulk material to be spread.

Figure 1. Agricultural gantry while conducting experimental studies, with a mineral fertiliser spreader installed at the front: a) general view; b) view with protective screens installed on both sides

Figure 2. The measuring apparatus which consisted of a frequency modulator and a K-505 measuring instrument

Results

To be able to carry out theoretical studies concerning the flight of a mineral fertiliser particle with the mass of M after being thrown from the disc tool of the mineral fertiliser spreader, the equivalent scheme must first and foremost be determined (Fig. 3) to be able to indicate the forces affecting it and its linear dimensions.

Corresponding to the equivalent diagram indicated in Fig. 3, the fertiliser particle, after having separated from the disc's edge (or from the tip of a vane that may be located on the spreader disk), and having attained the necessary speed required when leaving the disc, performs a movement in a plane that coincides with the direction of the absolute speed of spreading. Having performed free flight through the atmosphere, the particle must land on the surface of the arable (crop-bearing) area of the field without reaching the transport tracks in the engineering area of the field. During that process, the material particle with a mass of M is subject to the forces of gravity $\bar{G}$ and air resistance $\bar{R}_x$.

The differential equation for the movement of a fertiliser particle during its flight in the direction of the axis x is as follows:

$$M \cdot \ddot{x} = -R_x \cdot \quad (1)$$

Air resistance R_x can be determined as follows:

$$R_x = k \cdot \gamma \cdot F \cdot \dot{x}^2 , \quad (2)$$

where k is the drag coefficient (Hijazi *et al.*, 2010); γ is the air's specific gravity, kg·m^{-3}; and F is the particle's largest cross-section, m^2.

With small assumptions, the authors estimate that $\dot{x} = V_x$. In that case, after inserting Eq. (2) into (1) and performing mathematical transformations, they get:

$$\frac{dV}{V_x} = -k_s \cdot dx , \quad (3)$$

where k_s is the aerodynamic coefficient of the fertiliser particle, numerically equal to:

$$k_s = \frac{k \cdot F \cdot \gamma}{M} \cdot \quad (4)$$

When integrating the Eq. (3), they get:

$$\ln V_x = -k_s \cdot x + \ln C_1 , \quad (5)$$

where C_1 is the integration constant.

From Eq. (5), the expression of V_x is:

$$V_x = C_1 \cdot e^{-k_s \cdot x} . \quad (6)$$

The integration constant C_1 is determined from the initial conditions, *i.e.* whereupon x = 0, the particle's speed is $V_x = V_r$ where V_r is the fertiliser particle's linear speed upon moving along the disc's circumference.

Having determined the constant C_1 and having integrated Eq. (6) by time t, they get:

$$\frac{e^{k_s \cdot x}}{k_s} = V_r \cdot t + C_2 , \quad (7)$$

where C_2 is the integration constant.

The integration constant C_2 is also determined from the initial conditions, according to which upon t = 0, x = 0.

Then $C_2 = k_s^{-1}$. Accounting for that:

$$k_s \cdot x = \ln\left(k_s \cdot V_r \cdot t + 1\right) \cdot \quad (8)$$

From that, the expression for the flight distance as a function of time looks like this:

$$x = \frac{\ln\left(k_s \cdot V_r \cdot t + 1\right)}{k_s} . \quad (9)$$

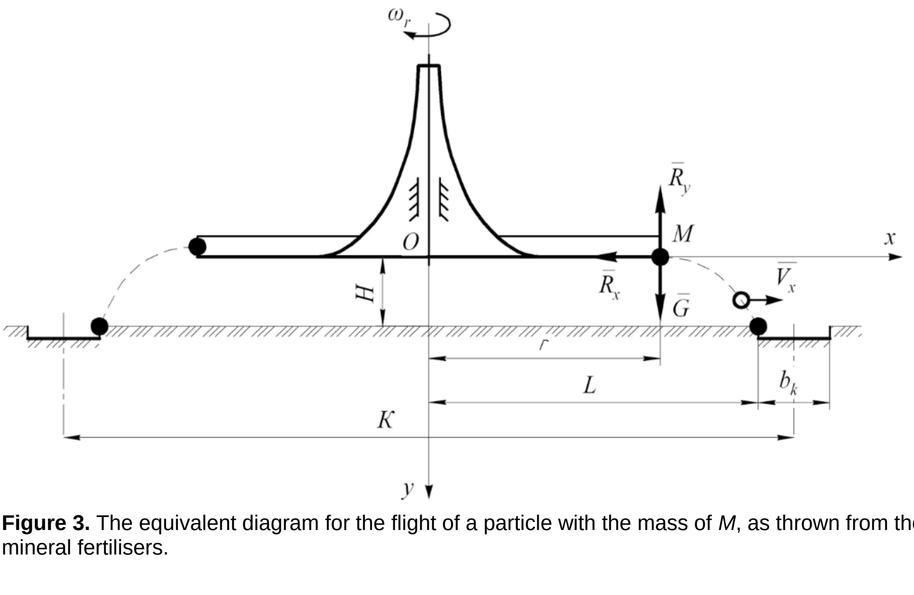

Figure 3. The equivalent diagram for the flight of a particle with the mass of *M*, as thrown from the disc-type tool when spreading mineral fertilisers.

To determine the flight time t of the fertiliser particle, its vertical movement is considered, *i.e.* along axis y under gravity and with air resistance R_y. As the movement speed of the material particle in that direction does not depend on its initial speed, and its falling height H has a negligible relation with the particle's flight distance, the effect of air resistance R_y can be neglected. Based on that, it can be assumed that when the fertiliser particle is in freefall, the height H is equal to:

$$H = \frac{g \cdot t^2}{2}, \tag{10}$$

where g is the freefall acceleration, m•s^{-2}.

From the expression (10), time t is expressed:

$$t = \left(\frac{2 \cdot H}{g}\right)^{\frac{1}{2}}. \tag{11}$$

When inserting the resulting expression (11) for time t in (9), the authors get the equation of the fertiliser particle's flying distance as follows:

$$x = \frac{\ln\left[k_s \cdot V_r \left(\frac{2H}{g}\right)^{\frac{1}{2}} + 1\right]}{k_s}. \tag{12}$$

According to the equivalent scheme shown in Fig. 1, the flying distance of the mineral fertiliser particle must not reach the wheel tracks in the field's engineering zone, ie:

$$x \le L, \tag{13}$$

where L is half the width of the agricultural (crop-bearing) area of the field that is being served by the agricultural gantry unit, m:

$$L = \frac{1}{2}\left(K - b_k\right), \tag{14}$$

where K is the distance of tracks, m, and b_k is the width of the wheel tracks in the engineering zone, m.

The width of the agricultural zone in the field in question, with that zone being served by an agricultural gantry unit, is determined by the distance of tracks K, reduced by the width b_k for the wheel tracks. The latter depends mostly upon the parameters of its transport system, *i. e.* the agricultural gantry (Bulgakov *et al.*, 2018[a]). This means that the maximum flying distance x of a mineral fertiliser particle must be equal to:

$$x = \frac{1}{2}\left(K - b_k\right) \cdot \tag{15}$$

When inserting the expression Eq. (15) into (12), this expresses the speed V_r that a mineral fertiliser particle must possess so that it falls in the correct location and not in the wheel tracks in the engineering zone. The equation is:

$$V_r = \frac{e^{\frac{0.5\cdot(K-b_k)}{k_s}} - 1}{k_s \cdot \left(\frac{2H}{g}\right)^{\frac{1}{2}}} \cdot \tag{16}$$

When analysing the Eq. (16), it can be noted that the speed V_r which a mineral fertiliser particle must possess so that it does not reach the wheel tracks in the engineering zone, is affected by the following:

- distance K and width b_k for the engineering zone's wheel tracks;
- the installation height H of the centrifugal tool;
- the aerodynamic coefficient k_s of the fertiliser.

If the centrifugal spreader tool has a constant radius of r along its entire circumference then, for practical calculations, it should be assumed that the mineral fertiliser particle leaves the vane or the disc's edge at an absolute speed that is approximately equal to the speed V_r, ie:

$$V_r = \omega_r \cdot r, \tag{17}$$

where ω_r is the angular speed of the disc-based centrifugal fertiliser spreader tool.

Inserting Eq. (17) into (16) results in a mathematical model which relates to the parameters of the centrifugal tool that is used to spread fertiliser through its operating mode and the parameters of the wheel tracks of the agricultural gantry unit:

$$\omega_r = \frac{e^{\frac{0.5\cdot(K-b_k)}{k_s}} - 1}{r \cdot k_s \cdot \left(\frac{2H}{g}\right)^{\frac{1}{2}}} \cdot \tag{18}$$

The dependency analysis (18) indicates that the highest area of impact on the rotation speed at the circumference of the centrifugal tool being used to spread mineral fertilisers comes from its installation height, the track width of the agricultural gantry, and the aerodynamic coefficient of the mineral fertiliser particles.

The graph of dependence between the angular speed ω_r of the centrifugal spreading tool and the distance of track K of the agricultural gantry unit, which has been prepared using PC software and which corresponds to expression Eq. (18), has an exponential character (Fig. 4).

The dependence analysis that is shown in Fig. 4 indicates that, for this agricultural gantry unit with its distance of track of K = 3.5 m, it is sufficient to have the centrifugal tool's angular speed at its circumference set at 15.5 rad•s^{-1}, which corresponds to its rotational speed (revolution per second) of 2.47 rps. With the increase in the distance of track of the agricultural gantry unit to 6 m, the necessary angular speed of the centrifugal tool being used for spreading mineral fertilisers increases exponentially to 318.2 rad•s^{-1} (50.67 rps). Naturally, such an increase in the rotation speed of the centrifugal spreader tool requires a corresponding increase of the power demand for driving it (Adamchuk *et al.*, 2016). Therefore the authors will further discuss the dependence of the power demand that is required to drive the centrifugal tool for spreading fertiliser in terms of its rotational speed.

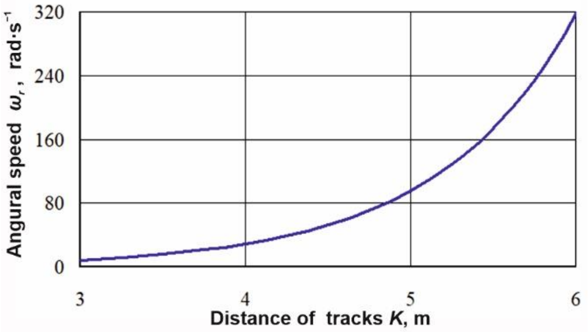

Figure 4. The dependence between the angular speed ω_r of the disc-shaped centrifugal tool for spreading mineral fertilisers and the distance of track *K* of the agricultural gantry

The total power *N* that is required to drive the centrifugal tool is presented as the sum of the power demand required to provide the fertiliser particles with the kinetic energy of N_1 so that they might exceed the air resistance upon moving along the vane and the disc N_2, to get past the impact on a vane at the position at which fertiliser is fed onto the disc N_3, and to exceed the resistance offered by the shaft's rotation on its supports N_4:

$$N = N_1 + N_2 + N_3 + N_4 . \qquad (19)$$

The power demand N_1 is determined as the kinetic energy of the mass of the fertiliser being passed through the unit, per second:

$$N_1 = \frac{Q \cdot \omega_r^2 \cdot r^2}{2}, \qquad (20)$$

where *Q* is the mass consumption of fertiliser, kg·s^{-1}.

To allow it to exceed the friction caused by the particles moving along the disc of the centrifugal tool, the power demand N_2 can be determined with sufficient precision:

$$N_2 = Q \cdot l \cdot f \cdot \left(0.7 \cdot \omega_r^3 \cdot r + 0.5 \cdot \omega_r^2 \cdot r + g\right), \qquad (21)$$

where *l* is the length of the spreader's vane, m; and *f* is the fertiliser's coefficient of friction on the disc.

The power demand N_3 is determined with the assumption that a vane's hit against the fertiliser stream is non-elastic:

$$N_3 = 2 \cdot \pi \cdot Q \cdot \frac{\omega_r^2 \cdot r^3}{L \cdot z}, \qquad (22)$$

where *z* is the number of vanes on a spreader disc.

To ensure that the power demand N_4 exceeds the friction caused by the shaft's supports, the required values can be determined as follows:

$$N_4 = 0.5 \cdot \left(m_d + \frac{Q \cdot l}{\omega_r \cdot r} \right) \cdot g \cdot f_n \cdot d, \qquad (23)$$

where m_d is the mass of the disc with its vanes, shaft, and driving wheel; f_n is the friction coefficient of the bearings; and *d* is the diameter of the groove on the bearing's inner ring, m.

When inserting the dependences Eq. (20) to (23) for the power demand for driving the spreader into Eq. (19) and solving the resultant dependence upon the speed ω_r for the centrifugal tool for spreading mineral fertiliser, the result is:

$$N = A_1 \cdot \omega_r^3 + A_2 \cdot \omega_r^2 + A_3 \cdot \omega_r^{-1} + A_0, \qquad (24)$$

where $A_1 = 0.7 \cdot Q \cdot l \cdot f \cdot r$;

$$A_2 = 0.5 \cdot Q \cdot l \cdot f \cdot r + \frac{Q \cdot r^2}{2} + \frac{2 \cdot \pi \cdot Q \cdot r^3}{L \cdot z};$$

$$A_3 = 0.5 \cdot g \cdot f_n \cdot d \cdot \frac{Q \cdot l}{r};$$

$$A_0 = Q \cdot l \cdot f \cdot g + 0.5 \cdot g \cdot f_n \cdot d \cdot m_d .$$

An analysis of dependence (24) indicates that the power demands that are required to drive the centrifugal tool when spreading mineral fertiliser depend upon the disc's angular speed at its circumference to the third power. The graph to show that dependence is provided in Fig. 5.

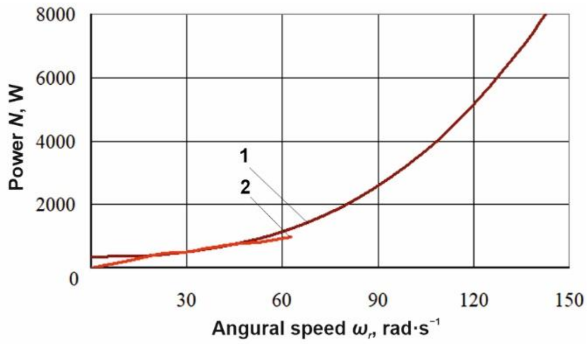

Figure 5. The dependence of the power demand *N* when driving the centrifugal tool for spreading mineral fertiliser in terms of the angular speed ω_r: 1) theoretical and 2) experimental dependence

An analysis of the graphs provided in Fig. 5 indicates that, for the physical object of the studies (the bulk material spreader on an agricultural gantry), the power demand required for driving the spreader is 0.35 kW. The result agrees quite accurately with the experimental data (Fig. 5). With an increase of the angular speed of the centrifugal tool for spreading fertiliser up to 140 rad·s^{-1} (22.2 rps), the power demand for driving the spreader increases to the third power and reaches 8.0 kW.

The results of these studies indicated that the individual power demand for driving the centrifugal tool for spreading mineral fertiliser in an agricultural gantry unit in comparison with the power demand for driving the agricultural gantry itself is negligible and makes up approximately 10% of the entire power demand.

Conclusions

1. As a result of the studies that have been carried out, it was determined that, for the automation of the process of applying technological bulk materials with an agricultural gantry unit, this purpose can be achieved when utilising an electric drive for the centrifugal fertiliser spreader. The highest impact on its angular speed at its circumference comes from its installation height above the soil, as well as from the agricultural gantry's track distance, and the fertiliser's aerodynamic coefficient.
2. The dependence of the angular speed of the spreader tool on the agricultural gantry's track distance has an exponential character. It was determined that, for an agricultural gantry with a distance of track of 3.5 m, it is sufficient to have the angular speed of a single-disc centrifugal tool be set at 15.5 rad·s^{-1} (2.47 rps). At such an angular speed of the spreader, the mineral fertilisers that are being spread onto the crop area of the agricultural gantry unit will not reach the wheel tracks of the engineering zone in the field. The power demand required for driving the spreader is 0.35 kW.
3. When using agricultural gantries unit with a track distance that was increased to 6m, the necessary angular speed of the centrifugal tool for spreading mineral fertiliser will exponentially increase to 318.2 rad·s^{-1} (50.67 rps). Naturally, such an increase in the angular speed of the centrifugal spreader tool requires the power demand to drive the spreader to be increased to the third power.
4. The results that have been accumulated from these theoretical and experimental studies have indicated that the individual power demand for driving the centrifugal tool for spreading mineral fertiliser from an agricultural gantry unit in comparison with the power demand required for driving the agricultural gantry unit itself is negligible and makes up approximately 10% of the total amount.

Conflict of interest

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

Author contributions

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

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