THEORETICAL DETERMINATION OF ABSOLUTE SPEED OF MINERAL FERTILISER PARTICLES FROM CENTRIFUGAL SPREADING DISC

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Abstract. One of the main technological approaches for ensuring favourable conditions of growth and development of plants is depositing mineral fertilisers. The quality of it influences the soil fertility and harvest of agricultural crops. We have developed a new construction of the spreader working body, the axis of which is at the angle to the horizon. Theoretical and experimental research is conducted on the kinematic parameters of such working body. The aim of the present research is determination of the constructive and kinematic parameters that ensure maximal distance of spreading mineral fertiliser particles from the spreading disc with the angle to the horizontal plane. In the research the methods of modeling, theoretical mechanics and mathematics, as well as calculations and presentations of graphical dependences are used. The present article describes the obtained analitical expressions for determination of the absolute speed of mineral fertiliser particles from the spreader disc with an inclined working body, considering the initial speed of moving the aggregate for spreading mineral fertilisers on the surface. The mineral fertiliser particle absolute speed from the spreading disc of the working body is presented as a vector through its projection on the axis of specially developed system of Cartesian coordinates at a moment of time. Based on the obtained analytical expressions, graphical dependences are presented characterising the studied process. It is proved that at increasing the coefficient of friction of the mineral fertiliser particles from 0.1 to 0.7, the angle of the mineral fertiliser particles leaving the disc increases from 2 to 33 deg at the initial speed of movement of the aggregate 2 $m \cdot s^{-1}$ and from 2 to 37 deg at the initial speed 4 $m \cdot s^{-1}$. Therefore, some of the fertiliser particles will leave the disc at the agle bigger than the inclination of the disc to the horizontal plane within 20…30 deg. Changes of the angle speed of the disc rotation do not essentially influence changes of the angle of the fertiliser particles leaving the disc.

Keywords: mineral fertilisers, particle, spreading, disc, absolute speed, distance.

Introduction

At present, in most countries of the world machines equipped with centrifugal working bodies for spreading mineral fertilisers are most widely used. It can be explained by the high productivity of these machines in comparison to other constructions, their simplicity and reliability in work. Still, in relation to increased necessity for spreading mineral fertilisers due to the development of industrial technologies for growing agricultural crops a problem exists, the essence of which is relatively low productivity of the machines for spreading mineral fertilisers and their technical – economical efficiency. Therefore, developers of new machine models try to develop more improved constructions to ensure higher productivity of the machines for spreading mineral fertilisers.

Nevertheless, it should be mentioned that improvement of the productivity of the machines for spreading mineral fertilisers at present is possible only by enlarging the width of the operation as the potential reserves to improve the productivity by the working speed of the aggregate and the coefficient of the usage of time have already been used. The mentioned problem is topical and needs to be investigated, and new constructions need to be developed.

Many scientists have investigated the process of spreading mineral fertilisers by disc fertilizer-dispersing working bodies [1-22]. They have discussed different problems in relation to the improvement of the productivity of the machines [23], their reliability in work and they have studied the influence of the construction elements of the working body, parameters and regimes of work on the quality of mineral fertiliser spreading, the distance and regularity of spreading on the soil surface and many other problems. In particular, theoretical investigations to determine the distance of mineral fertiliser particle spreading by the fertilizer-dispersing working body can be found in the articles [23-

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28]. Still, in the mentioned investigations the solutions of the investigated tasks were obtained at definite simplifications and the presented scientific results did not find practical application.

It should be mentioned that the distance of the mineral fertiliser particles essentially depends on the angle between the vector of absolute speed and the horizontal plane. Still, in the known centrifugal fertilizer-dispersing working bodies with the vertical axis of rotation the absolute speed of the mineral fertiliser particles can be increased only by increasing the relative speed, that is, the speed by which the fertiliser moves along the disc and blades.

At the same time, a great deal of the absolute speed of moving the fertiliser from the working body is dependent on the transfer speed and tractor power characteristics [30]. In relation to this fact we have developed a new construction of a centrifugal fertilizer-dispersing apparatus with a spreading disc the axis of which is inclined at an angle to the horizontal plane. It gave a possibility to essentially increase the angle between the vector of absolute speed of the fertiliser particle from the disc and the horizontal plane. Determination of the mentioned absolute speed in relation to the initial movement of the aggregate and rational importance of the angle of inclination to the horizontal plane is the subject of the present research as these parameters are important for determination of the distance of the fertiliser particles after they leave the disc of the working body and the working width of the machine for spreading mineral fertilisers.

Determination of the constructive and kinematic parameters that ensure maximal distance of the mineral fertiliser particles from the spreading disc with inclination to the horizontal plane was the aim of the research.

Materials and methods

To determine the absolute speed of the fertiliser particles from the disc (the end of the blade) that is inclined at the angle α to the horizon it is necessary to mention the following. The absolute speed of the fertiliser particle $\overline{V}_{GO}$ at any moment of time t is the vector sum of the relative speed $\overline{V}_{BC}$ of the movement of the particle along the blade at the end of the blade and the transfer speed $\overline{V}_{NC}$ of the end of the blade at rotation of the disc (Fig. 1).

As the vecor $\overline{V}_{BC}$ lies on the surface of the disc and it is in the direction to the radius of the disc, but the vector $\overline{V}_{NC}$ also lies on the surface of the disc and is in the direction to the tangent surface to the disc, also the vector $\overline{V}_{GO}$ lies in the plane of the disc as the sum of two vectors on the plane of the disc.

The main problem is that the angle between the vector $\overline{V}_{GO}$ and the horizontal plane at the moment of time t of the particle leaving the blade will change. If we consider also the forward movement of the inclined fertilizer-seeding working body, the task becomes more complicated.

Therefore, it is not possible to use in this case the usual way of constructing the vectors acording to the rules of paralelogram and the theorem of cosinuses for determination of the modules of these vectors. It is simpler for constructing of the vectors to present these vectors through their projection in the Cartesian system of coordinates. Also, the scalar and vectoral construction is quite simple.

It is only necessary to choose the Cartesian system of coordinates that the projections of the vectors we need can be determined at the moment of time t when the particle leaves the blade.

As we need to determine the angle between the vector of absolute speed of the fertiliser particle leaving the end of the blade V_a, considering the initial movement of the aggregate and the horizontal plane, at the beginning we choose the Cartesian system of coordinates $xOyz$, the beginning of which (point O) is at the centre of the rotating disc, the axis Oy lies on the horizontal plane and is directed vertically upwards.

Further, considering that the disc is inclined at the angles α to the horizon, we choose another system of coordinates $x_1Oy_1z_1$, which is formed in the result of turning the system of coordinates $xOyz$ around the point 0 at the angle α (angle of inclination of the rotating disc to the horizon) in the vertical plane yOz against the clockwise hand. Then the horizontal plane xOy will be in the surface of the disc, forming the plane x_1Oy_1 of the Cartesian system of coordinates $x_1Oy_1z_1$, the axis Oz will turn at the angle α, forming the axis Oz_1, which will be the perpendicular plane of the disc (Fig. 1).

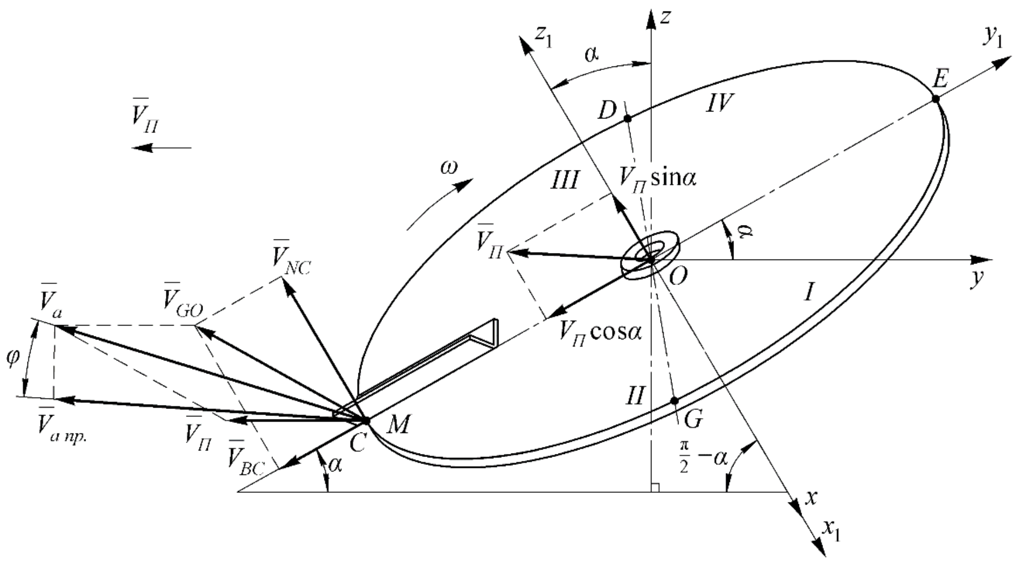

Fig. 1. **Equivalent system of fertiliser particle leaving the disc of the fertilizer-dispersing working organ considering the initial speed of the aggregate**

That way, the disc rotating along the axis coincides with the axis Oz_1 with constant angle speed ω clockwise. The fertiliser particle movement along the disc will take place in the plane x_1Oy_1, but due to this it will not be difficult to determine the projections of the time vectors of the particle movement in the given system of coordinates $x_1Oy_1z_1$.

As it can be seen in Fig. 1, in the system of coordinates $x_1Oy_1z_1$ the relative speed $\bar{V}_{BC}$ of the particle movement along the disc surface (to the blade) at the moment being at the edge of the disc can be presented by the vector:

$$\bar{V}_{BC} = \left\{ V_{BC} \sin \omega t, \quad V_{BC} \cos \omega t, \quad 0 \right\}. \tag{1}$$

Angular velocity $\bar{V}_{NC}$ of the particle can be presented by the vector:

$$\bar{V}_{NC} = \left\{ V_{NC} \cos \omega t, \quad -V_{NC} \sin \omega t, \quad 0 \right\}. \tag{2}$$

Then the summary speed $\bar{V}_{GO}$ of the fertiliser particle leaving the spreading disc will be equal to:

$$\bar{V}_{GO} = \bar{V}_{BC} + \bar{V}_{NC}. \tag{3}$$

Or, considering (1) and (2), we get that the speed $\bar{V}_{GO}$ will be equal to the following vector:

$$\bar{V}_{GO} = \left\{ V_{BC} \sin \omega t + V_{NC} \cos \omega t, \quad V_{BC} \cos \omega t - V_{NC} \sin \omega t, \quad 0 \right\}. \tag{4}$$

Further we determine the vector of velocity of the initial movement of the aggregate $\bar{V}_{П}$ in the system of coordinates $x_1Oy_1z_1$ that will be equal to: $\bar{V}_{GO}$

$$\bar{V}_{П} = \left\{ 0, \quad -V_{П} \cos \alpha, \quad V_{П} \sin \alpha \right\}. \tag{5}$$

Then the vector of the absolute speed of the fertiliser particle $\bar{V}_a$ at the time it leaves the disc considering the initial movement of the aggregate will be equal to:

$$\bar{V}_a = \bar{V}_{GO} + \bar{V}_{П}. \tag{6}$$

Or, considering (4) and (5), we get:

$$\bar{V}_a = \left\{ V_{BC} \sin \omega t + V_{NC} \cos \omega t, \quad V_{BC} \cos \omega t - V_{NC} \sin \omega t - V_{П} \cos \alpha, \quad V_{П} \sin \alpha \right\}. \tag{7}$$

Module of the vector $\bar{V}_a$ (i.e. value of the absolute speed) will be equal to:

$$V_a = \Big[\left(V_{BC}\sin\omega t + V_{NC}\cos\omega t \right)^2 + \left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha \right)^2 + \\ + \left(V_{\Pi}\sin\alpha \right)^2 \Big]^{\frac{1}{2}} . \tag{8}$$

Further we determine the angle of inclination of the absolute speed vector of the particle leaving the disc $\overline{V}_a$ to the horizontal plane at a moment of time t of the particle leaving the blade.

It is possible to determine the given angle of inclination of the absolute speed of the fertiliser particle from the blade to the horizontal plane (or field surface) $\overline{V}_a$ as the angle between the given vector $\overline{V}_a$ and its projection on the horizontal plane at a moment of time t when the particle leaves the blade.

Still, the projections of the vector $\overline{V}_a$ are determined in the system of coordinates $x_1Oy_1z_1$, expression (7), the axis of which Oz_1 and Oy_1 inclined from the axis Oz and Oy of the system of coordinates $xOyz$ at the angle α (Fig. 1). Then the axis Ox_1 and Ox coincide. Therefore, first the projections of the vector $\overline{V}_a$ should be determined in the system of coordinates $xOyz$, using the transform of the Cartesian system of coordinates at turning at an angle α around the initial coordinates. In the given case, as it was already mentioned above, turning of the system of coordinates $xOyz$ takes place against the clockwise hand at the angle α resulting in the system of coordinates $x_1Oy_1z_1$.

If we take the system $x_1Oy_1z_1$ as the initial system of coordinates in which the projections of the vector $\overline{V}_a$ are determined, the system of coordinates $xOyz$ will be turning in the system of coordinates $x_1Oy_1z_1$ at an angle $-\alpha$ (at angle α clockwise).

It is obvious that turning of the system of coordinates $x_1Oy_1z_1$ at the angle $-\alpha$ takes place at the axis Ox_1, therefore, the coordinate x_1 of any point at such turning remains the same, that is $x = x_1$.

Concidering the coordinates y_1 and z_1 of any point, it should be mentioned that they change according to the following expressions provided they turn against the clockwise direction at the angle α [29; 31]:

$$\left.\begin{aligned} y &= y_1\cos\alpha + z_1\sin\alpha, \\ z &= -y_1\sin\alpha + z_1\cos\alpha. \end{aligned}\right\} \tag{9}$$

As in the given case turning is at the angle $-\alpha$, replacing in the expressions (9) α for $-\alpha$, we get:

$$\left.\begin{aligned} y &= y_1\cos\alpha - z_1\sin\alpha, \\ z &= y_1\sin\alpha + z_1\cos\alpha. \end{aligned}\right\} \tag{10}$$

Changes in (10) relate to the changes of the point coordinates. These changes take place also at the changes of the coordinate vector. Using expression (10) considering (7), we get the vector of the absolute speed of the fertiliser particle leaving the disc V_a in the Cartesian system of coordinates $xOyz$ from its coordinates in the system $x_1Oy_1z_1$:

$$\overline{V}_a = \Big\{ V_{BC}\sin\omega t + V_{NC}\cos\omega t, \quad \left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha \right)\cos\alpha - \\ - V_{\Pi}\sin^2\alpha, \quad \left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha \right)\sin\alpha + V_{\Pi}\sin\alpha\cdot\cos\alpha \Big\}. \tag{11}$$

Projection $\overline{V}_{anp}$ of the vector $\overline{V}_a$ on the horizontal plane xOy can be presented as follows:

$$V_{a\,np.} = \Big\{ V_{BC}\sin\omega t + V_{NC}\cos\omega t, \quad \left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha \right)\times \\ \times\cos\alpha - V_{\Pi}\sin^2\alpha, \quad 0 \Big\}. \tag{12}$$

Then cosinus of the angle $\varphi = (\overline{V}_a, \overline{V}_{anp})$ between the vector $\overline{V}_a$ and the horizontal plane xOy at a moment of time t of the particle leaving the blade will be equal to:

$$\cos\varphi = \frac{\overline{V}_a \cdot \overline{V}_{a\,np.}}{V_a \cdot V_{a\,np.}}, \tag{13}$$

where $\overline{V}\cdot\overline{V}_{anp}$ – scalar construction of the vectors $\overline{V}_a$ and $\overline{V}_{anp}$;
V_a and V_{anp} – modules of the vectors $\overline{V}_a$ and $\overline{V}_{anp}$ accordingly.

Let us determine the scalar construction of the vectors $\bar{V}_a$ and $\bar{V}_{anp}$. We have:

$$\bar{V}_a \cdot \bar{V}_{a\,np.} = \left(V_{BC}\sin\omega t + V_{NC}\cos\omega t\right)^2 + \\ + \left[\left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha\right)\cos\alpha - V_{\Pi}\sin^2\alpha\right]^2. \quad (14)$$

Further we determine the modules of the vectors $\bar{V}_a$ and $\bar{V}_{anp}$ accordingly.

The module of the vector $\bar{V}_a$ will be equal to:

$$V_a = \left\{\left(V_{BC}\sin\omega t + V_{NC}\cos\omega t\right)^2 + \left[\left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha\right)\times \right.\right. \\ \times\cos\alpha - V_{\Pi}\sin^2\alpha\Big]^2 + \Big[\left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha\right)\sin\alpha + \\ \left.\left. + V_{\Pi}\sin\alpha\cdot\cos\alpha\right]^2\right\}^{\frac{1}{2}}. \quad (15)$$

$$\bar{V}_{a\,np.} = \left\{\left(V_{BC}\sin\omega t + V_{NC}\cos\omega t\right)^2 + \Big[\big(V_{BC}\cos\omega t - V_{NC}\sin\omega t - \right. \\ \left. - V_{\Pi}\cos\alpha\big)\cos\alpha - V_{\Pi}\sin^2\alpha\Big]^2\right\}^{\frac{1}{2}}. \quad (16)$$

Inserting (14), (15) and (16) in (13) we get:

$$\cos\varphi = \left\{\left(V_{BC}\sin\omega t + V_{NC}\cos\omega t\right)^2 + \Big[\big(V_{BC}\cos\omega t - V_{NC}\sin\omega t - \right. \\ \left. - V_{\Pi}\cos\alpha\big)\cos\alpha - V_{\Pi}\sin^2\alpha\Big]^2\right\} \cdot \left\{\left(V_{BC}\sin\omega t + V_{NC}\cos\omega t\right)^2 + \right. \\ + \left[\left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha\right)\cos\alpha - V_{\Pi}\sin^2\alpha\right]^2 + \\ \left. + \left[\left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha\right)\sin\alpha + V_{\Pi}\sin\alpha\cdot\cos\alpha\right]^2\right\}^{-\frac{1}{2}} \times \\ \times\left\{\left(V_{BC}\sin\omega t + V_{NC}\cos\omega t\right)^2 + \Big[\big(V_{BC}\cos\omega t - V_{NC}\sin\omega t - \right. \\ \left. - V_{\Pi}\cos\alpha\big)\cos\alpha - V_{\Pi}\sin^2\alpha\Big]^2\right\}^{-\frac{1}{2}}. \quad (17)$$

Then:

$$\varphi = \arccos\left\{ \left\{\left(V_{BC}\sin\omega t + V_{NC}\cos\omega t\right)^2 + \Big[\big(V_{BC}\cos\omega t - V_{NC}\sin\omega t - \right.\right. \\ \left. - V_{\Pi}\cos\alpha\big)\cos\alpha - V_{\Pi}\sin^2\alpha\Big]^2\right\} \cdot \left\{\left(V_{BC}\sin\omega t + V_{NC}\cos\omega t\right)^2 + \right. \\ + \left[\left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha\right)\cos\alpha - V_{\Pi}\sin^2\alpha\right]^2 + \\ \left. + \left[\left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha\right)\sin\alpha + V_{\Pi}\sin\alpha\cdot\cos\alpha\right]^2\right\}^{-\frac{1}{2}} \times \\ \times\left\{\left(V_{BC}\sin\omega t + V_{NC}\cos\omega t\right)^2 + \Big[\left(V_{BC}\cos\omega t - V_{NC}\sin\omega t - V_{\Pi}\cos\alpha\right)\times \right. \\ \left.\left. \times\cos\alpha - V_{\Pi}\sin^2\alpha\Big]^2\right\}^{-\frac{1}{2}} \right\}. \quad (18)$$

That way, we obtained expression for determination of the angle φ between the vector $\bar{V}_a$ and the horizontal plane at any moment of time t of the particle leaving the blade. This angle considerably influences the distance of the fertiliser particle after leaving the disc of the inclined fertilizer-dispersing working body and also the working width of the machine for spreading of mineral fertilisers.

Results and discussion

It should be mentioned that the initial speed of the aggregate movement also influences the value of the absolute speed of the fertiliser particle leaving the disc of the inclined working body, expression

(15). It also influences the angle φ between the vector $\overline{V}_a$ of the absolute speed of the fertiliser particle leaving the disc of the working body and the horizontal plane, expression (18).

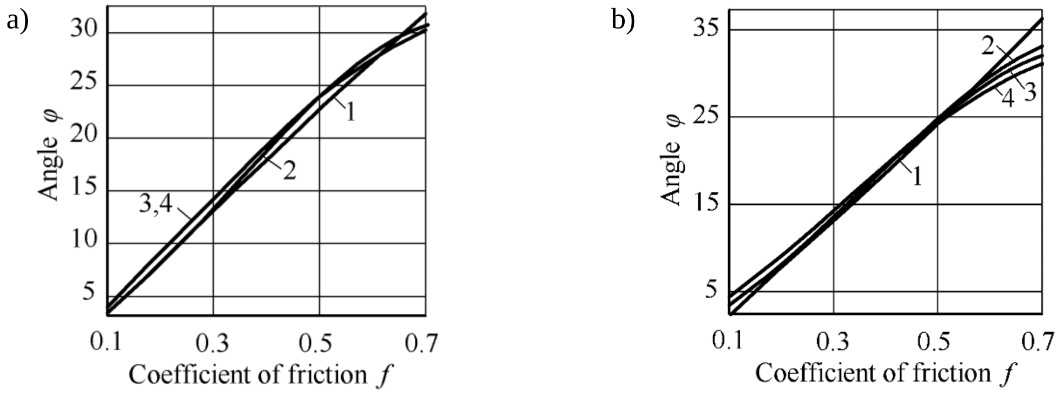

Fig. 2. **Dependence of the angle φ between the vector $\overline{V}_a$ of the absolute speed of the fertiliser particle leaving the disc of the working body and the horizontal plane on the coefficient of particle friction f_f and the angle speed ω of the working body disc:** 1 – ω = 30 s^{-1}; 2 – ω = 60 s^{-1}; 3 – ω = 90 s^{-1} $\omega = 90\ s^{-1}$; 4 – ω = 120 s^{-1}; a – $\overline{V}_{\Pi}$ = 2 $m \cdot s^{-1}$; b – $\overline{V}_{\Pi}$ = 4 $m \cdot s^{-1}$

Fig. 2 shows the graphs of the dependence of the angle φ between the absolute speed vector $\overline{V}_a$ of the particle leaving the disc and the horizontal plane on the coefficient of the particle friction f_f and the angle speed of the working body disc ω at the values of the initial speed of the aggregate $\overline{V}_{\Pi}$ equal to 2 and 4 $m \cdot s^{-1}$. As the presented graphs show, increasing the mineral fertiliser particle friction coefficient from 0.1 to 0.7, the angle of spreading mimeral fertilisers increases from 2 to 33 deg at the initial speed of moving the aggregate 2 $m \cdot s^{-1}$ and from 2 to 37 deg at the initial speed 4 $m \cdot s^{-1}$. Then some of fertiliser particles will leave the disc at the angle bigger than the angle of the inclination of the disk to the horiozontal plane as rational values of inclination of the disc of the working body to the horizontal plane are within 20º … 30º.

As the analysis of the research shows [32] – one of the versions of more uniform spreading of the fertiliser particles along the surface of the disc to obtain uniform spreading of them could be forced vibrations. Analysis of qualitative indices of performing the technological process depending on vibrations of the working body is presented in investigations [33; 34].

Changing the angle speed of the disc rotation does not have essential influence on the changes of the angle of the fertiliser particles leaving the disc.

Conclusions

1. Analytical expressions are obtained for determination of the absolute speed of the mineral fertiliser particle leaving the disc of the inclined fertilizer-dispersing working body considering the initial speed of the aggregate and the angle between the vector of the absolute speed and the horizontal plane.
2. The obtained parameters are the basic parameters for determination of the distance of the fertiliser particles after leaving the disc of the working body, and with this, also the working width of the machine for spreading mineral fertilisers.
3. Increasing the coefficient of friction of the mineral fertiliser particles from 0.1 to 0.7, the angle of the mineral fertiliser particles leaving the disc increases from 2 to 33 deg at the initial speed of movement of the aggregate 2 $m \cdot s^{-1}$ and from 2 to 37 deg at the initial speed 4 $m \cdot s^{-1}$. Some of the fertiliser particles will leave the disc at the agle bigger than the inclination of the disc of the working body to the horizontal plane within 20…30 deg.
4. Changes of the angle speed of the disc rotation do not essentially influence the changes of the angle of mineral particles leaving the disc.

Author contributions

All authors have contributed equally to creation of this article. All authors have read and agreed to the published version of the manuscript.

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