

# THEORETICAL SUBSTANTIATION OF THE DESIGN OF A SEEDING DEVICE FOR DIFFERENTIATED INTRA SOIL APPLICATION OF MINERAL FERTILIZERS

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## Abstract

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The existing seeding devices not fully provide quality of application of mineral fertilizers. Unevenness and instability of application reach 20–40% at demanded to 15%. It, first of all, associated with the absorption of fertilizers and imperfection of seeding devices for fertilizer.

For a solution of the problem of ensuring quality of application of mineral fertilizers at their intra soil differentiated application the original design of the pin reel of a seeding device is offered. Pins of the reel are executed in the form of the tetrahedral truncated pyramids located on crossing right and left multiple-helical lines on a reel surface. Theoretical researches relied on regularities of classical mechanics. As a result of theoretical researches the expression connecting all key design and technological parameters is received: reel radius, number of pins on it, their height and the sizes of the top and lower basis, diameter of a driving wheel, rate of application, aisle width, and transfer ratio of the driving mechanism.

Keywords: seeding device, mineral fertilizers, variable rate application, precision agriculture, pin reel, sliding gate, hopper

## INTRODUCTION

Feature subsurface application of mineral fertilizers – their exact placement relative to the roots of plants – determines the increased requirements to the design of fertilizer applying machines, seeding devices and fertilizers quality.

Analysis of existing seeding devices and various devices for seeding difficult bulk materials shows that the most appropriate is the use of seeding devices with tools that allow to actively performing selection difficult bulk material in the hopper and forced to move in opener fertilizer tube: Gribovskiy and Bildingmayer (1990), Semenov

(1955), Alshynbay (1955), Alshynbay (1999), Letoshnev (1955), Mordukhovich and Tompakov (1984), Nukeshev (2004).

Most appropriate to meet such requirements are kind of reel seeding machines – pins type, lobed or butterfly. They are widely used for seeding difficult bulk materials. However, our search results of the experiments showed that when a fertilizer moisture nonstandard fertilizer retained between pins in the so-called “passive zones.” Is their capacity and filled with a working area between the pins. As a result pin reel turns into a “cylindrical roller” and stopped seeding process: Doganovskiy (1972).

**The aim of the present work** is theoretical substantiation of the design of the new seeding device for differentiated application of mineral fertilizers.

## MATERIALS AND METHODS

### The Analysis of the Existing Sowing Devices

For work in the automatic change in dose fertilizing system for precision farming need highly adaptive, but simple in design, reliable devices. Most suited to these requirements is pin reel, where the pins are in the form of square-angled, truncated pyramids, located at the intersection of the right and left crossing multiple-helical lines on the reel surface – Nukeshev (2006), Fig. 1.

Performing pins in the shape of a truncated four-sided pyramid exclude “passive zone” inherent by reel-pin serial devices and their location at the intersection of the left and right multiple-helical line avoid fertilizer sticky.

Material supply control – dose application can provide by changes of the rotation frequency of the seeding reel or by changing the area of the seeding window.

For exploratory research were taken seeding machines with features making a change in dose

due to the sliding gate – Nukeshev (2011), Fig. 2 and rotating gate – Nukeshev (2010), Fig. 3.

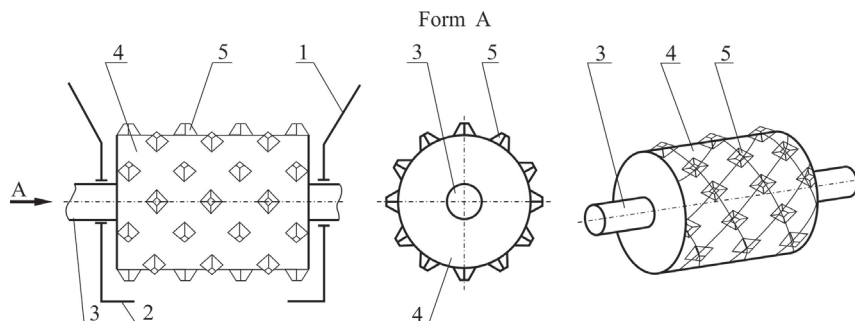
Determined unevenness between seeding devices, seeding instability and effort spent on the gate shaft rotation from 0 to 70 degrees and the force on the movement of the slide gate from the closed position to fully open and vice versa.

Analysis of the results of exploratory studies showed that the qualitative performance of seeding machine with horizontal sliding gate does not correspond to agro-technical requirements, and at higher doses seeding machine with a rotating gate to change doses of applying requires a sharp increase in the frequency of rotation of the reel.

### Design of the Seeding Device and Studying Methods

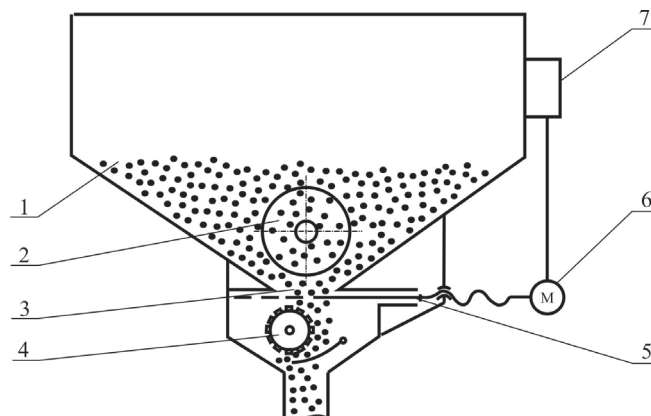
Based on the results of exploratory research, we propose a new design of the seeding device – Nukeshev (2014), Fig. 4. Seeded device consists of a hopper 1, gate 2, experimental pin reel 3, bottom 4, fan 5 and fertilizer tube 6. The distance between the reel 3 and bottomed 4 is regulated by rotation of the shaft, depending on the sizes of granules and physical properties of fertilizers. In the control device metering is accomplished by changing the working surface of the active reel.

Theoretical studies based on the laws of classical mechanics.



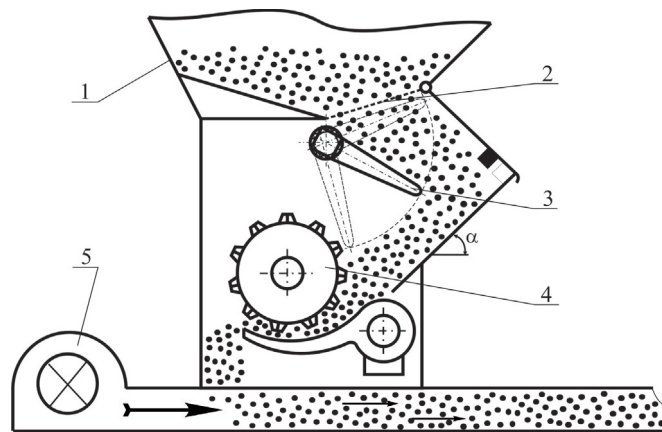
1: Experimental fertilizer seeding device

1 – hopper, 2 – housing, 3 – shaft, 4 – reel, 5 – pin



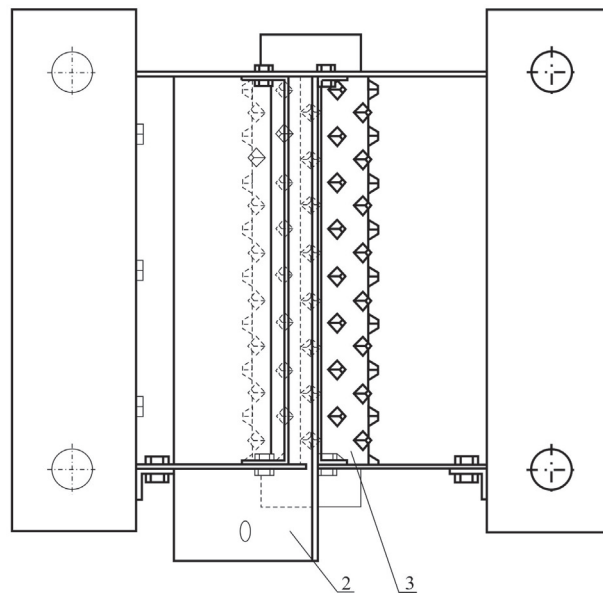
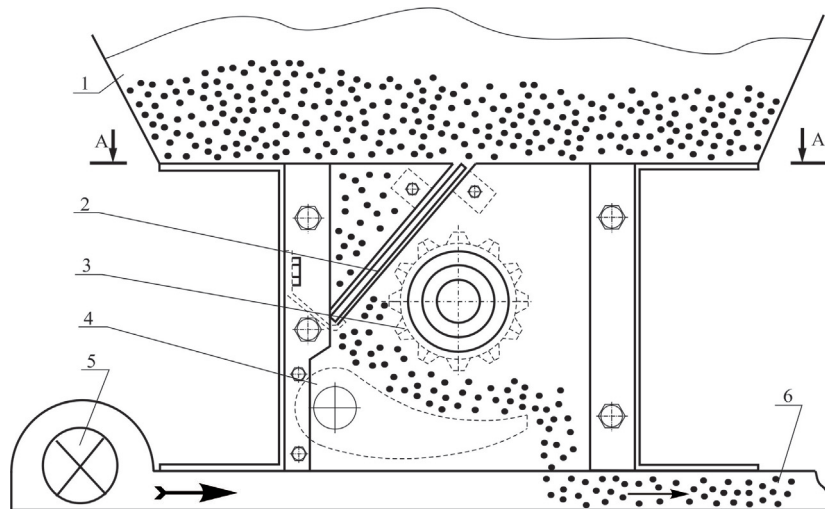
2: A seeding device with a horizontal sliding gate

1 – hopper, 2 – arch destroyer, 3 – seeding window, 4 – reel, 5 – sliding gate, 6 – stepper electromotor, 7 – control unit



3: A seeding device with a rotating gate

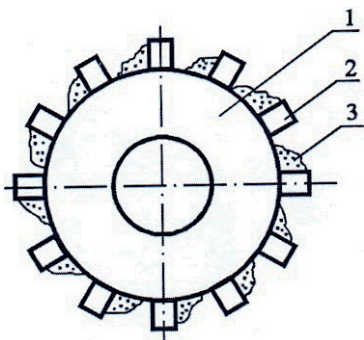
1 – hopper, 2 – seeding window, 3 – rotating gate, 4 – reel, 5 – fan



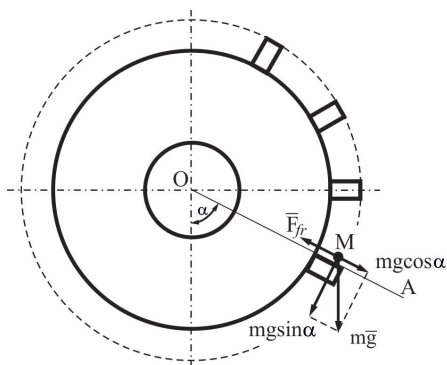
4: The experimental seeding device

## RESULTS

The main disadvantage of the series reel (with prismatic pins) is a continuous presence of a “passive zone” – zone located on the front side of the pin, at the bottom of the reel, Fig. 5.



5: A pin reel with prismatic pins  
1 – reel; 2 – pin; 3 – p “a passive zone”



6: The scheme of forces acting on a fertilizer granule (particle)

At application of wet fertilizers, fertilizers are trapped in “passive zone”. There is their building and the working zone between pins is filled. As a result the pin reel turns into “a cylindrical drum” and technological process of seeding stops.

At rotation of the pin reel the angle of rotation –  $\alpha$  changes. At a view of the reel sideways (Fig. 6), a granule (particle) of M can roll down from a pin at angle  $\alpha = \alpha_{cr}$ . It depends on an angle of friction of

a granule of M about a lateral surface of a pin and on an angle of internal friction between granules.

Gravity force of granules  $M - m\vec{g}$  can be decomposed into two components:  $mg \cos \alpha$  – rolling force,  $mg \sin \alpha$  – pressure force on the granule surface of the pin side. The first component of the friction force opposes

$$F_{fr} = fmg \sin \alpha,$$

where

$f$ .....coefficient of friction between a granule and a pin surface.

Two cases of a granule behavior are possible:

1. If  $F_{fr} < mg \cos \alpha$ , the granule rolls down the surface of the pin;
2. If  $F_{fr} \geq mg \cos \alpha$ , the granule remains stationary relative to the surface of the pin.

From these conditions, we can determine  $\alpha_{cr}$ , i.e.

$$fmg \sin \alpha_{cr} \leq mg \cos \alpha, \quad (1)$$

hence

$$f \leq c \tan \alpha_{cr},$$

$$c \tan(90^\circ - \varphi) \leq c \tan \alpha_{cr}, \quad 90^\circ - \varphi \leq \alpha_{cr}, \quad (2)$$

where

$\varphi$ .... angle of friction.

If:  $\alpha_{cr} \geq 90^\circ - \varphi$ ..... the granule M moves with a slow, creates stagnation.

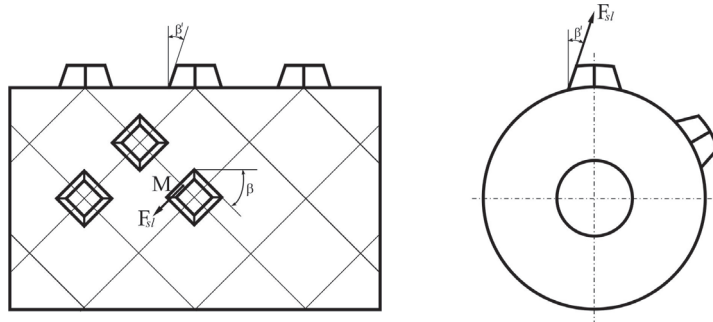
$\alpha_{cr} = 90^\circ - \varphi$ ..... critical state.

$\alpha_{cr} < 90^\circ - \varphi$ ..... the granule of M will roll down with acceleration.

In serial pin reels  $\alpha > \alpha_{cr}$ , so fertilizer granules do not have time to roll down the OA and remain on the surface of the pin reel in “passive zone”. This contributes to a right angle between the side surfaces of the pin and the cylindrical surface of the reel.

To eliminate a “passive zone” in the experimental reel pins are in the form of a truncated pyramid, Fig. 7. Surface lateral pins to proposed device form angles  $\beta$  and  $\beta'$  to generator reel and the vertical axis. In this case the granule M at any position of the reel is affected by rolling force on a pin surface:

$$F_{sl} = mg \cos \alpha \cos \beta. \quad (3)$$



7: Experimental pin reel of a fertilizer seeding device

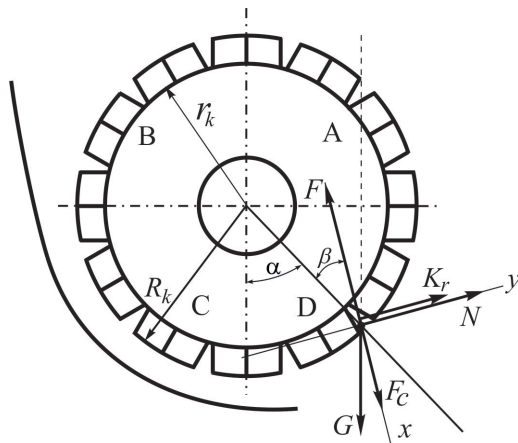
You can consider such cases.

1. If  $\alpha > \alpha_{cr}$ ,  $\tan\beta \leq f$ , then the granule M will rotate together with the edge of the pin.
2. If  $\alpha < \alpha_{cr}$ ,  $\tan\beta \leq f$ , the granule will roll down the sides of the pin.
3. If  $\alpha > \alpha_{cr}$ ,  $\tan\beta > f$ , then the granule will roll along the edge of the pin, parallel to it.
4. If  $\alpha < \alpha_{cr}$ ,  $\tan\beta > f$ , then the granule will roll along the edge and pin the sides, parallel to them.

Of these conditions can be seen that by choosing the angle  $\beta$  can cause motion of the granule M even when the rotational angle  $\alpha_k > \alpha_{kr}$ . It must be borne in mind that changes the condition of the granule from the surface rolling pin (2).

On the other hand to ensure efficient operation of the reel must be pinned to the post faces captured granules and move them in the direction of forming a reel. Therefore, a necessary condition to avoid "sticking" fertilizer –  $\beta_{cr} \geq \phi = \arctan f$ , i.e. the angle  $\beta$  must be equal to the angle of friction between the granule and the pin surface or more of it.

Filling with fertilizers the pins space (space between pins) of the reel has to begin already in a zone A. In the second half of zone B and zone C there is moving granules by pins. In zone D pins space unloaded from fertilizers, Fig. 8.



8: To definition of peripheral speed of the pin reel

By establishing a link between the peripheral speed and the angle of rotation of the reel define angular velocity of the reel (which pins are in the form of a truncated pyramid) at which the fertilizer discharges from pins space. If we assume that the granule is on the edge of the pin and at this point the relative velocity of the granule is zero, then, according to the principle of d'Alembert applied to the fertilizer granule forces on natural axes  $x, y$  will be in equilibrium:

$$G \cos(\alpha - \beta) + F_c - F = 0, \quad (4)$$

$$N + K_r - G \sin(\alpha - \beta) = 0,$$

where

N... the normal pressure of a pin,  
F<sub>c</sub>... the centrifugal force of inertia,  
K<sub>r</sub>... Coriolis force,  
F... granule friction force about a pin,  
G... granule weight force.

As can be seen from Fig. 8, the angle  $\beta$  is substantially less than the angle  $\alpha$ . In this connection, for the convenience of further calculations, without compromising the accuracy of the calculations, F<sub>c</sub> can be orientated to  $x$ . Also evident in the absence of relative motion Coriolis force is zero. Therefore, the second equation (4) we obtain:

$$N = G \sin(\alpha - \beta). \quad (5)$$

However:

$$F = fN.$$

Consequently, taking into account (5) we have:

$$F = fG \sin(\alpha - \beta). \quad (6)$$

In the first equation (4) components are equal members, see Tarasov (2012),

$$G = mg; \quad (7)$$

$$F_c = m\omega^2 R.$$

Substituting (6) and (7) into (4) we obtain:

$$g \cos(\alpha - \beta) + \omega^2 R - fg \sin(\alpha - \beta) = 0. \quad (8)$$

Perform the following transformation (8):

$$g \cos(\alpha - \beta) + \omega^2 R = fg \sin(\alpha - \beta),$$

$$\frac{\omega^2 R}{g \cos(\alpha - \beta)} = \frac{fg \sin(\alpha - \beta)}{g \cos(\alpha - \beta)} - 1.$$

$$\frac{k}{\cos(\alpha - \beta)} = f \tan(\alpha - \beta) - 1, \quad (9)$$

where

$k = \frac{\omega^2 R}{g}$  ..... coefficient of kinematic mode of the reel which pins are in the form of a truncated pyramid.

In (9), the coefficient of kinematic mode shows the ratio of the centrifugal acceleration of the granule to its acceleration of free fall, and can characterize the critical (boundary) value of the angular velocity of the reel in which the fertilizer granules will accumulate in between pins spaces or slide, freeing them.

Expression (9) may be converted:

$$k = f \tan(\alpha - \beta) \cos(\alpha - \beta) - \cos(\alpha - \beta),$$

$$k = f \sin(\alpha - \beta) - \cos(\alpha - \beta). \quad (10)$$



Obviously, for  $k = 1$ , centrifugal and free fall acceleration are equal. Therefore, this state of the reel can be considered critical – the boundary condition for accumulation of granules or their rolling from space between pins.

Substitute the value  $k = 1$  in (10):

$$1 + \cos(\alpha - \beta) = f \sin(\alpha - \beta),$$

$$\frac{1}{\sin(\alpha - \beta)} [1 + \cos(\alpha - \beta)] = f,$$

$$c \tan \frac{(\alpha - \beta)}{2} = c \tan(90 - \varphi),$$

$$\frac{(\alpha - \beta)}{2} = \left( \frac{\pi}{2} - \varphi \right),$$

$$(\alpha - \beta) = 2 \left( \frac{\pi}{2} - \varphi \right). \quad (11)$$

The figure shows that a stable rolling granule on the surface of the pin is possible with:

$$(\alpha - \beta) \leq 2 \left( \frac{\pi}{2} - \varphi \right). \quad (12)$$

From (10) we can determine the angular velocity of the reel, where the granule on the pin will be in the ultimate limit state

$$\omega = \sqrt{\frac{g}{R} [f \sin(\alpha - \beta) - \cos(\alpha - \beta)]}. \quad (13)$$

## DISCUSSION

Assuming the design angle  $\beta$  and the angle of discharge reel  $\alpha$ , with known coefficient of friction  $f$  we can determine the optimal value of the coefficient of kinematic mode  $k$ . So, if you take:

$$\alpha = \frac{\pi}{2}, f = 0.3, \beta = 20^\circ,$$

then from (10) we obtain:

$$k = 0.3 \times \sin 70^\circ - \cos 70^\circ,$$

$$k = 0.07.$$

By means of  $k$  in (9), we define:

$$\frac{\omega^2 R}{g} = 0.07,$$

$$\omega^2 = \frac{0.07 \times 9.81}{0.025} = 27.4,$$

$$\omega = 5.2 \text{ s}^{-1}.$$

where

$$R = 0.025 \text{ m} \dots \dots \dots \text{reel radius.}$$

Knowing the angular velocity of the reel it is possible to determine the number of revolutions per minute:

$$\omega = \frac{\pi \times n}{30} = 5.2,$$

$$n = 49.6 \text{ min}^{-1}.$$

It is known, see Turdin (1967), that the volume of material being made of one reel per revolution is equal to:

$$V_k = V_b + V_a, \quad (14)$$

where

$V_b$ ..... working volume of the reel,

$V_a$ ..... volume of the active layer.

The working volume of the reel obviously will be equal to:

$$V_b = V_e - V_i - V_p, \quad (15)$$

where

$V_e$ ..... volume of the reel by outside diameter,

$V_i$ ..... volume of the reel by internal diameter,

$V_p$ ..... volume of the pins.

Here

$$V_e = \pi R_k^2 L,$$

$$V_i = \pi r_k^2 L,$$

$$V_p = \frac{z_p h}{3} (a^2 + b^2 + ab), \quad (16)$$

where

$R_k$ ..... outer diameter of the reel,

$r_k$ ..... inner diameter of the reel,

$L$ ..... length of the reel,

$a$ ..... length of the lower base of the pin (truncated pyramid),

$b$ ..... length of the upper base of the pin,

$h$ ..... height of the pin,

$z_p$ ..... number of pins on the reel surface.

Substituting (16) into (15) we get:

$$V_b = \pi L (R_k^2 - r_k^2) - \frac{z_p h}{3} (a^2 + b^2 + ab). \quad (17)$$

According Turdin (1967), the volume of the active layer can be obtained from:

$$V_a = \pi (R_k + C_r)^2 L - \pi R_k^2, \quad (18)$$

where

$C_r = 3.2 - 5 \text{ mm}$ .... thickness of the active layer.

Taking into account (18) the working volume of the reel (14) takes the form:

$$V_k = \pi L \left[ (R_k^2 - r_k^2) + (R_k + C_r)^2 \right] - \frac{z_p h}{3} (a^2 + b^2 + ab) - \pi R_k^2. \quad (19)$$

At a given application rate of fertilizer for one revolution of the drive wheel should be sown:

$$Q_{1k} = \pi D_{dw} b_a z_{sa} Q \frac{1}{10^4},$$

where

$Q$  ..... given application rate,  
 $D_{dw}$  ... diameter of the drive wheel,  
 $b_a$  ..... width of the aisle,  
 $z_{sa}$  ..... number of seeding devices.

However, considering the density of the fertilizer and the slip of the drive wheel, one device must seeds the amount of fertilizer:

$$V_{1a} = \frac{\pi D_{dw} b_a Q}{10^4 (1-\xi) \rho}, \quad (20)$$

where

$\xi = 0.03 - 0.1$  ..... slip ratio of the drive wheel,  
 $\rho$  ..... fertilizer density.

However, given the transmit ratio between the drive wheel and reel, bulk seed for one revolution of the first will be:

While the working volume of the reel will be:

$$V_k = \frac{\pi D_{dw} b_a Q}{10^4 (1-\xi) \rho i}, \quad (21)$$

where

$i = n_{sa}/n_{dw}$  ..... transmit ratio between the drive wheel and the reels;  
 $n_{sa}$  ..... number of revolutions per minute of the reel;  
 $n_{dw}$  ..... number of revolutions per minutes of the drive wheel.

The expressions (19) and (21) can be equated:

$$\begin{aligned} \pi L \left[ (R_k^2 - r_k^2) + (D_k + C_r) \right] - \frac{z_p h}{3} (a^2 + b^2 + ab) - \pi R_k^2 = \\ = \frac{\pi D_{dw} b_a Q}{10^4 (1-\xi) \rho i}. \end{aligned} \quad (22)$$

Equation (22) connects all major structural and technological parameters. The design parameters include the radius of the reel, the number of pins

on it, and their height and dimensions of the upper and lower bases, the diameter of the drive wheel. Technological parameters are as follows: the application rate, the width of the aisle, transmit ratio.

From the expression (20) can be obtained seeding fertilizer in one revolution of the reel by weight:

$$Q_{1o} = \frac{\pi D_{dw} b_a Q}{10^4 (1-\xi) i}, \quad (23)$$

here

$$i = \frac{n_{sa}}{n_{dw}}, n_{sa} = \frac{30\omega}{\pi}, n_{dw} = \frac{60v_m}{\pi D_{dw}}.$$

Substituting these values into (23) we get:

$$Q_{1o} = \frac{2\pi Q b_a v_m}{10^4 (1-\xi) \omega}, \quad (24)$$

where

$v_m$  ..... traveling speed of the machine.

From the last expression in (24), we can obtain the minimum value of the angular velocity of the reel:

$$\omega_{\min} = \frac{2\pi b_a Q v_m}{10^4 (1-\xi) Q_{1o}}. \quad (25)$$

In general case falling of fertilizer granules from the surface of the pin will begin at (Fig. 8):

$$F = F_c$$

or, taking into account (5) and (7)

$$fmg \sin(\alpha - \beta) = m\omega^2 R_k.$$

We have got finally

$$\omega^2 = \frac{1}{R_k} fg \sin(\alpha - \beta),$$

$$\omega_{\max} = \sqrt{\frac{1}{R_k} fg \sin(\alpha - \beta)}. \quad (26)$$

Therefore, the angular velocity of the reel must be taken in the interval of values (25) and (26).

## CONCLUSION

For a solution of the problem of ensuring quality of application of mineral fertilizers at their intra soil differentiated applying the original design of the pin reel of the seeding device is offered. Pins of the reel are executed in the form of the tetrahedral truncated pyramids located on crossing of the right and left multiple-helical lines on a reel surface. As a result of theoretical researches the expression connecting all key design and technological parameters is received: radii  $R_k$  and  $r_k$  of the reel, number of pins  $z$  on it and their height  $h$  and the sizes of the lower  $a$  and top  $b$  basis, diameter of a driving wheel  $D_{dw}$ , application rate  $Q$ , aisle width  $b_a$  and the transmit ratio  $i$ .

Setting the demanded application rate it is possible to find necessary parameters of the offered seeding device.

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