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STUDY OF THE PERFORMANCE EFFICIENCY PARAMETERS OF A POTATO PLANTING MACHINE

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Abstract. This paper proposes a new design of a potato planter based on a scoop drum. In the study of individual performance parameters of the drum, its kinematic parameters have been substantiated for the first time. A feature of the proposed design is that the torque to the scoop drum is transmitted with a constant gear ratio, and the planting step of the potatoes is adjusted by changing the diameter of a variable-diameter wheel. As a result of calculations, the rotational frequency of the planting drum was established depending on the planting step of the potatoes and the translational speed of the unit. A model was constructed based on which the rotation angles of the drum cells were calculated under the condition of ejecting a single potato during its transportation to the furrow opener. The obtained results form the basis for substantiating other structural elements of the potato planter.

Key words: seed, potato, planting, potato planting machine, potato planter, scoop drum, coulter, seed tube, kinematic parameters, wheel, inertia force, friction force, coefficient of friction, transportation.

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1. INTRODUCTION

The technologies for growing agricultural crops involve many technological operations with varying degrees of labor intensity, especially when manual labor is used. Potato production is one of those areas where manual labor represents a significant share of the total workload. This issue becomes particularly critical in cases of insufficient mechanization of technological processes. This situation is typical mainly for small private farms. Moreover, household farms produce the bulk of the gross potato harvest in Ukraine [1, 20]. Among the most labor-intensive operations in potato production are planting and harvesting. While harvesting has been largely mechanized, planting in small farms is still often carried out manually or semi-manually. To address this shortcoming, there is a need to propose new designs for effective potato planting machines that are simple to use yet technologically efficient.

2. REVIEW OF RECENT RESEARCH AND PUBLICATIONS

An analysis of the market for such machines shows that the industry produces a wide range of brands and types of potato planters, which are quite technologically effective and each has its advantages and disadvantages. However, the issue of the rational design of the potato planting mechanism remains open for researchers and practitioners. The seed metering device is one of the key components of the potato planting mechanism. In practice, many design solutions for such devices can be observed [3–6, 8–10, 12–16, 24] – including elevator-type, cell-disk, cup-disk, tube-finger, pin-disk, spoon-drum with cells, pneumatic types, and others. These devices tend to show that simpler structural designs are usually less effective technologically, while the more effective ones are, conversely, structurally complex and therefore more expensive.

Various solutions and justifications for potato planting mechanism designs can be found in the works of researchers who have developed this topic in particular [2, 7, 11, 13, 21–23, 25].

Therefore, after analyzing the existing solutions, we conclude that there is a need to develop a new design for a drum-type potato planting mechanism within the framework of a patented potato planting method [17].

Based on the newly developed design of a drum-type potato planting mechanism, the objective is to justify the main parameters of its performance efficiency.

3. PRESENTATION OF THE MAIN MATERIAL.

The proposed conceptual solution for a method of potato planting, as outlined in works [17, 18], requires further development in the creation of an effective and simple seed metering device for planting seed potatoes. Before discussing the planting mechanism itself, it is important to note that the design of the potato planting machine is intended for use on small farms and must provide for a variable planting step (spacing) of potatoes in the row. In this context, the issue has been successfully addressed by using a variable-diameter wheel [19] (Fig. 1), which, depending on its configuration, allows the machine to travel different distances per wheel revolution. Accordingly, this enables the establishment of different planting steps for the crop.

Structurally, it is designed so that the minimum diameter of such a wheel will be $D_{\min} = 540$ mm. The diameter adjustment can be performed steplessly, though this somewhat complicates the setup. Therefore, it has been decided that the most practical approach for operational use is to implement discrete adjustment. This is achieved by moving spoke 1 and fixing it in holes 2 of guide rails 3 (Fig. 1, b).

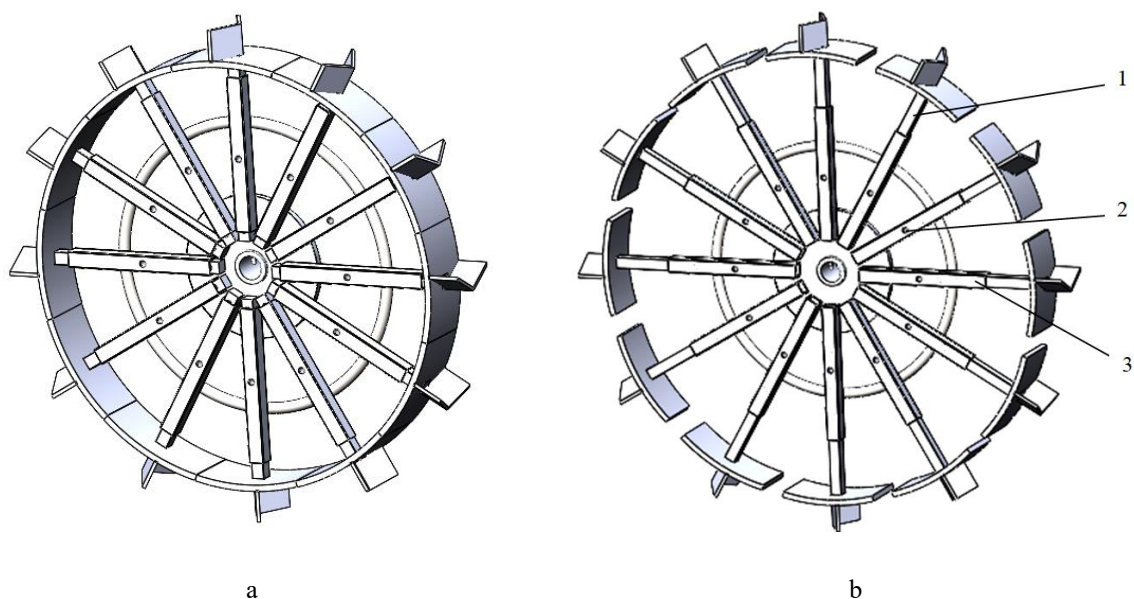


Figure 1. Variable-diameter wheel: minimum rim diameter – a; set increased rim diameter – b

Therefore, by performing such adjustments, the developed wheel design can achieve the following diameters: $D_1 = 540$ mm; $D_2 = 600$ mm; $D_3 = 660$ mm; $D_4 = 720$ mm.

These diameter ranges allow for the most commonly used potato planting steps to be achieved based on the distance the machine travels per one wheel revolution.

Accordingly, we obtain the following travel distances per wheel revolution: $L_1 = 1.696$ m; $L_2 = 1.885$ m; $L_3 = 2.073$ m; $L_4 = 2.262$ m.

Based on the minimum travel distance, we determine that the minimum planting step should be approximately 0.2 m. This can be achieved if the planting mechanism, from a design

standpoint, has fourteen cells for collecting seed potatoes and is connected to the drive axle of the support-drive wheels with a transmission ratio of 1.8.

With this configuration, the following potato planting steps can be achieved:
 $l_{ki} : l_{k1} = 0.218 \text{ m}; l_{k2} = 0.242 \text{ m}; l_{k3} = 0.267 \text{ m}; l_{k4} = 0.291 \text{ m}.$

These planting steps make it possible to cultivate both seed potatoes, which require smaller spacing, and table potatoes, which are planted with larger spacing.

The speed of the potato planting unit will range from 3 to 4 km/h. For preliminary calculations, we will assume a speed of 3.6 km/h (1 m/s).

Based on this, the angular velocity of the potato planting mechanism will be:

$$\omega_i = \frac{\mathcal{G}_M}{r_{ki} \cdot i_n}, \quad (1)$$

where $\mathcal{G}_M$ – is the forward speed of the potato planter;

r_{ki} – is radius of the variable-diameter wheel rim ($r_{ki} = 0.5D_i$);

i_n – is gear ratio from the support-drive wheel shaft to the drive shaft of the planting mechanism.

Hence, the rotational speed of the drum of the potato planting device will be:

$$n_i = \frac{30 \mathcal{G}_M}{\pi r_{ki} \cdot i_n}, \quad (2)$$

Taking into account the specified wheel diameters, we will have the corresponding rotational speeds of the planting drum, n_i : $n_1 = 19.649 \text{ rpm}$; $n_2 = 17.684 \text{ rpm}$; $n_3 = 16.076 \text{ rpm}$; $n_4 = 14.737 \text{ rpm}$.

The change in the rotational speed of the drum of the potato planting apparatus can be modeled for the entire range of the unit's translational speeds ($\mathcal{G}_M = 0.6 \dots 1.7 \text{ m/s}$) and wheel diameter variations ($D_i = 0.54 \dots 0.72 \text{ m}$), Fig. 2.

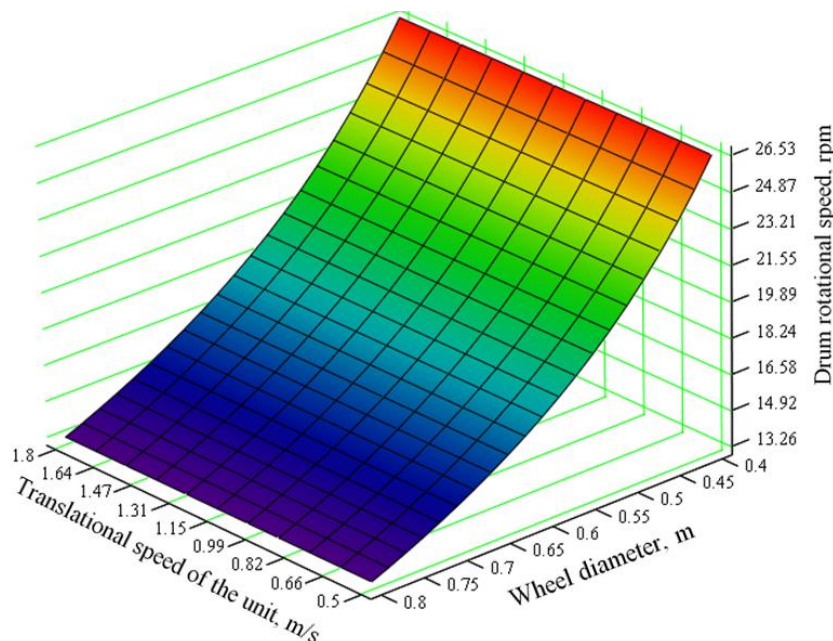


Figure 2. Graph showing the dependence of the planting drum rotation frequency on the unit's translational speed and wheel diameter

According to the analysis of dependence (2) and the graphical representation (Fig. 2), it is evident that the kinematic connection through a constant transmission ratio between the rotation frequency of the wheel shaft and the planting drum eliminates variations in planting step due to deviations of the unit's forward speed from the set value. In this potato planter design, the planting step depends solely on the selected wheel diameter.

The obtained approximate rotation frequencies of the potato planting mechanism serve as the basis for investigating the drum's ability to capture and transport the seed potatoes.

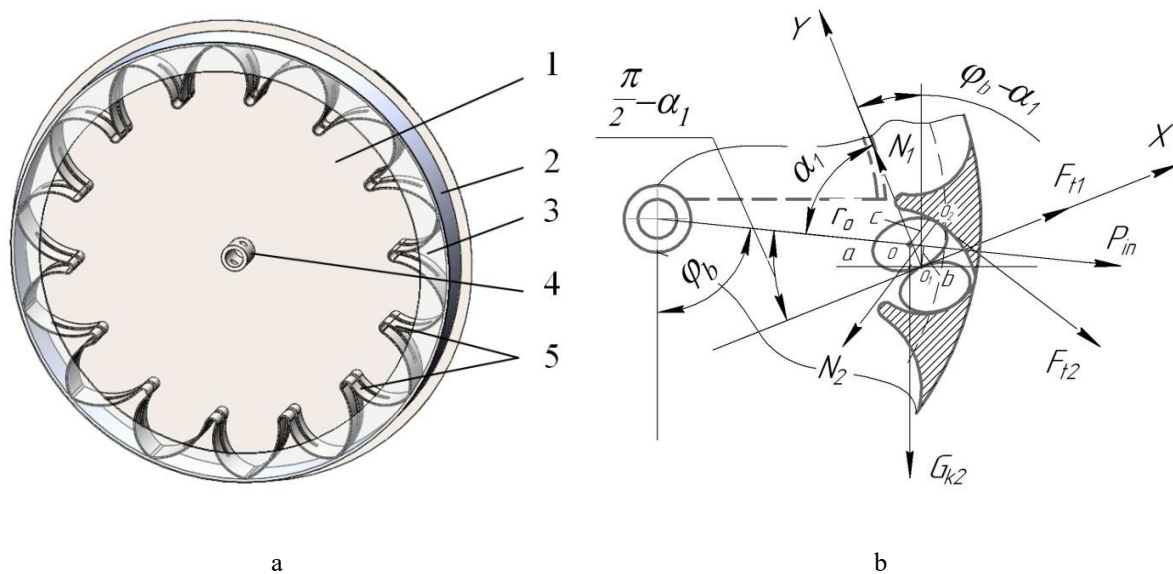


Figure 3. General view of the planting drum – a;
schematic action on the potato – b

The seed metering drum (Fig. 1a) is the main working component of the planting mechanism. It consists of a rear disk (1), a rim (2), a limiting disk (3), a hub (4), and seed metering cells (5).

With this drum design, filling of the seed metering cells (5) with seed potatoes is ensured, as the cells are arranged radially and are confined between the rear (1) and limiting (3) disks (see Fig. 3a). These cells pass under a shallow layer of potatoes supplied from the hopper (the hopper is not shown in Fig. 3a). One of the criteria for effective operation of the seed metering drum is that each cell (5) should deliver a single potato towards the seed tube and furrow opener.

Let us consider a specific case in which two potatoes of approximately the same size enter a single cell of the planting mechanism and remain there together at a certain rotation angle of the drum. Suppose the «extra» potato (potato 2) is held in the cell due to a jamming moment created by the friction force F_{t1} , which arises from the weight of the potato and the inertial force during contact with the cell and the first potato (potato 1), which acts as a support. Potato 1 is expected to remain in the cell and be delivered to the seed tube and furrow opener.

Then the moment equation with respect to point O_1 will be $\sum M_{O_1} = 0$.

In expanded form, we will write it as follows

$$-G_{K2} \cdot a + P_{in} \cdot b + F_{t_2} \cdot c = 0, \quad (3)$$

where G_{K2} – is the weight force of the potato 2;

a – is the moment arm of the force G_{K2} with respect to point O_1 ;

P_{in} – is the inertial force that arises from the rotation of the planting drum and acts at the center of mass of potato 2;

b – is the lever arm of the inertial force;

F_{t_2} – is the frictional force that arises when the potato is wedged by its weight in the cell of the planting mechanism;

c – is the lever arm of the frictional force F_{t_2} .

Another possible case is that potato 2 slips off potato 1.

This will be possible when the component of the weight force of potato 2 is greater than the friction force F_{t_1} and the component of the inertial force.

Let us consider the limiting case where potato 2 is in equilibrium.

By projecting the acting forces onto the X-axis, the equilibrium equation in vector form will be:

$$\overline{G_{K2X}} + \overline{P_{inX}} + \overline{F_{t_1X}} = 0, \quad (4)$$

Moreover, these two equations (3) and (4) can be considered independently of each other.

First, let us consider the condition for potato 2 to slip off potato 1 based on equation (4).

Let us rewrite equation (4) in expanded form:

$$G_{K2} \cdot \sin(\varphi_b - \alpha_1) + P_{in} \cdot \sin \alpha_1 + F_{t_1} = 0. \quad (5)$$

The condition for potato 2 to slip off potato 1 will be

$$G_{K2} \cdot \sin(\varphi_b - \alpha_1) \geq P_{in} \cdot \sin \alpha_1 + F_{t_1} = 0, \quad (6)$$

Let us determine the value of the component G_{K2} at which this condition will be satisfied. First, we will write out the expressions included in inequality (6).

The inertial force acting on potato 2 will be:

$$P_{in} = m_{K2} \cdot \omega_b^2 r_0, \quad (7)$$

where m_{K2} – is the mass of potato 2;

ω_b – is angular velocity of the planting drum;

r_0 – is the distance from the center of rotation of the planting drum to the center of mass of potato 2.

The friction force F_{t_1} will be determined according to the following relation:

$$F_{t_1} = f_1 N_1, \quad (8)$$

where f_1 – is the coefficient of friction that arises at the contact points between potatoes 1 and 2;

N_1 – is normal force that arises at the contact points between potatoes 1 and 2.

The expression for N_1 can be written by projecting the acting forces onto the Y-axis, i.e.

$$N_1 - G_{K2} \cdot \cos(\varphi_b - \alpha_1) - P_m \cdot \cos \alpha_1 = 0, \quad (9)$$

where

$$N_1 = m_{K2} (g \cos(\varphi_b - \alpha_1) + \omega_b^2 r_0 \cdot \cos \alpha_1). \quad (10)$$

Having obtained the main expressions that are part of condition (6), we will analyze the possibility of potato 2 slipping as the parameters change.

Let us rewrite condition (6) in expanded form:

$$g m_{K2} \cdot \sin(\varphi_b - \alpha_1) \geq m_{K2} \omega_b^2 r_0 \cdot \sin \alpha_1 + f_1 m_{K2} (g \cos(\varphi_b - \alpha_1) + \omega_b^2 r_0 \cdot \cos \alpha_1). \quad (11)$$

As we can see, the left and right sides of this expression include the mass of potato 2, which can be canceled out. Therefore, the fulfillment of the condition will depend only on the geometric and frictional parameters of the studied objects.

The geometric parameters will be expressed by the angle α_1 , which relates the geometric dimensions of the potato and the curvature of the planting drum cell.

It follows that the retention or, conversely, slippage of potato 2 from potato 1 will depend on their frictional properties, the angular velocity of the drum, and the combination of the geometric dimensions of the potato with the geometric parameters of the cell, which are characterized by the angle α_1 .

If under the given conditions jamming of the potato occurs in the cell of the planting drum, then it is worth analyzing the drum rotation angle φ_b , which would allow potato 2 to eventually fall out, so that only one potato (potato 1) is transported to the planting furrow.

Thus, after simplification in expression (11), we obtain the final form of the condition for the slippage of potato 2:

$$g \cdot \sin(\varphi_b - \alpha_1) \geq \omega_b^2 r_0 \cdot \sin \alpha_1 + f_1 (g \cos(\varphi_b - \alpha_1) + \omega_b^2 r_0 \cdot \cos \alpha_1), \quad (12)$$

For fixed values of angle α_1 , we will determine the range of values of angle φ_b for which this condition will be satisfied.

We will vary angle φ_b from 0 to $\frac{2\pi}{3}$, and the angular velocity of the drum ω_b will be adjusted according to the selected rotation frequencies corresponding to the planting pitch: $\omega_{b1} = 2.057 \text{ s}^{-1}$; $\omega_{b2} = 1.852 \text{ s}^{-1}$; $\omega_{b3} = 1.683 \text{ s}^{-1}$; $\omega_{b4} = 1.543 \text{ s}^{-1}$.

Under these conditions, and by analyzing separately the left-hand side of inequality (12) (Fig. 4 a), its right-hand side (Fig. 4 b), and establishing the difference between them (Fig. 4 c), we can determine the range of angle values φ_b for which condition (12) will be satisfied.

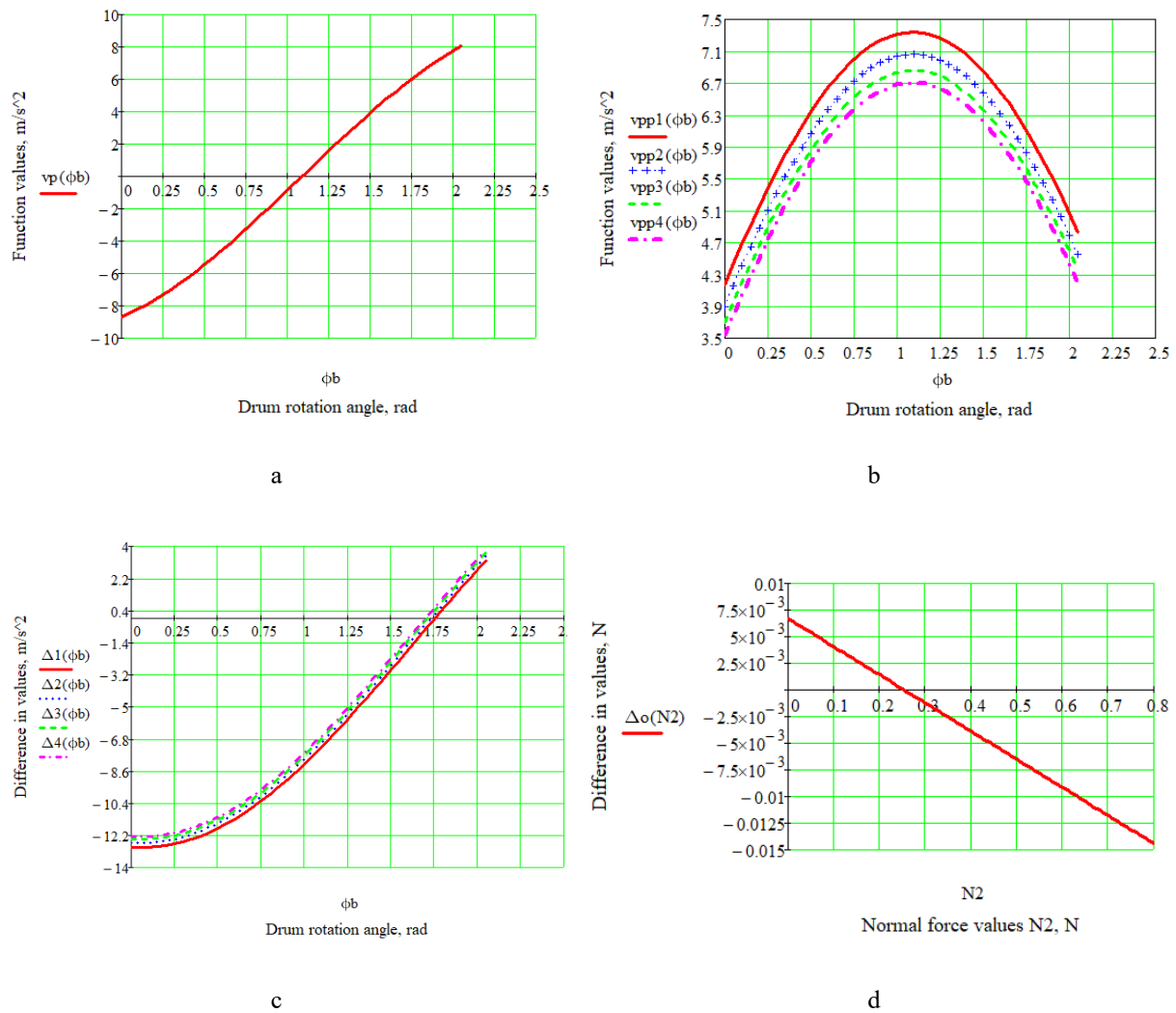


Figure 4. Graphs of the conditions for single potato ejection from the scoop drum cell

Thus, from the graphical dependencies (Fig. 4c), it is evident that the slippage of potato 2 is possible within the range of rotational angles of the planting drum relative to the vertical axis in the following limits: at the lowest rotation speed – $\varphi_b = 97.4^0$; and at the highest rotation speed – $\varphi_b = 100.8^0$. It is worth noting that the presented rotation angle is determined for the specifically considered cell filled with seed, and under conditions defined by the angle α_1 and friction coefficient f_1 . For other conditions, the initial data should be refined, but the same method can be applied.

Determining the range of angles at which the «extra» potato falls out is necessary for the next stage of research, namely establishing the position of the lower drum stop that forms the channel through which the potato is transported to the discharge zone into the seed tube.

Now, let us return to condition (3). If potato 2 rolls over potato 1 and remains held in place due to a jamming moment that arises from the friction force F_{t2} .

This case is valid only when the coefficient of friction f_1 between the potatoes reaches its maximum value.

This case is valid when the coefficient of friction between the potatoes has its maximum value. Let us rewrite condition (3) in expanded form:

$$-m_{K2}ga + m\omega_b^2 r_0 b + f_2 N_2 c = 0, \quad (13)$$

where f_2 – is the coefficient of friction between potato 2 and the material of the cell of the planting mechanism;

N_2 – is the normal force arising from the pressure of potato 2 against the wall of the cell of the planting drum.

The condition for potato 2 to fall out while rolling over potato 1 will be:

$$m_{K2}ga \geq m\omega_b^2 r_0 b + f_2 N_2 c. \quad (14)$$

The complexity in solving this inequality lies in the fact that potatoes have surfaces with non-ideal geometric shapes, which are theoretically difficult to describe. Moreover, each potato has a unique shape.

Therefore, the evaluation of inequality (14) will be carried out approximately, using experimental data. Let us consider a specific case in which two conditionally identical potatoes, each approximately 80 g and elliptically shaped, enter the same cell as shown in Fig. 3 b.

In this case, the lever arms a , b , and c are determined at the point O_1 of contact between potatoes 1 and 2. Under such conditions, the normal force N_2 , which creates the friction force F_{t2} , and consequently the torque from this friction force that prevents potato 2 from rolling (over potato 1), remains unknown.

We will approach this local problem in an approximate manner by reasoning «from the opposite».

That is, under these conditions, we will determine the torques generated by the weight and inertial force of potato 2 and add the torque from friction, then impose the condition for inequality (14) to be satisfied.

For such a local estimate, we will select one of the drum rotation angles within the sector where the «extra» potato may fall from the cell, and track the magnitude of the friction torque, estimating it through the normal force N_2 .

Based on the previously determined parameters, we construct a graphical dependency (Fig. 4 d) under the condition of the possibility for potato 2 to roll off, with the torque ($G_{K2} \cdot a$) created by the weight of potato 2 opposed by the torques from the inertial force ($P_{in} \cdot b$) and friction force ($F_{t2} \cdot c$).

From the analysis of the graph in Fig. 4d, it is evident that the «extra» potato may fall out until the normal force N_2 exceeds approximately 0.3 times the weight of potato 2. If the normal force N_2 becomes greater than this calculated value, then potato 2 will not freely fall out by rolling over potato 1. Instead, it will become jammed and continue to move within the cell together with potato 1 until it collides with the lower stop of the drum, which forms a guiding channel that allows only one potato to pass, limited by the height of the seed metering drum's cell. In the case of critical jamming of two small potatoes in the cell and their compacted entry into the guiding channel, they will no longer fall into the seed tube and furrow opener under their own weight. Therefore, the design of the seed metering drum includes a passive ejector. Its role is to forcibly push potatoes out of the drum's cells.

The ejector is mounted on the hopper housing and passes through slots in the plates that form the profile of the planting drum's cell.

4. CONCLUSIONS

Based on the newly developed design of the drum-type potato planting mechanism, a number of its parameters were substantiated.

A structural-kinematic relationship was established between the length of the rim of the variable-diameter wheel and the planting step of the potato planter. According to the adopted design of the support-drive wheel, the rim diameter D_i will be ensured in the following sizes: $D_1 = 540$ mm; $D_2 = 600$ mm; $D_3 = 660$ mm; $D_4 = 720$ mm. With the seed metering unit designed to have fourteen cells and with a fixed transmission ratio $i_n = 1.8$ from the wheels to the metering mechanism, the following potato planting steps were obtained: $l_{k1} : l_{k1} = 0.218$ m; $l_{k2} = 0.242$ m; $l_{k3} = 0.267$ m; $l_{k4} = 0.291$ m.

The forward speed of the unit ranges from 3 to 4 km/h, and for this calculation, a speed of 3.6 km/h (1 m/s) was used. Based on this, the rotation frequencies of the planting drum, corresponding to the planting steps, were determined as: $n_1 : n_1 = 19.649$ rpm; $n_2 = 17.684$ rpm; $n_3 = 16.076$ rpm; $n_4 = 14.737$ rpm.

When analyzing the conditions for a single potato to be delivered by the planting mechanism's cells, it was determined that for the "extra" potato to slip out, the drum's rotation angle φ_b relative to the vertical axis for the analyzed cell should be: at the lowest rotation speed – $\varphi_b = 97.4^\circ$; at the highest – $\varphi_b = 100.8^\circ$.

Considering the case where the second potato rolls over the first and is held in place due to a jamming moment created by frictional force F_{t2} , it was found that ejection is possible up to the point where the normal force N_2 increases to approximately 0.3 times the weight of the second potato. Otherwise, both potatoes will move together until the «extra» potato strikes the drum's lower stop, which forms a guiding channel.

Thus, the obtained kinematic and structural parameters of the planting drum allow for the selection of a rational kinematic operating mode for the mechanism and ensure a high-quality potato planting process.

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ДОСЛІДЖЕННЯ ПАРАМЕТРІВ РОБОТОЗДАТНОСТІ КАРТОПЛЕПОСАДКОВОГО АПАРАТУ

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Резюме. Вирощування картоплі має складний технологічний процес виробництва, який сповнений великою питомою часткою ручної праці. Особливо це є вираженням при посадці картоплі у невеликих господарствах. Причиною є недостатній рівень механізації технологічних операцій, що спонукає дослідників продовжувати пошук нових та ефективних конструкцій картоплепосадкових машин. Основним напрямком таких досліджень є пошук раціональної та простої конструкції картоплепосадкового апарату, а саме, вичерпуючого апарату. Тому в роботі запропоновано нову конструкцію вичерпуючого апарату барабанного типу, який буде в системі картоплепосадкової машини, що працює за запатентованим способом посадки картоплі. Особливістю запропонованої конструкції вичерпуючого барабану є те, що його вичерпуючі комірки розміщені радіально та обмежені двома дисками. Комірки проходять під невеликим шаром картоплі, що дозволяє їм гарантовано заповнюватися насінням. Але разом з тим виникає проблема виносу одиночної картоплини до насінепровода і сошника. Тому для такого апарату було обґрунтовано його кінематичні параметри, що забезпечують заданий крок посадки, який дискретно змінюється та становить 0,218 м, 0,242 м, 0,267 м, 0,291 м. Такий крок забезпечується при сталому передаточному числі 1.8 частот обертання вала опорно-приводних коліс і вала посадкових апаратів та за рахунок спеціально розробленого колеса змінного діаметра. Розглядаючи умови виносу одиночної картоплини комірками посадкового апарату, встановлено, що за умови зісковзування «зайвої» картоплини з «основної», що виноситься коміркою, кут повороту барабана відносно вертикальної осі для розглядуваної комірки повинен складати при найменшій частоті обертання – $97,4^{\circ}$; при максимальній частоті – $100,8^{\circ}$. При розгляді умови, коли «зайва» картоплина буде обкочуватися по «основній» та втримуватися за рахунок моменту заклинювання, який виникає від сили тертя, встановлено, що її випадання можливе до межі збільшення нормальної сили на стінку комірки, яка складає приблизно 0,3 ваги «зайвої» картоплини. В іншому випадку обидві картоплини рухатимуться разом, до моменту співударяння «зайвої» картоплини з нижнім обмежувачем барабана, що утворює направляючий канал. Таким чином, отримані значення кінематичних та конструктивних параметрів посадкового барабана дозволяють підібрати раціональний кінематичний режим роботи даного апарату та забезпечити якісний процес посадки картоплі.

Ключові слова: насіння, картопля, посадка, картоплесаджалка, картоплепосадковий апарат, вичерпуючий барабан, сошник, насінепровід, кінематичні параметри, колесо, сила інерції, сила тертя, коефіцієнт тертя, транспортування.

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