Determination of the optimal incline angle of the incision of the cutting machine of the tuber grinder of potatoes

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Abstract. For research, we used a root crop grinder with improved operational properties, which ensures the grinding of juicy vegetable raw materials (fodder, sugar and semi-sugar beets, rutabaga, turnips, carrots, potatoes) into pieces in the form of a parallelepiped of sizes corresponding to zootchnical requirements. The rationale for the action of forces on tubers in a stationary reference system in the process of cutting potatoes is given, the shape of which, with some assumption, is accepted as a ball. Based on the laws of mechanics, the authors obtained an analytical expression of the value of the optimum angle of inclination of the contradiction of the cutting apparatus of a particular chopper, depending on the size of the tuber, the height of the horizontal knife and the coefficient of friction. Given the values of these parameters, it is possible to fully carry out a theoretical and practical analysis of the limiting value of the angle of inclination of the contradiction of the cutting apparatus and its effect on the rolling of the tuber, as well as on its pinching.

1. Introduction
The use of root crops, tubers and fruits in the diet of animals is of great importance in achieving their productivity due to the high specific volume energy and good digestibility. For the preparation of feed in accordance with the zootchnical requirements, the most common process is the grinding of raw materials and the use of grinders with scientifically based design and technological parameters. A review of modern designs of feed choppers [1]-[5] showed that they differ from each other in the arrangement of working bodies and the degree of grinding of the material. The most promising, in our opinion, are two-stage choppers of potato tubers with a vertical arrangement of the chopping organ, roller support and flat knives mounted around the circumference.

One of the problems in the process of cutting solid raw materials is the rolling of tubers through a knife or their excessive pinching [6], which leads to increased release of juice from tubers. To solve this problem, the research goal was formulated: to determine the optimal angle of incidence of the contradiction of the cutting apparatus of the feed chopper depending on the size of the tuber, the height of the horizontal knife and the friction coefficient, at which the tuber is not rolled through the horizontal knife, and pinching does not result in crushing of the tuber.

2. Materials and methods
To study the process of potato tubers, an experimental shredder was used [1], [7]. In the installation, the vertical knives are mounted rigidly at an angle of 90° to the axis of the horizontal plane of the horizontal
knives, with the formation of vertical windows formed from above by the plane of the horizontal knife, below by the plane of the disk, and left and right by the planes of vertical knives, figure 1. The countercutter has the ability to interact with horizontal and vertical knives. The tuber, falling from the loading hopper onto the disk and, when interacting with the contradiction, is evenly distributed on its end surface and is processed. Horizontal and vertical knives exert a force on the product, resulting in its separation into pieces in the shape of a parallelepiped, one of the faces of which corresponds to the profile of the windows formed by the surfaces of the parts of the cutting apparatus.

Figure 1. Potato tuber chopper:
1 - motor shaft; 2 - a vertical knife; 3 - horizontal knife;
4 - cylindrical housing, which at the same time is a receiving hopper;
5 - contradictions; 6 - disks with knives; 7 - unloading hopper; 8 - throws.

Consider the moment of tuber pinching between horizontal, vertical knives and the counter, corresponding to the beginning of the cutting of the tuber figure 2. The quality of the cutting process is significantly influenced by the angle of inclination of the counter $\alpha$, which determines the moment of jamming of the tuber. When touching raw materials with a contradiction, a normal pressure reaction $P$ of the contradiction to the tuber occurs. At this moment, the total cutting forces from the horizontal $R_h$ and vertical knives $R_v$ and the friction forces arising on the surface of the contradiction $F_{fr}$ and the vertical knife $F_{fr1}$ also act on the tuber. In addition, in this case, the tuber gravity $G$ and the normal reaction of the $N$ disk, figure2. As a result, we get an arbitrary flat system of forces acting on the tuber.

Let us analyze the process of cutting solid raw materials on the example of potatoes, the shape of the tuber of which, as an assumption, we will take in the form of a ball of radius $r$. According to the theorems of statics [8], we compose the equation of the sum of the moments of all the forces acting on the tuber, relative to point $O$, the tangent point of the horizontal tuber knife:

$$
\sum_{k=1}^{m} m_{ok} = G \cdot r \cdot \cos \varphi - N \cdot r \cdot \cos \varphi + F_{hr} \cdot r \cdot \cos \alpha \cdot (\cos \alpha + \sin \varphi) + F_{hr} \cdot r \cdot \sin \alpha \cdot (\sin \alpha + \cos \varphi) - \\
- P \cdot r \cdot \sin \alpha \cdot (\cos \alpha + \sin \varphi) + P \cdot r \cdot \cos \alpha \cdot (\sin \alpha + \cos \varphi) = 0,
$$

(1)
where \( \phi \) - cutting angle of the horizontal knife.

At the moment the tuber begins to move, the reaction force of the support \( N \) will be infinitesimal, and the friction forces determined by the equalities

\[
F_{tr} = f \cdot P, \quad F_{tr} = fR_h,
\]

where \( f \) - coefficient of friction, reach the maximum value.

![Figure 2. Pinching of tubers vertically, horizontal knives and counter.](image)

In the limit equilibrium \([9]\), when the force of the contradiction is many times greater than the gravity of the tuber \( P >> G \), equation (1) takes the form

\[
F_{tr} \cdot r \cdot \cos \alpha \cdot (\cos \alpha + \sin \phi) + F_{tr} \cdot r \cdot \sin \alpha \cdot (\sin \alpha + \cos \phi) - P \cdot r \cdot \sin \alpha \cdot (\cos \alpha + \sin \phi) + P \cdot r \cdot \cos \alpha \cdot (\sin \alpha + \cos \phi) = 0.
\]

After dividing both sides of the resulting equation by \( P \), taking into account equalities (2), we will have

\[
f \cdot r \cdot \cos \alpha \cdot (\cos \alpha + \sin \phi) + f \cdot r \cdot \sin \alpha \cdot (\sin \alpha + \cos \phi) - r \cdot \sin \alpha \cdot (\cos \alpha + \sin \phi) +
\]

\[
+ r \cdot \cos \alpha \cdot (\sin \alpha + \cos \phi) = 0.
\]

From the geometry of figure 2 the equalities are true:

\[
r \cdot \sin \phi = r - h, \quad r \cdot \cos \phi = \sqrt{2rh - h^2},
\]

where \( h \) is the take-off height of the horizontal knife. Taking into account expressions (4) and the reduction of such terms, equation (3) is written

\[
f \cdot r + \cos \alpha \left( f \cdot (r - h) + \sqrt{2rh - h^2} \right) + \sin \alpha \left( f \cdot \sqrt{2rh - h^2} - (r - h) \right) = 0
\]

If we introduce the notation
\[ A = f \cdot (r - h) + \sqrt{2rh - h^2}, \quad B = f \cdot \sqrt{2rh - h^2} - (r - h), \]  
\[ f \cdot r + A \cdot \cos \alpha + B \cdot \sin \alpha = 0 \]

then equation (5) is reduced to the trigonometric equation

functions of the same argument \( \alpha \), corresponding to the optimal value of the incline angle of the contradiction of the considered chopper, at which the tuber will not roll and be destroyed by collapse.

Using universal trigonometric substitution \[10\]

\[ t = \tan \frac{\alpha}{2}, \quad \sin \alpha = \frac{2t}{1 + t^2}, \quad \cos \alpha = \frac{1 - t^2}{1 + t^2}. \]  

and the corresponding algebraic transformations, equation (7) is reduced to an ordinary quadratic equation of the form

\[ (fr - A) \cdot t^2 + 2t \cdot B + (fr + A) = 0 \]

which under the condition \( A^2 + B^2 > f^2 r^2 \) has real roots

\[ t_{1,2} = \frac{-B \pm \sqrt{B^2 - (f^2 r^2 - A^2)}}{fr - A}. \]

Then the desired angle is determined by the expression

\[ \alpha = 2\arctan \left[ \frac{-B \pm \sqrt{B^2 - (f^2 r^2 - A^2)}}{(fr - A)} \right]. \]

**Figure 3.** Graphs of the dependences of the angle of inclination of the cutter on the friction coefficient for various combinations of the height of the horizontal knife \( h \) and the tuber radius \( r \).
3. Results and discussion
After carrying out theoretical calculations, an analytical expression (9) was obtained, which determines the optimal value of the angle of inclination of the contradiction, from which it is possible to construct graphs of the dependences of the angle of inclination of the contradiction on the friction coefficient for various combinations of the height of the horizontal knife h and radius tuber, figure 3.

Analyzing figure 3, it should be noted that with an increase in the coefficient of friction, the angle of inclination of the contradiction decreases. When the angle α tends to 90°, the destruction of the tuber by crushing and the release of juice from the cut pieces of the tuber is manifested to a lesser extent, which is confirmed by studies [11-15].

When changing the height of the horizontal knife from 10 mm to 20 mm in increments of 2 mm, the range of values of the optimal angle of inclination of the contradiction with a tuber of radius 30 mm and a friction coefficient from the interval 0.1-0.5 ranged from 73° to 87°.

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