Reducing damage of melons and gourds during automated harvesting

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Abstract. Agricultural enterprises where harvesting is manual contribute significantly to the production of cucurbit crops in modern economic conditions. Their low automation level of harvesting is explained by the absence of modern highly productive machine-harvesters. The goal of the present study is to model the process, wherein cucurbit crops roll in on the floating skid of the guide of a pickup platform without being damaged. An analytical model was composed in order to model the process of interaction between the crops and the floating skid, which allowed to carry out the theoretical substantiation of the technical process. The study carried out resulted in modeling the technical process, wherein crops roll on the floating skid of the guide of a platform, as well as in a theoretical substantiation of the condition, at which the force of impact interaction between a crop and the floating skid must not exceed the ultimate pressure on a crop, which would result in its destruction. The value of this force depends above all on the strength properties and the size and weight characteristics of crops, as well as on the kinematic and structural parameters of the rolling-in device.

1. Introduction

Volgograd Region is amongst the key regions-producers of cucurbit crop cultures in Russia. Market sowing of cucurbit crops is localized to agricultural enterprises, farming companies, and major specialized farms for growing cucurbit crops in the Region. Each of them has its own specific production conditions of harvesting and storing the harvest, as well as different material and technical resources, and production experience. The square occupied by cucurbit crops is therewith at most 20 ha in most agricultural enterprises. Harvesting in such minor squares is carried out manually nearly everywhere [1]. The costs for manual labour for harvesting take up 40 to 60% of all the costs for growing these cultures in the structure of the prime cost of cucurbit crops [2]. The low automation level of the harvesting process is explained by the absence of modern highly productive machine-harvesters, the use of which would allow to decrease considerably the prime cost of the products obtained [3, 4, 5]. Previously developed melon field machine-harvesters are not virtually manufactured, but even these did not comply with the agrotechnical requirements under the quality parameters [6].

Therefore, a necessity to create a rotor machine-harvester has arisen, which would guarantee the obtaining of cucurbit crops products of high quality at the least costs [6]. The goal of our studies is to model the process, wherein cucurbit crops roll in on the floating skid of the guide of a pickup platform without being damaged.
2. Materials and methods
The analysis of the techniques and methods used nowadays for harvesting cucurbit crops, which we carried out, has demonstrated that total automated harvesting, which is performed along the field for a single pass, with the quality control of the crops at a stationary point, has the most efficiency in terms of quality and productivity of the technical process [7]. In order to introduce this prospective technology, a towed rotor pickup was developed, which carries out harvesting of ripe cucurbit crops in an aggregate with a tractor in a quality manner and guarantees the conformity with all the technical requirements specified for this type of machines [8]. The operating tool is designed in this machine as two honeycomb rotors, which rotate towards each other and seize and displace crops into the middle part of the machine, and then lift them on the platform and move them on the loading conveyor. The flow diagram of the rotor pickup proposed differs essentially from the conventional designs of picking-up devices so that picking up and loading crops are carried out without prior making rolls, which decreases significantly the costs and damage to the crops [9, 10].

The object of study we have considered is the technical process of picking up cucurbit crops by a harvesting rotor. When modeling the process, wherein cucurbit crops roll in on the floating skid of the guide of a pickup platform, the following assumptions were admitted: the rotor pickup moves evenly and rectilinearly; the harvesting rotors rotate at a constant angular velocity; the high of lifting crops on the platform does not vary in the course of harvesting; we admit the diameter and weight of the crops equal to the maximum value, and the shape of the crops as spherical.

3. Results and discussion
The theoretical researches carried out before have demonstrated that the technical process of picking up crops by the rotor pickup developed represents a sequence of operations, which are followed by each other, during which interaction between a blade of the harvesting rotor and a crop takes place: seizing of a crop by the blade, rolling it into a crop-receiving cell and moving along the field, rolling it in on the floating skid of the crop guide, lifting it on the platform, and releasing from the cell.

As a result of the theoretical substantiation of the interaction between cucurbit crops cultures and the operating tool of the pickup, it was found out that, after a crop is seized by a blade of the harvesting rotor and rolls into its crop-receiving cell, it is moved under the impact of impelling force $P_i$ along the surface of the field at speed $V_C$ in the direction towards the platform and spins therewith with angular velocity $\omega_C$ [11, 12].

The model of the motion of a crop, which performs a flat movement when this operation is carried out, can be presented as a rolling motion of a pseudo free ball-shaped body along a horizontal surface without gliding, with an instant speed center in point $P$, and the crop itself can be presented as a homogenous ball with weight $m$ and radius $r_C$. The next operation, which is carried out when cucurbit crops cultures are picked up, is rolling in crops on the guide, which is installed on the front bar of a platform and consists of separate floating skids (Figure 1) assembled so that it is possible for them to move freely in the vertical plane. Floating skids 1 are designed in the form of a horizontal section with thickness $h_{FS}$, which goes by the radius into the sloping section, which is installed at the angle coinciding with angle $\alpha$ of the slope of the platform to the horizon. Regulated support 2 is installed under each floating skid, which limits its sinking when the ground profile is copied or the platform is lifted into the transport position. The front bar and the regulated support of the platform are covered with delivery tray 3 at the top, in which slots are made in order to move the bars of the floating skid.

When the blades of the harvesting rotor rotate, the crops are moved to the platform and their contact with the floating skid takes place in point $A$ (Figure 2). At the moment of this contact, the center of the linear velocities of the crop points instantly moves from point $P$ to point $A$. In this case, the contact between the crop and the rolling motion surface disappears in point $P$ and the crop can be considered as a free body as the impact impulse coincides with the impulse of the supporting force in contact point $A$. 
Let us admit in terms of reducing the damage rate of the crops that a perfectly inelastic collision without a bounce, with coefficient of restitution $K = 0$, occurs at the moment of the contact between a crop and the floating skid.

![Diagram of interaction between a crop and the floating skid of the guide.](image)

**Figure 1.** The crop guide design: 1 – floating skid; 2 – regulated support; 3 – delivery tray.

The only support of the crop therewith shall be the edge of the floating skid (contact point $A$), which creates reaction $R$ preventing the crop from spinning. The line of action of this reaction will
pass through center of the crop \( O \) at angle \( \gamma \) between the vertical axis of the crop and the radius, which joins contact point \( A \) to center of the crop \( O \).

This angle \( \gamma \) can be determined from right-angled triangle \( OAK \), hypotenuse \( OA \) of which equals crop radius \( r_c \) and cathetus \( OK = r_c - h_{FS} \), from the expression:

\[
\gamma = \arccos \frac{r_c - h_{FS}}{r_c},
\]

where \( h_{FS} \) means the thickness of the floating skid, m.

The interaction between the crop and the floating skid results in the transformation of its flat motion into a spinning motion around contact point \( A \), which will have an impact character since the interaction time is little at this transformation. The horizontal trajectory of the motion of crop center \( O \), which was before the moment where the crop met the floating skid, goes therewith to the new trajectory of motion along the radius in relation to contact point \( A \) when the impact takes place. The trajectory of the motion of crop center \( O \) will be a horizontal line again only after point \( O_1 \) goes on vertical line \( O_1A \).

Hence, it follows that the rotational energy of a crop in relation to its own geometrical axis \( O \) is completely lost at the moment of impact of a free crop on the floating skid and the linear velocity of the crop center of mass \( V_c \) will change its direction as a result of the contact and it will become equal to \( U_c \) after the impact and angular rolling velocity of the crop \( \omega_c \) transforms into angular spin rate \( \omega_s \) of the crop around point \( A \) after the impact.

Let us determine a change in the kinetic momentum for the mechanical system “crop – floating skid” regardless of the proper rotation of the crop when it rolls in on the floating skid. Arbitrarily, let the axis, in relation to which a change in the kinetic momentum is formulated, pass through contact point \( A \) perpendicularly to the drawing plane.

Kinetic momentum \( K_M^1 \) before the impact is determined from the expression:

\[
K_M^1 = m v_c (r_c - h_{FS})
\]

After the impact, kinetic momentum \( K_M^2 \) is written as:

\[
K_M^2 = m u_c r_c
\]

The kinetic momentum of the mechanical system “crop – floating skid” before and after the impact will not change as the impact pulses will not create a momentum in relation to contact point \( A \) between the crop and the floating skid, i.e., we shall obtain the equality of expressions (2) and (3):

\[
m v_c (r_c - h_{FS}) = m u_c r_c
\]

Considering that the linear velocity of the crop equals \( V_c = \omega_c r_c \), and \( U_c = \omega_s r_c \), expression (4) will be as follows:

\[
m \omega_c r_c (r_c - h_{FS}) = m \omega_s r_c^2
\]

After the transformation of this equality, we shall obtain angular spin rate \( \omega_s \) of the crop around contact point \( A \):

\[
\omega_s = \omega_c \left(1 - \frac{h_{FS}}{r_c}\right)
\]

The model, wherein a free crop rolls in on the floating skid of a guide, which is presented in expression (6), demonstrates that if the thickness of the floating skid and the radius of a crop are equal, \( h_{FS} = r_c \), a direct impact occurs, wherein the kinetic energy of the motion of the crop is completely absorbed, which results in the crop stopping to spin in relation to contact point \( A \).

If the thickness of the floating skid is much less than the radius of a crop, \( h_{FS} \ll r_c \), an insignificant loss in the kinetic energy occurs, and the force interaction between the crop and the floating skid will be in this case characterized by impact pulse \( S_A^x \), which will allow us to obtain horizontal \( S_A^x \) and vertical \( S_A^y \) projections of this pulse, after being expanded along axes \( X \) and \( Y \) [13].

By using the momentum theorem, we shall find the projection of impact pulse \( S_A^x \) on axis \( OX \) by the expression:

\[
-S_A^x = m u_c^x - m v_c^x
\]

and the projection of impact pulse \( S_A^y \) on axis \( OY \):

\[
S_A^y = m u_c^y - m v_c^y
\]
By using the diagram, which is set out in figure 2, we shall find the projections of velocity vectors \( U_C \) and \( V_C \) on axes \( OX \) and \( OY \) and use them in expressions (7) and (8):

\[
-S_A^X = m \ u_C \cos \gamma - m \ v_C \tag{9}
\]

\[
S_A^Y = m \ u_C \sin \gamma - 0 \tag{10}
\]

By using them in expressions (9) and (10) \( V_C = \omega_C \ r_C \) and \( U_C = \omega_S \ r_C \), we shall obtain the constituents of the impact pulse:

\[
S_A^X = m \ r_C (\omega_C - \omega_S \cos \gamma) \tag{11}
\]

\[
S_A^Y = m \omega_S \ r_C \sin \gamma \tag{12}
\]

The modulus of resulting impact pulse \( S_\Lambda \), which effects on the crop on the side of the floating skid, is determined by the expression:

\[
S_\Lambda = \sqrt{(S_A^X)^2 + (S_A^Y)^2} \tag{13}
\]

With regard to expressions (11) and (12), we shall obtain:

\[
S_\Lambda = \sqrt{m^2 r_C^2 (\omega_C - \omega_S \cos \gamma)^2 + m^2 \omega_S^2 r_C^2 \sin^2 \gamma} \tag{14}
\]

By performing the conversion of this expression, after the extraction of the root, we shall obtain the modulus of the resulting impact pulse:

\[
S_\Lambda = m r_C \omega_C \sin \gamma \tag{15}
\]

In order to determine the force of impact interaction of a crop, which results in reaction \( R \) of the floating skid, let us use H. Hertz formula, which determines the relation between the impact force and the deformation of bodies coming into collision in the contact area:

\[
R = K_a^{3/2} \tag{16}
\]

where \( K \) means the coefficient, which depends on the properties of the material and the curvature of their surfaces in the contact area; \( a \) means the value of the resulting deformation of the crop and the floating skid.

As the material of the floating skid is considerably harder than the material of a crop, the deformation of the floating skid can be neglected and coefficient \( K \) will be determined by the following expression:

\[
K = \frac{4E\sqrt{R^*}}{3(1-\mu^2)} \tag{17}
\]

where \( E \) means the elastic modulus of the crop; \( \mu \) means Poisson coefficient; \( R^* \) means the equivalent radius.

Given that a crop on the contact surface has a sphere with radius \( r_C \), and the floating skid has a sphere with radius \( r_{FS} \), which equals \( h_{FS}/2 \) on the contact surface, the expression to determine the equivalent radius \( R^* \) is given by:

\[
R^* = \sqrt{\frac{r_C^2 h_{FS}}{r_C^2 + h_{FS}^2/4}} \tag{18}
\]

A deformation of a crop and a displacement of the center of gravity takes place in the process, wherein the crop hits on the floating skid when the relative velocity has its initial value \( v_o \). If counting these displacements from the moment of the contact between the crop and the floating skid, maximum deformation of the crop \( a_{max} \) will be determined by the expression:

\[
a_{max} = \left( \frac{5m}{4K} v_o^2 \right)^{2/5} \tag{19}
\]

By using expressions (17) and (19) in expression (16) and performing conversions, we shall obtain maximum impact force of the crop on the floating skid \( R_{max} \):

\[
R_{max} = \left( \frac{4E\sqrt{R^*}}{3(1-\mu^2)} \right)^{2/5} \left( \frac{5m}{4} v_o^2 \right)^{3/5} \tag{20}
\]

By substituting the product of mass \( m \) and relative velocity \( v_o \) with the value of resulting impact pulse \( S_\Lambda \), which is determined by expression (15) in this expression, we shall obtain:
The floating skid must not exceed the maximum pressure on a crop, which does not result in its destruction, N

\[ R_{\text{max}} = \left( \frac{4E\sqrt{R}}{3(1-\mu^2)} \right)^{2/5} \left( \frac{5(s_{\text{c}}^2)}{4m} \right)^{3/5} = \left( \frac{4E\sqrt{R}}{3(1-\mu^2)} \right)^{2/5} \left( \frac{5m r_c^2 \omega^2 \sin^2 \gamma}{4} \right)^{3/5} \]  

The value of this force is limited to the strength properties of crops [14, 15] and must not result in damage thereto, consequently:

\[ R_{\text{max}} = \left( \frac{4E}{3(1-\mu^2)} \right)^{2/5} \left( \frac{r_c^4 \sin^2 \gamma}{4} \right)^{3/5} \leq P_{\text{CP}} \]  

where \( P_{\text{CP}} \) means the maximum pressure on a crop, which does not result in its destruction, N.

4. Conclusion

The study carried out resulted in a model of the technical process, wherein crops roll in on the floating skid of the guide of a platform, and in the theoretical substantiation of the condition, at which the force of impact interaction between a crop and the floating skid must not exceed the maximum pressure on the crop, which would result in its destruction. The value of this force depends above all on the strength properties and the size and weight characteristics of crops, as well as the kinematic and structural parameters of the rolling-in device.

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