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SUBSTANTIATION OF CAPACITY OF SCREW CONVEYER OF HAULM-CUTTING MODULE

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Summary. The haulm-cutting module parameters based on the analysis of technological process of displacement of the plant components cut by a spiral conveyor have been substantiated in the article. Technological interrelation between structural-kinematic parameters of screw conveyor and per-second feed of plant components has been found dealing with the required capacity. To provide the best running of screw conveyor of haulm-cutting module the rational parameters of its process operation have been set.

Key words: haulm-cutting module, screw (spiral) conveyor, auger, per-second feed, haulm.

INTRODUCTION

Sustainable development of agricultural-industrial complex of Ukraine and world is impossible without development and introduction absolutely new and progressive methods which allow to create efficient technical facilities for agricultural crops seeding, cultivating and harvesting [1, 2]. Haulm removing of sugar beet crowns is one of the most work- and power-consuming processes at their harvesting. As Ukraine is one of the leading beet growing countries in the world, it’s necessary to produce beat harvesters by national machine building industry according to the highest world standards [3-6].

ANALYSIS OF RESEARCHES AND PUBLICATIONS

Analytical-applied model of supply of the plant components of beet crowns cut by a haulm-cutting module of a spiral conveyor has been developed and per-second feed change limits of plant components have been found on the analytical level which are used to calculate the screw conveyor capacity [7, 8].

OBJECTIVES OF RESEARCH

To formalize the process of displacement of the cut by haulm-cutters beet haulm and pests bulk and for further substantiation of the harvesting module we are going to study the calculation schema of screw conveyor 5 capacity (fig.1) combining functional scheme of the operation process and structural scheme of the tools providing the process [9, 10].

THE RESULTS OF RESEARCH

We are making the substantiation of the haulm-cutting module based on the analysis of technological process of displacement of the plant components cut by a screw conveyor 5 (fig.1) or the plant components displacement by spiral turns 11 of the auger 9 in trough 8 made by guiding jacket 4.

Fig. 1. Calculation schema of the auger capacity: 1 – frame; 2 – supporting wheel; 3 – rotor haulm cutter; 4 – guiding jacket; 5 – screw conveyor; 6, 10 – drum; 7 – knife; 8 – trough; 9 – auger; 11 – turn; 12 – output section; 13 – beet root

We assume that at the time \( t \) of the haulm-cutting module displacement along the beet roots rows 13 (fig.1) at forward motion velocity \( \nu \) haulm cutters 7 are cutting the haulm and pests bulk or plant components in amounts of \( H_k(t) \) which are displacing on the directed motion path towards the trough 8, auger 11 of the screw conveyor 5.

Spiral turns 11 are carrying the plant components along the auger rotational axis towards its output section 12 where the plant components after leaving the last spiral turn are either put into the swath or thrown on the harvested field.

We’ll find the technological interrelation between structural-kinematic parameters of screw conveyor and per-second feed of the plant components \( H_k \) on the basis of its required capacity analysis, where the screw conveyor capacity is regulated or completely depends on the auger 11 capacity (fig.1).

Screw conveyor or auger capacity \( Q_k \) is found by the known formula according to [11-14]:

\[
Q_k = 0.25(D_k^2 - d_m^2)\varphi \rho \psi \phi \varphi
\]

(1)
where: \( Q_k \) – screw conveyer capacity, kg/s; \( D_k \) – auger diameter, m; \( \vartheta_c \) – average theoretical velocity of the cut haulm displacement along the auger rotational axis, m/s; \( \psi_\vartheta \) – coefficient taking into account deviation (decrease) of average motion velocity of the cut haulm bulk regarding to average theoretical velocity of the cut haulm displacement along the auger rotational axis; \( \varphi_c \) – haulm bulk weight, kg/m³; \( \varphi_z \) – coefficient of working space of screw conveyer filling with the cut haulm.

Here, according to [11, 15-17] components (1) are found by the formula:

- average theoretical velocity \( \vartheta_c \) of the cut haulm displacement along the screw conveyer rotational axis:

\[
\vartheta_c = \frac{(S_i + \Delta S_i) \cdot \omega_c}{2\pi} \cdot \frac{(S_i + \Delta S_i) \cdot d\varphi_c}{dt},
\]

where: \( S_i \) – steps if the first spiral turn, m; \( \Delta S_i \) – stepping increment \( i \), m; \( \omega_c \) – auger angular velocity, rad/s; \( \varphi_c \) – turning angle of the auger, rad.; \( \psi_\vartheta \) taking into account deviation (decrease) of average motion velocity of the cut haulm bulk regarding to average theoretical velocity of the cut haulm displacement along the auger rotational axis:

\[
\psi_\vartheta = \psi_a \cdot \psi_y, \quad (3)
\]

where: \( \psi_a \) – coefficient showing the impact degree of lead angle \( \alpha \) of screw on line on the mid-radius of the last spiral turn of the auger; \( \psi_y \) – compression ratio of chopping plants by spiral turns of screw conveyer:

- space filling factor \( \varphi_z \) of screw conveyer filling with the cut haulm taking into account sectional filling of the volume of trough throat

\[
\varphi_z = V_z / V_w, \quad V_z = V_w - V_k; \quad V_k = V_u + V_b, \quad (4)
\]

or

\[
\varphi_z = \frac{V_w - V_k}{V_w} = 1 - \frac{V_k}{V_w} = 1 - \frac{V_u + V_b}{V_w}, \quad (5)
\]

where: \( V_z \) – volume of the trough throat filled with cut haulm; \( V_w \) – trough throat volume, m³; \( V_k \) – auger volume, m³; \( V_u \) – auger turns volume, m³; \( V_b \) – auger drum volume, m³.

According to [18-20] ratio \( \frac{V_k}{V_w} \) stands for \( k_v \) taking into account volume of that part of auger working members (spiral turns and auger tube) which they occupy in the trough throat volume, i.e.

\[
\frac{V_u + V_b}{V_w} = k_v.
\]

Then according to the dependence (5):

\[
\varphi_z = 1 - k_v. \quad (6)
\]

Here, according to [11-13] and fig. 1 components (5) are found by the formula:

- trough throat volume:

\[
V_z = 0.5S_{z1} + V_{z2},
\]

where: \( S_{z1} \) – cylinder volume, whose base diameter is \( D_{\infty} \), and height \( -L_k \); \( V_{z2} \) – parallelepiped volume, whose base length and width are, respectively, \( D_{\infty} \) and \( 0.5D_{\infty} \), and height \( -L_k \).

\[
V_w = 0.125\pi D_{\infty}^2 L_k + 0.5D_{\infty} D_k L_k = 0.5D_{\infty} L_k (0.25\pi D_{\infty} + D_k), \quad (7)
\]

where: \( D_{\infty} \) – trough inner diameter, m; \( L_k \) – effective auger length, m;

- volume \( V_v \), occupied by auger turns and auger drum volume \( V_b \):

\[
V_v = V_{iv} = V_w \cdot l_v; \quad V_{iv} = F_v \cdot h_v; \quad l_v = \delta_v h_v; \quad F_v = \frac{\pi D_k (D_k + d_m) \cos \arctg \frac{2S_1 + \Delta S}{D_k + d_m}}{2S_1 + \Delta S} \cdot z_k; \quad (8)
\]

where: \( V_{iv} \) – is volume occupied by the turns of one entry of auger \( (m^3) \); \( z_k \) – number of auger entries, times; \( F_v \) – cross-section area of auger turn blade, \( m^2 \); \( l_v \) – length of screw on line on the auger mid-diameter, m; \( h_v \) – height of auger turn blade, \( h_v = 0.5(D_k - d_m) \), m; \( d_m \) – drum diameter, m.

\[
V_v = \frac{\pi D_k (D_k - d_m)^2}{4S_1 + \Delta S} \cos \arctg \frac{2S_1 + \Delta S}{D_k + d_m} \cdot z_k; \quad (9)
\]

\[
V_b = 0.25\pi d_m^2 L_k.
\]

After volumes values substitution from (7) and (9) in formula (6) we obtain the dependence to find coefficient \( k_v \):

\[
k_v = \frac{(D_k - d_m)^2}{S_1 + \Delta S} \cos \arctg \frac{2S_1}{D_k + d_m} \cdot z_k + d_m^2 \cdot \frac{2D_{\infty} (0.25\pi D_{\infty} + D_k)}{2D_{\infty} (0.25\pi D_{\infty} + D_k)}. \quad (10)
\]

According to (10) and under initial conditions \( d_m = 0.1 \, m \), \( z_k = 1 \), \( \Delta S = 0.05 \, m \) the diagram of coefficient \( k_v \) changes is shown on fig. 2.
Fig. 2. Dependence of coefficient $k_v$ change: a – $k_v = f(D_k)$, b – $k_v = f(D_k)$

Coefficient $k_v$ varies from 0.3 to 0.39 depending on the auger diameter range $0.2 \leq D_k \leq 0.3 \, m$. Here step $S_1$ of the auger first spiral and stepping increment $\Delta S$ make the greatest impact on the coefficient $k_v$ change – when $S_1$ increases from 0.1 to 0.2 m the coefficient $k_v$ is 1.3 times smaller (fig. 2.a), and when $\Delta S$ increases from 0.03 to 0.07 m coefficient $k_v$ is 1.2 times smaller (fig. 2.b).

According to (1)-(3), (6) and (10) the screw conveyer capacity is found by the formula

$$ Q_k = \left( D_k^2 - d_m^2 \right) \frac{S_1 + \Delta S}{8\pi} \psi \alpha \psi \rho_v \times \left[ 1 - \frac{\left( D_k - d_m \right)^2}{S_1 + \Delta S} \cos \left( \arctg \frac{2S_1}{D_k + d_m} \right) \right]. $$

or

$$ Q_k = \left( D_k^2 - d_m^2 \right) \frac{S_1 + \Delta S}{8\pi} \psi \alpha \psi \rho_v \times \left( 1 - k_v \right) \frac{d\phi_v}{dt}. $$

(11)

(12)

Also the screw conveyer capacity can be found by well-known formula [11, 12] which functionally to a greater extent depends on the process parameters characterizing the material supply to the working bodies of screw transport mechanisms:

$$ Q_k = W_L \psi \alpha \psi \rho_v \phi_v \times. $$

(13)

where: $W_L$ – material specific volume per auger length unit, m$^3$/m.

For further analysis we’ll express the material specific volume $W_L$ per auger length unit as per-second feed of plant components $\Pi_k^t$, per auger length unit $L_k$:

$$ W_L = \frac{m_p \psi}{\rho_v L_k} = \frac{\Pi_k^t}{L_k}. $$

(14)

where: $m_p$ – mass of plant components supplied to the screw conveyer (kg) per time $t = 1 \, s$.

We substitute the values of per-second feed of plant components $\Pi_k^t$ from [7, 8] into formula (14) and obtain the dependence to find the specific per-second feed of plant components to the screw conveyer or specific per-second feed of plant components per auger effective length unit $L_k$, or:

$$ W_L = \frac{\theta_k \psi}{L_k} \frac{0.82 \cdot 10^{-3} \theta_k \Gamma_k \psi \left( \Delta U_{0, \Delta} \pm \Delta U_{0, \Delta} \right) + 0.9 \, M_{0, \Delta}}{L_k}. $$

(15)

Then the capacity $Q_k$ of screw conveyer is found by the formula

$$ Q_k = \frac{\theta_k \psi}{L_k} \left( \Delta U_{0, \Delta} \pm \Delta U_{0, \Delta} \right) + 0.9 \, M_{0, \Delta} \times \frac{\partial \psi \alpha \psi \rho_v \left( 1 - k_v \right)}{dt}. $$

(16)

We equate the right parts of the formula (12) and formula (16) between themselves. Then we obtain the equality:

$$ \left( D_k^2 - d_m^2 \right) \frac{S_1 + \Delta S}{8\pi} \psi \alpha \psi \rho_v \times \left( 1 - k_v \right) \frac{d\phi_v}{dt} = \frac{\theta_k \psi}{L_k} \left( \Delta U_{0, \Delta} \pm \Delta U_{0, \Delta} \right) + 0.9 \, M_{0, \Delta} \times \frac{\partial \psi \alpha \psi \rho_v \left( 1 - k_v \right)}{dt}. $$

(17)

or according to (1), (3) and (6):

$$ \left( D_k^2 - d_m^2 \right) \psi \alpha \psi \rho_v \times \left( 1 - k_v \right) \frac{d\phi_v}{dt} = \frac{\Pi_k^t}{\rho_v L_k}. $$

(18)

We’ll demonstrate the record (the equality) legitimacy by means of mathematical modeling of numerical calculations of screw conveyer capacity found by formulae (2.23) and (2.27) and their comparison with one another.

The diagrams of the auger capacity (fig.3) change are made on the basis of numerical calculations of screw conveyer capacity found by formulae (12) and (16).

Fig. 3. Diagram of auger capacity change in computational points

Analysis of numerical calculations of the auger capacity (fig. 3) proves that capacity indices $Q1$ of the auger found by the formula (16) and capacity indices $Q2$ of the auger found by formula (12) in computational points P1-P7 are practically the same – mean error of values varies from 1.5 to 1.6 %.

Then by formula (18) we find the auger diameter $D_k$, where:

$$ D_k = \sqrt{\frac{m_p \psi}{\rho_v L_k} \psi \alpha \psi \rho_v \times \left( 1 - k_v \right)}.$$
\[
\frac{\left(D_k^2 - d^2_n\right)}{4} \rho_v = \frac{\Pi^*_k}{L_k};
\]  \hspace{1cm} (19)
\[
D_k = \frac{4\Pi^*_k t}{L_k \rho_v} + d^2_n. \hspace{1cm} (20)
\]

For theoretical substantiation of screw conveyer auger diameter according to formula (20) we have built a nomogram to find \(D_k\) depending on per-second feed change \(\Pi^*_k\) of plant components by knives of rotor haulm-cutter to screw conveyer and auger length \(L_k\) as a functional dependence \(D_k = f(\Pi^*_k; L_k)\) shown on fig. 4.

[Image of a diagram showing the nomogram and charts labeled with Greek letters such as \(k_1\), \(k_2\), \(k_3\), \(k_4\), etc., and a graph with labeled axes such as \(D_k\) vs. \(\Pi^*_k\).]

**Fig. 4.** Dependence of auger diameter \(D_k\) change:
a – as function \(D_k = f(\Pi^*_k; L_k)\); b – nomogram to find auger diameter \(D_k\).

On the basis of fig.4 analysis we have found that to provide per-second feed of plant components within limits \(\Pi^*_k = 15...40\) kg/s, found according to [7] the auger diameter \(D_k\) must be limited from 0.25 to 0.4 m depending on its effective length \(L_k\). Here the auger effective length is found structurally and depending on the haulm-cutting module rows number (or root-harvesting machine rows number) and root crops planting width. Thus, at root crops planting width \(b_k = 0.45\) m and number of rows which are picked simultaneously \(N = 3\), auger effective length \(L_k = 1.35\) m, respectively at \(N = 6 - L_k = 2.7\) m.

To find \(D_k\) a nomogram shown on fig.4b is used. For example, at per-second feed of plant components to the screw conveyer \(\Pi^*_k = 35\) kg/s at simultaneous haulm cutting of rows \(N = 6\) (auger effective length \(L_k = 2.7\) m) the required diameter of auger providing the material displacement equals to \(D_k = 0.34\) m. Thus, at \(\Pi^*_k = 22.5\) kg/s and \(N = 4\) (auger effective length \(L_k = 1.8\) m) – \(D_k = 0.32\) m.

A step of auger spiral turns is chosen structurally under condition [3], when \(S_1 = (0.5...0.6)\) \(D_k\), i.e. \(S_1 = 0.12...0.2\) m.

The auger angular velocity \(\omega_k\) is found under condition characterizing the screw conveyer operation without plant components “unloading” during their carrying by the auger turns. The condition is satisfied when screw conveyer capacity \(Q_k\) is larger or equal to per-second feed \(\Pi^*_k\) i.e. \(Q_k \geq \Pi^*_k\).

Then according to (12) and taking into account (13) we can write:
\[
\left(\frac{D_k^2 - d^2_n}{4}\right) \frac{S_1 + \Delta S}{\rho_v} \psi_r \rho_v (1 - k_v) \omega_k \geq \Pi^*_k. \hspace{1cm} (21)
\]

From dependence (21) we find the auger angular velocity:
\[
\omega_k = \frac{8\pi \Pi^*_k}{\left(D_k^2 - d^2_n\right) \left[S_1 + \Delta S\right] \psi_r \rho_v (1 - k_v)}. \hspace{1cm} (22)
\]

With found values of the auger structural parameters and according to (22) and under initial conditions \(S_1 = 0.15\) m, \(\Delta S = 0.005\) m, \(k_v = 0.35\), \(\psi_r = 0.7\) [3] a dependence of auger angular velocity change as a function \(\omega_k = f_{\omega}(D_k; \Pi^*_k)\), shown on fig. 5.

[Image of a graph with labeled axes such as \(D_k\) vs. \(\omega_k\) with marked points and lines connecting them, showing the relationship between auger diameter \(D_k\) and angular velocity \(\omega_k\).]
Fig. 5. Dependence of auger angular velocity change as a function \( \omega_k = f_\omega(D_k; \Pi_k^*) \)

Fig. 6. Dependence of auger velocity change \( \omega_k \)
a – on per-second feed of plant impurities \( \Pi_k^* \); 1, 2, 3, 4 – respectively, \( D_k = 0.25, 0.3, 0.35 \) and 0.4 m; b – on auger diameter \( D_k \) 1, 2, 3 – respectively

Functional change of auger angular velocity depending on the change of per-second feed of plant impurities \( \Pi_k^* \) to screw conveyer and auger diameter \( D_k \) (fig. 5) is of dual character: is in direct proportion to per-second feed \( \Pi_k^* \) increase – when \( \Pi_k^* \) increases the auger angular velocity \( \omega_k \) increases; is reciprocal to the auger diameter \( D_k \) increase – when diameter \( D_k \) increases the auger angular velocity \( \omega_k \) decreases.

We have found that basic values of auger angular velocity \( \omega_k \) are within limits \( \omega_k = 5...39 \text{ rad/s} \) (6), and \( \omega_k \) change is mostly caused by both per-feed of plant components \( \Pi_k^* \) to the screw conveyer and by auger diameter \( D_k \) as well – under condition of \( \Pi_k^* \) change from 15 to 40 kg/s and \( D_k \) from 0.25 to 0.4 m the value of auger angular velocity \( \omega_k \) is approximately increasing into 2...2.5 times.

Figures 7 and 8 present the diagrams of screw conveyer capacity change \( Q_k \) depending on the auger parameters which are built according to formula (18) as a functional dependence; \( Q_k = f_Q(D_k; \omega_k) \), fig. 7; \( Q_k = f_Q(\omega_k) \), fig. 8a; \( Q_k = f_Q(D_k) \), fig. 8b.

Under conditions when \( S_i = 0.15 \text{ m}, \Delta S = 0.005 \text{ m}, k_v = 0.35, z = 1 \) and change of auger parameters the screw conveyer capacity \( Q_k \) is changing at rather great range – from 12 to 57 kg/s and is increasing due to both auger rotational frequency \( \omega_k \) increase and auger diameter \( D_k \) increase as well.

According to condition (21), to provide the most effective operation of screw conveyer or plant components carrying by auger without their “loading” the screw conveyer capacity \( Q_k \) must be not less the range of per-second feed change:

- of plant components 16...39 kg/s. Then on the basis of diagrams analysis presented by figures 7 and 8 we can prove that the condition is satisfied at the following parameters of auger:
Fig. 7. Dependence of screw conveyor capacity change as function \( Q_s = f_0(D_k; \omega_k) \)

Fig. 8. Dependence of screw conveyor capacity change \( Q_s : a - \) on the auger angular velocity change \( \omega_k \); \( Q 1, 2, 3, 4 \) – respectively, \( D_k = 0.25; 0.3; 0.35 \) and 0.4 m; \( b - \) on the auger diameter \( D_k ; 1, 2, 3 \) – respectively, \( \omega_k = 15; 35; 50 \) rad/s

- the low limit of per-second feed of plant components is achieved or the condition when \( Q_s \geq \Pi^*_k \geq 16 \) kg/s is satisfied when the auger diameter \( D_k \geq 0.35 \) m and auger rotational frequency \( \omega_k = 15 \) rad/s;
- the upper limit of per-second feed of plant components is achieved or the condition when \( Q_s \geq \Pi^*_k \geq 39 \) kg/s is satisfied when the auger diameter \( D_k \geq 0.4 \) m and auger rotational frequency \( \omega_k = 40 \) rad/s.

Thus \( S_1 = 0.15 \) m, \( \Delta S = 0.005 \) m, \( \psi_z = 0.7 \).

CONCLUSIONS

On the basis of analytical research we have found that to provide the most efficient operation of screw conveyer of haulm-cutting module the auger diameter must have limits from 0.25m to 0.4m, and its effective length is 1.8m. Diagrams of dependence of screw conveyor capacity change on the structural-kinematic parameters of the auger, namely dependence of auger angular velocity change on per-second feed of plant impurities and on its diameter have been built.

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