THEORETICAL ANALYSIS OF THE TECHNOLOGICAL FEED OF LIFTED ROOT CROPS
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ТЕОРЕТИЧНИЙ АНАЛІЗ ТЕХНОЛОГІЧНОЇ ПОДАЧІ ВИКОПАНОГО ВОРОХУ КОРЕНЕПЛОДІВ

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ABSTRACT
Based on the theoretical analysis of root crops lifting process, the simulation models are shown describing the relation of the feed per second of root crops coming to the cleaners, or the change of the cleaner required throughput capacity depending on the vibrating lifter design parameters, agro-biological characteristics of chicory root crops and working conditions of root-gathering machine.

РЕЗЮМЕ
На основі теоретичного аналізу процесу викопування коренеплодів наведено розрахункові математичні моделі, які характеризують взаємозв'язок секундної подачі вороху коренеплодів до очисників, або зміну необхідної пропускної здатності очисника залежно від конструктивних параметрів вібраційного копача, агробіологічних характеристик коренеплодів цикорію и умов роботи коренезбиральної машини.

INTRODUCTION
Separation of chicory root crops, which is dug by the working parts and subsequently enters the cleaning transport technology systems, is one of the most important and complex operations in the work of a root-gathering machine. The separation of soil, free and adhering to the surface of root crops, as well as plant impurities, is a priority in the general context of compliance with agronomic requirements for impurities purification process, namely with the quality of raw materials and final products of its processing *(Voytyuk et al., 2015)*.

In addition to their separating abilities, root crops cleaners are also characterized by operational and technological criteria, including technological throughput capacity, or feed per second of root crops regulates the cleaning performance of root-gathering machine working parts, or the ability to handle root crops components without their *loading* on the working surfaces while minimizing overall damage and loss of root crops *(Baranovsky V.M., 2008)*.

MATERIALS AND METHODS
To justify the rational constructive-kinematic parameters of the combined chicory root crops cleaner *(Ramsh et al., 2011)*, respectively, to minimize its parameters under satisfactory technical indicators and performance parameters, the first priority is the theoretical study of the final cleaner's capacity based on analysis of the feed per second of dug crops to its working parts.

The purpose of this research is the further development of the theoretical aspects of root crop cleaners' parameters and operating modes optimization.

RESULTS
The criterion for the calculation of a root crop cleaner operation process is based on the condition that the throughput capacity of a cleaner working parts within a time interval $t=1$ sec must be equal to or greater than the total feed per second of the crop feeding to them from the previous transport systems of a root-gathering machine, so the following condition should be provided:

$$dW_o / dt \geq dW_c / dt \text{, or } W_o \geq W_c \tag{1}$$

where W_o – throughput capacity (or performance) of a cleaner, [kg/s];

W_c – total feed per second of the crop, [kg/s].

To calculate the total feed per second of the crop W_{ck}, which is dug by the lifter of a root-gathering machine from n-th root rows and further theoretical substantiation of the crop cleaner parameters, consider the design scheme of digging root crops using vibrating lifter shown in fig. 1.

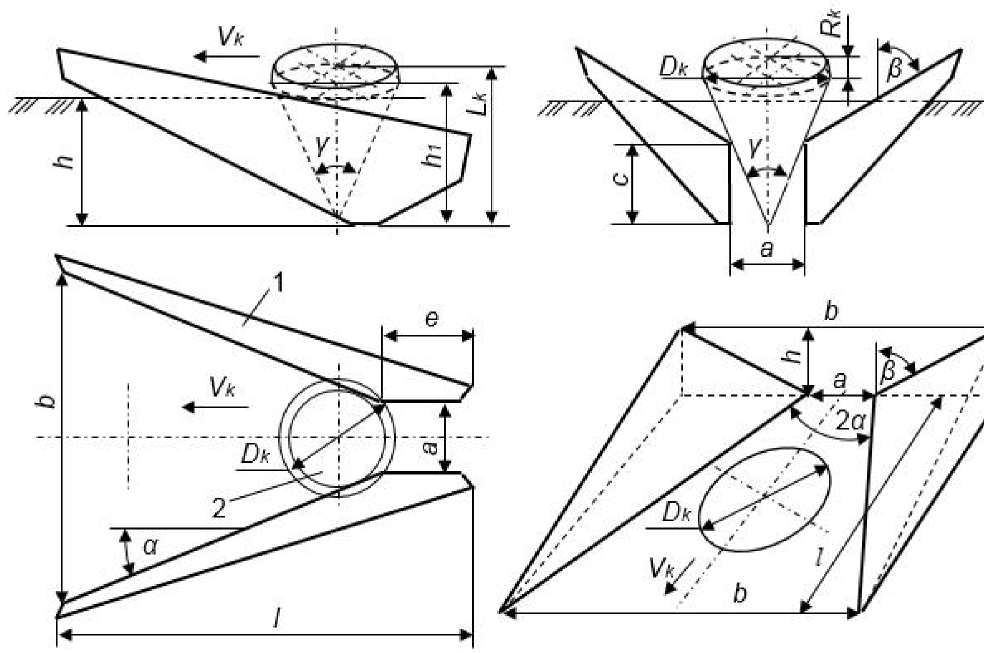

Fig. 1 - Scheme for calculating the crop feed using share-type lifter
1 - lifter; 2 – root crop

The total crop feed dW_c / dt, which will be supplied to the cleaner after lifter digging, except for the main operating factors (number of root crop rows being dug, lifter velocity, lifter running depth, level of root crop yield, agro-physical state of the soil, etc.) also depends on the separating capacity of the subsequent separating systems after the lifter, namely, on the value of free impurities separation factor.

Given (1) and assuming that there is no loss of root crops during the crops transfer by the transport systems to the cleaner, we can calculate *(Baranovsky V., 2014)*:

$$dW_o / dt \geq \left(dW_{ck} / dt\right)^{a} \text{, or } W_o \geq W_{ck}{}^{a} \tag{2}$$

where W_{ck} – the total feed per second of the root crops, [m/s];

^{a} – separation factor of free impurities on their path to the cleaner.

The feed of dug crops by vibrating lifter from one root crops row dW'_{ck} / dt is the feed sum of every j-th composite components of the crops: root crops dW_1 / dt, soil dW_2 / t, plant impurities dW_3 / dt, and:

$$\frac{dW'_{ck}}{dt} = \sum_{j=1}^{3} \frac{dW'_{ck_j}}{dt} = \frac{dW'_1}{dt} + \frac{dW'_2}{dt} + \frac{dW'_3}{dt} \tag{3}$$

where $\frac{dW'_{ck}}{dt}$ – feed of root crops from a single row, [kg/s];

$\frac{dW'_1}{dt}$, $\frac{dW'_2}{dt}$, $\frac{dW'_3}{dt}$ – feed of root crops, soil, plant impurities from a single row, respectively, [kg/s];

j = 3 – number of components of the crops: root crops, soil, plant impurities.

The total crop feed dW_c / dt from n-th root crops rows, which are dug simultaneously, equals the crop feed amount of each n-th row, or in accordance with (3) – the total feed amount of crop individual components of each n-the row: roots, soil and plant impurities:

$$\frac{dW_{ck}}{dt}=\left(\frac{dW_{11}}{dt}+\frac{dW_{12}}{dt}+...+\frac{dW_{1n}}{dt}\right)+\left(\frac{dW_{21}}{dt}+\frac{dW_{22}}{dt}+...+\frac{dW_{2n}}{dt}\right)+\left(\frac{dW_{31}}{dt}+\frac{dW_{32}}{dt}+...+\frac{dW_{3n}}{dt}\right) \quad (4)$$

where $\frac{dW_{11}}{dt}$, $\frac{dW_{21}}{dt}$, $\frac{dW_{n1}}{dt}$ – feed of root crops by the lifter from the first, second,..., n -th row, respectively, [kg/s];

$\frac{dW_{21}}{dt}$, $\frac{dW_{22}}{dt}$, $\frac{dW_{2n}}{dt}$ – feed of groundwater impurities by the lifter from the first, second,…, n -th row, respectively, [kg/s];

$\frac{dW_{31}}{dt}$, $\frac{dW_{32}}{dt}$, $\frac{dW_{3n}}{dt}$ – feed of plant impurities by the lifter from the first, second,…, n -th row, respectively, [kg/s].

To calculate the feed of crop components by the lifter from a single row, that is, root crops, soil and plant impurities that are dug directly by the lifter working body, consider the process of lifting chicory root by the working body of ploughshare type lifter and further transportation of excavated crops by the transport systems of the machine to the combined root crops cleaner.

Based on the postulate that the feed of any material is the mass of an object (body), which is dug in the time interval t [s], and the mass of a solid body in general is $m = V^{\circ}$, where V – body volume [m^3]; $^{\circ}$ – specific weight [kg/m^3] *(Byrd J., 2008)*, then and taking into account (4) we can write:

$$\frac{dm_{ck}}{dt}=\left(\frac{dV_{11}}{dt}+\frac{dV_{21}}{dt}+...+\frac{dV_{n1}}{dt}\right)^{\circ}{}_{1}+\left(\frac{dV_{12}}{dt}+\frac{dV_{22}}{dt}+...+\frac{dV_{n2}}{dt}\right)^{\circ}{}_{2}+ \\ +\left(\frac{dV_{13}}{dt}+\frac{dV_{23}}{dt}{}^{\circ}{}_{2}+...+\frac{dV_{n3}}{dt}\right)^{\circ}{}_{3} \quad (5)$$

where V_{11}, V_{21}, V_{n1} – volume of root crops, which are dug by the lifter from the first, second,..., n -th row, respectively, [m^3];

V_{12} , V_{22} , V_{n2} – volume of soil, which is dug by the lifter from the first, second,..., n -th row, respectively, [m^3];

V_{13} , V_{23} , V_{n3} – volume of plant impurities, which are dug by the lifter from the first, second,..., n -th row, respectively, [m^3];

$^{\circ}{}_{1}$, $^{\circ}{}_{2}$, $^{\circ}{}_{3}$ – specific mass of root crops, soil, plant impurities, respectively, [kg/m^3].

To determine the appropriate amount of roots, soil and plant impurities, consider the equivalent scheme, which is shown in fig. 2.

During the movement of the vibrating lifter 1 (fig. 1), with forward speed V_k , in the time at , it passes the way $S_k = V_k$at [m] and cuts a groove in the soil at a depth of plowshares stroke h , which is limited by the spatial shape contour $ABCDD_1C_1B_1A_1$ (fig. 2). In this space of the groove formed by plowshares in the time at , there are crop components: roots, soil and plant impurities, the amount of which constitutes the general crop feed dW_{ck} / dt , or adequate mass dm_{ck} / dt of the dug root crop, which is dug by the lifter from n -th rows in the time at .

In addition to it, the lifting process of root crop and its subsequent transportation by the transport systems has the following technological features:

- in the process of the mass of lifting root crop dm_{ck} / dt , which is inside the groove $ABCDD_1C_1B_1A_1$, part of the soil dm_2 / dt and plant impurities dm_3 / dt is extensively dressed, and some of the root crops dm_1 / dt is not lifted, or is lost in the course of its movement through the working bodies to the subsequent lifter transporting systems of the root-gathering machine *(Iamkov O.V., 2006)*;

- then, in the process of transporting the lifted soil and plant impurities, primary separated by the lifter, to the cleaner, their secondary separation is also performed on the working surfaces of the respective root-gathering machine transport systems.

The impurities separated and moved to the cleaner, together with supplied root crops, will compose the total crop dW_c / dt , which comes to the combined cleaner.

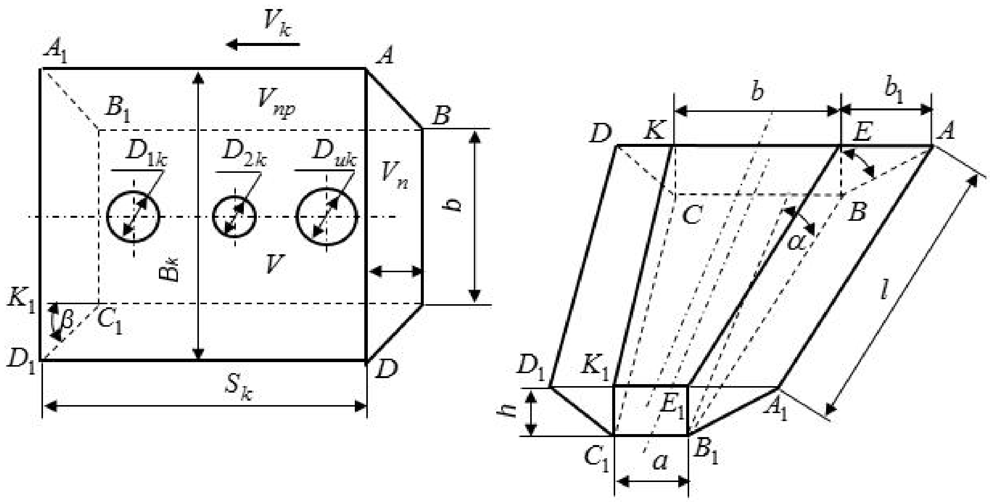

Fig. 2 – Scheme for calculating the groove volume

Then, to the specified pattern of the operation analysis of the lifter working bodies and root-gathering machine transport systems, we can write:

$$\frac{dW_c}{dt}=\frac{dm_c}{dt}=\left(\frac{dV_{11}}{dt}k_{1k}+\frac{dV_{21}}{dt}k_{2k}+\ldots+\frac{dV_{n1}}{dt}k_{nk}\right)\circ_1+ \\ +\left(\frac{dV_{12}}{dt}a_{1\circ}+\frac{dV_{22}}{dt}a_{2\circ}+\ldots+\frac{dV_{n2}}{dt}a_{n\circ}\right)\circ_2 a_2+ \\ +\left(\frac{dV_{13}}{dt}a_{1p}+\frac{dV_{23}}{dt}a_{2p}+\ldots+\frac{dV_{n3}}{dt}a_{np}\right)\circ_3 a_3 \qquad (6)$$

where k_{1k}, k_{2k},..., k_{nk} – accordingly, the loss factor of root crops by vibrating share-type lifter from the first, second,..., n-th rows;

$a_{1\circ}$, $a_{2\circ}$,..., $a_{n\circ}$ – respectively, soil separation factor by vibrating share-type lifter from the first, second,..., n-th rows;

a_{1p}, a_{2p},..., a_{np} – respectively, separation factor of free plant impurities by vibrating share-type lifter from the first, second,..., n-th rows;

a_2, a_3 – respectively, separation factor of soil and free plant impurities of root crops after their lifting and moving by root-gathering machine transport systems on the way to the combined cleaner.

Thus, in a first approximation, we can write that the total root crops feed going to the working bodies of the combined cleaner is:

$$\frac{dW_c}{dt}=\frac{dm_c}{dt}=\sum_{i=1}^{n}\frac{dW_{1_i}}{dt}k_k+\sum_{i=1}^{n}\frac{dW_{2_i}}{dt}a_{\circ}a_2+\sum_{i=1}^{n}\frac{dW_{3_i}}{dt}a_p a_3 \qquad (7)$$

where k_k, $a_{\circ}$, a_p – accordingly, the total loss factor of root crops, soil separation and free plant impurities from n-th rows.

To use the characteristics of plantations and root crops as a stationary random sequence for the analysis of lifters operation processes, they are reduced to the argument, which is adopted in dynamic problems: the time and the speed by converting the correlation rate and the corresponding spectral density *(Pogorely and Tatianko, 2004)*.

By the nature of auto- and inter correlation functions, it is found that the correlations of dimensional characteristics of adjacent root crops have a specific feature: close to a major root crop, there is often a small, and behind it - an average one *(Bulgakov et al., 2009)*.

On this basis, the root crop feed from a single line dW_1'/dt will be the sum of every root crop feed dimensional of every j-th dimensional parameters, that are inside the groove $ABCDD_1C_1B_1A_1$, while the functional dependence of root crops from one line takes the following form:

$$\frac{dW_1'}{dt} = f_1'\left(\sum_{j=1}^{u}\frac{dW_{1_j}'}{dt}\right) = f_1'\left(\sum_{k=1}^{N_1}\frac{dW_{1k}'}{dt} + \sum_{k=1}^{N_2}\frac{dW_{2k}'}{dt} + \ldots + \sum_{k=1}^{N_u}\frac{dW_{uk}'}{dt}\right) \tag{8}$$

where $\sum_{k=1}^{N_1}\frac{dW_{1k}'}{dt}$, $\sum_{k=1}^{N_2}\frac{dW_{2k}'}{dt}$,…, $\sum_{k=1}^{N_u}\frac{dW_{uk}'}{dt}$ – the total root crops feed of j-th dimensional parameter from a single line, respectively, [kg/s];

u –number of parametric root crops rows with the same dimension values, lifted from a single line;

N_1, N_2 ,…, N_u – number of identical root of j-th dimensional parameter lifted from a single line, respectively, [pcs.].

The total root crops feed $\sum_{i=1}^{n} dW_{1i} / dt$ consists of the sum of root crops feeds dW_1' / dt from every n-th row, and its functional relation is of the form:

$$\frac{dW_1}{dt} = f_1\left(\sum_{i=1}^{n}\sum_{j=1}^{u}\frac{dW_{1_j}'}{dt}\right) = f_1\left(\sum_{j=1}^{u}\frac{dW_{1_j}}{dt} + \sum_{j=1}^{u}\frac{dW_{2_j}'}{dt} + \ldots + \sum_{j=1}^{u}\frac{dW_{n_j}'}{dt}\right) =$$
$$= f_1'\left(\sum_{k=1}^{N_{11}}\frac{dW_{1k}'}{dt} + \sum_{k=1}^{N_{21}}\frac{dW_{2k}'}{dt} + \ldots + \sum_{k=1}^{N_{u1}}\frac{dW_{uk}'}{dt}\right) + f_2'\left(\sum_{k=1}^{N_{12}}\frac{dW_{1k}'}{dt} + \sum_{k=1}^{N_{22}}\frac{dW_{2k}'}{dt} + \ldots + \sum_{k=1}^{N_{u2}}\frac{dW_{uk}'}{dt}\right) + \ldots + \tag{9}$$
$$+ f_n'\left(\sum_{k=1}^{N_{1n}}\frac{dW_{1k}'}{dt} + \sum_{k=1}^{N_{2n}}\frac{dW_{2k}'}{dt} + \ldots + \sum_{k=1}^{N_{un}}\frac{dW_{uk}'}{dt}\right) = \frac{dm_1}{dt}$$

where N_{11}, N_{21} ,…, N_{u1}; N_{12}, N_{22} ,…, N_{u2} ;…; N_{1n}, N_{2n} ,…, N_{un} – number of root crops with the same j-th dimensional parameters of each n-th row, [pcs.].

After transformation and simplification, let's write the relation (9) in the following form:

$$\frac{dW_1}{dt} = f_1\left(\sum_{k=1}^{N_{11}+N_{12}+\ldots+N_{1n}}\frac{dW_{1k}'}{dt} + \sum_{k=1}^{N_{21}+N_{22}+\ldots+N_{2n}}\frac{dW_{2k}'}{dt} + \ldots + \sum_{k=1}^{N_{u1}+N_{u2}+\ldots+N_{un}}\frac{dW_{uk}'}{dt}\right). \tag{10}$$

The volume of root crop V_k (fig. 1) equals the sum of the volumes of a root crop head and body:

$$V_1 = \frac{1}{12}\circledR D_k^2 h_1 + \frac{1}{12}\circledR D_k^3 = \frac{1}{12}\circledR D_k^2\left(L_k - 0{,}5D_k\right) \tag{11}$$

where $h_1 = L_k - 0{,}5D_k$ – length of the root crop body, [m];

L_k, D_k – total length and diameter of the root crop head, respectively, [m].

Assume that:

$$N_{11} = N_{11}'\frac{dS_k}{dt};\; N_{21} = N_{21}'\frac{dS_k}{dt};\; N_{u1} = N_{u1}'\frac{dS_k}{dt};\; N_{12} = N_{12}'\frac{dS_k}{dt};\; N_{22} = N_{22}'\frac{dS_k}{dt};\, N_{u2} = N_{u2}'\frac{dS_k}{dt};$$
$$N_{1n} = N_{1n}'\frac{dS_k}{dt};\; N_{2n} = N_{2n}'\frac{dS_k}{dt} ,;\, N_{un} = N_{un}'\frac{dS_k}{dt} \tag{12}$$

where N_{11}', N_{21}' ,…, N_{u1}'; N_{12}', N_{22}' ,…, N_{u2}' ;…; N_{1n}', N_{2n}' ,…, N_{un}' – number of root crops with the same j-th dimensional parameters on one running meter of each n-th row, [pcs.];

dS_k / dt – number of linear meters run by the lifter in the time at, [r m/sec].

To simplify the problem, we take the basic assumption that the number of root crops of j-th dimensional parameter on one running meter in each n-th row is the same, that is $N_{11}' = N_{21}' = \ldots = N_{n1}' = N_1$, $N_{12}' = N_{22}' = \ldots = N_{n2}' = N_2'$, $N_{1u}' = N_{2u}' = \ldots = N_{nu}' = N_u$ we obtain the dependence for determining the total root crops feed dW_1 / dt, coming to the screws of the cleaner from n-th rows:

$$\frac{dW_1}{dt} = \frac{1}{12}\circledR{}^\circ{}_1 nk_k\frac{dS_k}{dt}\begin{bmatrix} D_{1k}^2 N_1\left(L_{1k} + 0{,}5D_{1k}\right) + D_{2k}^2 N_2\left(L_{2k} + 0{,}5D_{k_2}\right) + \\ + \ldots + D_{uk}^2 N_u\left(L_{uk} + 0{,}5D_{uk}\right) \end{bmatrix} = \frac{dm_1}{dt}k_k . \tag{13}$$

The total soil feed dW_2 / dt, dug by the lifter, is the sum of the soil feeds dW_2' / dt from every n-th row.

With that said, the soil feed V_2', inside the groove bounded by spatial figure $ABCDD_1C_1B_1A_1$ (fig. 2) immediately dug by the share-type lifter from a single row in the time at, equals the difference between the soil feed volume inside the groove dV/dt and the sum of underground parts volumes $d\sum_{j=1}^{u} V_{k_j} / dt$ of j-th dimensional parameters of root crops 2 (fig. 1) from the n-th row, inside the groove $ABCDD_1C_1B_1A_1$, that is:

$$\frac{dW_2'}{dt} = \left(\frac{dV}{dt} - \frac{d\sum_{j=1}^{u} V_{k_i}'}{dt} \right) \circ_2 = \left(\frac{dV}{dt} - \frac{d\left(\sum_{k=1}^{N_1'} V_{1k} + \sum_{k=1}^{N_2'} V_{2k} + ... + \sum_{k=1}^{N_u'} V_{uk} \right)}{dt} \right) \circ_2 \tag{14}$$

where V – volume of the groove of spatial shape $ABCDD_1C_1B_1A_1$ of a single row, [m^3];

$\sum_{j=1}^{u} V_{k_j}'$ – sum of underground parts volumes of root crops that are in the space of the groove $ABCDD_1C_1B_1A_1$ of a single row, [m^3];

V_{1k}, V_{2k}, ..., V_{uk} – volume of one root crop underground part of j-th dimensional parameter, in a single row, respectively, [m ^{3}].

The sum of underground parts volumes of root crops from a single row in the area of the groove $ABCDD_1C_1B_1A_1$ equals:

$$\sum_{j=1}^{u} V_{k_j}' = \frac{1}{12} ® \left[D_{1k}^2 N_1 (L_{1k} - 0{,}5D_{1k}) + D_{2k}^2 N_2 (L_{2k} - 0{,}5D_{k_2}) + .. + D_{uk}^2 N_u (L_{uk} - 0{,}5D_{uk}) \right] \tag{15}$$

where $\sum_{j=1}^{u} V_{k_j}'$ – sum of underground parts volumes of root crops from a single row in the area of the groove $ABCDD_1C_1B_1A_1$, [m^3].

Given (14), (15), the total feed of the soil dug directly by the lifter from n-th rows of root crops is determined by the formula:

$$\frac{dW_2}{dt} = \left\{ \frac{dV}{dt} - \frac{1}{12} ® \frac{dS_k}{dt} \left[\begin{matrix} D_{1k}^2 N_1 (L_{1k} - 0{,}5D_{1k}) + D_{2k}^2 N_2 (L_{2k} - 0{,}5D_{k_2}) + \\ + ... + D_{uk}^2 N_u (L_{uk} - 0{,}5D_{uk}) \end{matrix} \right] \right\} n \circ_2 . \tag{16}$$

The volume of the spatial figure groove bounded by $ABCDD_1C_1B_1A_1$, is the sum of the parallelepiped volume V_n and prism double volume V_{np} (fig. 2), and:

$$V = V_n + 2V_{np} = bhS_k + hb_1S_k = hS_k(b + b_1) = hS_k(b + htg \quad) \tag{17}$$

where h – average running depth of share-type lifter, [m];

b – front socks gap of plowshares at soil surface level, [m];

S_k – path run by the lifter at, [m];

– tilting angle of plowshare lateral plane to a vertical plane parallel to the velocity attitude of the lifter movement, [degrees].

Given (14) (16) (17) and with the assumption that $a_{1\circ} = a_{2\circ} = ... = a_{n\circ} = a_\circ$, we obtain the dependence for determining the total feed of soil dW_2/dt, coming on the screws of the cleaner from n-th rows:

$$\frac{dW_2}{dt} = \left\{ \begin{matrix} \frac{dS_k}{dt} h(b + htg \quad) - \frac{1}{12} \frac{dS_k}{dt} ® \times \\ \times \left[\begin{matrix} D_{1k}^2 N_1 (L_{1k} - 0{,}5D_{1k}) + D_{2k}^2 N_2 (L_{2k} - 0{,}5D_{k_2}) + \\ + ... + D_{uk}^2 N_u (L_{uk} - 0{,}5D_{uk}) \end{matrix} \right] \end{matrix} \right\} \circ_2 a_\circ a_2 n = \frac{dm_2}{dt} a_\circ a_2 . \tag{18}$$

Similarly, the total feed of plant impurities dW_3/dt, dug by the lifter, is the sum of plant impurities feeds dW_3'/dt from every n-th row.

Plant impurities feed dW_3'/dt, dug by the lifter from a single root crop row, according to assumption, is made up of the feed of free tops lost by tops-gathering machine, residues of tops on the heads of root crops and feed of weeds that are inside the upper area of the figure A_1ADD_1 (fig. 2), formed by the groove $ABCDD_1C_1B_1A_1$, that is:

$$\frac{dW_3'}{dt} = \frac{dW_{3v}'}{dt} + \frac{dW_{3b}'}{dt} + \frac{dW_{3z}'}{dt} \tag{19}$$

where $\frac{dW_{3v}'}{dt}$, $\frac{dW_{3b}'}{dt}$, $\frac{dW_{3z}'}{dt}$ – feed of lost tops, weeds and tops residues on the heads dug by the lifter from a single root crop row, [kg/s].

According to the agronomic requirements to tops-gathering machine, the loss of free tops, cut by the machine working bodies and tops residues on root crops heads must not exceed 10%, respectively 8% of its yield and weed weight - no more than 0,1 kg/m^2 *(Bulgakov et al., 2009, Baranovsky and Potapenko, 2016)*.

Then, taking the maximum values of these parameters and using (19), the feed of plant impurities dW_3'/dt, directly dug by vibrating lifter from a single root crops row, is determined by the formula:

$$\frac{dW_3'}{dt} = 0{,}1U_g\,\frac{dF_k}{dt} + 0{,}08U_g\,\frac{dF_k}{dt} + 0{,}1\frac{dF_k}{dt} = 0{,}1\frac{dF_k}{dt}\left(U_g + 1\right) + 0{,}08U_g\,\frac{dF_k}{dt} \tag{20}$$

where U_g – tops yield, [kg/m^2];

$F_k = S_kB_k = S_k\left(b + 2htg\ \ \right)$ – area of top base of the figure AA_1D_1D of the groove $ABCDD_1C_1B_1A_1$, [м^2];

B_k – coverage width of plowshares of vibrating lifter, [m].

Assuming $a_{1p} = a_{2p} = ... = a_{np} = a_p$, we obtain the dependence for determining the total feed of plant impurities dW_3/dt, coming on the cleaner screws from n-th rows:

$$\frac{dW_3}{dt} = \left[0{,}1\frac{dS_k}{dt}\left(b + 2htg\ \ \right)\left[\left(U_g + 1\right)a_p\,a_3 + 0{,}08U_g\right]\right]n = \frac{dm_3}{dt}\,a_p\,a_3\,. \tag{21}$$

Thus, given (13), (18), (21), the dependence for determining the total feed dW_c/dt of dug root crops from n-th rows, coming on the cleaner screws has the following form:

$$\begin{aligned}
\frac{dW_c}{dt} &= \frac{dm_1}{dt}k_k + \frac{dm_2}{dt}a_\circ a_2 + \frac{dm_3}{dt}a_p a_3 = \frac{dm_c}{dt} = \\
&= \frac{1}{12}®°_1 nk_k\,\frac{dS_k}{dt}\begin{bmatrix} D_{1k}^2N_1\left(L_{1k} + 0{,}5D_{1k}\right) + D_{2k}^2N_2\left(L_{2k} + 0{,}5D_{k_2}\right) + \\ + ... + D_{uk}^2N_u\left(L_{uk} + 0{,}5D_{uk}\right)\end{bmatrix} + \\
&+ °_2 a_\circ a_2 n\left\{\begin{aligned}&\frac{dS_k}{dt}h\left(b + htg\ \ \right) - \frac{1}{12}®\,\frac{dS_k}{dt}\times \\ &\times\begin{bmatrix} D_{1k}^2N_1\left(L_{1k} - 0{,}5D_{1k}\right) + D_{2k}^2N_2\left(L_{2k} - 0{,}5D_{k_2}\right) + \\ + ... + D_{uk}^2N_u\left(L_{uk} - 0{,}5D_{uk}\right)\end{bmatrix}\end{aligned}\right\} + \\
&+ n\left[0{,}1\frac{dS_k}{dt}\left(b + 2htg\ \ \right)\left[\left(U_g + 1\right)a_p a_3 + 0{,}08U_g\right]\right]
\end{aligned} \tag{22}$$

After simplifying equation (22) and taking, in accordance with (2) $a_2 = a_3 = a$ and denoting components $D_{1k}^2N_1\left(L_{1k} - 0{,}5D_{1k}\right) + D_{2k}^2N_2\left(L_{2k} - 0{,}5D_{k_2}\right) + ... + D_{uk}^2N_u\left(L_{uk} - 0{,}5D_{uk}\right) = n_{Vk_n}$, $b + 2htg\ \ = t_{VF}$, $D_{1k}^2N_1\left(L_{1k} + 0{,}5D_{1k}\right) + D_{2k}^2N_2\left(L_{2k} + 0{,}5D_{k_2}\right) + ... + D_{uk}^2N_u\left(L_{uk} + 0{,}5D_{uk}\right) = n_{Vk}$, we obtain the dependence characterizing the relation of change of root crops feed to the screws of combined cleaner or change of the cleaner required throughput capacity according to the vibrating lifter plowshares design parameters, agrophysical characteristics of root crops plantations and machine conditions:

$$W_c = n a_\circ a°_2 V_k\left\{\begin{aligned}&\frac{1}{12}®D_k^2N\left(\frac{°_1k_k\left(h + D_k\right)}{a_\circ a°_2} - 1\right) + \left[a + 2\left(l\,sin\sim + htg\ \ \right)\right]\times \\ &\times\left[h\left(1 - \frac{htg}{\left[a + 2\left(l\,sin\sim + htg\ \ \right)\right]}\right) + 0{,}1\left[\left(U_g + 1\right)a_p + \frac{0{,}08U_g}{a}\right]\right]\end{aligned}\right\} \tag{23}$$

where $dS_k/dt = P_k \cong V_k$, where P_k – number of running meters run by the lifter in the time of 1 s;

V_k – forward speed of the lifter [m/s], but in this case, dimension V_k, can be written as [r m/s] because of matching the symmetric difference of sets *(Husak and Brichkina, 2012)*;

$N_1 + N_2 + ... + N_u = N$, where N – average number of chicory root crops per 1 r m;

$D_{1k} = D_{2k} = ... = D_{uk} = D_k$, where D_k – average diameter of root crops head, [m];

$L_{1k} + 0{,}5D_{1k} = L_{2k} + 0{,}5D_{2k} = ... = L_{uk} + 0{,}5D_{uk} = L_{ck} + 0{,}5D_k = (h + 0{,}5D_{ck}) + 0{,}5D_k = h + D_k$, where L_k – average total length of sugar beet root crops, [m];

$L_{1k} - 0{,}5D_{1k} = L_{2k} - 0{,}5D_{2k} = ... = L_{uk} - 0{,}5D_{uk} = L_k - 0{,}5D_k = h$; $b = a + 2l\,sin\sim$, where a – rear plowshares gap, [m];

l – coulter blade length, [m];

$\sim$ – half angle of plowshares noses, [degrees].

In addition, formulas (13), (18) and (21) will have the form:

$$W_1 = \frac{®}{12} n_k \,°_1 k_k V_k D_k^2 N (h + D_k); \qquad (24)$$

$$W_2 = n_k \,°_2 ª \circ ª V_k h \left[(a + 2l\,sin\sim + htg\ \ ) - \frac{1}{12} ® D_k^2 N \right]; \qquad (25)$$

$$\frac{dW_3}{dt} = \left[0{,}1 \frac{dS_k}{dt} [a + 2(l\,sin\sim + htg\ \ )] [(U_g + 1) ª_p ª + 0{,}08 U_g] \right] n_k . \qquad (26)$$

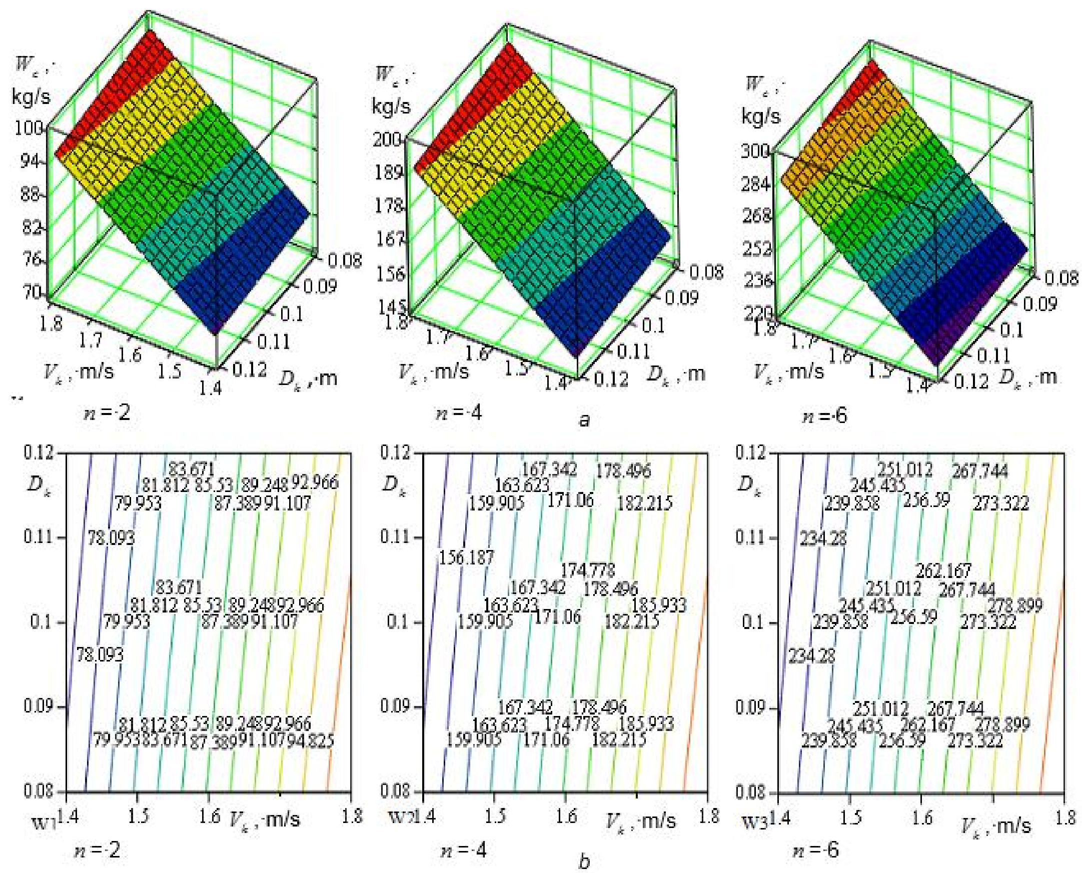

Fig. 3 – Dependence area between change of root crops feed per second W_c, lifter operating velocity V_k and root crops diameter D_k (a); б – dimensional section W_c

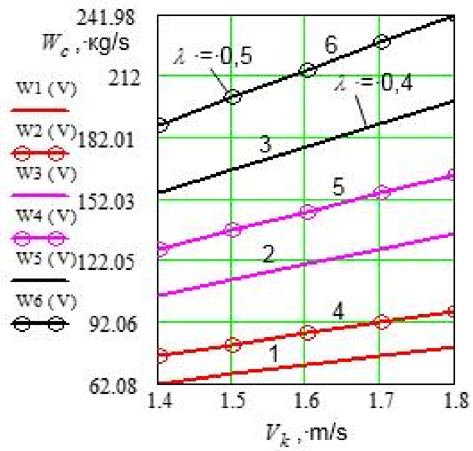

Fig. 4 – Dependence of change W_c and lifter operating velocity V_k

1, 2, 3 – n_k = 2, 4, 6; ª = 0,4; 4, 5, 6, – n_k = 2, 4, 6; ª = 0,5

At initial conditions, when $N =$ 6 [pcs.]; $a =$ 0.07 [m]; $l = 0.2$ [m]; ~ = 30 [degrees]; $h =$ 0.09 [m]; = 12 [degrees]; ª∘ = 0.4; ª$_p$ = 0.7; ª = 0.4; °$_2$ = 1500 [kg/m^3]; U_g = 3.0 [kg/m^3]; °$_1$ = 550 [kg/m^3]; k_k = 0.015 and according to formula (23), we constructed the dependence area between change of root crops feed per second W_c, coming to the combined cleaner screws and vibrating lifter operating velocity V_k and root crops average diameter D_k (fig. 3a) and its dimensional section (fig. 3b) for corresponding values for the number of rows n.

The analysis of the characteristic curve shows that changing the root crops feed per second W_c depending on the machine velocity V_k and the number of rows n, being collected at the same time, is directly proportional.

With the increase V_k from 1,4 to 1.8 m/s the root crops feed per second W_c, coming to the cleaner screws when gathering 2 rows of root crops with average diameter $D_k =$ 0.12 m increases from 76 to 96 kg/s, that is approximately 1.3 times (fig. 3). Accordingly, for the 4 and 6 rows - from 150 to 195 kg/s and 225 to 295 kg/s, that is also about 1.3 times, that is also characteristic to the analysis of straight proportional change of dependences W_c, which resulted in fig. 4, with the increase of rows number from 2 to 6, the root crops feed per second W_c coming to the cleaner screws increases by about 3 times.

Second serve lots W_c depending on the increase of diameter D_k of root crop from 0.08 to 0.12 (m) grows in insignificant limits – an average of 3.4 kg/s.

CONCLUSIONS

The obtained dependence is the simulation mathematical model which describes the relation between the changes of root crops feed per second W_c to the cleaner screws or change of the cleaner required throughput capacity W_o according to the design parameters of the vibrating lifter plowshares, agrophysical characteristics of root crops plantations and machine operating conditions.

This model is the optimization dependence in the context of further substantiation of constructive-kinematic parameters and operating modes of cleaning working bodies of root crops gathering machines.

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