УДК 631.361.2 DOI 10.36910/775.24153966.2025.81.25

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ФУНКЦІОНАЛЬНО-ЛАНКОВА СТРУКТУРНА МОДЕЛЬ ПРОЦЕСУ РОБОТИ КОРЕНЕЗБИРАЛЬНИХ МАШИН

На основі теоретичного аналізу розробленої функціонально-ланкової структурної моделі процесу роботи коренезбиральних машин, яку побудовано за блочно-модульним принципом та з застосуванням перетворень Лапласа, отримано математичні моделі, що описують процеси інтенсифікації відокремлення структурних компонентів домішок від коренеплодів, записаних в параметричній і операторній формі. Розроблені залежності, які характеризують коефіцієнт сепарації домішок кожної структурної ланки дозволяють проводити оптимізацію параметрів робочих органів кожного окремого модуля коренезбиральної машини.

Ключові слова: *матеріальний баланс, подача, коренеплоди, домішки, структурна ланка, оператор Лапласа, транспортне запізнення, коефіцієнт сепарації..*

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FUNCTIONAL-LINK STRUCTURAL MODEL OF THE WORKING PROCESS OF ROOT HARVESTING MACHINES

The efficiency of root harvesting machines is regulated by the quality indicators of their work in accordance with agrotechnical requirements, which primarily include indicators of loss, damage and contamination of dug up root crops with components of soil and plant impurities. The aim of the work is to reduce the amount of free soil and plant impurities in the collected heap by developing and analyzing theoretical prerequisites for the receipt and movement of the dug up heap by the working bodies of root harvesting machines. Based on the theoretical analysis of the developed functional-link structural model of the root harvesting machine operation process, which is built on the block-modular principle and using Laplace transforms, mathematical models were obtained that describe the processes of intensification of the separation of structural components of impurities from root crops, recorded in parametric and operator form. The developed dependencies that characterize the impurity separation coefficient of each structural link allow optimization of the parameters of the working bodies of each individual module of the root harvesting machine.

Keywords: *material balance, supply, root crops, impurities, structural link, Laplace operator, transport delay, separation coefficient.*

Formulation of the problem. Mostly, the structural and layout diagrams of self-propelled bunker harvesters and root harvesters of the world's leading companies are of the same type and have a similar structure, Fig. 1.

On the frame chassis, which rests on the support wheels, in front of the steered wheels of the machine, a stalk-collecting module is attached to implement a two-stage method of harvesting the stalk and a module for digging up root crops, in the inter-base space of the chassis – a root crop cleaning module and a module for accumulating cleaned root crops from impurities, which, as a rule, is made in the form of a root crop storage hopper and an unloading conveyor, and behind the storage hopper – a power module, or engine. The cabin with the machine controls and working bodies is installed above the front steered wheels of the machine.

The complexity of cleaning the excavated pile is functionally related to the need to separate soil and plant impurities that differ in their physical and mechanical states and properties, which are in a free and bound state relative to root crops [1].

The free state of soil impurities implies the presence of loose loose soil, loose shallow (20…50 mm) and fairly large (up to 100 mm) soil clods, and the free state of plant impurities implies the presence of free tops lost by the top-harvesting machine and plant impurities, or existing weeds. The bound state of impurities is soil adhering to the surface of the root crop body and the remains of the top on the heads of root crops, which remain after cutting off the main mass of the top [2, 3].

Therefore, to ensure the necessary cleaning of the excavated heap, or the quality of the harvested product (no more than 8…10% of impurities relative to the mass of root crops), it is necessary to provide for various types of physical and mechanical interactions and, as a result, multi-criteria options (schemes) for combining different types of cleaners of a rather significant length (8…14 m) and a significant path of cleaning impurities [4, 5].

The functional scheme of intensification of the process of separating impurities from root crops by the working bodies of root harvesting machines (Fig. 2) provides for three main stages of intensification of the process of cleaning the excavated heap from impurities: the stage of separating structural components of impurities from root crops in the process of digging them out by the working bodies of the root crop digging module; the stage of intensification of the process of separating impurities in the process of moving them by the working bodies of the root crop cleaning module; the stage of separation of free impurities in the process of their movement by the working bodies of the root crop loading or unloading module [6].

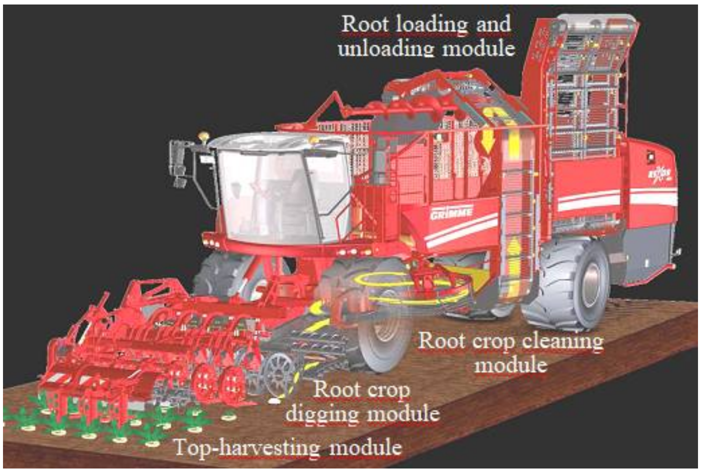

Fig. 1. **Modular block diagram of the structure of modern root crop harvesting machines**

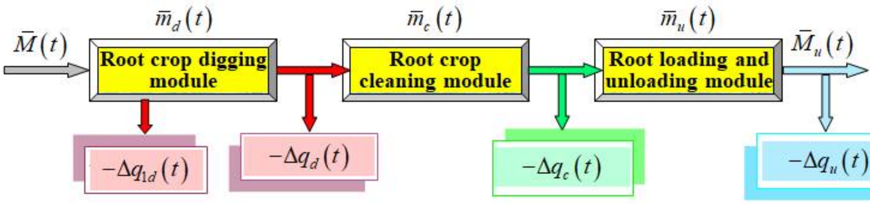

Fig. 2. **Functional diagram of the intensification of the process of separation of impurities from root crops by the working bodies of the root harvesting machine**

It is known that the flow of the input quantity $\bar{M}_i(t_i)$ of the excavated heap is linearly related to the speed of movement ϑ_d and the technological parameters (width of the capture, row spacing) of the root harvesting machine, and the flow of the output quantity $\bar{m}_i(t_i)$ of the cleaned heap by the working bodies of each stage satisfies the balance condition taking into account the amount of separated impurity components $\Delta\bar{q}_i(t_i)$ by each stage [7]. Applying the material balance equation of the change in the technological mass flow over time t_i, or the intensification of the process of separation of structural components of impurities from root crops by the working bodies of each stage (Fig. 2), we obtain [8, 9]:

$$\left.\begin{aligned}&\bar{m}_d(t_d)=\bar{M}(t_d)-\Delta\bar{q}_{1d}(t_d)-\Delta\bar{q}_d(t_d);\\&\bar{m}_c(t_c)=\bar{m}_d(t_d)-\Delta\bar{q}_c(t_c)=\bar{M}(t_d)-\Delta\bar{q}_{1d}(t_d)-\Delta\bar{q}_d(t_d)-\Delta\bar{q}_c(t_c);\\&\bar{M}_u(t_u)=\bar{m}_c(t_c)-\Delta\bar{q}_u(t_u)=\bar{M}(t_d)-\Delta\bar{q}_{1d}(t_d)-\Delta\bar{q}_d(t_d)-\Delta\bar{q}_c(t_c)-\Delta\bar{q}_u(t_u)\end{aligned}\right\}, \quad (1)$$

where $\bar{M}(t_d)$ is the input amount of the flow of the components of the excavated heap by the working bodies of the root crop digging module; $\bar{m}_d(t_d)$, $\bar{m}_c(t_c)$, $\bar{m}_u(t_u)$ are the output amount of the flow of the components of the cleaned heap, respectively, of each stage; $\Delta\bar{q}_d(t_d)$, $\Delta\bar{q}_c(t_c)$, $\Delta\bar{q}_u(t_u)$ – the separated amount of the flow of impurities by the working bodies, respectively, of the root digging module, the root cleaning module, the root loading and unloading module; $\Delta\bar{q}_{1d}\left(t_d\right)$ – the amount of the lost flow of root crops by the working bodies of the root digging module.

In this case, the differential equations of the material balance of the change in the flow of the heap at each stage according to (1) have the form:

$$\left.\begin{aligned}
&\frac{d\bar{m}_d}{dt_d}=\frac{d\bar{M}}{dt_d}-\frac{d\Delta\bar{q}_{1d}}{dt_d}-\frac{d\Delta\bar{q}_d}{dt_d};\\
&\frac{d\bar{m}_c}{dt_c}=\frac{d\bar{m}_d}{dt_d}-\frac{d\Delta\bar{q}_c}{dt_c}=\frac{d\bar{M}}{dt_d}-\frac{d\Delta\bar{q}_{1d}}{dt_d}-\frac{d\Delta\bar{q}_d}{dt_d}-\frac{d\Delta\bar{q}_c}{dt_c};\\
&\frac{d\bar{M}_u}{dt_u}=\frac{d\bar{m}_c}{dt_c}-\frac{d\Delta\bar{q}_u}{dt_u}=\frac{d\bar{M}}{dt_d}-\frac{d\Delta\bar{q}_{1d}}{dt_d}-\frac{d\Delta\bar{q}_d}{dt_d}-\frac{d\Delta\bar{q}_c}{dt_c}-\frac{d\Delta\bar{q}_u}{dt_u}
\end{aligned}\right\}, \tag{2}$$

Then the last differential equation of the system (2) taking into account the structural components of the impurities is written in the form

$$\frac{d\bar{M}_u}{dt_u}=\frac{d\left(\bar{m}_1+\bar{m}_2\right)}{dt_d}-\frac{d\left(\Delta\bar{q}_{1d}+\Delta\bar{q}_{sd}+\Delta\bar{q}_{pd}\right)}{dt_d}-\frac{d\left(\Delta\bar{q}_{sc}+\Delta\bar{q}_{pc}\right)}{dt_c}-\frac{d\left(\Delta\bar{q}_{su}+\Delta\bar{q}_{pu}\right)}{dt_u}, \tag{3}$$

where $\bar{m}_1$, $\bar{m}_2$ – the input mass of roots and impurities that are dug out by the working bodies of the root digging module; $\Delta\bar{q}_{sd}$, $\Delta\bar{q}_{sc}$, $\Delta\bar{q}_{su}$ – the separated mass of loose soil, soil clods, soil stuck to the underground part of the roots by the working bodies, respectively, of the root digging module, the root cleaning module, the root loading and unloading module; $\Delta\bar{q}_{pd}$, $\Delta\bar{q}_{pc}$, $\Delta\bar{q}_{pu}$ – separated mass of free and bound plant impurities, respectively, of the root crop digging module, the root crop cleaning module, and the root crop loading and unloading module.

It is also known that the technological process of intensification of the separation of structural components of impurities from root crops of a separate stage, or of the root harvesting machine in general, is generally described by a linearized differential equation [9]

$$a_0^{(i)}\frac{d\left[\Delta\bar{q}_i\left(t_i\right)\right]}{dt_i}=b_0^{(i)}\bar{m}_{i.in}\left(t_i-\tau_i\right)-c_0^{(i)}\bar{m}_{i.out}\left(t_i\right), \tag{4}$$

where $a_0^{(i)}$, $b_0^{(i)}$, $c_0^{(i)}$ – variable coefficients in the function of the parameters of the working bodies of the root harvesting machine, physical and mechanical properties of the soil, root crop yield, etc., which are determined experimentally; $\Delta\bar{q}_i\left(t_i\right)$ – separated amount of flow by the working bodies of each stage, kg/s, i = 1, 2,…,n; τ_i – delay time of flow movement, s; $\bar{m}_{i.in}$, $\bar{m}_{i.out}$ – input and output amount of pile flow, kg/s.

Based on (4) for any i-th stabilized technological mode of operation of a complex technical system, when the deviations of variable input factors (flows) are insignificant, the technological process of the root harvesting machine is described by a linearized differential equation, i.e.

$$\begin{aligned}
&a_1^{(d)}\frac{d\left[\Delta\bar{q}_1\left(t_d\right)\right]}{dt_d}+a_0^{(M)}\frac{d\left[\Delta\bar{q}_M\left(t\right)\right]}{dt}=a_1^{(d)}\frac{d\left[\Delta\bar{q}_1\left(t_d\right)\right]}{dt_d}+a_0^{(d)}\frac{d\left[\Delta\bar{q}_d\left(t_d\right)\right]}{dt_d}+a_0^{(c)}\frac{d\left[\Delta\bar{q}_c\left(t_c\right)\right]}{dt_c}+\\
&+a_0^{(u)}\frac{d\left[\Delta\bar{q}_u\left(t_u\right)\right]}{dt_u}=a_1^{(d)}\frac{d\left[\Delta\bar{q}_1\left(t_d\right)\right]}{dt_d}+a_{0\rho}^{(d)}\frac{d\left[\Delta\bar{q}_{\rho d}\left(t_d\right)\right]}{dt_d}+a_{0p}^{(d)}\frac{d\left[\Delta\bar{q}_{pd}\left(t_d\right)\right]}{dt_d}+a_{0\rho}^{(c)}\frac{d\left[\Delta\bar{q}_{\rho c}\left(t_c\right)\right]}{dt_c}+\\
&+a_{0p}^{(c)}\frac{d\left[\Delta\bar{q}_{pc}\left(t_c\right)\right]}{dt_c}+a_{0\rho}^{(u)}\frac{d\left[\Delta\bar{q}_{\rho u}\left(t_u\right)\right]}{dt_u}+a_{0p}^{(u)}\frac{d\left[\Delta\bar{q}_{pu}\left(t_u\right)\right]}{dt_u}=b_0^{(M)}\bar{M}\left(t-\tau_d\right)-c_0^{(d)}\bar{m}_d\left(t_d\right)+\\
&+b_0^{(d)}\bar{m}_d\left(t_d-\tau_c\right)-c_0^{(c)}\bar{m}_c\left(t_c\right)+b_0^{(c)}\bar{m}_c\left(t_c-\tau_u\right)-c_0^{(u)}\bar{m}_u\left(t_u\right)+b_0^{(u)}\bar{m}_u\left(t_u-\tau_u\right)-c_0^{(u)}\bar{M}_u\left(t_u\right)
\end{aligned}, \tag{5}$$

where $a_1^{(d)}$, $a_0^{(M)}$, $a_0^{(d)}$, $a_0^{(c)}$, $a_0^{(u)}$, $a_{0\rho}^{(d)}$, $a_{0p}^{(d)}$, $a_{0\rho}^{(c)}$, $a_{0p}^{(c)}$, $a_{0\rho}^{(u)}$, $a_{0p}^{(u)}$, $b_0^{(M)}$, $b_0^{(d)}$, $b_0^{(c)}$, $b_0^{(u)}$, $c_0^{(d)}$, $c_0^{(c)}$, $c_0^{(u)}$ are variable coefficients in the function of the parameters of the working bodies, respectively, the root digging module, the root cleaning module, the root loading and unloading module, the physical and mechanical properties of the soil, the yield of root crops, etc., which are determined experimentally; τ_d, τ_c, τ_u – the time delay of the pile movement during the work process, which occurs due to the accumulation, compaction, displacement, etc. of technological masses in the working area, respectively, the root crop digging module, the root crop cleaning module, the root crop loading and unloading module.

To solve linear differential equations (2)-(5), we will use a method based on transforming a real variable function into a complex variable function. In this case, the functional transformation method allows us to replace linear differential equations with algebraic ones.

To move from a real variable function to a complex variable function, we use the direct and inverse Laplace transform, which in the general case is described by the equations [10]

$$W(s)=\int_0^\infty f(t)e^{-st}dt\,;\; f(t)=\frac{1}{2\pi j}\int_{c-i\omega}^{c+i\omega} W(s)e^{-st}ds\,, \qquad (6)$$

where $s=c+i\varepsilon$ is a complex variable, or the Laplace operator (function); c, ε are real variables of the original (function) $f(t)\le c\varepsilon^{\alpha t}$, $c>0$, $\alpha\ge 0$, $t>0$, $W_{\alpha j}(s)\to 0$, $c=\mathrm{Re}\,s\to\infty$, $s>\alpha$, $\varepsilon\in R$.

Analysis of recent research and publications. Analysis of scientific works [11-14] showed that the main attention of the authors was paid to the implementation of stationary processes of cleaning the heap from general impurities. At the same time, the processes that describe the separation of individual structural components of impurities at the theoretical level by the working bodies of each individual structural module and the root-collecting machine in general are not fully disclosed and without taking into account the technological features and operating conditions of the harvesting units.

Therefore, the choice of methodology and calculation of rational parameters of the working bodies of the structural modules of root-collecting machines must be carried out on the basis of the implementation of models that take into account the change in technological flows of the excavated heap, taking into account the separated flow of structural components of impurities [15].

Setting tasks. The aim of the work is to study the process of intensification of the separation of structural components of impurities from root crops by developing a mathematical model that describes the functional relationships of the processes of cleaning the excavated heap by the working bodies of the structural modules and the root harvesting machine as a whole.

Presentation of the main material. To solve the differential equations (2)-(5), which describe the processes of intensification of the separation of structural components of impurities from root crops, a formalized structural-functional model of the serial connection of elementary links (structural modules) of the root harvesting machine was developed (Fig. 3) and which was built according to the scheme in Fig. 2. It should be emphasized that the degree of intensification of the separation of impurities generally depends on a certain weight volume capacity and the time of the heap on the working surfaces of each structural module of the root harvesting machine [16].

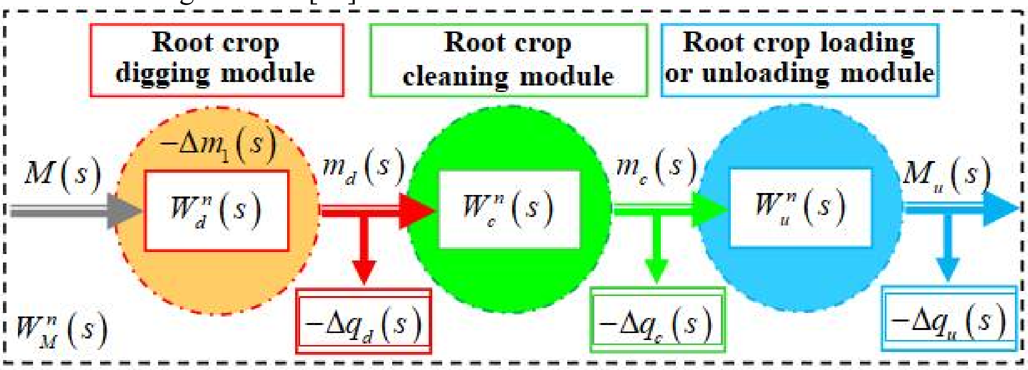

Fig. 3. **Structural-functional model of the connection of links (modules) of the root harvesting machine**

According to Fig. 3, we denote the transfer function of the serial connection of structural links (modules) of the root harvesting machine by $W_M^n(s)$ and which can be written as the product (*Д*) of analytical transfer functions $W_i^n(s)$

$$W_M^n(s) = \underset{i=1}{\overset{n}{Д}} W_i^n(s); \; W_i^n(s) = \frac{m_{out.i}(s)}{m_{in.i}(s)} = \frac{1}{T_i s + 1}, \tag{7}$$

where $m_{out.i}(s)$, $m_{in.i}(s)$ are the Laplace representations of the output and input values of the corresponding module of the root harvesting machine; T_i is the time constant corresponding to the module of the root harvester.

The time the heap is on the working surfaces of each module of the root harvester, or the time constant T_i, is defined as the ratio of the throughput P_i of the module to the corresponding amount of the processed input flow $m_{in.i}(s)$ of the heap

$$\left.\begin{aligned}
T_d &= \frac{P_d}{M(t)} = \frac{P_d}{m_1(t)+m_2(t)};\\
T_c &= \frac{P_c}{m_c(t_c)} = \frac{P_c}{m_1(t)+m_2(t)-\Delta q_1(t_d)-\Delta q_d(t_d)};\\
T_u &= \frac{P_u}{m_u(t_c)} = \frac{P_u}{m_1(t)+m_2(t)-\Delta q_1(t_d)-\Delta q_d(t_d)-\Delta q_c(t_c)};\\
T_M &= \frac{P_M}{M(t)} = \frac{\sum_{i=1}^{n} P_i}{M(t)} = \frac{P_d+P_c+P_u}{m_1(t)+m_2(t)}
\end{aligned}\right\}, \tag{8}$$

where T_d, T_c, T_u, T_M – respectively, the time of the heap on the working surfaces, or the time constant of the corresponding module of the system as a whole, s; P_d, P_c, P_u, P_M – weight capacity of the corresponding module and the system as a whole, kg.

After substituting the value of the time constant T_i from (8) into system (7), we obtain the equation of the transfer function in operator form for each module and the root-collecting machine as a whole

$$\left.\begin{aligned}
W_u^n &= \frac{m_u(s)}{m_c(s)} = \frac{1}{T_u s+1} = \left\{\left[\frac{P_u}{m_1(t)+m_2(t)-\Delta q_1(t_d)-\Delta q_d(t_d)-\Delta q_c(t_c)}\right]s+1\right\}^{-1};\\
W_M^n(s) &= \left[W_d^n(s)\right]\cdot\left[W_c^n(s)\right]\cdot\left[W_u^n(s)\right] = \left[\frac{1}{T_d s+1}\right]\cdot\left[\frac{1}{T_c s+1}\right]\cdot\left[\frac{1}{T_u s+1}\right] =\\
&= \left\{\left[\frac{P_d}{m_1(t)+m_2(t)}\right]s+1\right\}^{-1} \times \left\{\left[\frac{P_c}{m_1(t)+m_2(t)-\Delta q_1(t_d)-\Delta q_d(t_d)}\right]s+1\right\}^{-1} \times\\
&\times \left\{\left[\frac{P_u}{m_1(t)+m_2(t)-\Delta q_1(t_d)-\Delta q_d(t_d)-\Delta q_c(t_c)}\right]s+1\right\}^{-1}
\end{aligned}\right\}, \tag{9}$$

Then the differential equations of system (9), which describe the functional process of intensification of separation of impurity components from root crops by the root crop digging module, the root crop cleaning module, the root crop loading and unloading module and the root harvesting machine in general with the transport delay of the pile movement along their working bodies in the classical (time) form and according to (5), will have the form

$$\left.\begin{aligned}
&\left(\frac{P_d}{m_1(t)+m_2(t)}\right)\frac{d\left[m_d(t_d)\right]}{dt_d}=M(t-\tau_d)-m_d(t_d);\\
&\left(\frac{P_c}{m_1(t)+m_2(t)-\Delta q_1(t_d)-\Delta q_d(t_d)}\right)\frac{d\left[m_c(t_c)\right]}{dt_c}=m_d(t_d-\tau_c)-m_c(t_c);\\
&\left(\frac{P_u}{m_1(t)+m_2(t)-\Delta q_1(t_d)-\Delta q_d(t_d)-\Delta q_c(t_c)}\right)\frac{d\left[m_u(t_u)\right]}{dt_u}=m_c(t_c-\tau_u)-m_u(t_u);\\
&\left(\frac{P_d+P_c+P_u}{m_1(t)+m_2(t)}\right)\frac{d\left[M_u(t_u)\right]}{dt_u}=M(t-\tau_M)-M_u(t_u)
\end{aligned}\right\}, \quad (10)$$

Based on the identification of the root harvesting machine development process [17], a formalized structural and functional model of the process of intensification of the separation of impurity components from root crops by working bodies was constructed, Fig. 4. The formalized functional model provides for a branching node of the structural links of the root harvesting machine modules into separate elementary links of general soil and plant impurities of the heap, which in turn branch into structural sub-links, respectively: free and adhered soil, soil lumps; free plant impurities and residues of the tip on the heads of root crops. It is necessary to emphasize that the degree of intensification of the separation of impurities from root crops depends not only on a certain weight capacity of each module and the time the heap is on their working surfaces, but also on the coefficient that takes into account the degree of reduction of the output flow of the technological mass of the heap relative to its input flow.

The coefficient that takes into account the degree of reduction of the output flow of the technological mass of the heap relative to its input flow of each module and the root harvesting machine in general from the point of view of controlled dynamic systems is the amplification coefficient, which we characterize as the coefficient of technological efficiency of each module and the root harvesting machine in general and which we denote by $K_i = m_{out.i}(t)/m_{in.i}(t)$ [18].

Then the coefficient of technological efficiency of each module and the root harvesting machine in general, taking into account (1)-(3), is determined by the relation

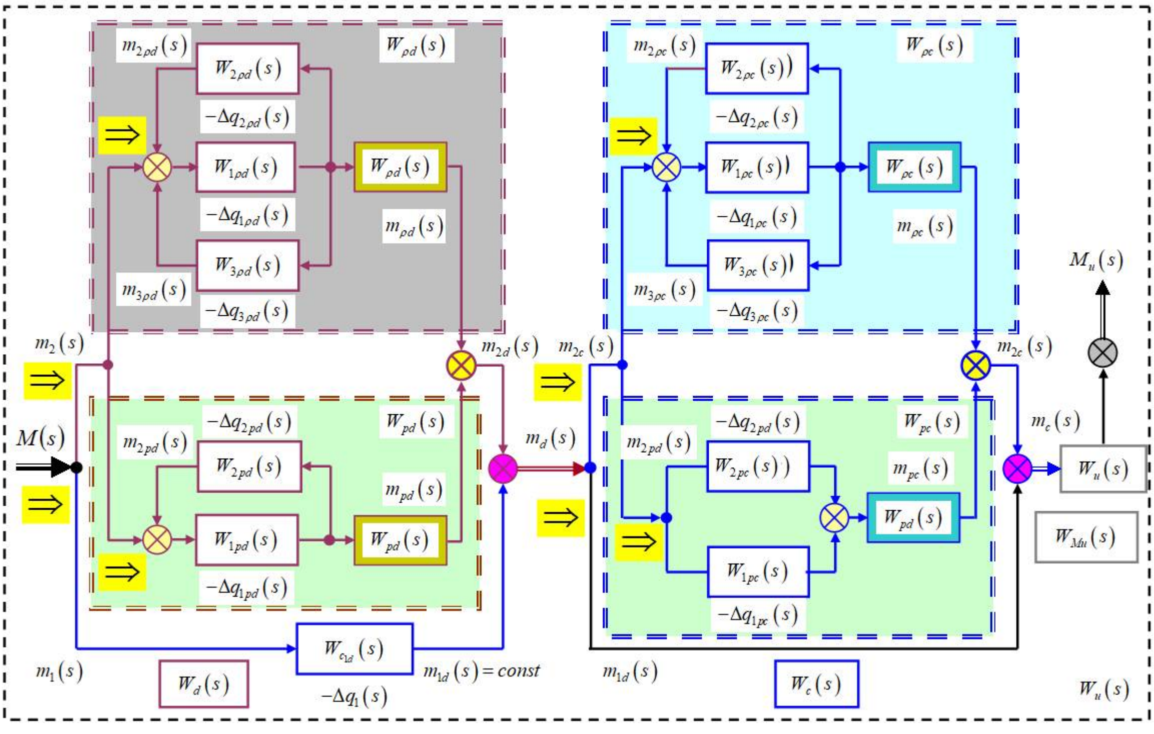

Fig. 4. **Structural and functional model of the process of intensification of the separation of impurity components from root crops by the working bodies of the root harvesting machine**

$$\left.\begin{aligned}
&K_d=\frac{m_d\left(t_d\right)}{M\left(t\right)}=\frac{M\left(t\right)-\Delta q_1\left(t_d\right)-\Delta q_d\left(t_d\right)}{M\left(t\right)}=1-\frac{\Delta q_1\left(t_d\right)+\Delta q_d\left(t_d\right)}{M\left(t\right)};\\
&K_c=\frac{m_c\left(t_c\right)}{m_d\left(t_d\right)}=\frac{m_d\left(t_d\right)-\Delta q_c\left(t_c\right)}{m_d\left(t_d\right)}=1-\frac{\Delta q_c\left(t_c\right)}{m_d\left(t_d\right)};\\
&K_u=\frac{M_u\left(t_u\right)}{m_c\left(t_c\right)}=\frac{m_c\left(t_c\right)-\Delta q_u\left(t_u\right)}{m_c\left(t_c\right)}=1-\frac{\Delta q_u\left(t_u\right)}{m_c\left(t_c\right)};\\
&K_M=\frac{M_u\left(t_u\right)}{M\left(t\right)}=\frac{M\left(t\right)-\Delta q_1\left(t_d\right)-\Delta q_d\left(t_d\right)-\Delta q_c\left(t_c\right)-\Delta q_u\left(t_u\right)}{M\left(t\right)}=\\
&=1-\frac{\Delta q_1\left(t_d\right)+\Delta q_d\left(t_d\right)+\Delta q_c\left(t_c\right)+\Delta q_u\left(t_u\right)}{M\left(t\right)}
\end{aligned}\right\}, \qquad (11)$$

In this case:

- taking into account the dynamic processes (properties) of the controlled dynamic system - the presence of moving masses, or the inertia of the process of moving the heap flows along the working bodies of the modules, their links, which branch into parallel sublimes in the direction of branching (division) $\Rightarrow,\Leftarrow$ (Fig. 4) will be represented in the form of an aperiodic link of the 1st order (inertial link), which we will denote by P;

- taking into account the presence of branching of the links, or parallel connection of structural sublimes, their transfer function $W_i^P\left(s\right)$ is determined as the sum of the transfer functions of the sublimes that form this connection;

- taking into account the presence of positive feedback (in the $W_{\rho d}\left(s\right)$ link, the $W_{1\rho d}\left(s\right)$ sublime is covered in the form of feedback by the $W_{2\rho d}\left(s\right)$ and $W_{3\rho d}\left(s\right)$ sublimes, in the $W_{pd}\left(s\right)$ link, the $W_{1pd}\left(s\right)$ sublime is covered by the $W_{2pd}\left(s\right)$ sublime, in the $W_{\rho c}\left(s\right)$ link, the $W_{1\rho c}\left(s\right)$ sublime is covered by the $W_{2pc}\left(s\right)$ and $W_{3\rho c}\left(s\right)$ sublimes), their transfer function will be represented in the form of $W_{iz}\left(s\right)$;

- taking into account the delay of the movement of technological masses in time τ_i, the transfer function in the operator form for the transformation of technological flows $m_i\left(t\right)$ of each module and the root-picking machine as a whole, which we will denote by $W_i\left(s\right)$, can be represented as the product of the analytical transfer function of the aperiodic link of the 1st order and the analytical transfer function of the link with transport delay, which we will denote by $W_{del.i}\left(s\right)=e^{-s\tau_i}$.

Accordingly, we have:

$$W_i^P\left(s\right)=\frac{m_{oup.i}}{m_{in.i}}=\frac{K_i}{T_i s+1};\ W_i\left(s\right)=\sum_{i=1}^{z}W_i^p\left(s\right),\ i=1,2,\ldots,z;\ W_{iz}\left(s\right)=\frac{W_{1i}\left(s\right)}{1+W_{1i}\left(s\right)\cdot W_{2i}\left(s\right)}; \qquad (12)$$

$$W_i\left(s\right)=\frac{m_{oup.i}}{m_{in.i}}=W_i^P\left(s\right)\cdot W_{del.i}=\frac{K_i}{T_i s+1}e^{-s\tau_i}. \qquad (13)$$

Substituting the values of the coefficient of technological efficiency of work K_i (11) and the time constant T_i (8) of each module and the root-harvesting machine as a whole and taking into account the identity (13), we obtain the equation of the transfer function $W_i\left(s\right)$ and the differential equation with transport delay in operator form:

- for the structural transport link of the root digging module

$$W_d(s)=\frac{m_d(s)}{M(s)}=\frac{W_{1\rho d}(s)\cdot W_{3\rho d}(s)}{1+W_{1\rho d}(s)\cdot\left[W_{2\rho d}(s)+1\right]}+\frac{W_{1\rho d}(s)}{1+W_{1\rho d}(s)\cdot W_{2\rho d}(s)}+W_{c_{1d}}(s)=\frac{K_d}{T_d s+1}e^{-s\tau_d}, \quad (14)$$

or

$$m_d(s)\left[\frac{P_d}{m_1(t_d)+m_1(t_d)}s+1\right]=M(s)\left[1-\frac{\Delta q_1(t_d)+\Delta q_d(t_d)}{M(t)}\right]e^{-s\tau_d}; \quad (15)$$

- for the structural transport link of the root cleaning module

$$W_c(s)=\frac{m_c(s)}{m_d(s)}=\frac{W_{1\rho c}(s)\cdot W_{3\rho c}(s)}{1+W_{1\rho c}(s)\cdot\left[W_{2\rho c}(s)+1\right]}+W_{1\rho c}(s)+W_{2\rho c}(s)+W_{d_{1d}}(s)=\frac{K_c}{T_c s+1}e^{-s\tau_c}, \quad (16)$$

or

$$m_c(s)\left[\frac{P_c}{m_1(t_d)+m_1(t_d)-\Delta q_1(t_d)-\Delta q_d(t_d)}s+1\right]=m_d(s)\left[1-\frac{\Delta q_d(t_d)+\Delta q_c(t_c)}{m_d(t_d)}\right]e^{-s\tau_c}; \quad (17)$$

- for the structural transport link of the module for loading and unloading root crops

$$W_u(s)=\frac{M_u(s)}{m_c(s)}=W_{\rho u}(s)+W_{pu}(s)+W_{c_{1d}}(s)=\frac{K_u}{T_u s+1}e^{-s\tau_u}, \quad (18)$$

or

$$M_u(s)\left[\frac{P_u}{m_1(t_d)+m_1(t_d)-\Delta q_1(t_d)-\Delta q_d(t_d)-\Delta q_c(t_c)}s+1\right]=m_c(s)\left[1-\frac{\Delta q_u(t_u)+\Delta q_d(t_d)}{m_c(t_c)}\right]e^{-s\tau_u}; \quad (19)$$

- for the root-harvesting machine as a whole

$$\begin{aligned}W_M(s)&=\frac{M_u(s)}{M(s)}=W_d(s)\cdot W_c(s)\cdot W_u(s)=\\&=\left[\frac{W_{1\rho d}(s)\cdot W_{3\rho d}(s)}{1+W_{1\rho d}(s)\cdot\left[W_{2\rho d}(s)+1\right]}+\frac{W_{1\rho d}(s)}{1+W_{1pd}(s)\cdot W_{2pd}(s)}+W_{c_{1d}}(s)\right]\times\\&\times\left[W_{\rho c}(s)+W_{pc}(s)\right]\times\left[\frac{W_{1\rho d}(s)\cdot W_{3\rho d}(s)}{1+W_{1\rho d}(s)\cdot\left[W_{2\rho d}(s)+1\right]}+W_{1pc}(s)+W_{2pc}(s)+W_{d_{1d}}(s)\right]\times\\&\times\left[W_{\rho u}(s)+W_{pu}(s)+W_{d_{1d}}(s)\right]=\frac{K_M}{T_M s+1}e^{-s\tau_M}\end{aligned}, \quad (20)$$

or

$$M_u(s)\left[\frac{P_d+P_c+P_u}{m_1(t_d)+m_1(t_d)}s+1\right]=M(s)\left[1-\frac{\Delta q_{1d}(t)+\Delta q_d(t_d)+\Delta q_c(t_c)+\Delta q_u(t_u)}{M(t)}\right]e^{-s\tau_M}; \quad (21)$$

A comprehensive assessment of the parameters of each module and the root harvesting machine as a whole, or the corresponding coefficient of technological efficiency K_i, the time constant T_i and the delay time τ_i of the flow of technological masses allows for a deeper and more detailed analysis of the technological process of intensification of the separation of impurities from the excavated heap and optimization of the structural and kinematic parameters and modes of operation of the working bodies of the root harvesting machine.

Conclusions. Increasing the technological efficiency of root harvesting machines is achieved by additional intensification of the processes of cleaning root crops from impurities through constructive development and optimization of the parameters of the working bodies of modular systems.

To implement the process of intensification of the separation of structural components of impurities from root crops, a functional-link structural model has been developed, which combines the sequence of

constructive placement of *N* working modules and the sequence of performing technological stage-by-stage *n* operations of the process of separating impurities from root crops in difficult operating conditions of root harvesting machines. A method for developing a mathematical model is proposed, which functionally describes the step-by-step process of separating structural components of impurities from root crops depending on the time of presence of the constituent components of impurities on the working bodies of each module and the root harvesting machine as a whole.

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